Can wobble board training improve balance in the elderly and diabetic population with and without peripheral neuropathy

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A Thesis submitted

for the Degree of Doctor of Philosophy

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October 2024

Thesis summary

Diabetes mellitus (DM) affects 537 million adults, and this number is expected to increase to 634 million by 2030. Long-term, exposure to diabetes can result in diabetic peripheral neuropathy (DPN), which is characterised by a progressive deterioration of the sensorimotor system. It leads to neurogenic muscle atrophy and loss of muscle strength, ultimately contributing to impaired balance and an increased risk of falling. Thus, there is a need to lower the fall risk of people with diabetes (PWD), particularly those with DPN, since fall-related injuries can significantly affect quality of life and associated treatment costs.

Therefore, a wobble board (WB) training programme was suggested, which is proven to improve balance in young adults and athletes. Three studies were conducted to investigate the effectiveness of WB training. The first study used a systematic literature review to determine the effectiveness of WB training for improving balance in healthy elderly individuals. The result of this review was a recommendation to assess WB improvement via a multi-modal assessment.

The second study investigated the effect of biological sex, anthropometrics, footwear, physical activity and DT on static balance and WB performance in healthy adults, to provide normal values for use. The findings of this study indicate that females outperform males with respect to balance. The Wilcoxon test was used to test the differences between singles and DT, as well as between with and without footwear. In both sexes, footwear and DT has a minimal influence on static balance and WB performance, except during double leg stance with eyes close (DLSEC), static balance performance was better without footwear than with footwear in both sexes, but with footwear resulted in better static balance performance and WB performance during single leg stance (SLS) in males only, with no large effect size (the large ES ≥0.9 or ≤ -0.9). Being taller, heavier or having a larger upper torso are associated with poorer static balance and WB performance.

The third study determined the effects of age, anthropometrics, severity of DPN, neuropathic pain, duration of DM, balance confidence, muscle strength and physical activity on static balance and on WB performance among PWD and individuals with DPN. Spearman's rho correlation test was used to determine the relationship between previous baseline characteristics and static balance, as well as WB performance. Overall, anthropometrics factors affect static balance and WB performance.

By benefitting from previous studies and their findings, a progressive, six-weeks WB training programme for PWD and individuals with DPN was implemented. The programme's effect on static balance, WB performance, severity of DPN, neuropathic pain, balance confidence, muscle strength and physical activity were investigated. Positive results (P-value ≤ 0.001) were achieved after six weeks in terms of improved most of the previous factors, with large effect size. It is concluded that WB training is successful in improving sensorimotor system, which is responsible for controlling balance.

بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ

In the name of Allah

Acknowledgements

The completion of this thesis has been achieved despite the challenges of collecting data during the lock downs and uncertainty surrounding the Covid-19 pandemic. Therefore, I would like to thank all those who have assisted me in realising and complete this thesis, whether in the UK or Saudi Arabia.

Firstly, I would like to especially thank my academic supervisors, Dr. Michael Jones and Dr. Jonathan Williams, for their continued support, advice and inspiration throughout my PhD journey. I deeply appreciate Dr. Jonathan Williams, who was more than a supervisor and provided me with motivation and encouragement to continue my PhD despite the difficult moments. May God reward both of them bountifully for all the good they did for me.

Secondly, I would like to thank Dr. Peter Theobald for his support previously.

Thirdly, I wish to acknowledge the School of Health and Rehabilitation Sciences, and the Department of Rehabilitation, at Princess Nourah Bint Abdulrahman University, especially Prof. Reem Alwahibi, Dr. Afrah Almuwais and Dr. Zizi Ibrahim, as well as the Saudi Arabian Cultural Bureau in the UK, for giving me the opportunity to gain a scholarship study at Cardiff University and undertake this PhD research.

Fourthly, I am grateful to the Health Sciences Research Centre at King Abdullah bin Abdulaziz University hospital in Saudi Arabia, for allowing me to collect my data at this centre and for providing me with support and equipment, especially Dr. Abdullah Alghannam, Mr. Mohanad Aljabiri, and Dr. Shaima Alothman.

Finally, I would like to thank those people behind the scenes; my family, and in particular my parents, brother, two sisters and my friends Amal Jaber and Ferdous, for encouraging and supporting me throughout the entire course of this PhD. Without them this work would not have been possible. I say Allah (God) bless you.

List of thesis publications

The original research articles published as part of this research are presented in the following articles, which can be accessed in Appendix B of this thesis:

1. Aljawaee, M. A., Jones, M. D., Theobald, P. S., & Williams, J. M. (2021). Does wobble board training improve balance in older adults? A systematic review. *Physical Therapy Reviews*, *26*(6), 447–456. https://doi.org/10.1080/10833196.2021.1987042
2. Aljawaee, M., Williams, J. M., & Jones, M. D. (2024). Informing wobble-board training and assessment through an investigation of the effect of biological-sex, anthropometrics, footwear and dual-tasking in young adults. *Journal of Back and Musculoskeletal Rehabilitation*, *37*(2), 305–315. https://doi.org/10.3233/BMR-230020
3. Aljawaee, M., Williams, J. M., & Jones, M. D. (2024). An investigation into the influence of biological-sex, anthropometrics, footwear and dual-tasking on balance. *Physiotherapy Practice and Research Journal.* 45(2),169-180. https://doi.org/10.3233/PPR-230806

Conference Presentation

The following conferences were presented as part of this research.

1. Aljawaee, M., Williams, J. M., & Jones, M. D. (2023). Improving balance; the effect of wobble board exercises on ankle muscles strength among individuals with diabetic peripheral neuropathy. Conference proceeding in World Physiotherapy Congress (WPTC) (2023), Dubai, UAE. https://wp2023.world.physio/#/programme/presentation/da7ad0c0-3ed1-4500-1346-020000000668 WP2023 (world.physio)
2. Aljawaee, M., Williams, J. M., & Jones, M. D. (2024). The effect of novel progressive WB training in static balance among diabetic peripheral neuropathy individuals. Conference proceeding in pathways for successful in physiotherapy research society conference, Bournemouth, UK.

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List of abbreviations

Abbreviation	Full name
ABC	Activities-Specific Confidence scale
ACSM	American College of Sports Medicine
ADA	American Diabetes Association
ADL	Activities of Daily Living
AGS	American Geriatrics Society
AGEs	Advanced glycation end-products
AP	Anteroposterior
APAs	Anticipatory postural adjustments
APSI	Anteroposterior Stability Index
AR	Aldose reductase
BBS	Berg Balance Scale
BESS	Balance Error Systems Test
BESTest	Balance Evaluation Scoring Systems Test
BGS	British Geriatrics Society
BMI	Body Mass Index
BoS	Base of Support
CPAs	Compensatory postural adjustments
Cm	Centimetre
CNS	Central Nervous System
CoG	Centre of Gravity
CoM	Centre of Mass
CoP	Centre of Pressure
CVA	Cerebral Vascular Accident
DFD	Diabetes-related foot disease
DLS	Double leg stance
DLSEC	Double leg stance eyes closed
DLSECN	Double leg stance eyes closed with narrow base of support
DLSECS	Double leg stance eyes closed shod
DLSECDTS	Double leg stance eyes closed dual task shod
DLSECUS	Double leg stance eyes closed unshod
DLSECDTUS	Double leg stance eyes closed dual task unshod

Abbreviation	Full name
DLSECW	Double leg stance eyes closed with wide base of support
DLSEO	Double leg stance eyes open
DLSEON	Double leg stance eyes open with narrow base of support
DLSEOS	Double leg stance eyes open shod
DLSEODTS	Double leg stance eyes open dual task shod
DLSEOUS	Double leg stance eyes open unshod
DLSEODTUS	Double leg stance eyes open dual task unshod
DLSEOW	Double leg stance eyes open with wide base of support
DM	Diabetes Mellitus
DNES	Diabetic Neuropathy Examination Score
DPN	Diabetic Peripheral Neuropathy
DSPN	Distal Symmetrical Polyneuropathy
DT	Dual Tasking
EMG	Electromyography
ES	Effect Size
FP	Force plate
FRT	Functional Reach Test
FSS	Foot sole sensation
IFD	International Diabetes Federation
% Inner Time	Percentage of time spent in A and B zones
IQR	Interquartile range
Kg	Kilogram
LADA	Latent autoimmune diabetes in adults
LAF	Large afferent fibres
Lt	Left
M	Meter
MAD	Median absolute deviation
MDC	Minimal Detectable Change
Med	Median
Mins	Minutes
ML	Mediolateral
MLSI	Mediolateral Stability Index
MNDS	Modified Neuropathy Disability Score

Abbreviation	Full name
MMT	Manual Muscle testing
MNSI	Michigan Neuropathy Screening Instrument
Ms	Milliseconds
N	Newton
NCS	Nerve Conduction Studies
NDS	Neuropathy Disability Scale
NINDS	National Institute of Neurological Disorders and Stroke
NHS	National Health Service
NICE	National Institute for Health and Care Excellence
% Outer Time	Percentage of time spent in C, D, and out zones
OVR	Occurrence variance reporting
PNS	Peripheral Nervous System
PPA	Physiological Profile Approach
PRISMA	Systematic Reviews and Meta-Analyses
PWD	People with Diabetes Mellitus
R	Spearman's rho correlation
RCT	Randomised Controlled trials
RMS	Root Mean Square
Rt	Right
RP	Correlation coefficient of Person's correlation test
ROS	Reactive oxygen species
SAFs	Sensory afferent fibres
SD	Standard Deviation
SDH	Sorbitol dehydrogenase
SLS	Single leg stance
SLSDTS	Single leg stance dual task shod
SLSDTUS	Single leg stance dual task unshod
SLSS	Single leg stance shod
SLSUS	Single leg stance unshod
SOT	Sensory organisation test
SR	Systematic Review
T0	Baseline time interval
T1	First assessment time interval after two weeks

Abbreviation	Full name
T2	Second assessment time interval after four weeks
T3	Third assessment time interval after six weeks
T4	Fourth assessment time interval after eight weeks
TCNS	Toronto Clinical Neuropathy Score
TENs	Transcutaneous Electrical Nerve Stimulation
TUG	Timed Up and Go test
UENS	Utah Early Neuropathy Scale
VAS	Visual Analogue Scale
WB	Wobble Board
WBB	Wii Balance Board
WHO	World Health Organisation

Chapter 1: Introduction

Diabetes mellitus (DM) is a chronic metabolic disease characterised by a persistently high level of blood glucose (or blood sugar) (World Health Organisation (WHO), 2023). Blood glucose concentration is physiologically regulated by the hormone insulin, which is secreted by the pancreas (Leahy, 2005). Chronic exposure to an elevated blood glucose concentration (hyperglycaemia) can result in an insensitivity to insulin (insulin resistance) or a decrease in insulin secretion (WHO, 2023). Additionally, chronic exposure to elevated glucose can result in a deterioration of blood vessels, the heart, kidneys and nerves (WHO, 2023).

There are two main types of DM:

1. Type I diabetes, also known as juvenile diabetes or insulin-dependent diabetes, which occurs when the pancreas is unable to secrete insulin (WHO, 2023).
2. Type II diabetes, that is the most common type in elderly, occurs when the body becomes resistant to insulin or unable to produce sufficient insulin (American Diabetes Association (ADA), 2021a; WHO, 2023). This type will be focused on this thesis.

There are an estimated 537 million adults between the ages of 20-79 with DM worldwide and this number is expected to rise to 634 million by 2030 and 784 million by 2045 (International Diabetes Federation (IDF) Diabetes Atlas, 2021). DM is associated with an increased rate of mortality, becoming the ninth leading cause of death in 2019, with an estimated 1.5 million deaths being attributed to DM directly (WHO, 2023). The greater rates of morbidity and mortality are, in part, due to diabetic peripheral neuropathy (DPN), a diabetes related degeneration of peripheral nerves (Wang et al., 2014), which has a higher incidence among the Saudi Arabian population, compared with the international prevalence (Wang et al., 2014). DPN is defined as the presence of symptoms and/or signs of peripheral nerve dysfunction in people with diabetes (PWD) after the exclusion of other causes (Boulton, 1998a). This peripheral nerve dysfunction is caused by hyperglycaemia (Quiroz-Aldave et al., 2023). The nerve cell (neuron) consists of 4 areas; the cell body, axon, dendrites and presynaptic terminals (Kandel et al., 2021). The axon extends from the cell body and transmits the signal to other neurons; the dendrites, are tree like shaped and are responsible for receiving signals from other neurons and presynaptic terminals (synapses), which transmit signals to other neurons, synapse refers to the specialised region of communication near an axon's ends (Kandel et al., 2021). Synaptic transmission is a "fundamental neurobiological process by which neurons interact with each other and non-neuronal cells" (Ovsepian et al., 2020, p.1). The axon is largely covered by a myelin (insulating) sheath, that is produced by glial cells called Schwann cells, which are responsible for enhancing the speed of impulse transmission along the axon (Waxman, 2024). Hyperglycaemia damages Schwan cells, leading to demyelination, a loss of myelin sheaths, in the most severe DPN cases (Quiroz-Aldave et al., 2023). The prevalence of DPN is correlated with age, middle-aged (defined as 50-60 years old) is associated with an estimated prevalence of 5.5% of unselected community-dwelling population, increasing with age to 13% over the age of 70 years (Hanewinckel et al., 2016).

Poor glycaemic control among that same population of old-aged (mean age 64 years), is significantly correlated with balance (Emam et al., 2009). This might be explained due to nerve damage caused by chronic hyperglycaemia, since balance control requires an intact nervous system to be regulated (Emam et al., 2009). A further consideration is that balance is regulated by the interaction of afferent inputs from the visual, vestibular and somatosensory systems, the central nervous system (CNS) and efferent outputs from the musculoskeletal system, as demonstrated in Figure 1 (Cook and Horak, 1986; Horak, 1987).

Poor glycaemic control in the elderly population who are above 65 years with type II DM, is suggested to contribute to an annual risk of falling of approximately 39%, which refers to thirty patients from the total of 77 who had suffered at least one fall in the last year (Tilling et al., 2006). A fall can be defined as an unexpected, unplanned and abrupt occurrence that causes someone to impact a lower-level surface or the ground (Thurman et al., 2008). An impact of the body with a firm unyielding surface, results in the rapid transference of forces to an individuals' bodily structures, which if they exceed material tolerance thresholds result in bodily injury (Masdeu et al, 1997). An ability to resist those forces associated with postural imbalance by applying a resistive force on the body requires regulation by the nervous and musculoskeletal systems to balance (Horak, 2006). Balance is defined as the ability to maintain the centre of gravity (CoG) of a body within a base of support (BoS) (Horak, 1997). In the analysis of a body subject to a gravitational force, the CoG is the point about which a body's weight is equally balanced in all directions, or the point about which the sum of the rotational forces, produced by the weight of the body segments equals zero (Egoyan and Moistsrapishvili, 2013). The BoS during standing is the area outlined by the contact points of an individual's feet with the ground (Lockhart, 2023).

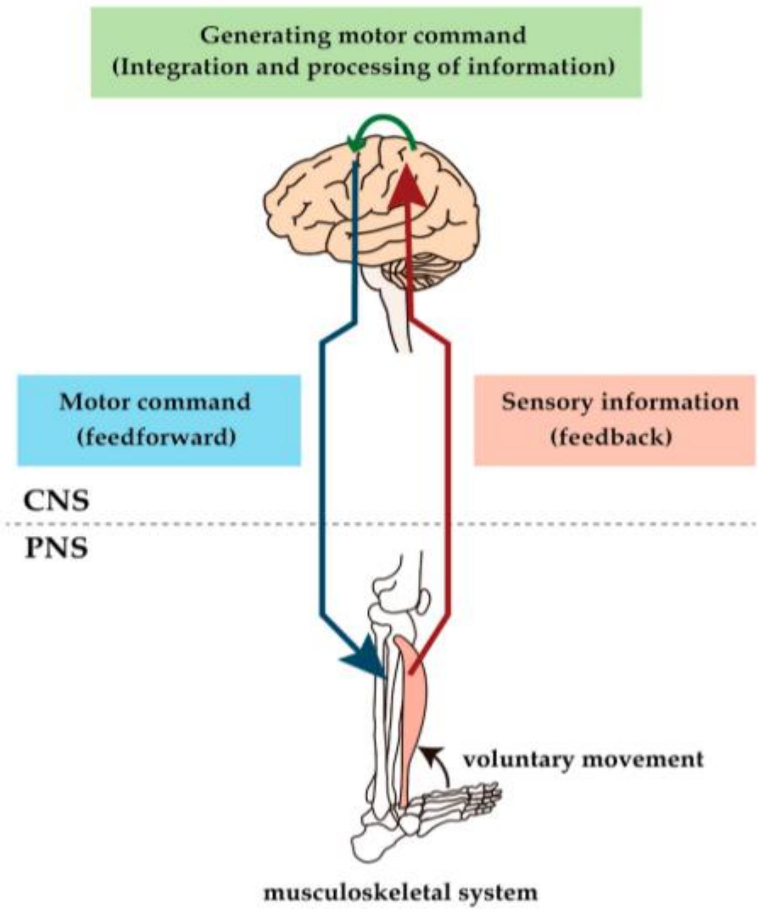


Figure 1. Sensorimotor control concept diagram. Source: adopted from Muramatsu (2020).

The interaction between the afferent and efferent systems is called the 'postural control system' (Cook and Woollacott, 2016). When performing tasks, an individual is required to control the steadiness of their body or posture in the environment; this is called 'postural control' (Cook and Woollacott, 2016). These tasks include the performance of static or dynamic control that maintains the body's CoG within its limit of stability (Burdet and Rougier, 2007). Thus, balance can be classified as static or dynamic. Static balance denotes the ability of the individual to maintain the CoG within a BoS, during a relatively static-still upright position, such as standing or sitting (Yim-Chiplis and Talbot, 2000), whereas dynamic balance denotes the same ability to maintain the balance but in non-static situations, such as the movement of both the CoG and BoS, or when the CoG is extended beyond the BoS (Woollacott and Tang, 1997).

In the human body, the CoG is situated in the pelvis (Nashner, 1997). From a biomechanical perspective, an individual's limits of stability are determined by the angles of sway (Nashner, 1997). If the angles are exceeded, the CoG is placed outside the BoS, producing a loss of balance and ultimately an increased risk of falling (Nashner, 2019).

Another definition of balance is the maintenance of the centre of mass (CoM) within BoS, "the CoM is a point that represents the average position of the body's total mass" (Mancini et al., 2020, p.1), or "the point equivalent of the total body mass in a global reference system" (GRS) which is "the weighted average of the CoM of each body segment in 3D space" (Winter, 1995a, p.3). The GRS "is the three-dimensional spatial reference system with the gravitational vector as the primary reference" (Winter, 1995a, p.3). In humans the CoM is determined by the task, for instance, during standing, it is located approximately 2 centimetre (cm) in front of the second sacral spinal vertebrae (S2); during hip flexion, it is in front of the body (Mancini et al., 2020). The CoM moves continually with respect to the BoS, even when attempting to stand still; this is called 'postural sway' (Mancini et al., 2020).

Somatosensory information from the support surface is required to maintain balance, especially during standing on a firm and stable surface (Mancini et al., 2020). Controlling the CoM over its BoS during standing requires less forces and energy, due to upright orientation of the trunk with respect to gravity (Mancini et al., 2020). This postural orientation involves arranging the body part in relation to the surrounding environment, while considering the support surface, gravity and visual cues (Mancini et al., 2020). This arrangement is necessary for accomplishing tasks effectively, interpreting sensory inputs and anticipating potential balance perturbations (Mancini et al., 2020).

Physical therapy can assist in terms of balance training, having proven effective in improving balance and reducing falls among the elderly (Sherrington et al., 2019). Similarly, a recent systematic review (SR) conducted by De Oliveira Lima et al. (2021) has produced evidence that the studies included in the present review have shown positive effects of balance training among PWD and individuals with DPN. However, this improvement is questionable given the small sample size, low quality of the evidence and short duration of follow-up according to the Cochrane Reviewers Handbook's criteria to identify risk of bias in the included studies of the SR conducted by De Oliveira Lima et al. (2021). Additionally, static balance was assessed during single leg stance (SLS) only and dynamic balance was assessed by functional balance tests only (De Oliveira Lima et al., 2021). SLS is a static timed balance test to examine the steadiness of an individual when standing on one leg during eyes open and closed condition (Goldie et al., 1992). Therefore, to obtain clarification with respect to the efficacy of balance training, there is a need to clinically assess balance and design interventions to improve balance and thereby, potentially reduce the risks of falling in PWD and individuals with DPN (Khan and Andersen, 2022).

A WB is typically a circular board positioned on a small hemisphere that allows omnidirectional tilting (Burton, 1986). Balance training, including WB training is suggested to reduce injury risk (particularly sport-related) (Hübscher et al., 2010) and improve neuromuscular function (Webster and Gribble, 2010; Emery et al., 2019). Despite a widespread application of WBs in clinical practice, sport rehabilitation and training facilities, few studies have systematically investigated the potential benefits of WB training for improving static and dynamic balance or the intra individual factors that may affect balance training. Specific to PWD and individuals with DPN, very little research has been conducted into the use of WB for mitigating the deleterious effects of DM on neuromuscular coordination related to balance. Thus, WB as a dynamic balance tool for assessment and training will be the focus of the present study, which aims to investigate the factors that affect WB assessment and training, explore the efficacy and efficiency of WB training in the elderly population by the design and implementation of a SR and a WB training programme to improve balance in PWD and individuals with DPN. Furthermore, understanding systems underlying balance is essential to understanding and developing effective balance assessment and rehabilitation (Horak, 2006). Maintaining balance is diminished by advancing age, leading to an increased tendency to falling, this is due to a deterioration in the integration of the neuromusculoskeletal system, which is a requirement for controlling balance (Kim et al., 2019). The integration of sensory information from somatosensory, visual and vestibular systems is a requirement for balance maintaining on unstable surfaces or moving from one sensory context to another and it is called the re-weighting of the sensory system (Horak, 2006). Individuals with DPN are known to have limitations in their ability to re-weight during balance tasks (Horak 2006). This limitation may result in an increased risk of falling, particularly in specific sensory contexts, such as movable surfaces (Horak, 2006). Balance impairment in individuals with DPN during exposure to movable surfaces may be due to somatosensory deficits, rather than vestibular or visual deficits (Di Nardo et al., 1999). So, when a support surface becomes unstable, individuals may shift their dependence more towards intact systems to provide the required vestibular and visual information for balance (Mancini et al., 2020). This is apparent in individuals with DPN when they are examined with sensory organization test (SOT) (Di Nardo et al., 1999), which examines the sensory factors that contribute to balance by tilting a support surface or visual surround, indicating accurate vestibular system function and that the system is not causing balance impairment in PWD (Di Nardo et al., 1999; Mancini and Horak, 2010). The SOT is available commercially by a Neurocom device to objectively quantify balance systematically (Mancini and Horak, 2010). However, there is an insufficiency of evidence in the literature regarding factors that may influence balance, especially in movable surface, such as a WB. Therefore, there is a need to understand what factors might lead to loss of balance and eventually falling, and how static balance and WB performance is affected by baseline characteristics, such as biological sex, weight, height and anthropometrics, as well as the effect of wearing footwear and dual tasking (DT). All previous factors will be discussed in the following sections.

1.1 Fall related factors

Whilst there are many reasons why an individual might fall, they can generally be subdivided into extrinsic factors, which are environmental factors and intrinsic factors, which are subject-related factors (Granacher et al., 2011a). Intrinsic factors include muscles weakness and balance impairment (Granacher et al., 2011a).

Many falls are associated with slipping and tripping mechanisms (Batterman and Batterman, 2005), which are affected by age-related sensorimotor degradation in the elderly (Granacher et al., 2011a). A slip is a potential loss of balance due to balance perturbation, which involves a loss of footing, associated with a slide of the foot or feet, large enough to be perceptible to the walker (Batterman and Batterman, 2005). Slips are often related to environmental hazards, for example, a surface contaminated by water or oil, making it slippery, (Lockhart, 2023). Trip and fall mechanism, is where one catches one's foot, such that the CoM is accelerated beyond the BoS (Lockhart, 2023). Trips are often associated with absence of toe clearance, for example an uneven floor (Merryweather et al., 2011).

During slip, trip and fall scenarios, a balance related response mechanism is initiated called the recovery phase, which requires control from the CNS to detect and prevent falling (Lockhart, 2023). If a fall is to be prevented or compensated for by a recovery phase, the CNS has to go through specific processing phases (detection and recovery phases) (Lockhart, 2023). During the detection phase, a trigger stimulus needs to be transmitted to the CNS's motor control areas, via the sensory feedback system (Lockhart et al., 2003). These triggers are termed sensory inputs and they are in form of visual, vestibular and somatosensory function, which initiate the process of integration (Winter, 2009). Somatosensory function involves neurons from the lowest to the highest level of CNS, from the reception of signals from position sense receptors, which are called proprioceptors and integration and interpretation of those signals from other sensory systems, such as visual and vestibular systems (Winter, 2009; Cook and Woollacott, 2016). Visual system function is the identification of objects and surfaces and the determination of whether they are moving or not through pathways from the retina to the visual cortex (Cook and Woollacott, 2016). The vestibular system provides essential information regarding head position in space and any sudden change in head movement (Cook and Woollacott, 2016). Any deterioration in the inputs signal's quality at this point may possibly contribute to slips and falls (Lockhart, 2023). Regarding the recovery phase, this requires a rapid re-alignment of the bodies CoM, within stable limits after the initiation of a perturbation (Lockhart, 2023). This is achieved by various alterations to the kinetic and kinematic mechanisms and the mechanisms of muscle co-contraction (Cham and Redfern, 2001). Muscle co-contraction refers to simultaneous activation of both agonist, which is the prime mover and antagonist, which is performing an opposing movement, around the desired joint (Koelewijn and Bogert, 2022). When recovering from a slip, the musculature of the lower extremities is co-contracted to decrease the slipping foot's displacement (Brady et al., 2000). However, the slower rates associated with age and DM are related to a greater risk of slip-induced falls in these individuals (Winter, 2009).

The WHO (2021), states that the elderly population, defined as those over the age 65, are at a high risk of falling. Falling is deemed to be the second largest cause of accidental injurious death in this population (Wang et al., 2014). According to the National Institute of Clinical Excellence (NICE) guidelines (2013), 30% of over 65-year-olds and 50% of over 80-year-olds typically fall once a year. Falling poses a significant risk to an individual in terms of their quality of life and confidence and to the wider community in terms of healthcare costs (NICE, 2013), since the estimated cost of treating falls in National Health Service (NHS) hospitals is over £630 million annually (NHS Improvement, 2017). Therefore, preventing falls, slips, and trips, especially among elderly individuals, is required and can be assisted by performing balance training exercises according to recommendation from the American College of Sports Medicine (ACSM) (ACSM, 2021). Thus, the next section will investigate balance assessment, factors that affect balance and balance training interventions among elderly, PWD and individuals with DPN.

1.2 Balance assessment and factors affecting it

Balance impairment is considered to be one of the most identifiable risk factors associated with falls (Frank and Patla, 2003) and in response, a few fall preventive programmes focussing on balance improvement have been developed and summarised by the American Geriatrics Society (AGS), British Geriatrics Society (BGS) and the ACSM (AGS and BGS, 2011; ACSM, 2021). One such effective approach is specific balance training, since it addresses both intrinsic risk factors of balance impairment, including addressing muscle weakness among vulnerable populations, such as the elderly, as well as extrinsic factors of balance by considering the mitigation of environmental hazards (Granacher et al., 2011a; Sherrington et al., 2019). Before exploring the balance training effect in PWD, those with DPN and the elderly, it is necessary to comprehend how to assess balance, motor theories underlie balance and the factors that can affect balance assessment, through exploring the various assessment methods currently available, as described in the below sections.

1.2.1 Balance assessment

Clinical balance can be categorised into three primary approaches (Horak, 1987). Functional, systematic and quantitative approaches (Horak, 1987). The functional balance assessments consist of either multiple motor tasks, that are rated using a three- to five-point scale, or a test of the ability to maintain balance in a certain posture, measured using a stopwatch, aiming to assess balance impairment consequences in real environment during performing certain tasks, which resemble activities of daily living (ADL), which result in multidimensional balance outcome measures (Horak, 1987). Systematic approach means to evaluate the underlying system that causes balance impairment (Horak, 1987; Dixon et al., 2017), which will be discussed in further detail in chapter two. Both clinical and functional balance assessments are used to determine whether there is a balance problem to predict risk, whereas systematic and quantitative approaches are used to identify the causes of balance impairment through determination of which system is affected and aiming to treat it (Horak, 1987). Quantitative measures for balance are divided into static and dynamic balance measures (Sandrini et al., 2018) and discussed in the below section.

1.2.1.1 Static balance

There are various objective quantitative measures for static balance (Sandrini et al., 2018), for example, SLS test, as described earlier. The abnormality of this test, such as returning a raised leg to the floor during an eyes open condition, indicated the existence of peripheral neuropathy (Ashton-Miller et al., 1996; Richardson and

Ashton-Miller, 1996; Hurvitz et al., 2001). An abnormality of the SLS test was apparent in individuals with mild to moderate DPN, when they were required to transfer weight from a bipedal, standing on both feet stance to a unipedal SLS (Richardson et al., 1996). Individuals with DPN were able to maintain a SLS test for 3 seconds, 12 % of the time, compared to matched controls who were successful 58% of the time (Richardson et al., 1996). Time spent during this test can identify not only the presence of DPN but also its severity and functional significance, such as maintaining a SLS for more than10 seconds in any of three given trails, indicates normal peripheral nerves, while individuals with functionally significant DPN fails to exceed 5 seconds in any of the given three trials (Richardson and Hurvitz, 1995). Thus, this test is considered sensitive (Richardson and Ashton-Miller, 1996). It lacks, however, objectivity; therefore, it is necessary to seek objective measures for static balance. The main objective balance measure is posturography using force platforms (Sandrini et al., 2018). Force platforms consist of complex and costly force transducers, which enable the calculation of the centre of pressure (CoP), the distribution of total forces applied to the supporting surface (Winter, 1995a), in the anteroposterior (AP) axis in the sagittal plane and mediolateral (ML) axis, in the frontal plane (Sandrini et al., 2018).

The assessment of static balance via static posturography enables the detection of small changes in postural sway and assists the identification of DPN in the elderly at risk of falling (Corriveau et al., 2000). Three pressure-sensing strain gauges located under the platform translate the forces exerted by the feet via a computer-controller in the platform; it can detect postural sway during quiet standing on a stable support surface (Uccioli et al., 1995; Visser et al., 2008). Additionally, this device is a validated and objective measure for static balance and considered as a “gold standard” for static balance assessment (Nardone, 2016; Sandrini et al., 2018). Furthermore, the platform is sensitive to variations in the control of balance in the young, middle-aged and elderly (Schieppati et al., 1994). However, caution about the position of feet and the instruction or command given to the participant must be considered (Nardone, 2016).

Additionally, static posturography produces kinetic and kinematic parameters. Kinetic parameters include information derived from CoP, shear forces; that is defined as a parallel force applied to surface, which is in this case the force plate (FP), torque; which refers to the rotational force at the joint generated by coupled forces and moment of force; which is defined as the turning effect produced by force around any certain point (Nigg and Herzog, 2007; Visser et al., 2008). Kinematics parameters include the CoG, postural compensatory strategies, and segment motion which are assessed by using motion sensors and optical motion analysis (Winter, 1995a; Visser et al., 2008). There is currently no consensus, however, regarding the most clinically relevant parameters that should be examined (Smith et al., 2019). CoP as the total forces are weighted as an average of all areas of pressure applied to the supporting surface, can be used to examine balance (Winter et al., 1990; Palmieri et al., 2002). There are two factors in determining the movement of CoP, which are CoG movement and muscle force projection, which are essential for movement production and control (Palmieri et al., 2002). Furthermore, during CoG change of movement, the CoP moves more than the CoG, to maintain the balance; therefore, CoP parameters are used frequently in research to quantify balance (Palmieri et al., 2002). Specifically, CoP was used widely by previous studies to measure static balance and perturbed standing (Paillard and Noé, 2015). The CoP average lies between the two feet when both feet are in contact with ground (Winter, 1995a). Moreover, CoP measures are valid and reliable for assessing balance in the elderly (Li et al., 2016). Finally, CoP displacement is a global static postural control measure (Granacher et al., 2011b). Therefore, due to all previous reasons, CoP was used in this present study to assess static balance.

1.2.1.2 Dynamic balance

There are various objective quantitative measures for dynamic balance (Sandrini et al., 2018), examples include stereophotogrammetric devices and wearable inertial sensors (Sandrini et al., 2018). The stereophotogrammetric devices are utilised to quantify the entire body motion via retroreflective markers detection (Sandrini et al., 2018). Wearable inertial sensors are advanced electronic technology sensors embedded in clothes or skin and are used to track functional activities, such as sensorised insoles that are used to assess plantar pressure (Sandrini et al., 2018).

Furthermore, there are clinical balance tests for assessing dynamic balance (Horak, 1987). For example, the Timed Up and Go Test (TUG), which consists of sitting on a chair, rising up, walking 3 metres, turning around, walking back and sitting down (Mathias et al., 1986) and the Berg Balance Scale (BBS), which consists of 14-item functional activities, ranging from sitting to standing, to performing postural transitions, each activity is rated from 0 to 4 points with a maximum total score of 56 (Berg and Norman, 1996), as discussed in further detail in Appendix 1, they have inter- and intra-rater reliability (Vaz et al., 2013). These same tests, in addition to the Functional Reach Test (FRT), which consist of measuring the maximum distance an individual can reach beyond the arm's length , whilst maintaining a standing BoS (Duncan et al., 1990), as discussed in Appendix 1, and the Dynamic Gait Index (DGI), which are utilised to evaluate an individual's ability to adjust their gait in response to altering task demands (Cook and Woollacott, 2016), were employed by other diabetic studies, because they are easy to administer in a clinical setting and are considered viable for measuring either static or dynamic balance (Jernigan et al., 2012).

It should be noted that the validation of previous clinical measures was based on fall risk only, and not specific sensory deficit (Dixon et al., 2017). However, the somatosensory and visual systems are challenged by some of these clinical measures, such as the BBS, as noted in Appendix 1 (Mancini and Horak, 2010). In addition, some of these measures, such as the FRT and TUG, can be considered functional performance or functional mobility measures, rather than clinical balance measures, as their purpose is to determine balance status and to track any progress in treatment (Mancini and Horak, 2010). All previous functional tests are summarised in Appendix 1, which specifies the content, advantages and disadvantages of each.

For the reasons discussed above, these functional clinical balance measures do not cover all the systems of balance, which includes the sensory system and hence may necessitate the use of other measures, such as Balance Evaluation System Tests (BESTest) (Dixon et al., 2017), as noted in Appendix 1. This clinical measure includes six balance systems: postural responses, anticipatory postural adjustment, biomechanical constraints, limits of stability, sensory orientation and dynamic stability (Dixon et al., 2017). While it is time-consuming, since it takes 30 minutes (mins), a new short version called the mini BESTest exists that takes just 10 mins to complete (Mancini and Horak, 2010) (see Appendix 1). However, as with most of the functional clinical tests discussed previously (Dixon et al., 2017), the mini BESTest lacks validity and objectivity for use among PWD and individuals with DPN (Mancini and Horak, 2010). Therefore, it is recommended that dynamic posturography, which creates external perturbations is used to quantify postural sway, when reducing visual feedback, or changing the surface, such as when using a foam cushion (Visser et al., 2008; Sandrini et al., 2018). These perturbations are created by a apparatus that consists of a dual force plate (FP), or a foam cushion connected to a computer-control that governs a movable support surface (Di Nardo et al., 1999; Sandrini et al., 2018). When using this method, the individual is intentionally exposed to controlled alterations in vision, surface, or both, to identify flaws in their adaptive mechanisms that cause a failure to select the appropriate sensory and motor responses (Sandrini et al., 2018). Dynamic posturography is considered a "gold standard" for measuring sensory and motor impairment that contributes to balance disorders (Black, 2001; Mancini and Horak, 2010). While it is not able to specify the lesion site, diagnose diseases, or reveal further details about the aetiology (Mancini and Horak, 2010), it can distinguish a variety of impairments in the balance system; for instance, it is able to differentiate balance impairment, due to proprioception and vision, from those of the inner ear (Di Nardo et al., 1999). However, dynamic posturography is expensive, time consuming and when it is utilised solely is unable to identify lesion site, diagnose the case, or provide information about aetiology (Horak, 1987; Sandrini et al., 2018).

A recent study used an objective low-cost alternative tool, called the Nintendo Wii balance board (WBB) to assess balance in the elderly with DM and individuals with DPN (Vargas Matamala et al., 2023). The study was cross-sectional, with small sample size that might limit its generalisability. Moreover, the study failed to address other factors that can affect balance in the elderly, such as osteoporosis, and to assess quantitively the small diameter afferent fibres that can be affected in individuals with DPN (Vargas Matamala et al., 2023). Therefore, there is a need to use a low-cost tool, such as WB to assess both static and dynamic balance. Therefore, this thesis was intended to use WB, as a low-cost tool, but due to Covid-19 circumstances, other device that resembles the WB function, was selected and the below section explained the selected device utilised to conduct studies in this thesis.

1.2.1.3 PROKIN (252)

The stabilometric assessment device (ProKin 252) is used for assessing both static and dynamic balance (ProKin 252, TecnoBody, 2021). The ProKin consists of four strain measuring transducers (strain gauges with a sampling frequency of 40 Hz located under a circular platform of 55 cm diameter, processed by a computer for CoP analysis (ProKin 252, TecnoBody, 2021). The Prokin (252), acts as a dynamic platform, closely resembling a WB, with additional safety measures, including surrounding parallel bars and a safety stop button to arrest an unstable board (ProKin 252, TecnoBody, 2021). Furthermore, the ProKin can provide visual feedback (ProKin 252, TecnoBody, 2021), whereas a WB cannot. A Prokin study, Jain et al. (2023), has reported a high reliability and moderate validity during static and dynamic balance assessments for incomplete spinal cord injury.

Due to the previous justification for choosing CoP as static balance parameter, two CoP parameters were selected, length path distance of CoP displacements in both the X and Y axes which is called perimeter (measured in mm) and ellipse area, which is the 90-95% of the total area covered in both axes (measured in mm^2) (Paillard and Noé, 2015). Two parameters are proposed for the quantification of the dynamic balance in Prokin (252), which are the stability index, the inclination angle of the dynamic force platform and time spent in five zones. The inner and outer zones, which was calculated in percentages, named alphabetically as A, B, C, D and outside zones (ProKin 252, TecnoBody, 2021). Time spent in A and B zones is called inner zone and time spent in zones C, D, and out of zone is called outer zone (ProKin 252, TecnoBody, 2021). The greater the time spent in the inner zone, the better the balance control, the greater the time spent in outer zone, the poorer the balance (ProKin 252, TecnoBody, 2021). These two parameters were applied to assessment of dynamic balance by utilising the same device in individuals with chronic neck pain by Saadat et al. (2018). However, the device has not been previously applied to the study of PWD and individuals with DPN for balance assessment and training. Therefore, this device was selected to be utilised for all studies conducted for this thesis. When referring to static balance and WB performance, it will indicate the Prokin (252) dual functions, as explained above. This Prokin (252) might be a new environment for an individual, therefore, it is essential to comprehend the theories underpinning how an individual masters balance in this new environment, which is discussed in the section below.

1.2.2 Motor learning theories

Learning how to balance in a new environment or to master a novel task requires cortical control facilitated reward-based learning, through the basal ganglia and error-based learning, through the cerebellum (Mancini et al., 2020). Error-based learning is a motor learning process based on learning from errors during movement, which are recognised by sensory systems to update information of motor command, for subsequent action (Seidler et al., 2010). This process is based on the forward model control theory (Miall and Wolpert, 1996; Diedrichsen et al., 2010), that is a prediction by the motor system about a subsequent action, based on current motor command (Miall and Wolpert, 1996). Sensory systems use information to change motor commands for the subsequent actions when they recognise errors in movement (Seidler et al., 2013). However, there is a time delay between the first motor command and the arrival of sensory feedback, which prevents effective motor modifications when relying just on sensory feedback (Seidler et al., 2013). Thus, another motor learning process is implemented, the reward-based learning, where successful action outcomes are rewarded, while those that lead to an unsuccessful consequence are avoided (Spampinato and Celnik, 2021). In this process individuals must “discover” which actions can result in successful outcomes, disregarding the method of execution (Spampinato and Celnik, 2021). Thus, exploring various actions that are reinforced (either repeated or avoided) depending on the result is essential to motor learning via reinforcement (Spampinato and Celnik, 2021). So, after mastering balance skills by previous motor learning processes, they become automatic, which diminishes the important role of cortical control in maintaining balance, until unanticipated change in the desired movement or posture or an alteration in the environment occurs (Mancini et al., 2020; Spampinato and Celnik, 2021). Examples of these mastering activities under balance control are walking, standing, changing postures and reacting to perturbations, while still completing a cognitive task, that is called dual tasking (DT) in healthy individuals (Mancini et al., 2020).

After exploring various balance assessment tests and devices, it is essential to investigate the effect of DT, footwear, biological sex and anthropometry on both static balance and WB performance. Therefore, the following section provides this investigation.

1.2.3 Factors that affect balance

There are various factors, such as DT, footwear, biological sex and anthropometry, which are believed to affect both static balance and WB performance. So, the below section will explore these factors.

1.2.3.1 Dual tasking (DT)

There is debate in the literature concerning the effect of DT on static balance during upright standing, with some investigators reporting that engaging in DT results in better static balance (Boisgontier et al., 2013), whilst others report no effect (Lüder et al., 2018), or even an adverse effect on balance (Yardley et al., 1999). The term "dual task cost" refers to the deterioration in balance performance while performing a cognitive task and maintaining balance (Papegaaij et al., 2017). This effect of DT seems to be more obvious in cognitively impaired older adults than non-cognitively impaired adults (Boisgontier et al., 2013). However, there is a lack of clarity in the literature about the real effect of DT on static balance assessment and WB performance separately. This has created confusion over the optimal approach for static balance assessment and rehabilitation, as well as WB performance within the contexts of research and clinical practice. So, this thesis will describe attempts to clarify this confusion by investigating the effect of DT on static balance and WB performance.

1.2.3.2 Footwear

The wearing of footwear is a further factor that has been suggested to influence static balance assessment and WB performance (Runge et al., 2000). However, there is a lack of agreement over its real effect on static balance performance during quiet standing, with some authors reporting that footwear results in better balance (Germano et al., 2012), whilst others fail to show any effect (Alghadir et al., 2018). Similarly, dynamic balance was reported to be unaffected by footwear when utilising a single axis of WB called rocker board (Zech et al., 2018) and this was supported by another study which utilised a foam rubber surface, such as a dynamic balance assessment tool (Alghadir et al., 2018). Thus, due to previous lack of agreement over the real effect of footwear on static balance and WB performance during quiet standing, this thesis will examine the effect with footwear and without footwear on static balance and WB performance.

1.2.3.3 Biological sex

A final consideration that might influence static balance and WB performance is biological sex for which, there is debate in the literature. Previous studies have suggested that balance seems to be affected by biological sex (Era et al., 2006), whilst others have suggested this may not be the case (Palazzo et al., 2021). Some differences may be due to the relative anthropometry of individuals, rather than biological sex (Maki et al., 1990; Ku et al., 2012), or through measuring different aspects of balance.

No studies, to date, have integrated measurements of static balance and WB, exploring performance and its relationship to a range of anthropometric variables, biological sex, footwear and DT. Therefore, this study will aim to explore the relationship between those previous variables during static balance assessment and WB performance.

1.3 Clinical intervention for diabetes mellitus and diabetic peripheral neuropathy

Prolonged exposure, severity and poor glycaemic control of DM and the development of DPN increasingly affect balance and increase the risk of falling, especially during ADL (Timar et al., 2016; Khan and Andersen, 2022), resulting in a sedentary lifestyle, which in turn increases the incidence of DM and thereby, increases the risk of mortality and morbidity (Quiroz-Aldave et al., 2023). Advancing age and DM, even without evidence of DPN, leads to the gradual damage of the sensory system, which plays an essential role in regulating balance (Deshpande et al., 2017). This damage is evident in visual and vestibular systems, which are contributed to underlying mechanism of balance due to hyperglycaemia (Deshpande et al., 2017). All previous systems damage might lead to diminish the remaining sensation required for the CNS to regulate balance, especially during challenging conditions, such as performing tasks with closed eyes (Deshpande et al., 2017). Therefore, balance impairment in PWD, the elderly and individuals with DPN requires concentrated effort to improve balance and thereby, to reduce falls.

Increased risk of falling was also observed in PWD because of many reasons, including compromised mechanical and metabolic muscle function, due to a reduced mitochondrial oxidative phosphorylation, which in turn reduces glucose transport and glycolytic phosphorylation (Kelley et al., 2002). Thus, in turn, leading to an increase in fatty-acid metabolism, which results in the abnormal accumulation of free fatty acids and triglycerides in skeletal muscle cells (Kelley et al., 2002). This can result in a decline in muscle strength and function among PWD, especially if they are elderly (Hewston and Deshpande, 2016). An additional explanation of motor deficit in those individuals, is an impaired peripheral nervous system (PNS) and the CNS (Muramatsu, 2020). Impaired DPN includes impaired peripheral nerves, which are responsible for controlling movements, as well as loss of large fibres responsible for sensing position, which are called proprioceptive and somatosensory feedback receptors, which contribute to motor neuropathy (Cavanagh et al. 1992). The interaction between these systems, that is, PNS and CNS is required to regulate balance, as mentioned previously (Mancini et al., 2020). This is justified by the sensorimotor system control concept, which explained by the existence of ascending pathways, that carry signal via peripheral secondary nerves to the brain to provide feedback to the muscles in the limbs, to produce voluntary movement via spinal cord through descending pathways and this is controlled by a system called pyramidal system (Hewston and Deshpande, 2016; Mustapa et al., 2016; Mancini et al., 2020; Muramatsu, 2020). However, there are involuntary movements, such as posture, which is controlled by the extrapyramidal system responsible for the indirect pathway to the spinal cord via the nucleus of the brainstem (Mancini et al., 2020; Muramatsu, 2020). Impairment of the sensory, vestibular and musculoskeletal systems of balance, increases the risk of falling in individuals with DPN (Deshpande et al., 2017). For example, muscle atrophies were observed in individuals with DPN that could be explained by the incomplete reinnervation of axonal loss (Andersen et al., 1998). This axonal degeneration and demyelination were assessed by nerve conduction and amplitude studies and shown to contribute to the underlying mechanism of those muscle atrophies (Boulton et al., 2005). Therefore, there is a need to improve balance and reduce the risks of falling in both PWD and individuals with DPN.

The SR of Ites et al. (2011) investigating the effectiveness of interventions to improve balance among individuals with DPN, despite a diagnosis of DM and the potential consequence of DPN, suggest that balance can still be improved. However, the magnitude balance change was considered small and of questionable clinical significance (de Oliveira Lima et al., 2021). The term “clinically significant” is employed in clinical research to describe outcomes or results that are relevant to clinical practice and are used to evaluate the effectiveness or efficacy of a treatment approach (Sharma, 2021). In this context, the term “clinically significant” findings refer to the results and findings that contribute to an improvement in the patient’s quality of life and lead to good function (Armijo-Olivo, 2018).

Achieving small perceived improvement might be a result of various reasons, such as the low power or quality of an included study that assessed static balance, the minimal detectable change (MDC) being small and the nature of the intervention not being in a progressive pattern. MDC refers to the smallest amount of change in score of assessment tool required to ensure that change is clinically meaningful and not due to measurement error (Stratford et al., 1996; Stokes, 2010). A progressive pattern is recommended during balance training because it is based on the dynamic systems theory (McKeon, 2009), which is related to the behaviour of the most important system in balance, the sensorimotor system (Mancini et al., 2020). The system is free to adapt, allowing self-organisation around certain tasks and environmental constraints, prior to being progressed with greater demands and a higher difficulty level (McKeon, 2009). During this approach, there is alteration in the sensorimotor system coordination, depending on the demands placed by the movement goal (McKeon, 2009). The sensorimotor system can improve a movement objective in a few ways, depending on the environmental cues it receives while completing the task, due to this spontaneous (goal-oriented) self-organisation approach (McKeon, 2009).

The efficacy of WB training, as mentioned previously, has been demonstrated for reducing injury risk (Hübscher et al., 2010), especially risk of sport-related injury and improvement of neuromuscular function (Webster and Gribble, 2010; Emery et al., 2019). Despite widespread application, only a few trials have investigated the potential benefits of WB training for improving static and dynamic balance in PWD and individuals with DPN. For example, Chaitali (2016) demonstrated improvements in dynamic balance and gait, in individuals with DPN, as measured by the TUG and 6-minute walking tests, which is a measure of the distance that an individual walks in a 6-minute period-of-time, following WB training. Akbari et al. (2012) showed improvement in dynamic balance, as measured by a stability index, which refers to deviation in any direction from the horizontal plane of a Biodex balance system device, which is utilised for measuring balance, following WB training among individuals with DPN. These demonstrated that such interventions demonstrate promise for balance rehabilitation in individuals with DPN.

WB training is a relatively novel approach that may improve not only balance but can significantly improve other abilities, such as lower limb muscle strength, proprioception and latency time, the time delay between the stimulus and muscle action (Balogun et al., 1992; Schäfer et al., 1999; Waddington and Adams, 2004; Clark and Burden, 2005). Therefore, there is the possibility that WB training could be used to enhance balance in PWD and individuals with DPN.

1.4 Purpose of the studies

The effectiveness of WB training in the elderly is still subject to debate. Thus, a SR was conducted to investigate the efficacy and effectiveness of this training among the elderly, which was the purpose of the first study. Additionally, there are many potential factors regarding WB training, which are considered likely to affect performance and need specific consideration. A review of the balance literature produced several factors (confounding factors), which are considered critical to the investigation of WB performance generally and balance improvement in PWD and individuals with DPN specifically. Thus, a second study was conducted to explore the effect of confounding factors on the performance of WB balance training, including biological sex, anthropometrics, footwear, DT and physical activity level, which were anticipated to provide insights into defining the experimental parameters for the clinical study, as explained previously. There is a gap in the literature about the effect of the confounding factors on both static balance and WB performance.

Filling this gap was the purpose of the second study. Therefore, there is a need to examine the effect of the factors above in a comprehensive manner among healthy individuals. Finally, the results from this SR and second study, assisted the author in planning the third study, which was a progressive intervention with WB training and to investigate the effectiveness of this intervention, in terms of balance and related underlying mechanisms in PWD and individuals with DPN, which was the main purpose of this present study.

1.5 Research questions

Based on the lack of consensus in the literature, the following research questions were addressed during the present study will be presented throughout this thesis.

1. Does WB training enhance balance efficiently and effectively among the elderly?
2. What are the comprehensive influences of biological sex, anthropometrics, footwear, physical activity level and DT on static balance and WB performance?
3. What is the effect of a six-week progressive WB training programme, involving PWD and individuals with DPN, on their static balance, WB performance, ankle muscle strength, balance confidence, severity of neuropathy, neuropathic pain and physical activity level?

1.6 Aims and objectives

The primary aim of this research was to investigate the effect of WB training to improve balance among PWD and individuals with DPN. To achieve this aim, the following objectives were identified:

1. The first objective was to systematically review the literature about the efficacy of WB training among the elderly. This objective was achieved through the critical appraisal and synthesis of the literature on older adults, that utilised WB training to improve balance and thereby reduce falls among that population.
2. The second objective was to obtain an understanding of the impact of biological sex, anthropometric characteristics, footwear, DT and physical activity level on both static balance and WB performance, leading to draw enhanced clinical conclusions. These, in turn, would lead to an informed understanding of the factors considered significant in their effect on WB performance and assessment

and included: biological sex, anthropometrics, footwear, DT and physical activity level, that could affect static balance assessment, WB performance and training, and thereby would lead to the optimal approach to static balance assessment, WB performance and intervention, which are essential in conducting balance assessment and training during physiotherapy session and clinical practice. Furthermore, the following hypotheses were expected to be tested:

a. Biological sex will not affect static balance assessment or WB performance.
b. Anthropometric characteristics will not affect static balance assessment or WB performance.
c. Footwear will not affect static balance assessment or WB performance.
d. DT will not affect static balance assessment or WB performance.
e. Physical activity level will not affect static balance assessment or WB performance.

3. The third objective was to develop training protocol based on previous motor learning theories and dynamic systems theory, which included six-week progressive WB training programme and investigated its effect in PWD and individuals with DPN. During this training, static balance, WB performance, ankle muscle strength, severity of neuropathy, neuropathic pain, balance confidence, and physical activity level were assessed. To be precise, assessment was taken place pre and post training and on a bi-weekly basis, except for the physical activity which was assessed only pre and post training. Each of previous parameters was identified and discussed in chapters two and three. Subsequently, during the two-week period after the end of the training, which was called the washing out period, the same parameters were assessed. This study provided an essential understanding of the real effect of WB training and the mechanism behind this effect in PWD and individuals with DPN.
4. Final objective was to understand the confounding factors that might affect static balance WB performance in PWD and individuals with DPN, which was achieved by studying the relationship between baseline characteristics, such as age, anthropometric characteristics, physical activity level, duration of DM, severity of neuropathy, neuropathic pain, balance confidence and muscle strength.

Therefore, the following hypotheses were expected to be tested:

1. Whether a six-week progressive WB training involving PWD and individuals with DPN will result in static balance improvements.
2. Whether a six-week progressive WB training involving PWD and individuals with DPN will result in WB performance enhancement.
3. Whether a six-week progressive WB training involving PWD and individuals with DPN will result in WB performance progression, relative to each participant's initial level of success. However, WB performance will deteriorate, once WB training ceases, after the 2-week washing out period.
4. Whether a six-week progressive WB training involving PWD and individuals with DPN will result in strength gain of ankle muscles.
5. Whether a six-week progressive WB training involving PWD and individuals with DPN will result in enhancement of balance confidence.
6. Whether a six-week progressive WB training involving PWD and individuals with DPN will result in a reduction in the severity of neuropathic scores.
7. Whether a six-week progressive WB training involving PWD and individuals with DPN will result in relief of neuropathic pain.
8. Whether a six-week progressive WB training involving PWD and individuals with DPN will result in improvement in physical activity level.
9. Age will not affect static balance assessment or WB performance in PWD and individuals with DPN.
10. Anthropometric characteristics will not affect static balance assessment or WB performance in PWD and individuals with DPN.
11. Physical activity level will not affect static balance assessment or WB performance in PWD and individuals with DPN.
12. Duration of DM will not affect static balance assessment or WB performance in PWD and individuals with DPN.
13. Severity of neuropathy will not affect static balance assessment or WB performance in PWD and individuals with DPN.
14. Neuropathic pain will not affect static balance assessment or WB performance in PWD and individuals with DPN.
15. Balance confidence will not affect static balance assessment or WB performance in PWD and individuals with DPN.
16. Ankle muscles strength will not affect static balance assessment or WB performance in PWD and individuals with DPN.

1.7 Thesis structure

This thesis was organised into the following chapters.

Chapter 2 was divided into three sections. The first section presented the literature review, first, were defined DM and DPN, as well as the severity, signs and symptoms of DPN were classified. It also explored the physiology of this disease, how it can influence balance and how to assess these symptoms. The second section defined balance, classified its types and postural responses, explained the internal and external factors that might affect static balance and WB performance in normal healthy individuals. Additionally, it justified how the consequences of aging affect balance and provided existing method devices available for balance assessment and training among elderly, PWD and individuals with DPN.

Chapter 3 explained the first study and divided into three sections. First section identified the methodology of the first study, which was a SR, designed to investigate the effectiveness of WB training for enhancing balance among elderly. Second section critically appraised the studies included in this SR. This critical appraisal was performed by following the Downs and Black appraisal checklist tool, which is tool used in physical therapy field to critically appraise previous studies (Downs and Black, 1998) and those scores were presented in tables. Final section discussed these findings of this SR, based on existing literature and compared to discuss whether WB training can benefit older adults by improving their balance.

Chapter 4 explored the second study, which was divided into three sections. First section outlined the methodology of this study, which was an observational study conducted among healthy adults to determine the factors, such as biological sex, anthropometrics, footwear, DT and physical activity level that can have a potential effect on static balance assessment and WB performance. Additionally, it described how the Prokin (252) device was utilised to assess dynamic balance, acting as an instrumented WB as well as static balance, acting as force plate (FP). Second section presented the results of this observational study, conducted in healthy adults. These results were displayed individually in tables that explored the effect of biological sex, anthropometrics, footwear, DT and physical activity level in both static balance and WB performance. Third section discussed these results of the second study to determine how to assess static balance and WB performance, that was, whether with or without footwear, with or without DT, as well as how biological sex, anthropometric measurements and physical activity level might or might not affect static balance assessment and WB performance. All these factors were compared to the current literature and formed a discussion.

Chapter 5 investigated the third study and divided into three sections. First section established the methodology of this study, which was an experimental study involved development and designing a six-week progressive WB training programme in PWD and individuals with DPN to improve balance and other measures and parameters, such as muscle strength, neuropathy scores, pain, and physical activity level. The second section presented the outcomes of this designated training programme and divided them into two sections, one dealt with the effect of this training and the other with the correlation of baseline characteristics with static balance and WB performance. Both sections were supported by tables and figures to demonstrate the findings of this study. The third section was divided according to the previous sections into two sections; one explored the efficacy of the six-week progressive WB training programme and the other one determined the correlations between the baseline characterises, static balance and WB performance.

Chapter 6 included in depth discussion of all previous studies and the findings of these studies were compared against relevant literature and the potential effects on the clinical practice of WB assessment and training in elderly, PWD and individuals with DPN, were considered.

Chapter 7 highlighted limitations and conclusion. It summarised all three studies, highlighted all limitations among them and drew guidelines for future studies through suggesting recommendations.

Chapter 2: Literature review

2.1 Aim and objectives

This chapter reviews the extant literature concerning diabetes mellitus (DM) and diabetic peripheral neuropathy (DPN) in three sections: (i) definitions of DM and DPN, along with their severity, signs and symptoms, including balance deficits among the target population; (ii) in depth literature about the nature of this balance deficits, including definitions of balance, the underlying systems involved in balance, balance types and postural balance related responses when standing and factors potentially affecting balance assessment and training in healthy and elderly individuals; (iii) forms of physiotherapy utilised to improve balance and prevent falls, focusing on the elderly population and individuals with DPN and DM specifically, detailing how age and DPN cause a decline in the muscles and nerves required for good balance and how balance can be assessed and trained in those individuals.

2.2 Diabetes mellitus

2.2.1 Definition of diabetes mellitus and its complications

DM is a chronic metabolic disease characterised by a high level of blood glucose (or blood sugar) that can cause a deterioration in the blood vessels, heart, kidneys and nerves (World Health Organisation (WHO), 2023). This high blood glucose level is called 'hyperglycaemia' and occurs in the context of insulin resistance and impaired insulin secretion in the body (WHO, 2023). The term 'insulin resistance' describes partial or total lack of insulin action in the tissues that respond to insulin, including adipose tissue, hepatic tissue and skeletal muscle (Lee et al., 2022a). Hepatic tissue is tissue located in the liver and is primarily responsible for glucose production from lactate, glycerol and amino acid (Chiang, 2014). Adipose tissue is the most metabolically active and largest endocrinal organ, responsible for regulating glucose and it changes according to aging, environment, lifestyle and nutritional condition (Liu et al., 2020).

There are five types of diabetes:

1. Type I diabetes: ‘juvenile diabetes’ or ‘insulin-dependent diabetes’, which occurs when the pancreas is unable to secrete insulin independently (WHO, 2023).
2. Type II diabetes: the most common type in adults and the elderly and the focus of the current thesis. Type II diabetes occurs when the body becomes resistant to insulin or unable to produce sufficient insulin (American Diabetes Association (ADA), 2021a; WHO, 2023).
3. “Specific types of diabetes due to other causes, for example, monogenic diabetes syndromes (such as neonatal diabetes and maturity-onset diabetes of the young), diseases of the exocrine pancreas (such as cystic fibrosis and pancreatitis) and drug- or chemical-induced diabetes (such as with glucocorticoid use, in the treatment of HIV/AIDS, or after organ transplantation)” (ADA, 2021a, p.15).
4. “Gestational diabetes mellitus (diabetes diagnosed in the second or third trimester of pregnancy that was not clearly overt diabetes prior to gestation)” (ADA, 2021a, p.15).
5. Latent autoimmune diabetes (LADA) is a slow progressive autoimmune DM with onset occurred at adulthood (ADA, 2021a).

DM is related to ethnicity, for example the elderly African American, Hispanic American and Native American populations have the highest prevalence (ADA, 2021b). Since type II diabetes is the focus of this thesis, the remainder of this chapter concentrates on this type.

Certain diseases and conditions are associated with type II DM. Cardiovascular disease, peripheral vascular disease and stroke are associated with a two- to four-fold higher risk among diabetics (ADA, 2021b). Additionally, type II DM can result in blindness, kidney failure and lower limb amputation (WHO, 2023). The most critical complication is ketoacidosis, which arises due to an insufficient supply of glucose to different cells, including skeletal muscle cells (Alberti and Zimmet, 1998). This creates an excess of ketones, which are the chemicals produced by the liver due to increased breakdown of fatty acids in the adipose tissues (Alberti and Zimmet, 1998). Untreated, ketoacidosis can engender coma, partial loss of consciousness, or even death (Alberti and Zimmet, 1998). The primary hormone responsible for controlling blood glucose levels is insulin (Leahy, 2005). Insulin is produced and secreted by the Pancreatic ß-cells into the blood stream and delivered the hormone to insulin responsive tissues, such as the hepatic tissue, skeletal muscle and adipose tissue (Leahy, 2005). According to Lee et al. (2022a), impaired insulin function plays a role in heightening blood glucose levels both during fasting and after meals. Further details regarding the changes associated with DM are discussed in the next section.

2.2.2 Changes associated with diabetes mellitus

The precise mechanism of how DM affects the sensory neurons remains unknown (Quiroz-Aldave et al., 2023). However, one cause of disruption to nerve function may be hyperglycemia or poor blood supply to the peripheral nerves, that affect the Schwann cells, which may be reduced in people with diabetes (PWD), reducing nerve conduction velocity (Najafi et al., 2013; Quiroz-Aldave et al., 2023). According to Ang et al. (2014), maintaining of good glycaemic control can delay the progression of DPN in PWD. DPN occurs in 30-50% of PWD and can progressively cause damage to, and the death of, peripheral sensory axons, although the cell bodies of theses neurons tend to remain relatively preserved (Quiroz-Aldave et al. (2023). This may explain why the initial symptoms appear at farthest ends of nerves, before progressing towards the centre of the cell bodies (Quiroz-Aldave et al., 2023). Moreover, DPN mainly affects the sensory and autonomic axons, then progresses to the motor axons (Quiroz-Aldave et al., 2023). A sensory axon is an axon, responsible for sensation transmission, via sensory receptors to the central nervous system (CNS), such as temperature, pain, touch and proprioception. The autonomic axon is located in the autonomic nervous system and is responsible for involuntary movements, such as, heart, respiratory rates and digestion (Kandel et al., 2021). Motor axons transfer signals from the CNS to the muscle to produce contraction and execute the desired movement (Kandel et al., 2021). The next section explores the sensory, CNS and PNS and the musculoskeletal changes associated with PWD and individuals with DPN.

2.2.2.1 Sensory changes associated with diabetes mellitus

Many systems that control balance are affected by DM, for example, the sensory system includes visual and vestibular elements that play an essential role in balance

(Deshpande et al., 2017). In the early stages of hyperglycemia, there may be changes associated with visual contrast sensitivity, which refers to the ability to distinguish differences in shading and patterns and associated with the elderly (Alghwiri and Whitney, 2020; Pramanik et al., 2020). Preceding the onset of DPN, other visual issues can manifest, including glaucoma, cataracts or diabetic retinopathy (Bonnet and Ray, 2011). Glaucoma is characterised by gradual deterioration of the optic nerve (the nerve responsible for vision) and may lead to a loss of visual field (Ling and Bell, 2018). Cataracts cause clouding of lens in the eyes, which can lead to reduce visual acuity and blindness (Thompson and Lakhani, 2015). Diabetic retinopathy can arise from chronic hyperglycaemia, which destroys the body's circulatory system (Hewston and Deshpande, 2016).

Another system that can also be affected is the vestibular system (D'Silva et al., 2016). The extant literature reported that inner ear tissues are sensitive to the metabolism of glucose and in a study of mice with diet-induced type II DM, Perez et al. (2001) found associated physiological changes in the vestibular end organ. Examples of these changes included delayed latency time (the time delay between stretching the muscle and producing of muscle action) occurring in evoked potential responses, relative to control mice (Schäfer et al., 1999; Perez et al., 2001). The mechanism of vestibular system dysfunction may be due to oxidative stress caused by hyperglycaemia (D'Silva et al., 2016). Oxidative stress characterised as a disturbance in the prooxidant-antioxidant balance in favour of the prooxidant (Sies, 1985), which may lead to potential damage (Sies and Jones, 2007). Antioxidant refers to delay or prevention of oxidative stress, due to the presence of low concentrations of certain substances, whereas prooxidant refers to promotion of oxidative stress, due to the production of reactive oxygen species (ROS) (Halliwell and Gutteridge, 2015). ROS is essential for normal physiology but excess can lead to complications, such as accelerating the aging process and cellular and nerve fibre damages (Vincent et al., 2004; Muramatsu, 2020). Additionally, oxidative stress can cause increased production of extracellular matrix and the accumulation of lysosomes and lipid in both the utricle and the saccule (Myers and Ross, 1987). Lysosomes are organelles surrounded by a membrane that contains various enzymes, which can break down carbohydrates, lipid and polymers-protein (Cooper and Kenneth, 2023). The utricle and the saccule are sensory areas located in the inner ear and responsible for the position of the head in space (Waxman, 2020). Consequently, an impairment of the diffusion of oxygen and waste products and the degeneration of hair cells is likely in the saccule, due to excessive extracellular matrix deposition (Myers, 1998). Additionally, Myers (1998) observed that the vestibulocochlear nerve in rats with DM was disrupted, manifesting as large sections of deterioration in the myelin sheath, thinning of this sheath and a smaller axonal fibre diameter.

The vestibular system plays a crucial role in both the sensory and motor systems (D'Silva et al., 2016). It provides information about head movement and position in space to the central nervous system (CNS), which is integrated by the CNS, along with information from the visual and somatosensory systems (D'Silva et al., 2016) to draw an internal map detailing the position and movement of the entire body within the environment (D'Silva et al., 2016). Inaccurate information from the vestibular system, regarding head movement, can result in dizziness and disorientation, increasing the risk of falls in elderly PWD (Hewston and Deshpande, 2016). Even in the absence of evidence of DPN, elderly PWD exhibit a gradual but noticeable, deterioration in their sensory abilities (Deshpande et al., 2017); thus, the sensory system may be affected. This may arise due to prolonged hyperglycaemia, with potential to cause gradual deterioration in the sensory nerve fibres within the somatosensory system (Hewston and Deshpande, 2016). Therefore, it is recommended that the sensation of the feet in PWD be tested using the Weinstein monofilament test (Mahieu et al., 2016), which as discussed in detail in section 2.4.1. Furthermore, DPN can affect other senses, such as vibration, touch and position perception, namely proprioception, engendering a decrease in, or absence of ankle reflexes (Cavanagh et al., 1993). Consequently, all these previous senses and ankle reflexes should be tested using a clinical testing scale, such as the Toronto Clinical Scoring Systems (TCSS) (Carmichael et al., 2021) (see section 2.4.2).

2.2.2.2 Central nervous system and peripheral nervous system changes associated with diabetes mellitus

As discussed previously, type II DM can cause deficiencies in each of three relevant sensory systems. Even if deficiencies are small, they can reduce the sensory redundancy that the central nervous system (CNS) relies on to maintain balance, particularly in challenging conditions, such as standing on a foam surface, or performing tasks with closed eyes (Deshpande et al., 2017). This is detected by a delay in central sensory conduction velocity at any stage of insulin dependent and non-insulin-dependent DM (Pozzessere et al., 1988) and can cause limitations to the cognitive processing required for difficult postural tasks, for instance maintaining balance during quiet standing (Horak, 2006). Recent cognitive impairment research has correlated Alzheimer’s disease and DM, demonstrating an impact on the neurons and glial cells of the CNS damaged by DM ultimately causing dysfunction and cell death (Muramatsu, 2020). Cognitive impairment in older individuals with type II DM can compromise balance and increase a risk of falling, strongly linking incidence of falls with cognitive impairment and this disease (Hewston and Deshpande, 2016).

2.2.2.3 Musculoskeletal system changes associated with diabetes mellitus

Regarding the musculoskeletal system, changes in muscle power, mass and quality are detected before those in muscle contractile force (Le Corre et al., 2023). Muscle quality is defined as the ability of a muscle to generate force and power, per muscle mass unit; the ability to generate muscle force or power relies on neural factors, such as synaptic transmission at the neuromuscular junction, the “junction where motor neuron meets the muscle and where impulses from the motor neuron are transmitted to the muscle”, or motor unit, which is “a set of muscles fibres that are innervated by the same motor neuron” recruitment (Nigg and Herzog, 2007, p. 54-55; Le Corre et al., 2023). In the study by Andreassen et al. (2006), this was found to be evident in the ankle dorsiflexors and plantar flexors, as they associated muscle weakness with neuropathy scores. Notably, the ankle and toe flexors can cause impairment throughout the course of the disease (Monteiro et al., 2018). It is, therefore, important weaknesses in intrinsic muscles in PWD are examined physically in the early stages of the disease, to detect any signs of foot impairment, due to neuropathy complications, to avoid ulceration and the need for amputation (Mahieu et al., 2016). Altered intrinsic foot muscle action may prove to be a significant contributory factor to balance impairment (Bus et al., 2002).

Postural change refers to an involuntary movement controlled by the extrapyramidal system responsible for the indirect pathway to the spinal cord, via the nucleus of the brainstem (Muramatsu, 2020) (see chapter one). Balance is regulated by the interaction between the PNS and the CNS (Mancini et al., 2020), both of which are affected in PWD (Muramatsu, 2020), contributing to motor deficits, especially those with type II DM (Hewston and Deshpande, 2016).

A rapid and noticeable decline in skeletal muscle mass and function is related to several clinical features in type II DM (Kelley et al., 2002). This may be due to the significant accumulation of intramuscular fat in the distal leg muscles, which can cause muscle weakness (Almurdhi et al., 2016). Previous studies have found that the muscles of PWD frequently demonstrate higher levels of intracellular fat accumulation than controls (Volpato et al., 2012). This can lead to muscle stiffness, limiting the contractile ability of the muscle, reducing muscle quality and the ability to generate force (Rahemi et al., 2015). Another possible explanation may be an impairment of the muscle protein metabolism caused by reduced insulin production in the ß cells and damaged insulin signalling transduction in PWD (Alberti and Zimmet, 1998). Insulin regulates the metabolism of amino acids and muscle proteins; therefore, impaired insulin sensitivity in skeletal muscle tissue and or a reduced circulation of insulin, may negatively influence skeletal muscle quality (Alberti and Zimmet, 1998). Additionally, insulin resistance can produce muscle wastage by causing the protein in the muscles to breakdown (Wang et al., 2006).

Mitochondria, contribute adenosine triphosphate (ATP), energy for many biological processes including skeletal muscle contraction and relaxation (Murgia et al., 2009). The most widely known functions of mitochondria in skeletal muscle are the synthesis of the metabolism of energy substrates and the production of ROS (Murgia et al., 2009; Murphy, 2009).

Furthermore, there is association between the loss of skeletal muscle mass and function in elderly PWD (Park et al., 2006; Park et al., 2007), which is referred to ‘sarcopenia’ (Park et al., 2007). Decreased skeletal muscle mass typically appears in PWD five years after the onset of type II DM (Maliszewska et al., 2019). Atrophy of the small muscles in the ankle can occur before the detection of clinical DPN symptoms (Greenman et al., 2005). Not only can type II DM affect metabolic changes in the muscles but it can also impact contractile activity (Roden, 2015). Decreased contractile activity is believed to be associated with raised intramuscular fat infiltration (Allen al., 2014a), or “myosteatosis” referring to the accumulation of fat in skeletal muscles (Wang et al., 2024).

The metabolic and mechanical deficiencies in the muscles engender inadequate muscle responses in those required for balance (Hewston and Deshpande, 2016). For example, when pulling the handle of a cord, while standing on a faceplate, there may be imbalance in the force in the body, causing a backwards lean that requires correction to restore an upright posture (Lee et al., 2018a). From a biomechanical perspective, counteracting the backwards imbalance force necessitates joint torques that cause a forward body rotation, including hip flexion, knee extension and ankle dorsiflexion (Lee et al., 2018a). Inadequate muscle responses reduce the ability to generate torques, especially in elderly PWD (Lee et al., 2018a). Ankle torque is required for ankle strategy, that is a postural control strategy know by early dorsal ankle muscle activation, followed by activation of the dorsal thigh and trunk muscles but this strategy is reduced due to the weakness of the ankle muscles, causing an increase in the AP axis in elderly PWD (Horak and Nashner, 1986; Lee et al., 2018a) (see section 2.6.2). This muscle weakness and the decreased plantar sensitivity required for a reactive balance response, created by an unexpected balance disturbance is reduced in elderly PWD, for the reasons previously discussed (Lee et al., 2018a). This section has discussed the physical changes associated with PWD before the onset of DPN. The next section explores the physical changes affecting individuals with DPN.

2.3 Diabetic peripheral neuropathy

2.3.1 Definition of diabetic peripheral neuropathy, its signs, symptoms and complications

A simple definition of DPN is “the presence of symptoms and or signs of peripheral nerve dysfunction in people with diabetes after the exclusion of other causes” (Boulton et al., 1998b, p.508). Previous studies correlated the rate of neuropathy positively with age, with individuals below the age of 50 constituting around 300 cases of DPN per 100,000 people a year and people above the age 75 constituting 32% of the total population (Feldman et al., 2019); 0.75% of PWD with a body mass index (BMI) above 25 had neuropathy (Aghili et al., 2013). A high BMI and obesity can impact PWD, slowing their metabolic status and insulin resistance and raising the prevalence of its complications (Aghili et al., 2013). However, prevalence of DPN among the middle-age population may be as high as 9.4%, as it may be vastly underdiagnosed (Hanewinckel et al., 2016). Moreover, DPN can be idiopathic, acquired, or hereditary and progression of symptoms can vary in severity, duration and form (Sommer et al., 2018; Lehmann et al., 2020). The changes associated with DPN are discussed further in the next section.

2.3.2 Changes associated with diabetic peripheral neuropathy

After exploring the changes associated with DM, the below section explores the sensory, CNS, PNS and musculoskeletal changes in individuals with DPN.

2.3.2.1 Sensory system changes associated with diabetic peripheral neuropathy

Sensory symptoms occur before physical impairment and can progress rapidly over a number of weeks or months, slowing over the course of several years (Sommer et al., 2018; Lehmann et al., 2020). Sensory symptoms can include paraesthesia and numbness, which affect the peripheries, such as the hands and feet and can progress to severe sensorimotor symptoms, extending from peripheral to proximal aspects (Hoffman et al., 2015; Sommer et al., 2018; Lehmann et al., 2020). Additionally, sensory symptoms, such as burning or stabbing sensations may become worse at night (Shakher and Stevens, 2011). The variability of symptoms of DPN is categorised in different forms, such as distal symmetric polyneuropathy, cranial neuropathy, diabetic amyotrophy, focal, sensory, autonomic and motor neuropathy (see section 2.3.3).

Additional sensory impairment, caused by disturbances in small fibres in the cutaneous tactile sensation receptors plays a significant role in maintaining balance by informing the CNS how the body's centre of mass (CoM) and centre of pressure (CoP) are moving in relation to the base of support (BoS) (Nardone et al., 2007; Li et al., 2019). Tactile sensation refers to touch sensation, triggered by cutaneous receptors in the skin (Cook and Woollacott, 2016). An additional role of the cutaneous tactile sensation receptors in the soles of the feet is that they offer continuous feedback on a terrain's surface properties (Li et al., 2019). This feedback is crucial for determining if a surface is slippery, unstable or irregular (Li et al., 2019). Therefore, loss of foot sole sensation (FSS) can be one of the earliest clinical signs of the disease and can be an independent predictor of the risk of falling in individuals with DPN, especially type II DM (Zhang and Li, 2013; Timar et al., 2016). Studies by Corriveau et al. (2000) and Lafond et al. (2004) have demonstrated the presence of a significant increase in the touch pressure sensation threshold in individuals with DPN. Furthermore, individuals with DPN may have limitations re-weighing sensory information, based on sensory context, which can cause them to become vulnerable to falls in specific sensory contexts (Horak, 2006). Sensory re-weighting refers to the ability of the sensory system to assign relevance to the intact sensory signals available, based on the usefulness of the information these cues provide (Cook and Woollacott, 2016). A consequence of this limitation would be the inability to integrate accurate and appropriate postural control information, causing balance impairment (Jyoti, 2016). Further examples may be walking blindfolded or with experimentally reduced somato-sensation, requiring acute somatosensory reweighting (Li et al., 2019). However, prolonged reweighting may be a consequence of neuroplastic changes to the CNS, caused by chronic impairment (Li et al., 2019).

Other complications that can affect balance include a reduction in, or loss of, ankle joint proprioception, which is defined as joint position sense (Laskowski et al., 2000; Li et al., 2019). However, since most types of DPN are progressive, individuals are generally able to adapt to proprioceptive impairments, due to neuroplasticity (Li et al., 2019). Neuroplasticity describes the ability of the nervous system to modify its mechanisms to enable proper function, caused by malfunction, due to neurodegenerative disease (Cook and Woollacott, 2016). This was evidenced in Bloem et al's (2002) study, which identified no differences in lower leg proprioceptive dysfunction and balance-correcting responses between individuals with DPN and healthy controls.

The ankle proprioceptor achieves balance regulation through the stretch reflex, providing information about the relationship between the large afferent fibres (LAF), the CNS, and α-motoneuron stimulation of skeletal muscle must be considered when examining balance (Li et al., 2019). Balance is controlled by a medium and long motor reflex, triggered by inputs from both proprioception and the entire loop from the spinal cord, brain stem and cortical pathways and not by input from other systems, such as the vestibular or visual system (Mirka and Black, 1990). Additionally, the stretch reflex arc is regulated by the sensory feedback, provided by muscle spindles and is classified under primary and secondary components (Li et al., 2019). Large-diameter type Iα sensory neurons are used by primary spindle fibres to transmit feedback regarding the velocity at which, muscle length changes, while smaller type II sensory neurons are used by secondary spindle fibres to transmit information concerning static muscle length (Li et al., 2019). A reflecting skeletal muscle contraction, known as the Hoffman reflex (H-reflex), triggers a reaction to the electrical stimulation of the sensory afferents that accompany the spindle (Li et al., 2019). Contrasting with the stretch reflex, the latency of the H-reflex illustrates the effectiveness of the functioning of the synaptic transmission between the afferents and α-motoneurons (Li et al., 2019). Additionally, the amplitude of the H-reflex indicates the α-motoneurons' excitation level (Li et al., 2019).

A conceptual model representing the impact of chronic DPN on the balance, suggesting the relationship between the balance and the feedback of the sensory afferent fibres (SAF) and the LAF, which is frequently impaired by DPN. For example, if an individual stands on a platform with support from both the LAF in the centre and the SAF around the perimeter but the LAF function is impaired, this will not challenge the balance system, assuming the SAF function remains normal (Li et al., 2019). This is because the primary support of the balance system comes from the SAF, which are columns in the perimeter (Li et al., 2019). Conversely, if the SAF (pillars at the perimeter) are impaired, the balance system may be compromised, although this may not be apparent clinically if the LAF (support columns in the centre of the platform) are functioning normally (Li et al., 2019). Nevertheless, the balance system may be compromised if the SAF are impaired and challenged by a perturbation (Li et al., 2019), because the LAF offer a considerably smaller base of support (Li et al., 2019).

Additionally, DPN can impair the proprioception, potentially caused by sensory ataxia (Cavanagh et al., 1993). The sensory ataxia refers to sensory nerve root disorders that impair vibration and proprioception as manifested by balance, gait disorders and loss of sensation, which are referred to as paraesthesia (Gwathmey and Pearson, 2019). Loss of, or reduced, ankle joint proprioception can affect postural control (Li et al., 2019; Reeves et al., 2021), and can be divided into passive and active control (Li et al., 2019). The term 'passive control' describes the kinematic proprieties and stiffness of the relevant anatomical structures, such as the bones and other components of the joints, as well as the force of gravity acting on them, to provide energy input and weight support (Bauby and Kuo, 2000). In contrast, 'active control' concerns how the neural system regulates skeletal muscle, requiring energy expenditure (Bauby and Kuo, 2000); active control is essential for maintaining balance during standing, because it detects sway correcting postural imbalance (Li et al., 2019). Complex interaction between the skeletal muscles, joints and both the CNS and PNS is necessary for active postural control (Li et al., 2019). All four components of the nervous system play an essential functional role in active control: stimulation collection, via sensory receptors; the transmission of afferent signalling, via sensory neurons; the control of information processing and decision-making in the CNS and the transmission of efferent signalling to the skeletal muscles, via motoneurons (Li et al., 2019).

Feedback control regulates the current movement utilising the information acquired by the sensory receptors and sent to the CNS via sensory neurons (Li et al., 2019). Therefore, a loss of sensory feedback or proprioception in the feet, especially the loss of, or reduction in ankle joint proprioception, can affect balance (Li et al., 2019; Reeves et al., 2021).

According to Horak et al. (2002) and Bonnet et al. (2009), inappropriate integration of the information available for postural control provided by the CNS is one of the causes of balance impairment in individuals with DPN. This inappropriate integration of the peripheral sensory information may explain the increased postural sway found in individuals with DPN, when they open their eyes halfway through a trial, compared with both healthy controls and the same individuals with DPN, with eyes open from the outset of a trial (Boucher et al., 1995; Bonnet et al., 2009).

2.3.2.1.1 Visual system changes associated with diabetic peripheral neuropathy

Diabetic retinopathy is a neurovascular complication of DM types I and II, which affects the retina's small blood vessels, leading to visual complications, such as reduced vision and ultimately blindness (Lopez-Galvez et al., 2014). It has a high prevalence and a strong association with duration of disease and level of glycaemic control (Solomon et al., 2017). According to, Simoneau et al. (1994) visual contrast sensitivity at higher frequencies, does not cause balance impairment, as differences in the centre of pressure excursion assessed by force plate (FP), between three groups, who were PWD, individuals without DM and with DPN were non-significant. Their findings may be explained by the small deficits in certain aspects of visual function present in the previous three groups involved in the Simoneau et al.'s (1994) study, as well as minor differences in ankle and foot mobility and reductions in ankle and foot muscle strength. However, visual impairment undoubtedly contributes to balance impairment in individuals with DPN, especially elderly with reduced contrast sensitivity, as they cannot assess balance threats, such as environmental hazards and obstacles (Lord and Dayhew, 2001; Bonnet and Ray, 2011; Mustapa et al., 2016).

2.3.2.1.2 Vestibular system changes associated with diabetic peripheral neuropathy

Vestibular impairment can cause symptoms of dizziness and disorientation, due to inaccurate head movement information that potentially increases the risk of falls in individuals with DPN, especially if they are elderly (Hewston and Deshpande, 2016; Mustapa et al., 2016). However, Horak and Hlavacka (2001) attributed changes in the postural control strategy of individuals with DPN, to an increase in the use of vestibular information, that is assumed to be intact in this population. Further explanation is based on sensory reweight theory, which suggests these individuals rely more on other intact sensory input, when a specific sensory input provides insufficient information about an environmental context (Cook and Woollacott, 2016). However, even an intact vestibular system can provide incomplete compensation for any muscular impairment observed in individuals with DPN (Bonnet et al., 2009).

2.3.2.2 Central nervous system and peripheral nervous system changes associated with diabetic peripheral neuropathy

In DPN, the PNS is affected by cellular damage to the sensory neurons, due to hyperglycemia, which activates the ROS, polyol pathway hyperactivity and advanced glycation end-products (AGEs) (Muramatsu, 2020). The polyol pathway is a metabolic pathway, that assists the conversion of glucose to fructose, however, during hyperglycaemia, increased amounts of glucose are converted to sorbitol by an enzyme called aldose reductase (AR), resulting in the accumulation of sorbitol (Brownlee, 2001). Sorbitol is metabolised to fructose by sorbitol dehydrogenase (SDH) (Brownlee, 2001). The oxidation of sorbitol increases Advanced Glycation End-products (AGEs) (Brownlee, 2001), which are produced via a series of biochemical process when proteins or lipids are non-enzymatically glycated, due to sugar exposure (Twarda-clapa et al., 2022). AGEs in turn bind with a Receptor for Advanced Glycation End-products (RAGE) that triggers inflammatory pathways, increasing in oxidative stress (Uribarri et al., 2007; Muramatsu, 2020), damaging nerve fibres and cells (Muramatsu, 2020).

Therefore, the primary source of cellular damage is thought to be the oxidative stress imbalance and inflammation in cells, caused by a variety of factors (Pop-Busui et al., 2017). Evidence from neuroimaging studies has shown that central sensorimotor regions have been damaged in individuals with DPN, in a process concurrent with but separate from, peripheral microvascular complications (Ferris et al., 2020). For example, Eaton et al. (2001) found there were structural alterations in the spinal cord of individuals with DPN, which is crucial for producing and transmitting motor commands. However, this was a pilot study with a small sample size and limited generalisability. There remains a need for further research to investigate the progression of microvascular complications in both PNS and CNS, since it is unclear which of these systems are affected first.

Neurological impairment may limit cognitive processing, causing the engagement of more of the available cognitive processing to control balance (Horak, 2006). According to Horak (2006), these impairments cause functional loss, including the inability to perform activity of daily living (ADL), such as to dress independently, to ascend stairs or to walk normally. However, importantly, disabilities do not always cause functional loss, depending on the type of disability and the compensatory mechanisms and strategies employed, as some individuals with a given impairment, function better than others (Horak, 2006).

Therefore, deficiencies in each of three relevant sensory systems, even when small, can reduce the sensory redundancy that the CNS relies on to maintain balance, particularly in challenging conditions, such as standing on a foam surface, or performing tasks with the eyes closed (Deshpande et al., 2017). For example, Pozzessere et al. (1988), reported a delay in the central sensory conduction velocity at any stage of insulin dependent and non-insulin-dependent DM. This can limit the cognitive processing that may be required when performing difficult postural tasks, such as maintaining the balance during quiet standing, as discussed previously (Horak, 2006). Cognitive impairments may affect the balance negatively, because to maintain balance, the brain provides commands to the muscles in the limbs that play an essential role (Mustapa et al., 2016). As discussed previously, recent cognitive impairment research correlated Alzheimer's disease and DM, demonstrating an impact on the neurons and glial cells of the CNS damaged by DM, which may ultimately cause dysfunction and cell death (Muramatsu, 2020). Moreover, as noted previously, cognitive impairment in elderly PWD may compromise their balance, causing an increased risk of falling, given the strong evidence for both the relationship between falls and cognitive impairment and this disease (Hewston and Deshpande, 2016; Mustapa et al., 2016).

2.3.2.3 Musculoskeletal system changes associated with diabetic peripheral neuropathy

Significant skeletal muscle deficits can be caused by DPN, such as neurogenic muscle atrophy, loss of muscle strength and power and reduced ability to generate force (Andersen et al., 1997; Bus et al., 2002; Andersen et al., 2004; Greenman et al., 2005; Andreassen et al., 2006). These limitations increase as the diabetes worsens, becoming significantly worse when DPN commences (Le Corre et al., 2023); notably, ankle and toe flexors can be impaired throughout the course of the disease (Monteiro et al., 2018). According to Andreassen et al. (2006), this was also evident in the ankle dorsiflexors and plantar flexors, as muscle weakness was associated with neuropathy scores. It can be a particular issue in elderly individuals with DPN, who have significant differences in the muscle strength of their ankle plantar flexors, compared with the healthy (aged matched) elderly population (Corriveau et al., 2000). Both muscle atrophy and loss of strength were found to be greater distally in the leg, rather than proximally (Andersen et al., 1997; Andersen et al., 2004). Muscle atrophy may be due to incomplete reinnervation of axonal loss among individuals with DPN (Andersen et al., 1998). According to Boulton et al.

(2005), the underlying mechanism of this muscle atrophy is the axonal degeneration and demyelination, evident in the reduction in nerve conduction and amplitude, as demonstrated in electrophysiology studies. Consequently, an additional effect of DPN on the skeletal muscle is the rapid loss of motor axons (Allen et al., 2014a; Allen et al., 2014b; Hansen and Ballantyne, 1977). This loss was reported in various ankle muscles, such as the intrinsic foot muscles (Hansen and Ballantyne, 1977) and dorsiflexors (Allen et al., 2015; Allen et al., 2014b). Loss of motor axons was more evident in individuals with DPN than in age-matched healthy controls (Allen et al., 2014b). Moreover, individuals with DPN seemed to experience greater motor unit loss than PWD without neuropathy (Hansen and Ballantyne, 1977). Furthermore, an inability to produce ankle torque, due to the decline of the lower-extremity muscles in the elderly with DPN, may cause increased postural sway in the AP axis, because ankle muscle strength is an important determinant for COP movement in the AP direction (Lee et al., 2018a).

Late in the course of the disease, small intrinsic muscles in the hands and feet begin to deteriorate, due to denervation that can cause weakness and deformity (Cavanagh et al., 1993). Furthermore, reduced muscle spindle function in the lower limbs can be associated with DPN, engendering balance control (Deursen and Simoneau, 1999). For example, if the tibalias anterior muscle is affected in individuals with DPN, this will cause rapid involuntary foot drop, engendering reduced shock absorption of the foot during the initial phase of gait in the heel strike (Kutty and Majida, 2013). Consequently, abnormal gait is evident in individuals with DPN, due to intrinsic foot muscle dysfunction (Andersen, 2012), which may increase the risk of tripping, falling and compromised balance, during ADL (Timar et al., 2016).

Furthermore, mechanical and metabolic muscle function can be affected, due to the dependency on oxidative phosphorylation for energy production in PWD (Kelley et al., 2002), which reduces phosphorylation and glucose transport and increases fatty-acid metabolism, potentially causing an abnormal accumulation of free fatty acids and triglycerides in the skeletal muscle cells (Kelley et al., 2002). This can cause a decline in muscle strength and function among PWD, especially the elderly (Hewston and Deshpande, 2016). Furthermore, interaction between glucose-protein or glucose-lipid via glycation causes the production of AGEs (Shamsi et al., 2019), which can affect the vascular smoothness of the muscle cells and damage tissue (Lee et al., 2022b). Additionally, metabolic muscle function impairment is correlated with reduced muscle mitochondrial response to insulin, because of insulin resistance (Lowell and Shulman, 2005). All of these impairments can cause a significant decline in overall muscle strength and function in the elderly with type II diabetes (Hewston and Deshpande, 2016), especially metabolic changes and blood flow associated with DPN, which can enhance fatigability (Parasoglou et al., 2017). This decline in muscle performance can include dorsiflexor muscle fatigue (Orlando et al., 2017), indicated by a shorter time to task failure (Parasoglou et al., 2017), which can cause a decrease in muscular endurance in individuals with DPN that is greater than in PWD without neuropathy (Allen et al., 2015). Examples of functional declines that may appear in DPN are difficulty in executing ADL, such as ascending and descending stairs, the use of assistive walking aids and an increased risk of falls (Callaghan et al., 2015; Hoffman et al., 2015), as well as difficulty in performing ADL that require static and dynamic balance (Richardson and Ashton-Miller, 1996).

The different forms of DPN are discussed in the next section.

2.3.3 Different forms of diabetic peripheral neuropathy

According to the American Diabetes Association (ADA), DPN can be classified under two main types: (1) diffuse symmetric (distal symmetric polyneuropathy and autonomic); (2) mononeuropathy (mononeuropathy, multiple mononeuropathies, drop foot, Charcot joint and radiculopathy) (Pop-Busui et al., 2017; ADA, 2024a). Additional forms of neuropathies were classified by the ADA (2024b), such as cranial neuropathy, diabetic amyotrophy, focal neuropathy, autonomic neuropathy, sensory neuropathy and motor neuropathy. These categories are discussed in further detail below.

2.3.3.1 Distal symmetric polyneuropathy (DSPN)

This type of DPN can occur in both type I and type II DM. While it may not exhibit noticeable symptoms for an extended period of time, during a clinical examination the most obvious manifestation is symmetrical sensory loss in the feet (Kasznicki, 2014). Additionally, polyneuropathy can be defined as a disorder that causes damage to sensory, motor, and/or autonomic peripheral nerves, over time (Sommer et al., 2018). This abnormal muscle sensory function can cause balance impairment and impaired gait (Deursen et al., 1998). Painful DPN occurs in around 12.5% to 39.3% of cases and is often left undiagnosed and untreated (Daousi et al., 2004). Individuals with this type of DPN commonly describe pain subjectively as a deep ache, burning, tingling, or a prickling sensation (Apfel et al., 2001). Furthermore, there may be a loss of protective sensation, tingling and numbness, indicating that large fibre involvement may be present in DSPN (Pop-Busui et al., 2017). Protective sensation refers to the ability to feel and respond to harmful stimuli, such as pressure or temperature changes (Volmer-Thole and Lobmann, 2016). This absence of protective feeling may lead to diabetic foot ulcers (Pop-Busui et al., 2017).

The associated pain is often symmetrical, distal and can be worse at night (Apfel et al., 2001). The term ‘distal’ means that it affects the hands and lower extremities, especially feet, causing the condition to be called “stocking and glove distribution” (Feldman et al., 2019).

2.3.3.2 Mononeuropathies and radiculopathy

Mononeuropathy can develop when a nerve become compressed (Dyck, 1997; Collins, 2014). This neuropathy is more prevalent in people with DM than in general individuals (ADA, 2024b). It appears that there are two forms of nerve injury (ADA, 2024b). In the first, nerves become compressed where they have to cross a lump of bone or squeeze through a narrow tunnel (ADA, 2024b). PWD are more vulnerable to compression nerve injury, called compression mononeuropathy (Dyck, 1997; Collins, 2014). For example, carpal tunnel syndrome is a common form of neuropathy among PWD and refers to median nerve compression and can cause hand or finger numbness (Dyck, 1997; Yavuz, 2022). This type of neuropathy is associated with an increased risk of entrapment syndromes (Yavuz, 2022). Therefore, entrapment at certain point, such as beneath the carpal ligament occurs in median nerve compression cases (Dyck, 1997). The second form of injury that occurs, is when diabetes-related blood vessel disease limits blood flow to a specific area of the nerve (ADA, 2024b), with symptoms depending on which nerve is affected (Collins, 2014). When pain is reported in the lower back, front of the thigh, foot, abdomen or chest (Dyck, 1997), it is called thoracic/lumbar radiculopathy and one or both sides of the chest or abdominal wall may be affected (Dyck, 1997; ADA, 2024b). Pain due to carpal tunnel syndrome can be relieved by allowing the affected arm to hang at the side (ADA, 2024b). However, in severe cases, surgery can provide total pain relief (ADA, 2024b).

Neuropathies can manifest and be observed in various regions of the body, such as the elbow (ulnar neuropathy), wrist (median neuropathy) and fibular head (peroneal neuropathy) (Dyck, 1997). When neuropathies occur in the upper extremities, they are more likely to be mononeuropathies or multiple mononeuropathies than polyneuropathies (Collins, 2014).

The most common compression nerve in the lower limb is the peroneal neuropathy (Thatte and De Jesus, 2024). When the peroneal nerve is compressed or vascular disease damage the leg's peroneal nerve, this might lead to foot drop (inability to raise the foot) (ADA, 2024b), which left untreated can cause degeneration in the bones and joints and may lead to the severe deformity, called Charcot's joint destruction (Edmonds, 1999). Therefore, early diagnosis of this condition is crucial, to prevent deformity and avoid falling by receiving rehabilitation sessions, which include splints, braces, nerve stimulation and therapeutic exercises (National Institute of Neurological Disorders and Stroke, (NINDS), 2024; Thatte and De Jesus, 2024).

2.3.3.3 Cranial neuropathy

The 12 pairs of nerves related to the brain and regulate taste, hearing, sight and eye movement are impacted by cranial neuropathy (ADA, 2024b). The neuropathy first manifests as pain on one side of the face, close to an affected eye (ADA, 2024b). The eye muscle can become subsequently paralysed, that consequently may lead to double vision (ADA, 2024b). Within two to three months, the symptoms of this type of neuropathy typically improve or disappear (ADA, 2024b).

2.3.3.4 Diabetic amyotrophy

Diabetic amyotrophy primarily impairs the nerves in the hips, thighs, buttocks or legs, causing difficulty during standing, walking, or when ascending stairs (Yavuz, 2022). This condition is also known as 'proximal neuropathy' or 'femoral neuropathy' and is commonly observed in individuals with type II DM, especially the elderly (Boulton et al., 2005). Its main signs and symptoms are progressive, acute, muscular weakness and pain in the proximal lower extremities (Pasnoor et al., 2013). It can consequently engender disability with various degrees of recovery possible (Nagsayi et al., 2010). Symptoms typically manifest on one side of the body, causing severe pain in the hip, thigh, or buttock, along with muscle weakness and atrophy in the hip, abdominal swelling and weight loss (Boulton et al., 2005). Corticosteroid doses can be prescribed for pain relief in some cases (Pasnoor et al., 2013).

2.3.3.5 Focal neuropathy

Focal neuropathy impairs the nerves in the facial region or central portion of the body (Yavuz, 2022). A single nerve or group of nerves can be affected (ADA, 2024b), resulting in sudden pain or weakness (ADA, 2024b). It can also result in double vision, Bell's palsy, a facial paralysis on one side and other areas of the body (ADA, 2024b).

2.3.3.6 Sensory neuropathy

Sensory neuropathy is considered one of the most debilitating forms of nerve dysfunction (Gwathmey and Pearson, 2019). Signs and symptoms initially manifest in the distal part of the extremities, then gradually progresses in a proximal pattern in the form of stocking-glove distribution (Bowker and Pfeifer, 2007). Progression causes a diminished ability to perceive light touch and proprioception, consequently causing ataxic gait and balance impairment, as well as weakness in the intrinsic muscles of the feet (Bowker and Pfeifer, 2007). Ataxic gait refers to a specific walking pattern, characterised by deviation from a straight-line gait path with a wide base of support, resembling stumbling (Morton and Bastian, 2009). Additionally, the stocking-glove distribution specifically degrades leg and foot proprioception, engendering a preference for hip strategy, instead of ankle strategy for balance recovery (Cavanagh et al., 1992). Hip strategy involves the activation of the trunk and thigh muscles, radiating in a proximal-to-distal pattern to other muscle groups (Morasso, 2022) and will be discussed in further detail in section 2.6.2. However, up to 50% of the DPN population may be unaware of this peripheral nerve dysfunction, because it is asymptomatic (Pop-Busui et al., 2017). Failure to address symptoms can engender serious complications, such as foot ulceration and possibly lower limb amputation (ADA, 2021b). Notably, sensory neuropathy itself may not cause direct ulceration and limb loss because it progresses chronically. Therefore, early diagnosis and intervention can help prevent future complications (Boulton, 1998a).

2.3.3.7 Autonomic neuropathy

This form arises when the nerves responsible for regulating involuntary bodily functions are damaged, usually 20 years after developing the disease (Yavuz, 2022). It impairs the autonomic neurons of either one or both of the parasympathetic and sympathetic nervous systems (Pop-Busui et al., 2017). Initially, skin break and sweating abnormalities of the feet can indicate autonomic neuropathy, which is often associated with somatic polyneuropathy (Mayhfield et al., 1998). A sensitive indicator of the skin is called ‘plantar callus’ (hyperkeratosis), meaning thickening of tissue under weight-bearing areas due to repetitive high pressure, characterised by hard yellow plaques (Booth and McInnes, 1997; Boulton, 2022). Further foot complications of autonomic neuropathy are increased cutaneous blood flow, increased skin temperature and dilation of the dorsal veins in the foot (Edmonds et al., 1982; Corbin et al., 1987).

2.3.3.8 Motor neuropathy

Motor neuropathy occurs when the nerves responsible for controlling movement are impaired (Bowker and Pfeifer, 2007). It causes muscle weakness and the nerves affected fail to transmit signals properly, engendering imbalance between the flexor and extensor muscles (Bowker and Pfeifer, 2007). These signals are called ‘somatic feedback receptors’ (Cavanagh et al., 1992). This imbalance can cause foot deformities, such as clawing of the toes, characterised by proximal interphalangeal joint flexion along with metatarsophalangeal joint hyperextension (Myerson and Shereff, 1989; Bowker and Pfeifer, 2007), ultimately engendering abnormal distribution of plantar pressure, due to diminished subcutaneous tissue thickness at the metatarsal heads and the displacement of the sub-metatarsal fat pads anteriorly (Bowker and Pfeifer, 2007). A further effect of the loss of somatic feedback from the receptors in the legs and feet, associated with muscular weakness from this type of neuropathy, can cause abnormal posture and gait in PWD (Cavanagh et al., 1992).

This motor nerve dysfunction manifests as a loss of contractile tissue and fat infiltration in individuals with DPN (Andersen, 2012). This neuromuscular control is vital for balance control and delay of this control, as well as the loss of peripheral foot sensation, causing balance impairment in individuals with DPN (Reeves et al., 2021).

The above sections discussed DM, definition, types, changes associated with this disease and DPN various forms. The following sections explore how symptoms associated with this disease can be diagnosed and assessed. For example, pressure foot sensation, neuropathy severity, pain, muscle strength and physical activity level assessment and diagnosis.

2.4 Assessment and diagnosis of foot sensation, diabetic peripheral neuropathy severity, pain, muscle strength, and physical activity level in people with diabetes mellitus and those with diabetic peripheral neuropathy

2.4.1 Assessment and diagnosis of foot sensation

Foot sensory response to pressure, termed light sensation is currently assessed with a Semmes-Weinstein monofilament (10 gram) applied to four sites of the plantar surface of the foot, which are the metatarsal base and head for the big toe, metatarsals base of third and fifth toes (see Figure 13 in chapter five) (Singh et al., 2005). The nylon filament is pressed perpendicular to the skin until it buckles, forming the letter ‘C’, for one second (Singh et al., 2005). An inability to perceive 10g of force of this monofilament, applied to four sites of the foot, is associated with clinically significant large-fibre neuropathy (Armstrong, 2000; Perkins et al., 2001).

2.4.2 Assessment and diagnosis of diabetic peripheral neuropathy severity

Nerve conduction studies (NCS) are considered the “gold standard” for clinical diagnosis of DPN and are conducted by a trained neurophysiologist (Carmichael et al., 2021). However, due to the expensive and time-consuming nature of this diagnostic method, the following alternative clinical diagnosis scales are suggested for assessing neuropathy and its severity (Carmichael et al., 2021):

- Michigan Neuropathy Screening Instrument (MNSI) (Ahmad et al., 2020). Offers an accurate and comprehensive assessment test for DPN severity but has low sensitivity to mild DPN cases, which are unlikely to be detected (Perkins et al., 2001; Carmichael et al., 2021);

- Toronto Clinical Neuropathy Score (TCNS) (Carmichael et al., 2021);
- Utah Early Neuropathy Scale (UENS) (Singleton et al., 2008);
- Diabetic Neuropathy Examination Score (DNES) (Carmichael et al., 2021);
- Neuropathy Disability Score (NDS) (Carmichael et al., 2021).

Current ADA (2024a) guidelines insist upon assessment of the DPN for type II DM at diagnosis, 5 years after type I DM and at least once annually after that. This assessment should be comprehensive and consists of temperature and pinprick sensation testing, to assess small fibre function, vibration sensation with a tuning fork of 128 Hertz, to assess the large fibre function, as well as the 10-g monofilament testing, annually (ADA, 2024a). Therefore, the Toronto Clinical Neuropathy Score (TCNS) was used here, due to its comprehensiveness, its validity and reliability when used in clinical practice and clinical research trials and its ability to classify the severity of DPN (Bril and Perkins, 2002; Bril et al., 2009). Thus, TCNS is preferred choice over other neuropathy scales for both clinical practice and research because of its comprehensive approach, ease of use, reliability, sensitivity to disease progression, and focus on diabetic neuropathy only (Bril and Perkins, 2002; Bril et al., 2009). Validity has many types but key are: content validity, which refers to the degree of comprehensiveness a test to cover a specific area of interest, construct validity indicating the ability of the test to assess what aims to assess and criterion validity, which means the statistical correlation between a certain test and other tests (Parrott, 1991; Gallagher and Yalch, 2023). Due to both the content and criterion validity against sural nerve fibre density for DPN, it is recommended the TCNS be used in the early diagnosis of DPN (Perkins et al., 2001; Bril and Perkins, 2002). Its construct validity is proven for assessing and classifying DPN severity, compared with nerve conduction (Bril and Perkins, 2002). As noted previously, although NCS are the gold standard, they are expensive, requiring specialist examiners and equipment (Tesfaye et al., 2010; Carmichael et al., 2021). Therefore, NCS are inappropriate as screening tests (Carmichael et al., 2021). The TCNS was, therefore, employed for the purpose of the present study, due its ease of application, its high degree of patient acceptance and its ability to assess and classify the severity of DPN with clinical changes across the progression phases of DPN (Bril and Perkins, 2002). The TCNS is scored out of a maximum of 19, as follows: 0-5 (no DPN); 6-8 (mild DPN); 9-11 (moderate DPN); and ≥ 12 (severe DPN) (Ahmad et al., 2020).

2.4.3 Assessment and diagnosis of pain

Increased pain threshold and reduced pain sensation can cause skin breakdown, engendering Charcot's joint destruction (ADA, 2021b), foot ulcers and lower limb amputation (Pop-Busui et al., 2017). Pain in PWD is commonly assessed, via the visual analogue scale (VAS) questionnaire, or the McGill questionnaire, both of which are commonly used globally as a multi-dimensional pain scale (Carmichael et al., 2021). The McGill pain questionnaire was created by the pioneer Melzack (1975), to provide a comprehensive evaluation of pain, encompassing the severity or intensity, emotional effect and significance of the pain to participants. Later, the VAS questionnaire was designed, as self-reported measure of pain intensity (Downie et al., 1978). It was validated and widely used, because it is simple and easy to complete (Downie et al., 1978) and moderate to good test-retest reliability (Krabbe, 2017). Thus, this questionnaire was chosen for the purpose of the present study. Each participant was asked to mark his/her perceived level of pain on a 10-cm VAS, where 0 indicated 'no pain' and 10 'unbearable pain' (see Figure 12 in chapter five). The mechanism of pain in PWD is explained via a process known as 'central sensitisation', which refers to an increased influx of nociceptors, where they enter the spinal cord, alleviating synaptic transmission (Quiroz-Aldave et al., 2023). An additional mechanism that may enhance the synaptic signalling in the spinal cord are brain-derived neurotrophic factors (BDNF) that are released by the microglia, aggravating mechanical pain-related hypersensitivity, refer to enhanced reaction due to a normal painful stimulus (Jensen and Finnerup, 2014; Salter and Beggs, 2014; Quiroz-Aldave et al., 2023). Neurotrophic factors are proteins produced by nervous system cells, which are responsible for protecting, promoting and enhancing neuron function, growth and survival (Puglielli et al., 2022). Microglia are types of cells in the CNS, which play an essential role in shaping activity in healthy individuals and responding to injury in case of disease or infection (Salter and Beggs, 2014). There is a need to reduce pain in PWD and DPN using electrotherapy and foot massage (Akbari et al., 2020). Additionally, some types of exercise are recommended, due to their ability to induce hypoalgesia, which means reduced pain sensitivity, although further studies are required to investigate the effect of exercise for improving the magnitude of exercise-induced hypoalgesia, across different populations and especially among the elderly, with long-term follow up, to assess duration of effects (Song et al., 2023). Therefore, the present study, conducted for this thesis, designed an exercise programme intended not only to improve balance but also to relieve pain. Pain was assessed via the VAS, to determine whether the exercise training was able to alleviate pain in PWD and individuals with DPN.

Pain relief medications recommended for neuropathic pain, include Duloxetine, Amitriptyline, Pregabalin, Gabapentin and opioid analgesia (National Institute for Health and Clinical Excellence (NICE), 2010).

Furthermore, DPN can affect the senses, such as vibration, touch and position perception, causing a decrease in, or absence of, ankle reflexes (Cavanagh et al., 1993). It can also impair proprioception, engendering sensory ataxia (Cavanagh et al., 1993). Late in the course of the disease, the small intrinsic muscles in the hands and feet begin to deteriorate, due to denervation, which can consequently cause weakness and deformity (Cavanagh et al., 1993).

2.4.4 Assessment and diagnosis of muscle strength

According to Beld et al. (2006), muscle strength should be tested using a reliable device such as handheld dynamometer. The digital handheld dynamometer (MicroFET®2, Hoggan Health Industries) equipped with different headings that can be used with various muscle sizes (see Figure 14, in Chapter 5). The interrater reliability has been previously established in older adults ($ICC_{3,1}$ = 0.78–0.94) (Spink et. al 2010). Strength of the ankle dorsiflexors in various individuals, mainly those with hemiparesis secondary to cerebral vascular accident (CVA), demonstrates a high interrater reliability when using a hand-held dynamometer (Bohannon and Andrews, 1987) and previous DPN studies used a hand-held dynamometer to measure muscle strength (Simoneau et al., 1994; Corriveau et al., 2000; Kruse et al., 2010). Normative values were obtainable for ankle dorsiflexors and ankle plantar flexors in all ages (Andrews et al., 1996; Bohannon, 1997; McKay et al., 2017), but no normative values for ankle invertors or evertors (Morin et al., 2022). Therefore, this device was selected for study three in this thesis.

2.4.5 Assessment and diagnosis of physical activity level

According to Baecke et al. (1982), physical activity should be assessed using a questionnaire, to assess an individual's habitual physical activity. Since the Baecke questionnaire is a simple tool, consisting of three indices concerning (1) work, (2) sport and (3) leisure time, it was selected for use here. The items on this questionnaire were scored on a scale from one (minimum) to five (maximum) (Baecke et al., 1982). It is valid and reliable for use with adults with a medium to high level of education (Tebar et al., 2022), whilst also being short, friendly-use and simple to complete, thereby, reducing the burden on participants. The Arabic version used in this study was the same as that employed by Gillani et al. (2018). Finally, this questionnaire was applied among Saudi population and has resulted in a strong inverse correlation between level of physical activity assessed via this questionnaire and type II DM (Gillani et al. 2018). Therefore, this questionnaire was selected for studies two and three in this thesis.

In summary, the above sections defined the types of DM and DPN and explored the different assessment methods used to assess the signs and symptoms associated with PWD and DPN, to select those most appropriate for use in the context of this study.

2.5 Falling in people with diabetes mellitus and those with diabetic peripheral neuropathy, especially the elderly

The factors discussed above, such as impairments to sensation and proprioception, muscle deficits, shifts in movement strategy and disorientation, can cause balance impairments in individuals with DPN (Ahmad et al., 2017; Reeves et al., 2021). Therefore, PWD and individuals with DPN are at a greater risk of slipping, tripping and falling than other individuals (Jyoti, 2016), with an annual incidence rate of 39% from total of 77 elderly over 65 years of age with type II DM (Tilling et al., 2006). Falling represents the second most frequent cause of accidental fatal injuries among individuals aged 65 years old and above (Wang et al., 2020). Approximately 30% of these individuals experience at least one annual fall; this percentage rises to 50% for those aged over 80 (NICE, 2013).

Furthermore, age and the duration of living with DM are predisposing factors for acquiring neuropathy; more than 50% of individuals with type II DM are aged over 60 years (Young et al., 1993). Long duration of diabetic foot disease (DFD), such as the previously mentioned conditions of callus formation and claw toes, due to DM, can cause a decrease in the muscle functions of the feet, ankles and knees; delays in lower extremity muscle reflex responses and an inability to balance during walking, all of which can consequently increase the risk of falling (Reeves et al., 2021). Indeed, Seo et al. (2023) found that more fallers than non-fallers reported having experienced DFD for more than one year. Furthermore, the severity of DPN, individual's age and presence of symptoms of depression can be key, as such factors can be independent predictors of risk of falling in individuals with DPN (type II DM) (Timar et al., 2016). Reduced cognitive function, orthostatic hypotension and hypoglycaemic episodes can be additional factors that increase risk of falls in individuals with DPN (Khan and Andersen, 2022). There are two types of cutaneous sensation in the sole of the foot, superficial sensation and deep sensation (Waxman, 2020), loss of either sensation impair balance, increasing the risk of falling, especially in elderly individuals with DPN (Menz et al., 2004). Cutaneous sensation includes touch, pain and temperature and deep sensation involves vibration sense, muscle sense, proprioception and deep muscle pain (Waxman, 2020). Any alteration in external environment (touch, vibration and hearing) or internal environment (muscle length or joint position sense) caused by mechanical stimuli are detected by specialised cells called mechanoreceptors (French and Torkkeli, 2009). There are different types of mechanoreceptors, such as Ruffini endings of joints, skin, muscle spindles and Golgi tendon organs, which are sensory organs containing nerve fibres located throughout the vertebrae and near the muscle-tendon junction, that typically react to sustained deformation and are sensitive to contraction produced by the muscles (Nigg and Herzog, 2007; French and Torkkeli, 2009). Examples of theses receptors are Meissner and Pacinian corpuscles within the skin, which are responsible for reactions to stimuli that change quickly, including vibrations or the skin moving over uneven surfaces (French and Torkkeli, 2009).

Moreover, obesity, associated with a body mass index (BMI) >30 and presence of one or more co-morbidity is considered to be a risk factor for falling (Van Schie, 2008). Falling can occur during static positioning, where the BoS remains stable, such as quiet standing, or dynamic positioning, where the BoS is moving, such as walking, due to the disturbance of the afferent and efferent receptors (Kutty and Majida, 2013; Ahmad et al., 2017), especially if the individual is elderly (Maurer et al., 2005).

In their study, Nardone and Schieppati (2004) demonstrated that there is a correlation between postural sway and nerve conduction velocity in PWD, especially those with DPN. A significant relationship was found between postural instability and the involvement of the SAF, because postural control especially during standing requires intact tactile sensory feedback, particularly that related to touch and pressure, as sensed by Merkel’s cells and Ruffini endings and then transmitted via smaller diameter type II neurons (Nardone et al., 2000; Nardone et al., 2006; Nardone et al., 2007). This disturbance of the mechanoreceptors is due to decreased sensitivity in the sole of the feet, causing balance impairment in the elderly and PWD (Santos et al., 2008), increasing the risk of falling, limiting the functional ability and reducing the quality of life for individuals with DPN (Van Schie, 2008). Surprisingly, individuals with DPN have the capacity to develop good balance during dynamic tasks, such as on unstable platforms, as they can learn to adopt anticipatory postural strategies (Nardone et al., 2006), based on past experience or sensory feedback, the later varying according to the severity of the DPN and the individual’s history of DM (Toosizadeh et al., 2015; Cook and Woollacott, 2016). Surprisingly, in the study by Horak et al. (2002), the control group, when standing on any sway-referenced surface, swayed significantly more than the group of individuals with DPN, when standing on firm surface, indicating that sway-referencing disrupts somatosensory information, compared with the disruption caused by severe DPN. A sway-referenced surface is a method used in balance studies, to assess the somatosensory system response, where the support surface is rotating the toes up and down in a servo-controlled mechanism, in relation to specific sway-related variable and in a way that the somatosensory system fails to predict the movement because it was provided by inaccurate information (Horak et al., 2002).

This balance impairment is more evident when there is an absence or degrading of visual or vestibular cues in individuals with DPN than in the same-aged-matched PWD without DPN and in control populations of healthy individuals without DM, during quiet standing (Simoneau et al., 1994). The elderly, who prioritise vision for controlling balance, because they depend on exteroceptive information (Hatzitaki et al., 2009) exhibit greater stability than young adults during eyes-closed task (Benjuya et al., 2004). This is because they have adopted alternative strategies, such as increasing muscle co-contraction between the soleus and tibialis anterior muscles, unlike young adults, who rely solely on their receipt of richer sensory information (cutaneous and proprioceptive) during increased sway, to replace other sensory inputs (Benjuya et al., 2004). Muscle co-contraction, as explained previously in chapter one, refers to simultaneous activation of both agonist and antagonist (Koelewijn and Bogert, 2022).

Weakness in the lower limbs can be a strong predictor of falls in PWD, as well as in the elderly (Vincent and Joseph, 2017; Chatzistergos et al., 2020). Therefore, there is a demand to return the body to the equilibrium by employing specific movement strategies, such as ankle and hip strategies (Horak, 1987; McIlroy and Maki, 1996). The ankle strategy is reduced by aging (Horak et al., 1989) and by the presence of DPN (Jyoti, 2016), resulting in shifting from an ankle to a hip-based strategy in the elderly and in individuals with DPN (Inglin and Woollacott, 1988; Jyoti, 2016).

There is, therefore, similarity in the causes of postural control instability in both the elderly and individuals with DPN, all of which contribute to an increased risk of falling in these populations. Hence, there is a need to assess the risk of falls when initiating an exercise intervention in these individuals (Hansen et al., 2013), since exercise programmes can enhance the risk of fall-related incidents in older individuals and those with DM (Pafili and Papanas, 2022). Since there is currently a scarcity of relevant studies and significant variation between those studies that do exist, this should be noted when analysing findings (Chapman et al., 2017). Nevertheless, due to the increased prevalence of DM among the elderly, exercise interventions may offer promising strategies for enhancing falls-related outcomes (Chapman et al., 2017).

Falls are a key reason why the elderly >65 years visit emergency departments (Samaras et al., 2010). Being elderly and diabetic with DPN can raise the incidence of falls when standing and walking by up to 15 times, compared with the same-aged-matched population without neuropathy (Cavanagh et al., 1992). Furthermore, greater postural instability is reported among elderly individuals with DPN during quiet standing, when measured according to both COP and COM than among healthy age-matched individuals (Corriveau et al., 2000). Thus, DPN in the elderly plays a significant role in the falls experienced by these individuals (Maurer et al., 2005). This raises the cost of treating DM, which is already at $23.7 billion, annually, for the treatment and management of DM in the United Kingdom (International Diabetes Federation (IDF) Diabetes Atlas, 2021). There is, therefore, a demand to reduce falling among PWD and those with DPN, as this will be beneficial for both the individuals concerned and for the wider society. One effective physical intervention for improving balance and reducing the risk of falls among PWD and individuals with DPN is balance training (Ahmad et al., 2017) (see section 2.6.10). Before exploring balance assessment and training effect in PWD, those with DPN and the elderly, it is necessary to understand the multiple systems that underlie postural control for effective balance assessment and rehabilitation for balance disorders (Horak, 2006), as detailed in the next section.

2.6 Balance

2.6.1 Definition of postural control and the systems responsible for balance

An understanding of the systems that underlie postural control is crucial for developing effective balance assessment and rehabilitation (Horak, 2006), therefore, Table 1, which presents the three systems required for postural control, namely the sensory system, the CNS, and the musculoskeletal system (Winter et al., 1990).

Table 1. The systems essential for postural control and the underlying structures and their functions (Source: adapted from Winter et al., 1990, p.31).

Name of the system	Underlying systems and structures, which regulate postural control system	Function related to postural control regulation
Sensory system	• Vestibular system; • Visual system; • Proprioceptive system, which includes muscle, joint, and cutaneous receptors.	• Recognition of body orientation; • Recognition of environment and body orientation and movement; • Recognition of sense of joint movement and environment.
Central nervous system	Afferent receptors.	Plan an appropriate response based on inputs received by afferent receptors.
Musculoskeletal system	• Spatio-temporal muscle activation; • Muscle synergies.	Execution of the planned response, in terms of controlled movement and posture.

Postural control has two main functions: postural orientation and postural equilibrium (Horak, 2006). Postural orientation is derived from the vestibular, visual and somatosensory systems, whereas postural equilibrium is derived from the sensorimotor system that stabilises the CoM, using strategies, during both static and dynamic balance (Horak, 2006). An understanding of the physiological systems that underlie task performances, such as sit-to-stand and walking safely in the environment is essential for comprehending postural control (Horak, 2006). There are six essential resources for postural control, which are discussed in the below section and shown in Figure 2, which reveals why elderly people are more likely to fall (Horak, 2006).

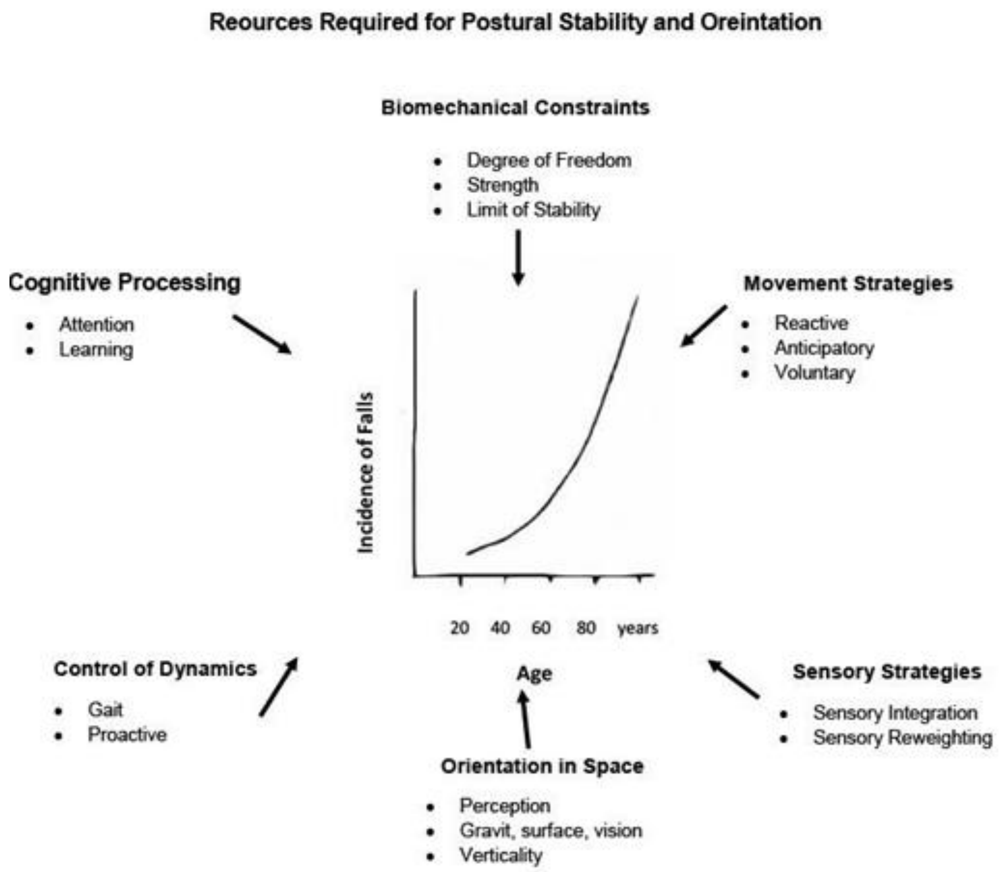


Figure 2. Essential resources for postural control, derived from Horak, 2006, p.ii8.

2.6.2 Movement strategies

Three movement strategies are essential for postural control, two of which require a foot to remain in contact with the floor, whereas the third changes the BoS, via stepping or reaching (Horak, 2006). The first strategy called the 'ankle strategy', as shown in Figure 3, and includes activation of the ankle muscles, followed by the activation of the thigh and trunk muscles in a distal to proximal pattern (Morasso, 2022). This strategy is required for whole-body movement as a single-segment inverted pendulum, to reposition the CoP by exerting torque at the ankle (Nashner and McCollum, 1985). This strategy is evident, on a firm surface, when CoP movement is small and at low velocity (Palmieri et al., 2002; Cook and Woollacott, 2016). A single inverted pendulum model was introduced by Winter et al. (1995) that differentiates between the CoP and the CoG. This differentiation was explained by Hof (2006), who investigated that the CoG exerts this force by gravity on the human body and the point of this exertion is called CoP. The human body in this model is represented as a stick, which is placed on the floor, at the CoP and its mass is the CoM, that when the body moves to the right (Rt), once the CoM reaches the CoP's Rt and vice versa (Winter, 1995; Hof, 2007). This is evident when maintaining balance during an unperturbed upright standing position, this model was applied by adjusting the CoP movement through muscle action to keep the CoM within the limit of stability (Hof, 2007).

Biomechanically, the ankle strategy is utilised during an unperturbed upright standing position, which is typically characterised as a pure rotation of the body around the ankle joint, with minimal motion occurring at the higher joints (Nashner and McCollum, 1985), as shown in Figure 3. This allows the body to function as a single-segment inverted pendulum, controlled by ankle joint torque (Morasso, 2022). In healthy individuals, when standing on a stable and rigid surface, the default method employed is the ankle strategy (Morasso, 2022). This strategy relies on the foot's ability to apply torque on the supporting surface, to maintain balance (Morasso, 2022). However, the effectiveness of this strategy can reduce when there is a narrow base of support or a non-rigid supporting surface (Morasso, 2022). In situations that involve a narrow base of support, the range of motion of the CoP of the ground reaction force is limited, such that during single leg stance (SLS) on moveable surface, such as wobble board (WB) (Hof, 2007; Silva et al., 2016). A WB, as mentioned previously in chapter one, is typically a circular board positioned on a small hemisphere that allows omnidirectional tilting (Burton, 1986). Range of motion is crucial for enabling the ankle torque to counteract dynamically the toppling torque generated by gravity, which is influenced by the position of the CoM in the standing position (Morasso, 2022). This mechanism is called the counter-rotation mechanism, where free segments are able to move around the CoM, such as arm, trunk or the free leg during SLS (Silva et al., 2016).

Figure 3. Ankle strategy derived from Horak et al. 1989, p.729.

The second strategy is called the ‘hip strategy’, as shown in Figure 4 (a). It consists mainly of the activation of the trunk and thigh muscles, radiating in a proximal-to-distal pattern to other muscle groups (Morasso, 2022). Specifically, this strategy involves the forward and downward rotation of the upper body, producing a backward rotation of the lower body (Runge et al., 1999). This implies whole-body movement in the form of a double-segment pendulum, necessitating use of the hips and producing counter-phase motion at both the hip and ankle (Cook and Woollacott, 2016). This pendulum is extended to include the hip joint (Park et al., 2004) and in the presence of the biomechanical constraint of the ground reaction torque, there is an increase in hip gains, which refers to increase in the amount of hip joint torque and decrease in ankle gains, in a linear pattern with perturbation magnitude (Park et al., 2004). This strategy appears as a response to larger and quicker perturbations in the presence of a compliant surface or a narrow BoS, to restore the CoM within the BoS (Horak and Nashner, 1986; Horak, 2006). Furthermore, restoration of the CoM can be accompanied by head movement in the opposite direction, to compromise postural orientation in space (Mancini et al., 2020). This strategy is often adopted by the elderly and by individuals with DPN (Inglin and Woollacott, 1988; Jyoti, 2016).

The final strategy is called the ‘stepping strategy’, as shown in Figure 4 (b). It is used when both of the previous strategies, namely the ankle and hip strategies, are insufficient (Horak and Nashner, 1986) and is utilised to maintain balance during gait, or when maintaining the feet in position is not required (Horak, 2006). This strategy occurs in the presence of exposure to a very quick or large perturbation that can be balanced by placing the BoS under a new CoG using rapid steps, hops, or stumbles (Horak and Nashner, 1986). This strategy will not be considered during the present study, and is outside the main focus of this thesis, which is static balance and WB performance for assessment and training.

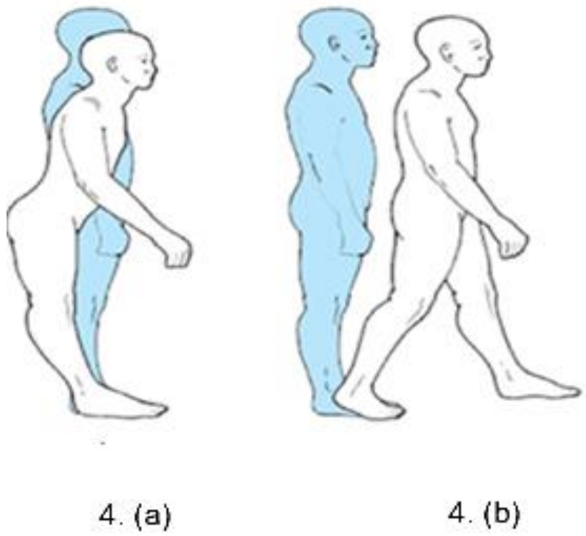


Figure 4. Hip and Stepping strategy derived from Horak et al. 1989, p.729. (a). Hip strategy and (b). Stepping strategy

However, before undertaking voluntary limb movements, the postural muscles in the trunk and leg are activated to provide balance by compensating for the destabilising forces associated with moving a limb; this is called ‘anticipatory postural adjustments’ (APAs) or ‘proactive balance’, the function of which is to elicit postural control by restoring the CoP before the onset of the voluntary muscles that precede the perturbation, to minimise the disturbance to the balance (Lee et al., 2018b). Postural muscles refer to the skeletal muscles that contain slow-switch muscle fibres, which play a significant role in maintaining posture through postural tone and do not easily fatigue (Paassen and Gramsbergen, 2005). Similarly, Behm et al. (2013) suggest training on an unstable surface is considered as a low intensity contraction, which may lead to activate the slow twitch, type I fibres.

In the elderly, APAs differ from those in young adults, in terms of the muscle recruitment patterns involved, as the utilisation of the hip strategy is preferred in response to postural disturbance, as explained previously (Inglin and Woollacott, 1988; Bleuse et al., 2006). The reactive balance control is called 'compensatory postural adjustments' (CPAs), the function of which is to elicit postural control by restoring the CoM, via compensatory postural adjustment, after a perturbation has already occurred (Maki and McIlroy, 1996); they are detected by peripheral sensory feedback signals (Horak et al., 1996; Park et al., 2004). Moreover, CPAs are not evident immediately after the perturbation but instead when measured at the tibialis anterior, taking 73–110 milliseconds (ms) to be apparent during backward sway perturbations, and from 74 to 102 ms during forward sway perturbations, when measured at the gastrocnemius (Horak and Nashner, 1986). This latency onset is delayed in the elderly, with shorter recruitment of postural muscles before, or after activation of the prime movers (Kanekar and Aruin, 2014).

2.6.3 Sensory strategies

Interpretation of complex sensory environments requires integration of sensory information from the somatosensory, visual and vestibular systems (Horak, 2006). This is known as the re-weighting of sensory information and is crucial for maintaining balance, especially when moving from one sensory context to another. For example, when an individual moves from a well-lit area to a dimly lit one, since it necessitates the integration of various sensory inputs to maintain the balance in this changing environment (Horak, 2006). Another example is when individuals stand on an unstable surface, there is a notable increase in the sensory weighting that is reliant on vestibular and visual information, while the reliance on surface somatosensory inputs for postural orientation is reduced (Peterka, 2002). Thus, individuals with DPN, who have somatosensory loss, are limited in their ability to re-weight sensation during balance tasks (Horak, 2006). This limitation increases fall risk, particularly in specific sensory contexts (Horak, 2006).

2.6.4 Biomechanical constraints

One type of postural control constraint is biomechanical constraint, which concerns the magnitude and quality of the BoS, namely the feet (Horak, 2006). The magnitude of the BoS is a determining factor in balance (Horak, 2006). A narrowing of the base of support causes greater postural sway in the elderly than in young adults (Nagy et al., 2007). It is easier to widen the area of the support base than to narrow it, because with widening base of support the distance from the CoG to the edge of the base is reduced, producing improved balance (Alonso et al., 2012).

Limitations in both the range of motion, muscle strength, and sensory input is also a determinant factor of balance (Horak, 2006). Maintaining balance is regulated by the CNS, depicted by a cone, as shown in Figure 5 (Horak, 2006), which illustrates normal and abnormal stability limits, via the correlation of age and the size of the cone; the older the person, the poorer their balance (Horak, 2006). The difference in postural sway between the children and the elderly is apparent (Hytönen et al., 1993). Postural control ability is described as a dynamic process that changes according to lifestyle (Granacher et al., 2011a). The correlation between postural sway as a measure of static balance and age, can be represented by a U-shaped dependency (see Figure 6) (Hytönen et al., 1993). While other factors can affect balance, there is lack of agreement over which, as discussed in section 2.6.8.

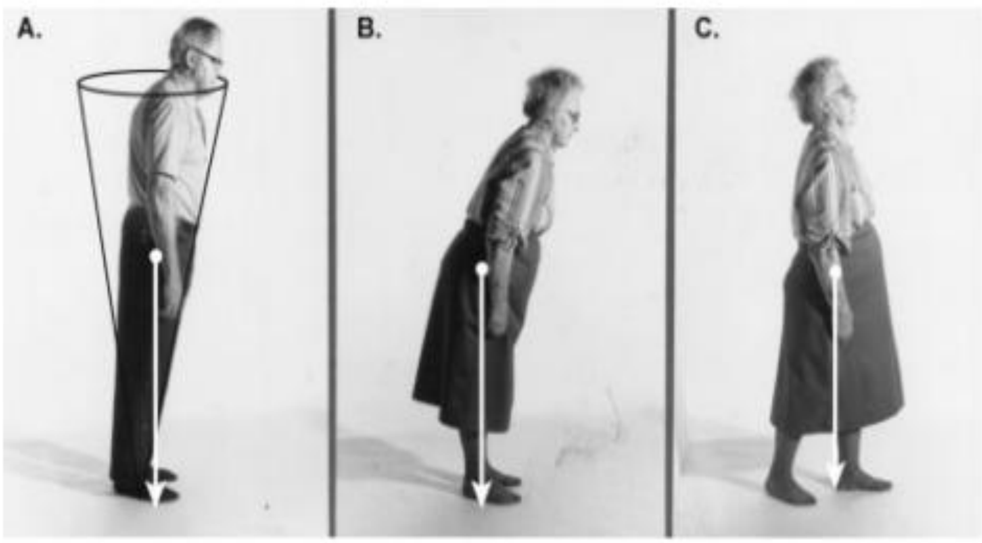


Figure 5. Normal and abnormal postural limits, adopted from Horak, 2006, p.729.

(a) Healthy man leaning forward from the ankle to bring the CoM (the white arrow) towards the front of the feet. (b) Multisensory deficient woman leaning forwards from the hips, flexing them, limiting the CoM to move forward. (c) Multisensory deficient woman leaning backwards and taking an immediate step, to enlarge her BoS, causing the CoM to fall between her legs.

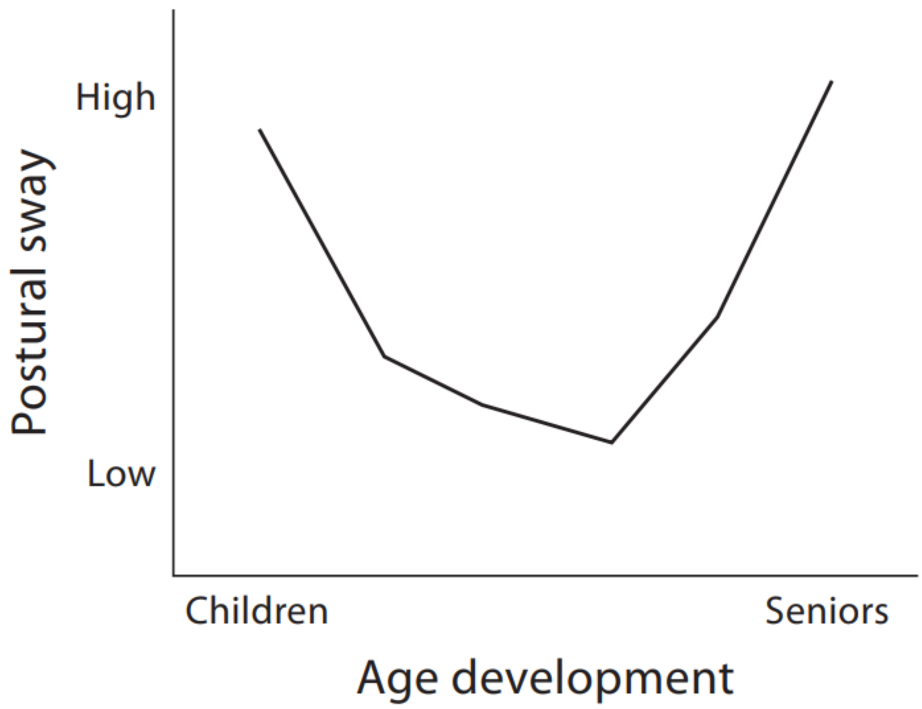


Figure 6. Degree of postural sway during static balance across the life span, derived from Hytönen et al. 1993.

2.6.5 Orientation in space

A fundamental component of postural control is the ability to orientate various body parts in relation to gravity, the support surface and the visual surroundings (Horak, 2006). This ability to orientate the body in space can be adjusted automatically by a healthy nervous system integrating of multiple systems (somatosensory, proprioceptive, cutaneous, visual and vestibular systems), depending on the context and the task (Horak ,2006; Mancini et al., 2020). This automatic adaptation ensures the internal presentation of the body in space achieves effective postural control in diverse conditions (Horak, 2006; Mancini et al., 2020).

For example, an individual can use their body orientation ability to remain perpendicular to a support surface; if the support surface tilts, they promptly orientate their posture so that it is aligned with gravity (Horak, 2006). This is called ‘perception of verticality’ (Horak, 2006). However, if verticality is compromised, the automatic postural alignment can become misaligned, ultimately contributing to poor balance (Horak, 2006). Therefore, accurately representing vertical orientation is vital to maintain balance (Horak, 2006).

2.6.6 Cognitive processing

Management of the ‘conscious’ components of postural stability is controlled by the basal ganglia-cortical network (Boisgontier et al., 2013). As Raftopoulos (2005) explained, this ensures postural regulation includes both higher ‘controlled’ and lower ‘automatic’ levels of cognitive processing. This suggests engagement of the basal ganglia-cortical loop in higher level processing (Jacobs and Horak, 2007) and of brainstem synergies in lower-level processing (Honeycutt et al., 2009). The previous literature indicated that any decline in the conscious regulation of attention concerning postural control can increase risk of poor balance and interrupt coordination (Wulf et al., 2001; Masters and Maxwell, 2008), potentially due to movement-specific reinvestment (Masters, 1992; Masters and Maxwell, 2008).

This reinvestment theory suggests performance can be disrupted, if attention is directed internally to control movement that would otherwise be automatic (Wulf et al., 2001; Masters and Maxwell, 2008). This theory suggests both aging (Schaefer et al., 2015) and neurological diseases (Masters and Maxwell, 2008) are conditions commonly associated with increased reinvestment (Ghai et al., 2017).

During quiet standing, cognitive processing occurs, as evidenced by longer reaction times observed in individuals when they are standing, compared with when they are sitting with support (Horak, 2006). More challenging tasks necessitate higher cognitive engagement to maintain balance (Horak, 2006). Reward-based learning is a motor learning process in which individuals discover, experientially, how to distinguish between successful and unsuccessful outcomes by rewarding the successful outcomes and avoiding the unsuccessful outcomes (Spampinato and Celnik, 2021). In contrast, in error-based learning the individual learns from the errors detected by the sensory system and updates the information provided to the motor command in subsequent actions (Seidler et al., 2010). Individuals exhibit longer recall with success-based feedback, despite learning by reward-based learning being a slower process than error-based learning (Spampinato and Celnik, 2021). Balance can be acquired via learning processes, such as error-based and reward-based learning; this applies to the two types, static and dynamic. The next section discusses quiet standing and perturbation in detail.

2.6.7 Balance during quiet standing

The ability to stand on a firm and stable surface seems to depend on the somatosensory information received from the support surface for maintaining balance (Mancini et al., 2020). The maintenance of balance involves balancing within the limits of stability, which is defined as the 'sway boundary', in which an individual maintains balance without changes to the BoS (Kisner and Colby, 2012). Previous studies have limited stability during stance to the physical characteristics of the BoS (the feet), rather than the above-mentioned interactions of postural control (Cook and Woollacott, 2016). Body sway is represented by an inverted pendulum during ankle strategy (Winter, 1995b). Ankle muscles, such as the ankle plantar flexors/dorsiflexors and the invertors/evertors, play an essential role in counteracting the body sway in various directions (Kisner and Colby, 2012). Other muscles are also activated to prevent hip extension and to maintain static balance, including the gluteus medius, tensor fasciae late, iliacus and the psoas major, as well as the thoracic paraspinal muscles (Daube, 1981). Furthermore, three motor reflexes are believed to affect posture (Di Nardo et al., 1999), the first of these is the short or segmental arc reflex, which controls muscular stiffness, with little or no direct influence on balance and has a latency of between 40-45 ms (Di Nardo et al., 1999). The second and third are called the 'medium' and 'long' latency and are automatic responses (Mirka and Black, 1990). It is thought that the latter two motor reflexes are induced by input from muscle proprioception, as well as by the entire loop, including the spinal cord, brain stem and cortical pathways (Mirka and Black, 1990). A recent study extended the boundaries of stability, according to the task, to include the interaction between the individual and muscle strength, range of motion, the characteristics of the CoM, and different aspects of the environment (Mancini et al., 2020).

2.6.7.1 Postural control during perturbated standing

When the support surface becomes unstable, individuals shift their dependence towards vestibular and visual information (Mancini et al., 2020). Perturbations during standing may occur due to anticipated forces, either internally, such as voluntary movement of the body, or externally, such as forces applied to the body (Winter et al., 1990). The counteracting of both types of perturbation requires the activation of muscle synergies and the appropriate timing of postural response (Winter et al., 1990). For example, anticipatory postural response is required for internal perturbation, whereas reactive postural response is required for external perturbation (Winter et al., 1990). Previous platform movement studies provided a greater understanding of postural strategies and the associated muscles activation during unexpected perturbated standing (Nashner, 1977; Nashner, 1982; Pai et al., 2003). For example, Pai et al. (2003) demonstrated that the stability of the position of the CoM and velocity require advanced adaptive adjustment provided by the CNS, while Nashner (1977) identified a reflex called the 'functional stretch reflex', which is a preprogramed response among the leg and trunk muscles prior to antero-posterior (AP) sway, after an AP tilt of a platform. Moreover, Nashner (1982) reported that the reflex contraction of the gastrocnemius is elicited as a response to an upward rotation of a platform, giving the false impression of forward falling; however, repetition of this tilt diminished the gastrocnemius response until it disappeared completely by the fourth repetition. Therefore, slip mechanisms were used in sit to stand tasks in older adults in the first trial conducted by Pai et al. (2003), followed by non-slip mechanisms, then finally re-slip trials, which confirmed that older adults are able to recognise optimal movement to avoid slips, preventing balance loss and falls.

Before discussing how balance can be assessed and trained, it is important to understand the factors that can affect it, as detailed in the next section.

2.6.8 Factors that affect balance

Balance is influenced by many intrinsic (human) and extrinsic (environmental) factors (Granacher et al., 2011a). The greatest effect of these factors are the intrinsic factors, which are recommended to be counteracted to reduce risk of falling (Granacher et al., 2011a). One such intrinsic factor is biological sex, which is suggested to have greatest effect on static and dynamic balance (Maki et al., 1990;

Era et al., 2006). Additionally, extrinsic factors, can have considerable impacts on static and dynamic balance, which are footwear and dual tasks (DT) (Runge et al., 2000; Boisgontier et al., 2013). However, there is a lack of consensus in the current literature concerning the real impact of biological sex, footwear and DT on static and dynamic balance.

Therefore, this present study included the development of fundamental understandings about the impact of such factors, which are footwear, DT, biological sex and anthropometric characteristics on static balance and dynamic balance, which referred in this context to WB performance, to advance understanding and benefits researchers and clinicians when drawing clinical conclusions and investigating interventions.

The following section examines the previous factors and their effect on static balance and WB performance.

2.6.8.1 Biological sex and anthropometry

The real influence of biological sex on balance performance is currently the subject of debate. Some previous studies suggested that static and dynamic balance is moderated by biological sex (Maki et al., 1990; Era et al., 2006), while others report that this may not be the case (Palazzo et al., 2021). Some of the differences can be attributed to the anthropometric differences between individuals, rather than their biological sex (Maki et al., 1990; Ku et al., 2012). However, to date, no studies have integrated the measurements of WB performance to explore performance and its relationship to a range of anthropometric variables. This comparison is important to enable clinicians to determine balance impairments and to set rehabilitation goals by comparing individuals with normative databases or clinical norms. Arguably, a comparison of performance scores against same sex cohorts or mixed cohorts should ideally be performed by clinicians. Surprisingly, despite this ambiguity, no previous studies have assessed static balance and WB performance systematically in females and males, while investigating performance correlations with various anthropometric variables.

2.6.8.2 With footwear versus without footwear

Whether or not footwear should be used in the assessment and rehabilitation of balance is a factor that should be considered by clinicians and individuals, especially those who may have a balance impairment, such as the elderly, PWD and individuals with DPN. Some previous studies have reported that wearing footwear influences static balance (Runge et al., 2000) by altering the somatosensory input (Lee et al., 2019), or by physically restricting the movement of both the ankles and the feet (Runge et al., 2000). Furthermore, practising certain activities, with or without footwear, can influence tactile sensitivity and balance. For example, when engaged in specific activities that are conducted barefoot, such as gymnastics and Tai Chi, participants are often able to detect plantar pressure distribution and to facilitate tactile sensitivity (Schlee et al., 2007). The athletic population falls outside the scope of this present study.

Although a study conducted by Alghadir et al. (2018) found that wearing footwear fails to produce any difference in terms of performance during dynamic balance, Germano et al. (2012) reported that doing so has the potential to affect dynamic balance positively. There is a paucity of studies in this field and those that do exist have certain limitations, such as being confined to a single gender cohort or to a certain task, such as a SLS or a single axis WB or foam surface (Alghadir et al., 2018; Zech et al., 2018). There is, therefore, a need to fill this gap in the literature by investigating the effect of footwear systematically across a range of tasks and conditions during static balance and by using a multiple axes WB, to determine whether assessment and rehabilitation should be executed when wearing footwear.

2.6.8.3 Primary and secondary tasking

Due to the fast pace of modern life, individuals often perform multiple tasks concurrently. This is called secondary or dual tasking (DT). While DT has recently gained popularity in the context of balance assessment, there is some debate concerning the real effect of DT during static and dynamic balance or an unstable surface; specifically, whether it produces an improvement (Boisgontier et al., 2013) or deterioration (Yardley et al., 1999) in balance performance, or if there is no difference (Lüder et al., 2018). Deterioration in performance, due to DT, is called ‘dual task cost’ (Papegaaij et al. 2017), and is evident when a task is combined with verbalisation, such as counting aloud during a balance task (Yardley et al., 1999). This may be linked to the simultaneous engagement of the muscles required for balance and verbalisation (Yardley et al., 1999). Most literature in this field has observed the highest cost among elderly individuals with cognitive impairments, while the influence among young, healthy adults without cognitive impairments is less clear.

Uncertainty about the real impact of DT on balance performance during static balance and WB performance among young healthy adults causes ambiguity regarding optimal static balance assessment and the utilisation of a WB for balance assessment and training within research and clinical practice contexts (Ruffieux et al., 2015), thus indicating a need for additional research.

2.6.8.4 Balance confidence

Balance can be impaired by a fear of falling and low confidence, even when the musculoskeletal system is intact (Mancini et al., 2020). Moreover, of relevance here, an individual’s degree of confidence in their balance abilities can impact the effective use of WB training (Schilling et al., 2009). Therefore, it is essential to assess balance confidence using the ‘activities-specific balance (ABC) scale’, which is a self-reporting assessment of an individual’s confidence level in static and dynamic balance when engaged in ADL (Powell and Myers, 1995). For data analysis, the percentage scores of 16 questions were totalled to yield a single ABC score, ranging from 0 to 100% (Powell and Myers, 1995). The higher the score, the more confident an individual is. Psychometric testing of this scale has shown it is reliable and valid, with excellent internal consistency for older adults (Powell and Myers, 1995; Myers et al., 1996). It is also a good indicator of balance ability and predictor of fall risk, as a score below 67% indicates an elevated falls risk (Lajoie et al., 2002; Lajoie and Gallagher, 2004). The Arabic version of this scale (A-ABC) also has a good reliability and validity (Alghwiri et al. 2016).

As this questionnaire is useful for assessing balance confidence in any balance assessment or intervention study, it was employed for the present study.

2.6.8.5 Physical activity level

A sedentary lifestyle that lacks exercise can be a primary factor contributing to the prevalence of DM type II among the Saudi Arabian population (Naemi et al., 2015). Indeed, a study by Cassidy et al. (2016) that assessed 233,110 UK Biobank participants, observed that individuals with type II DM, whether with or without complications, adopted sedentary lifestyle habits and a low activity level. Since reduced physical activity can potentially contribute to increased morbidity and mortality (Harrington and Henson, 2021), it is important to encourage participation in physical activity intervention programmes that aim to mitigate these complications. While many online courses provide lifestyle counselling to help with weight loss and to promote physical activity among PWD (Chao et al., 2019), additional resources for improving activity levels in individuals with DPN might include educational booklets (Monteiro et al., 2020). Following an individuals' engagement in a training programme, it is necessary to assess their physical activity level. Moreover, the individual's age and previous physical activity level should be considered when customising an exercise regimen to their needs (ADA, 2021b).

The next section explores how balance can be assessed and trained in PWD and those with DPN.

2.6.9 Balance assessment in the elderly, PWD, and those with DPN

PWD, elderly and those with DPN, who are at risk of falling, as discussed earlier require physical therapy interventions to restore the health of the neurons concerned, progressing to sensory integration and compensatory strategies (O'Sullivan et al., 2019). Therefore, this study includes a plan for an intervention focused on balance training, which aims to improve balance among PWD and individuals with PDN. Thus, it was necessary to review the literature regarding how to assess and train balance among these populations.

2.6.9.1 Static balance

Static posturography is a valid and objective measure for static balance and is considered a gold standard for static balance assessment (Nardone, 2016; Sandrini et al., 2018). This device was employed previously in studies of DPN to assess static balance, as it is able to measure body sway objectively (Simoneau et al., 1994;

Boucher et al., 1995; Uccioli et al., 1995; Giacomini et al., 1996; Uccioli et al., 1997; Nardone et al., 2006). Different static balance outcomes were investigated and individuals with DPN showed postural instability, as demonstrated by an increased area of centre of pressure (CoP), (Simoneau et al., 1994; Uccioli et al., 1995; Giacomini et al., 1996), increased CoP sway length, (Boucher et al., 1995; Uccioli et al., 1995; Katoulis et al., 1997; Uccioli et al., 1997), increased CoP velocity, which is calculated by dividing the CoP excursion by trial time and increased values of CoP net (t), which is the weighted sum of the CoP's time-varying position from two force plates (Lafond et al., 2004). Previous studies showed that individuals with DPN had postural instability during quiet standing with both eyes open and closed, compared to healthy individuals (Boucher et al., 1995; Uccioli et al., 1995; Uccioli et al., 1997; Lafond et al., 2004; Simoneau et al., 2006). This postural instability, during static balance assessment, is due to somatosensory impairment (Kars et al., 2009). Interestingly, even with their eyes open, individuals with DPN demonstrated increased body sway, suggesting a deterioration in balance performance compared with healthy controls (Boucher et al.,1995; Uccioli et al.,1995; Uccioli et al., 1997; Nardone et al., 2000; Lafond et al., 2004; Nardone et al., 2006; Simoneau et al., 2006). Finding that individuals with DPN have poor balance in all sway testing conditions, compared to healthy controls, suggests vision cannot compensate fully for reduced somatosensation (Boucher et al., 1995; Nardone et al., 2006).

2.6.9.2 Dynamic balance

In terms of dynamic balance, a number of clinical balance tests were used during previous studies of PWD and individuals with DPN to assess dynamic balance, such as the Berg Balance Scale (BBS) and the Timed Up and Go test (TUG) tests (El-Wishy, 2012; Eftekhar-Sadat et al., 2015; Jyoti, 2016; Alshimy et al., 2017; Jannu et al., 2017; Ahmad and Hussain, 2018; Maruboyina et al., 2018; Ajitha and Roopalokesh, 2020; Daud et al., 2021).

However, most of these tests are not validated for the diabetic population, especially type II and do not cover all aspects of the balance system (Dixon et al., 2017) but tests, such as TUG, BBS and FRT, demonstrate validity for other populations, such as stroke individuals and those with Parkinson's disease (Blum and Korner-Bitensky, 2008; Dibble et al., 2008; Jernigan et al., 2012). Therefore, a quantitative balance assessment is required, such as dynamic posturography, to specify balance impairments in PWD that are due to somatosensory deficit, rather than vestibular or visual deficits (Di Nardo et al., 1999). This is achieved using a sensory organisation test (SOT) consisting of six conditions, that examine the ability to balance on a support surface that varies from stable to unstable, with the eyes open and closed and within different surrounding environments (Di Nardo et al., 1999). The condition in which the support surface and the surrounding area moves indicates the presence of an accurate vestibular system function and, thus, when an individual scores well under this condition, it shows it is not responsible for causing balance impairment in PWD (Di Nardo et al., 1999). However, this dynamic posturography used in the study by Di Nardo et al. (1999), only allowed horizontal perturbation and did not measure motor function selectively. An example of dynamic posturography that was utilised previously in studies of PWD and individuals with DPN is the Biodex Balance system, which involves a static and dynamic board with adjustable instability levels (Akbari et al., 2012; El-Wishy, 2012; Alshimy et al., 2017). However, this system has only 12 levels of instability and the lowest stability levels have a poor reliability in the scores over time, that may cause it to be used inappropriately as an objective marker of progression (Cug and Wikstrom, 2014). The biodex system has been shown to have repeated measure's reliability values of as low as 0.58 but perhaps more importantly large MDC values across time (3 times the measured value in some cases) (Cug and Wikstrom, 2014). On the other hand, the Prokin (252) has 50 levels of instability, acting as both a WB, as well as FP (ProKin 252, TecnoBody, 2021), will be justified in the below section for using it for the present study.

2.6.9.3 Justification for using Prokin (252)

For the purpose of the present study, it was necessary to seek an alternative form of dynamic posturography to allow more tilted angles with higher reliability, such as the Prokin (252) (Prokin 252, TecnoBody, 2021). The selection of this device added novelty since it was conducted among PWD and individuals with DPN, who had not been assessed previously using it. This device was demonstrated recently to possess a high reliability and moderate validity during static and dynamic balance assessments for incomplete spinal cord injury (Jain et al., 2023), as well as being able to act dynamically as a WB in all directions and with an instability degree of zero, indicating a very low level of resistance to movement, with high instability, resembling a WB, with 50 levels of instability, unlike the Biodex system that has 12 levels of instability (Cug and Wikstrom, 2014; ProKin 252, TecnoBody, 2021). Furthermore, the Prokin (252) includes safety measures, in the form of surrounding parallel bars and a safety button to stop an unstable board, which a WB alone cannot.

Finally. this device is validated for static balance assessment (Mauch and Kälin, 2011). Both perimeter and ellipse area achieved by using the Prokin (252) were employed by previous studies to assess static balance in individuals with cerebral ataxia (a clinical condition that arises from impairment, diseases or malfunction of the cerebellum), cerebrovascular disease, osteoporosis, athletes (such as soccer players), acromegaly (a long-lasting debilitating disease caused by excessive release of growth hormone) and fibromyalgia (chronic radiated pain) (Schweiger et al., 2017; Gunay et al., 2018; Haliloglu et al., 2019; Toprak Celenay et al., 2019; Arcuria et al., 2020; Meiners and Loudon, 2020). Therefore, the Prokin (252) was deemed suitable for use during the current studies, since it can obtain CoP displacement, which is called perimeter, as discussed in chapter one.

In summary, the above sections defined balance, exploring the underlying systems of balance and investigating the constraints on postural control systems, that may cause PWD and those with DPN to be more vulnerable to falling. Ultimately, an explanation and justification were provided for choosing Prokin (252) as the device for balance assessment and training in this study.

2.6.10 Balance training in PWD and individuals with DPN

The use of therapeutic exercises can empower individuals to preserve their remaining biomechanical ability to enable safe walking and standing, potentially aiding in the prevention of tissue breakdown and reducing the risk of falling (Sacco and Sartor, 2016). Furthermore, the AGS and the ADA recommend that balance exercises should be performed to reduce the risk of falls in the elderly and individuals with DPN (Garber et al., 2011; AGS, 2020; Harrington and Henson, 2021). However, views differ regarding the optimal way to enhance balance among the elderly and individuals with DPN (Ites et al., 2011; Lesinski et al., 2015a).

One option is to use a WB to challenge balance, due to its ability to enhance the neuromuscular function (Webster and Gribble, 2010), minimise the risk of injury (Hübscher et al., 2010), reduce the risk of sport-related injury (Emery et al., 2019) and enhance balance rehabilitation (Williams and Bentman, 2014; Fusco et al., 2019). Although it is common in sport rehabilitation and clinical practice, there is dearth of studies that systematically explore the efficiency and effectiveness of WB training to improve balance in the elderly. However, due to the similarities between the elderly and individuals with DPN, there is a systematic review (SR) regarding the effectiveness of balance intervention generally but not specifically for WB training, to improve balance intervention among individuals with DPN (Ites et al., 2011). Although, there is robust evidence for the effectiveness of interventions that improve balance, quality of life and reduce the fear of falling, there is none pertaining to the risk of falling among individuals with DPN, specifically the combination of gait, balance and functional training (De Oliveira Lima et al., 2021). There is also a lack of valid balance assessments, integrating all the underlying systems of balance in PWD, especially those with type II DM (Dixon et al., 2017). There is, therefore, a need to investigate the effectiveness of physical therapy interventions to enhance balance, assess it and explore its related factors comprehensively, among these individuals. Furthermore, it is necessary to explore the effectiveness of WB training in the elderly and further understanding of the factors that impact static balance assessment and WB performance.

As discussed previously, there is value in assessing prior literature exploring the efficacy of different types of exercise, especially balance training in different forms, as a way to improve balance and prevent falls among the elderly, PWD and individuals with DPN. Therefore, the next section explores the concept of balance training among these individuals.

2.6.10.1 Static balance

In total, seven studies explored the effect of training using a WB or movable surface, such as the Biodex stability system or foam, for improving static balance among the elderly and individuals with DPN (Balogun et al., 1992; Schilling et al., 2009; Kosse et al., 2011; Morioka et al., 2011; Ogaya et al., 2011; Salsabili et al., 2011; Song et al., 2011). However, these produced conflicting findings regarding significant changes in static balance, after training, among the participants (Schilling et al., 2009; Kosse et al., 2011; Ogaya et al., 2011). This discrepancy may be explained by differences in the outcomes measured, sample size and population and/or the nature of the intervention.

There is a debate whether balance training can only improve the tasks, which are trained (Kümmel et al., 2016). This may arise because the balance training concept is considered to involve the acquisition of a transferable skill, rather than a general ability (Giboin et al., 2015; Kiss et al., 2018). The study by Giboin et al. (2015) investigated the degree of this transferability in non-trained tasks post balance training, reporting transferability was highly targetable and specific, even if the balance training was performed by healthy individuals using the same device but with different direction perturbations or with a different balance device and the same direction of perturbation (Giboin et al., 2015).

A range of dynamic balance training was utilised by these previous studies, including multimodal training interventions that involved unstable surface training on foam and on a trampoline, which were effective for improving static balance parameters, such as body sway distance measured using Biodex stability systems and the reduction in time spent during a SLS task by individuals with DPN (Song et al., 2011). Although, this improvement was assessed by a recent SR and a meta-analysis and showed small differences in favour of intervention, the quality of the evidence was low (de Oliveira Lima et al., 2021). A progressive pattern was recommended for balance training based on dynamic systems theory (McKeon, 2009), concerning the behaviour of the most important system in balance, namely the sensorimotor system (Mancini et al., 2020). The sensorimotor system alters coordination to self-organise around a certain task, responding to environmental constraints and progressing to create greater demands at a higher difficulty level, engendering more significant improvements, to achieve goals (McKeon, 2009).

Assessment of postural sway is considered a difficult static balance test, because it involves the ability to remain relatively still, in response to postural challenges derived internally (Haines et al., 2007), whereas a WB is considered to derive perturbation externally.

Since it remains controversial whether dynamic balance training can affect static balance, there is a need to conduct studies with individuals who are vulnerable to falling, such as the elderly, PWD and those with DPN, to train them in a progressive pattern using a movable surface, such as a WB and to assess the progression of their static balance. Hence, this study addressed this issue by SR the literature to investigate the efficiency of WB training, utilising this information to plan a progressive training programme using a WB to improve static balance among PWD and individuals with DPN.

2.6.10.2 Dynamic balance

Some previous studies employed a WB, or other movable surface, for dynamic balance training and achieved a significant improvement in dynamic balance (Allet et al., 2010; Salsabili et al., 2011; Song et al., 2011; Akbari et al., 2012; El-Wishy, 2012; Kutty and Majida, 2013; Eftekhar-Sadat et al., 2015; Chaitali, 2016; Alshimy et al., 2017; Elshinnawy et al., 2018; Ahmad et al., 2020; Ajitha and Roopalokesh, 2020; Iram et al., 2021), however, three previous studies reported conflicting results regarding a lack of effect of WB training, favouring a stability trainer instead (Jannu et al., 2017; Maruboyina et al., 2018; Ajitha and Roopalokesh, 2020). These conflicting findings may be due to the range of assessments and interventions used for balance evaluation and training. The interventions concerned included multisensory training with WB training that showed a significant improvement in the TUG test and six-minute walking test (Chaitali, 2016), as well as dynamic balance improvement measured by stability indices in the anteroposterior (AP) direction but not in the mediolateral (ML) direction with closed eyes (Akbari et al., 2012). However, WB training was found to be less effective than stability training in studies in which, all the participant groups received multimodal interventions (Jannu et al., 2017; Maruboyina et al., 2018; Ajitha and Roopalokesh, 2020). This may be due to an inaccurate prescription of WB training or to the misinterpretation of the normative value of the BBS, as both groups involved reported normal scores of BBS, in which a score from 41.73 and 39.84 to 56 indicated good balance in individuals with neurological disorders, such as stroke patients (Blum and Korner-Bitensky, 2008). However, the study by Chaitali (2016) found that WB training outperformed the use of a compliant surface (balance pad) post six-week training among individuals with DPN, as measured by the TUG and the six-minute walking test.

In the studies by Akbari et al. (2012) and El-Wishy (2012), balance training was provided to PWD and individuals with DPN via a Biodex stability system. Both studies achieved improvements in the dynamic balance parameters, especially during double leg stance with eyes open (DLSEO) and eyes closed (DLSEC), however, during DLSEC in the study by Akbari et al. (2012), the AP axis showed significant improvement, reflecting the findings of the study by Lafond et al. (2004), in which a larger displacement in the AP axis of the CoP was identified among individuals with DPN. This may be explained by the reduced ankle strategy, present among the elderly and individuals with DPN (Inglin and Woollacott, 1988; Jyoti, 2016), or may have been due to weakness in the ankle plantar flexors and dorsiflexors among individuals with DPN (Akbari et al., 2012); these muscles contribute to the control of displacement in the AP axis (Winter et al., 1993).

Balance training in the form of sensorimotor training is considered a global approach (Ahmad et al., 2019). It is effective because it encourages the sensorimotor system to function as a unit by regulating movement via the CNS, stimulating sensory input and the proprioceptive response of various muscles to stabilise the joint (Salsabili et al., 2011). Ahmad et al. (2019) employed such an intervention with elderly individuals with DPN for eight weeks, progressing balance training from a stable to an unstable surface, such as foam or a trampoline, which was found to yield a significant improvement in the dynamic balance scores assessed using the TUG and FRT.

Furthermore, this form of training was employed with individuals with DPN in a randomised controlled trial (RCT) by Ahmad et al. (2020), involving progressive movement of the WB from bidirectional to multidirectional and from a double leg stance (DLS) progressing to a SLS over the course of eight weeks. This training was shown to improve the dynamic balance in all directions, when assessed using a mini-board, known as the ‘Pedalo ® -Sensamove balance test Pro’, whereby the participants were required to tilt the board to its maximum tilt angle in four directions, namely front, back, right (Rt) and left (Lt) (Ahmad et al., 2020). Meanwhile, Allet et al. (2010) employed multimodal training, including various forms of mixed balance training, gait and strength training to individuals with DPN for eight weeks, with a washing out period (period of inactivity) of six months, producing a significant improvement in dynamic balance as assessed using the Biodex after eight weeks, although the improvement was not retained after six months. Similarly, balance and strength training was provided by Kruse et al. (2010) to individuals with DPN for three months, with a washing out period, to assess the progression of their dynamic balance using both the BBS and the TUG after six and 12 months; it was found to yield a non-significant difference between the control and intervention groups both six and 12 months after controlling the confounders.

In addition, WB training was used in a programme called 'task-oriented training' by Alshimy et al. (2017) and Elshinnawy et al. (2018), in which the training was multidirectional and progressed from eyes open to closed and from sitting to standing. The study by Alshimy et al. (2017) employed a progression of WB training in the form of providing a hand support then removing it. Both studies yielded improvements in dynamic balance, assessed via the Biodex, in both axes (AP and ML axes) but the AP axis was found to improve more than the ML axis (Alshimy et al., 2017; Elshinnawy et al., 2018).

Meanwhile, Song et al. (2011) and Lee et al. (2013) provided elderly individuals with DPN with an intervention in the form of a six-week whole body vibration and multimodal training, which involved unstable surface training on foam and a trampoline. The intervention was reportedly effective for improving dynamic balance, assessed using the BBS and TUG (Lee et al., 2013). However, the findings were appraised by recent SR and found to yield low certainty evidence and non-significant differences, based on a meta-analysis (De Oliveira Lima et al., 2021).

A normal response to a perturbation requires an adequate muscle force to maintain the body's CoM over its base of support, this is not the case for individuals with DPN, suffering from diminished ankle strength and their rate of force production may consequently cause balance impairments (Ites et al., 2011). However, even with somatosensory loss, Horak et al. (2002) found that individuals with DPN performed similarly to those in a control group during standing on a sway-referenced support, because the individuals relied on visual and vestibular information over surface orientation cues.

From the above section, it appears that there is lack of consensus about the effect of dynamic balance training, specifically WB training on WB performance. Thus, the present study, sought to address this lack with WB progressive training programme, aiming to enhance WB performance in PWD and individuals with DPN.

2.6.10.3 Muscle strength

The 'Dutch Physical Activity Guidelines recommend that balance training incorporates exercises that strengthen muscles and bones at least twice weekly for the elderly population (Weggemans et al., 2018). Additionally, the ADA recommends that flexibility, balance training, yoga and Tai Chi are used to strengthen muscles, two to three times per week in elderly people with type II DM (Colberg et al., 2016; Elsayed et al., 2023a). There is growing evidence regarding the effect of various forms of training for strengthening the muscles of PWD and individuals with DPN. For example, Allet et al. (2010), Morrison et al. (2010), Song et al. (2011) and Ahmad et al. (2020) found that dynamic balance training is beneficial for strengthening the lower limb muscles in these populations. For instance, progressive sensorimotor training, along with gait and balance training, was conducted by Allet et al. (2010) and Ahmad et al. (2020), reportedly producing gains in the strength of the hip, knee and ankle muscles. The intensity of the balance training involved was varied in these training programmes. In the study by Allet et al. (2010), the progression moved from a stable to an unstable surface (WB), whereas in the study by Ahmad et al. (2020), a WB was utilised first in a bidirectional pattern, then in a multidirectional pattern, progressing from a DLS task to a SLS. Muscle strength was assessed differently by these two studies and the assessed muscle groups were different. For instance, in the study by Allet et al. (2010), the hip, knee and ankle (flexors and extensors) were assessed using a digital handheld dynamometer (MicroFET®2, Hoggan Health Industries), with no actual value of muscle strength gain reported. Furthermore, the washing out period, in this study was six months and yielded no significant difference in ankle plantar flexor strength. It is, therefore, uncertain whether the gain in muscle strength, after training, lasts and the period of washing remains controversial. Meanwhile, in the study by Ahmad et al. (2020), the actual value of ankle muscle activity was reported using electromyography (EMG). The study found that the intervention involved increased activity of the ankle muscle groups that are required for improving postural control.

Nevertheless, the incorporation of strengthening exercises with balance training with WB was found to be beneficial for preventing sport-related injury, particularly in the knee and ankle among youth population (Emery et al., 2019). Similarly, combining strengthening exercises with balance training proved effective in preventing the risk of falls in elderly individuals with DPN in the study by Foster and Armstrong (2018), while Morrison et al. (2010) reported that elderly and middle-aged individuals (50-75 years old), with mild to moderate DPN and type II DM, can benefit from these types of exercises for strengthening both the ankle and knee muscles. The strength assessment of these muscle groups was conducted, via a functional balance assessment known as the PPA analysis, which involves aspects, other than muscle strength, to be examined, such as vision, peripheral sensation, vestibular function, reaction time and postural sway to determine which type of balance disorder depends on which underlying physiological system (Lord and Clark, 1996; Mancini and Horak, 2010; Morrison et al., 2010). Further information about the PPA approach, can be found in Appendix 1.

Finally, Waddington and Adams (2004) found balance training conducted using a WB on daily basis for five weeks was helpful for achieving significant ankle movement (inversion) in elderly individuals wearing shoes, compared with a barefoot control group. The mechanism behind this improvement was unclear, although it may have been due to neuroplasticity, which means that neural adaptation may have occurred during the short period of the intervention (Balogun et al., 1992; Schoenfeld, 2010). However, the more complex the intervention, the longer the time required to enhance this neural adaptation, which might explain why the training induced improvement in agonist, antagonist, stabiliser and synergist coordination, rather than muscle activation (Rutherford and Jones, 1986). Meanwhile, gains in lower limb muscle strength, when using a WB, may be due to the muscle hypertrophy that is necessary for improving balance among the elderly (Waddington et al., 1999). In addition, perturbations, such as WB training, may utilise the ankle strategy, as discussed previously, which is one of the postural control strategies that is characterised, primarily by early dorsal ankle muscle activation, followed by activation of the dorsal thigh and trunk muscles (Horak and Nashner, 1986). This is because the trunk and hip muscles are usually not affected by DPN and the proprioceptive information from the muscle spindles or Golgi tendon organ receptors

(Horak et al., 2002). Such WB training not only improves muscle strength but can also achieve neural adaptation, post WB training, at the subcortical integration areas, such as the basal ganglia and cerebellum (Silva et al., 2016; Silva et al., 2018). This controversial aspect of the mechanisms of WB training requires a consensus regarding the length of time the gain in muscle strength remains after pausing the intervention and whether this effect is achieved among PWD and individuals with DPN. Therefore, the study conducted for this thesis investigated the effect of a progressive WB training program on muscle strength by assessing ankle muscle strength weekly and after washing out period.

2.6.10.4 Balance confidence

The existing literature reported conflicting findings regarding whether balance training can improve the level of balance confidence, as assessed by the Activities specific Balance Confidence (ABC) questionnaire scores (Richardson et al., 2001; Schilling et al., 2009; Dougherty et al., 2011; Londhe and Ferzandi, 2012; Sartor et al., 2014). However, there are conflicting findings in the study by Dougherty et al. (2011), who did not report any significant differences or actual values but a small magnitude of improvement in the ABC scale scores (3.8 points: 4%) was reported by the study conducted by Schilling et al. (2009), although this was of questionable significance, due to the MDC of 15 (Wang et al., 2018). Similarly, two studies, with conflicting findings, that assessed the effect of strengthening and balance training on balance confidence in the individuals with DPN, as determined by the ABC questionnaire were observed (Richardson et al., 2001; Sartor et al., 2014). The study by Richardson et al. (2001) did not report any significant differences or actual values but a small magnitude of improvement in the isolated activities of ABC scale scores, such as ascending and descending stairs after the intervention exercises. Alternatively, a small magnitude of improvement in the ABC scale scores (3 points) was reported by the study conducted by Sartor et al. (2014), although this was of questionable significance, due to the MDC of 15 (Wang et al., 2018). Additionally, there were certain limitations in the studies conducted by Richardson et al. (2001) and Sartor et al. (2014), including performance bias and small sample size that may reduce the generalisability of the findings. However, a higher magnitude of improvement in the ABC questionnaire score was reported by Londhe and Ferzandi's (2012) study, which was conducted in individuals with DPN, following an eight-week duration of balance training alone and the same training coupled with resistance training, namely 13% and 20% points, respectively. Therefore, there is a need to investigate the effect of balance training, specifically with WB training on balance confidence among a population with balance impairment, such as PWD and individuals with DPN. Thus, this present study, explored the effect of a progressive WB training programme on balance confidence among these populations.

2.6.10.5 Neuropathic scores

While the current literature provides little supporting evidence regarding the ability of therapeutic exercise in improving neuropathic scores, therapeutic exercises that target the ankle and foot can play a significant role in addressing this subject (Sacco and Sartor, 2016). Such exercises initially address the musculoskeletal structure at the distal regions, which are particularly impaired in individuals with DPN (Sacco and Sartor, 2016). Despite the paucity of evidence for the impact of exercise on neuropathic scores, significant improvement was observed in the severity of individuals with DPN, despite the variation in the training regimen provided, which included strengthening, gait and balance training (Monteiro et al., 2020); treadmill exercises (Dixit et al., 2014); strengthening and aerobic training (Kluding et al., 2012) and balance board training (Ravand et al., 2021). However, the study by Sartor et al. (2014) reported that there was a non-significant improvement in the neuropathic scores in individuals with DPN. All of the aforementioned studies employed the MNSI scores to assess the degree of neuropathy concerned. Individuals with DPN may be reluctant to adopt a prescribed exercise regimen for the foot and ankle for two reasons (Sacco and Sartor, 2016). First, due to fear within the clinical team that exercise may worsen the mechanical stress on tissues, which in reality, is not the case (Mueller et al., 2013) and second, there is widely held belief that muscle weakness and joint limitations are irreversible, although this is not entirely the case (Sacco and Sartor, 2016). Due to these controversial opinions, regarding the ability of therapeutic exercise to improve neuropathic scores significantly, the current study conducted for this thesis assessed these scores pre and post a progressive WB training programme and during weekly assessment.

2.6.10.6 Neuropathic pain scores

There is demand for health care practitioners to assess pain subjectively in individuals with DPN, regardless of whether they have clinical neuropathic symptoms (Abbott et al., 2011). This is because one third of all PWD in the UK have painful neuropathic symptom, regardless of whether or not they have been clinically diagnosed as having neuropathy (Abbott et al., 2011). However, while medication remains the initial choice for addressing neuropathic pain, therapeutic exercises represent a viable and economic alternative (Leitzelar and Koltyn, 2021).

Physiotherapy interventions used to relieve neuropathic pain include electrotherapy, such as transcutaneous electrical nerve stimulation (TENS), electro-acupuncture, acupuncture and low-level laser, in addition to Thai massage and foot massage (Akbari et al., 2020; Nupoor and Sripriya, 2022).

Recently, two SRs reported that various physiotherapy interventions can relieve neuropathic pain in individuals with DPN (Akbari et al., 2020; Nupoor and Sripriya, 2022). However, the study by Toth et al. (2014), which utilised balance and aerobic training exercises with individuals with DPN, failed to find significant changes in their neuropathic pain, compared with the control group. The level of pain experienced by the participants in the study, which was an RCT, was assessed using the VAS scale. The generalisation of the study's findings may be limited, due the fact that the participants were recruited from primary care and tertiary care clinics, as well as by the fact that there was small sample size, a high dropout rate and an inappropriate exercise programme (Toth et al., 2014).

Since disagreement remains in the extant literature regarding the relieving effect of exercises for neuropathic pain among PWD and those with DPN, there is a need to enhance understanding of the value of exercise for relieving pain and enhancing overall well-being (Butchart et al., 2009). Consequently, physical activity should be encouraged among individuals with DPN (Colberg et al., 2016), an issue discussed further in the next section. Therefore, the present study evaluated pain levels, both pre and post a progressive WB training programme and at every weekly assessment.

2.6.10.7 Physical activity level

A range of questionnaires exist to assess the level of physical activity in PWD and individuals with DPN, including the 'patient neurotoxicity questionnaire' and the 'generic quality of life measure: health status questionnaire' (SF-36) (Kutty and Majida, 2013; Mi et al., 2020). The patient neurotoxicity questionnaire is a five-point Likert scale, which assesses the impact of motor and sensory disturbance on activity of daily living (ADL) (Mi et al., 2020). The study by Gillani et al. (2018) employed the validated Arabic version of the Baecke physical activity questionnaire to assess physical activity levels among the participants and a strong negative correlation was found between the level of physical activity assessed by the questionnaire and individuals with type II DM in the Saudi population. This questionnaire uses a five-point Likert scale that evaluates energy consumption according to three indices: work, sport and leisure time (Baecke et al., 1982).

Therefore, this questionnaire was employed by the present study conducted for this thesis, as its validity and reliability were demonstrated previously among adults with a medium to high level of education (Tebar et al., 2022) and the validity and reliability of the Arabic version was confirmed by Gillani et al. (2018). In addition, it is short and simple to complete, thereby reducing the burden on the participants (Tebar et al., 2022) and demonstrates good validity and better accuracy and sensitivity, compared with a wearable accelerometer transducer worn among community-dwelling adults, particularly those with a medium to high level of education level (Tebar et al., 2022). Although the ADA recommended that an accelerometer with wearable sensors and other such technological devices be used to monitor blood glucose levels, for the purpose of improving the quality of life of PWD and individuals with DPN, especially during the Covid-19 lockdown periods, which the benefits were demonstrated (ADA, 2019; Elsayed et al., 2023b) the cost of such devices, the complexity of their data processing, their calibration techniques, energy efficiency and patient acceptance are prohibitive for their widespread use (Arvidsson et al., 2019; AlShorman et al., 2021). Therefore, the present study employed the Arabic version of the Baecke physical activity questionnaire to monitor the physical activity level pre and post a progressive WB training programme training, with PWD and Individuals with DPN.

In summary, the above section explored the effect of balance training and other physical therapy interventions on static balance, dynamic balance, muscles strength, neuropathic severity, pain and physical activity level among PWD and individuals with DPN.

2.7 Summary

This chapter discussed the definition of balance, DM and DPN, along with the classification of the severity of DPN and its signs and symptoms, definitions and types of balance, along with postural responses, balance during standing and the internal and external factors that can affect static balance and WB performance. A lack of consensus emerged regarding the factors that affect static balance and WB performance; thus, the present study investigates these factors using a comprehensive approach. Additionally, the physiology of DPN disease and its impact on balance were explored, along with the approaches to, and devices employed for balance assessment and training among PWD and individuals with DPN. Although WB training is recommended widely for improving balance and is employed in clinical practice, since there remains a gap in the literature regarding its effectiveness among the elderly, PWD and individuals with DPN. Thus, there is a need to address this by exploring the effectiveness and efficacy of WB training among these individuals, to investigate its effect on static balance and WB performance and the mechanisms underpinning the findings. These issues formed the three distinct focuses of the present thesis. The next chapter explains the first study's method and methodology, explores the results and findings of this study and discusses these findings and relates them to the current literature.

Chapter 3: Study one: Systematic review (SR) of the efficacy and efficiency of wobble board (WB) training in elderly populations

Chapter two provided evidence supporting the potential value and importance of wobble board (WB) balance training programme for improving balance among elderly. However, there is a gap in the literature regarding its effectiveness among those population. Thus, there is a need to address this issue by exploring the effectiveness and efficacy of WB training among those individuals. Therefore, the aim of study one is to conduct a systematic review (SR) to investigate the efficacy of WB training for improving balance among elderly. Due to its rigorous approach to searching, which involves applying specific inclusion and exclusion criteria, a SR appraises evidence critically, assessing for risks of bias (Munn et al., 2018). Moreover, when performing a SR, the researcher summarises each individual study, to generate a “summary of findings” to answer specific questions to enhance clinical practice, compared to other types of review, such as narrative and scoping, which do not include the synthesis of data (Munn et al., 2018).

This chapter is divided into three sections. Firstly, the method utilised in this study will be identified. Second the results and findings of this SR will be explored. Finally, those findings will be discussed related to the literature about efficiency and efficacy of WB training for the elderly.

3.1 Methods and methodology of study one

3.1.1 Methods and material of study one

The SR was conducted in accordance with the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). The majority of SRs concentrate on issues concerning the efficacy of medical intervention (Munn et al., 2018), this SR, however, aims to explore the efficacy and effectiveness of WB training among the elderly population. SRs typically formulate research questions following a Population, Intervention, Control and Outcomes (PICO) approach (Munn et al., 2018). Therefore, to determine a suitable research question for this SR, the PICO approach was applied. The population in this context were the elderly, the intervention was balance training, specifically the WB training or training on any other similar movable surface, the control was the healthy control group and the outcomes were the balance outcome measures.

3.1.2 Search strategy

A search of the literature was systematically undertaken during the period of July - August 2020, using a number of electronic databases, including Medline, Scopus, EBSCO, CINAHL, Science Direct and Google Scholar. The search employed Boolean logic, that means using conjunction, such as, and, or to join the key terms (Higgins et al., 2019), as listed in Table 2 and focused solely on peer-reviewed journals and English language articles, as well as scanning reference lists to identify additional relevant articles. Following the removal of duplicates, this resulted in a total of 261 articles of interest, for which the titles and abstract were screened to remove those lacking relevance to the research question. A full- text review of twenty remaining articles was subsequently independently undertaken by two authors against established inclusion and exclusion criteria. This search strategy is explained in further detail in Figure 7, following the PRISMA flow diagram.

Table 2. Search terms using Boolean logic.

Key concept	Search terms
Older adult	Elderly OR Aged OR Older OR Elder OR Geriatric OR Elderly people OR Old people OR Senior
	AND
Wobble board	Wobble board OR Wobbleboard OR Wobble platform OR Unstable platform OR Biomechanical ankle platform OR Ankle disc platform OR Balance platform OR balance board OR Balance board Electronic OR Tiltboard OR Balance disc OR Dynadisc OR Unstable surface
	AND
Balance	Balance OR Static balance OR Dynamic balance OR Postural balance OR Postural stability OR Postural control OR Postural sway OR Standing sway OR Standing balance OR Perturbation OR Proprioceptive* OR Somatosensory OR Neuromuscular OR Sensorimotor
	AND
Exercise	Exercise OR Exercises OR Activity OR Intervention OR Training

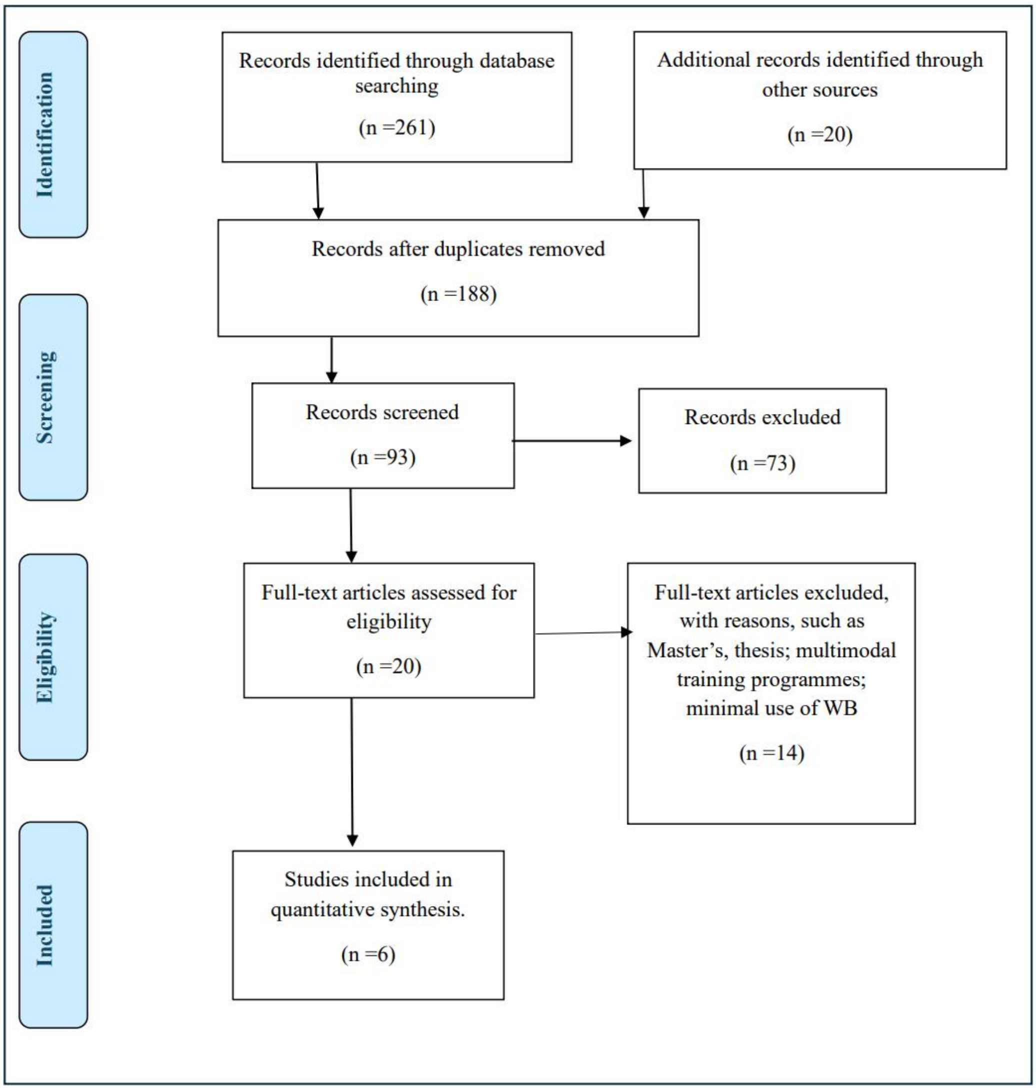


Figure 7. PRISMA flow-diagram of search strategy.

3.1.3 Inclusion and exclusion criteria

Since this review focused on the elderly, it only included studies of healthy older adults, that is, those healthy individuals aged sixty and above. In addition, the intervention needed to be based on WB training and assessment measuring a specific balance outcome. All balance outcome measures, that the studies reported, were included in this review and no decisions were made, a priori, about which balance outcome measures were to be included or excluded. Therefore, the study excluded: (1) multimodal intervention studies; (2) those containing any declared neurological, rheumatological, vestibular, vascular or musculoskeletal disorder, considered likely to affect balance; (3) studies written in non-English language; (4)

any conference proceedings, theses or discussion pieces and (5) based on methodological quality, no studies were excluded.

3.1.4 Quality index and data extraction

The study used the modified version of the Downs and Black (1998) checklist to assess the methodological quality of the selected studies. This was chosen, due to being confirmed as a robust and valid tool for literature appraisal and capable of being applied to both randomised and non-randomised studies (Downs and Black, 1998). Quality appraisal was completed by two researchers, each blinded to the other's scores and the results compared, with any discrepancies resolved by means of consensus.

The studies from which data could be extracted for variables reported in more than one article were identified and used to calculate the overall weighted average percentages, which was the sum of ESs. This ES was calculated based on the differences between means for post and pre values of a certain balance test divided by pooled standard deviation (SD), this calculation is called Cohens d (Field, 2017). Pooled SD is an overall SD for two or more SDs, if the sample sizes are similar and calculated by the sum square of pre and post scores of SD from the sample (Field, 2017).

3.2 Results and findings of study one

3.2.1 Study selection and characteristics

The search strategy for the SR identified six relevant studies, consisting of four randomised controlled trials (RCTs) (Schilling et al., 2009; Hande et al., 2014; Ogaya et al., 2011; Smee et al., 2014); one pilot study (Dougherty et al., 2011); and one repeated measure single-subject design (Kosse et al., 2011). In total, 149 healthy elderly participants (who aged sixty years and over) received balance training by means of WB, in studies undertaken in the Netherlands, America, Canada, Australia, Japan and India.

3.2.2 Intervention

The nature of WB training varied and involved rocking horizontally and laterally to achieve balance, and then stabilise, keeping a WB level, following an on-screen cursor and utilising the WB as an input into exercise-gaming or performing closed kinetic chain exercises, such as squats and lunges. All of the studies employed a WB, apart from Dougherty et al. (2011), who used an IndoFLO balance board, which acts in a similar manner, being a flat board with an unstable base. The IndoFLO ® Balance Cushion acts as a multiaxial fulcrum, onto which a board is placed.

The period of WB training ranged between three and sixteen weeks, with a mean of eight weeks. This period of WB training assisted the author in planning for the subsequent study conducted in PWD and individuals with DPN. The training frequency ranged between three and four sessions per week, with a mean of three sessions per week. The single training session lasted between six and thirty minutes (mins), with a mean of fifteen mins.

3.2.3 Outcome measures

The studies employed several multidimensional balance outcome measures. Three studies used the TUG test (Schilling et al., 2009; Ogaya et al., 2011; Hande et al., 2014). One utilised the Continuous Scale-Physical Functional Performance 10 (SCS-PEP10) (Smee et al., 2014) and three studies used The Berg Balance Scale (BBS) (Kosse et al., 2011; Hande et al., 2014; Dougherty et al., 2011). In addition, three studies assessed postural sway (Schilling et al., 2009; Ogaya et al., 2011; Kosse et al., 2011), which involved tasks ranging from double leg stance (DLS), tandem stance, which refers to placing the toes of one foot directly in front of the heel of the other foot (Schilling et al., 2009) and single leg stance (SLS) (Schilling et al., 2009; Ogaya et al., 2011).

3.2.4 Methodological quality

All of the studies were assessed independently, using the Modified Downs and Black appraisal checklist, which results in a maximum of 27 points, with all found to score between 15 and 23. Despite many of the studies sharing common threats to validity, none were excluded due to their poor methodological quality. Overall, these studies produced an improvement in at least one balance-related outcome measure.

The studies from which data could be extracted for variables reported in more than one article were identified and used to calculate the overall weighted average percentages. The weighted average percentage improvement in BBS (or similar) was 4.4% and for TUG, 6.3%. The effect size (ES) was calculated with mean ES ranging from 0.09 (Ogaya et al., 2011) to 0.96 (Hande et al., 2014), as demonstrated in the forest plot (see Figure 8). This ES was calculated based on the differences between mean for post-values TUG and pre-TUG values divided by pooled standard deviation (SD). The weighted ES= 0.5, as demonstrated in the forest plot (see Figure 8). A forest plot is a crucial tool for displaying the effect size, providing a visual indication of the amount of research heterogeneity and summarizing data from individual studies in a single picture (Fagerland. 2015). Pooled SD was calculated by the sum square of SD for pre and post TUG values.

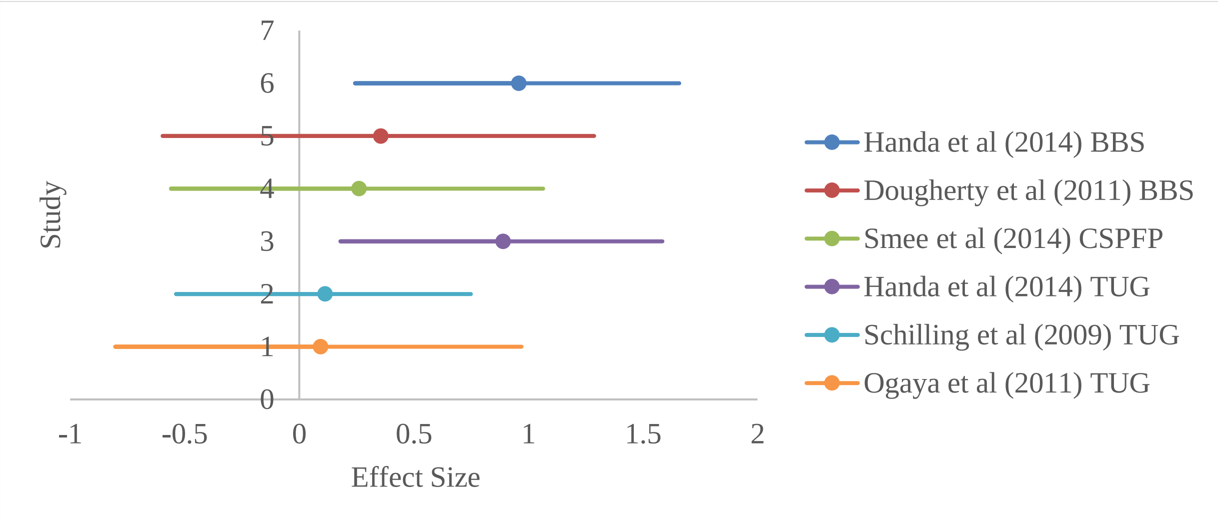


Figure 8. Forest plot for the effect of WB training on balance in elderly population.

3.2.5 Quality index and data extraction

The quality index of the six reviewed studies is listed in Table 3. As the focus of this review investigated the effectiveness of WB training programmes for improving the balance of healthy older adults, the data extraction concentrated on the type of balance board, the duration of the intervention and the balance measurement (Table 4).

Table 3. Methodological quality assessment results using a modified version of the Downs and Black appraisal tool (Downs and Black, 1998).

Author and date	Question number from the Downs and Black appraisal tool (Downs and Black, 1998)																											
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	Total
Smee et al. (2014)	y	y	y	y	y	y	y	n	y	y	y	y	y	n	n	y	y	y	y	y	y	y	n	n	y	y	y	22
Schilling et al. (2009)	y	y	y	y	y	y	y	y	y	y	y	y	y	n	n	y	y	y	y	y	y	y	y	n	n	y	y	23
Ogaya et al. (2011)	y	y	y	y	y	y	y	y	y	n	y	y	y	n	n	y	y	y	y	y	y	y	n	n	y	u	y	22
Kosse et al. (2011)	n	y	y	y	y	y	n	n	n	n	y	y	y	n	n	n	y	y	u	y	y	y	n	n	u	u	y	15
Dougherty et al. (2011)	y	y	y	y	y	y	y	n	y	y	y	y	y	n	n	n	y	y	u	y	y	y	n	n	y	y	y	19
Hande et al. (2014)	y	y	n	y	n	y	y	y	y	y	n	n	y	n	n	y	y	y	y	y	u	y	n	n	n	y	y	16

(1 = Yes, 0 = No or unable to determine; question 5, 2 = Yes; 1= partially 0 = No).

Table 4. Data Extraction concentrated on the type of balance board, the duration of the intervention and the balance measurement.

Author and date	Participants and study type	Type of WB and intervention	Balance Measurement	Findings
Smee et al. (2014)	• Aged 65-96 years (mean 77.7 years). • 16 participants in the WB group (7 females). • Recruitment was from the community dwelling centres. • RCT study	• Three sessions per week of six minutes (mins) for 16 weeks. • The WB group assigned for the following tasks: 1. Side-to-side rocking. 2. Forward/backward rocking. 3. Trying to maintain WB level. • Type of balance board: "standard" WB with 42 cm diameter.	• Continuous Scale-Physical Functional Performance 10 (SCS-PEP10).	• Significant increase in SCS-PEP10 balance domain: Pre 51.0 ± 12.7 and Post 54.2 ± 11.8.
Schilling et al. (2009)	• Aged 60-68 years. • 10 participants in WB group (5 females). • No information regarding the source of participants' recruitment. • RCT study.	• Three sessions per week of 15-30 mins for five weeks. • WB group assigned for the following tasks: • A mix of open and closed kinetic chain WB exercises, such as squats, lunges and reaching tasks. • Type of balance board: VersaDisc and Coredisc device.	• Postural sway from force plate performing the following standing tasks: 4. Single leg stance 5. Double leg stances, (both eyes open and closed). 6. TUG test. 7. ABC questionnaire.	• No significant difference in postural sway. • No significant difference in TUG test: Pre-TUG 5.6 ± 0.6 seconds (s) and Post-TUG 5.5 ± 0.6 s. • Significant increase in ABC questionnaire: Pre-ABC 92.8 ± 4.3% and Post-ABC 96.6 ± 3.6%

Author and date	Participants and study type	Type of WB and intervention	Balance Measurement	Findings
Ogaya et al. (2011)	• Aged > 70 years (mean 84.2 years). • 12 participants in the WB group (11 females). • Recruited from the same nursing home. • Double-blinded and controlled trial.	• Barefoot WB training: two sessions per week of 10 mins for nine weeks. • The WB group assigned for the following tasks: • Trying to maintain WB level. • Cursor matching task. • Three levels of progression for each task. • Restriction to forward/backword tilt. • Type of balance board: DYJOC board plus SV-200, (Sakai Medical Co. Ltd., Tokyo, Japan).	Postural sway from centre of foot pressure, measuring: 8. Single leg stance (SLS) standing time. 9. Unsupported standing time on balance mat. 10. Limit of stability. 11. Functional reach test. 12. TUG. 13. WB stance time.	• No significant difference apparent in the Root Mean Square (RMS) sway area: Pre 2.9 ± 2.4 cm^2 and Post 1.7 ± 0.9 cm^2. • No significant difference in SLS time: Pre 19.6 ± 30.0 s and Post 27.0 ± 40.2 s. • Significant increase in limit of stability AP excursion: Pre 8.7 ± 1.9 cm and Post 10.3 ± 2.5 cm. • No significant difference in the mean range of angular fluctuation: Pre 1.7 ± 1.2° and Post 0.9 ± 0.6° • Significant increase in standing time on WB: Pre 41.6 ± 41.6 s and Post 88.8 ± 38.8 s. • No significant difference in ML excursion: Pre 16.1 ± 3.4 cm and

Author and date	Participants and study type	Type of WB and intervention	Balance Measurement	Findings
				Post 14.3 ± 5.3 cm. • No significant difference in functional reach test: Pre 26.3 ± 8.6 cm and Post 22.9 ± 7.8 cm. • No significant difference in TUG: Pre 14.7 ± 13.6 s and Post 13.7 ± 6.8 s.
Kosse et al. (2011)	• Aged > 65 years (mean 77 years). • 10 participants in the WB group (5 females). • Recruited from 'older adults' apartments. • Repeated measure, single subject design.	• Three sessions per week of 20 mins for six weeks. • The WB group assigned for the following tasks: 14. Side-to-side rocking 15. Lateral rocking • Progressed to: Cursor matching tasks. • Type of balance board: SensBalance Fitness Board; Sensamove®, the Netherlands.	• Time to complete figure-of-eight walking test. • BBS. • Postural sway during the following tasks: 16. Tandem stances. 17. SLS with eyes open. 18. SLS with eyes closed.	No actual number reported. -Figure-of-eight test improved significantly. -BBS improved significantly. -Tandem stance and SLS with both eyes open and closed did not significantly improved.
Dougherty et al. (2011)	• Aged > 65 years (mean 74.8 years).	• 3 sessions per week of 10 mins for five consecutive weeks.	• BBS • Wii-Fit balance age (WFA) • ABC questionnaire	• Significant increase in BBS: Pre BBS 53.4 ± 2.2 and Post BBS 54.3 ± 2.6.

Author and date	Participants and study type	Type of WB and intervention	Balance Measurement	Findings
	• 9 participants in the WB group (3 females). • Participants were recruited from local community centre for older adults. • Pilot study.	• The WB group assigned for the following task: • Trying to maintain WB level. • Type of balance board: Indo Board Balance Trainer utilised IndoFLO ® Balance.		• No significant difference in WFA: Pre WFA 67.7 ± 11.0 years and Post WFA 66.2 ± 15.6 years. • Significant increase in ABC questionnaire: No reporting of actual values.
Hande et al. (2014)	• Aged ≥60 years. • 18 participants in the WB group. • Unavailability about sex breakdown. • No information was provided about the source of recruitment. • RCT study.	• Both groups: four sessions per week of four mins for three weeks • The WB group assigned for the following (15 mins) tasks: • Forward/backword rocking. • Side-to-side rocking. • Cursor matching task. • Type of balance board: Electronic Balance Board (EBB), (My Fitness Trainer MFT®)(www.myfitnesstrainer.net) .	• TUG • BBS • EBB	• A significant increase in TUG: Pre-TUG 15.4 ± 1.7s and Post-TUG 13.7 ± 2.1 s. • Significant increase in BBS: Pre-BBS 48.5 ± 3.1 and Post-BBS 50.8 ± 1.4. • Significant increase in EBB.MFT mediolateral: Pre 3.8 ± 0.3 cm and Post 3.3 ± 0.5 cm. • Significant increase in EBB.MFT anteroposterior: Pre 3.8 ± 0.3cm and Post 3.2 ± 0.3cm.

3.3 Discussion of study one

The aim of this SR is to investigate the efficacy of WB training to improve balance in elderly. Included studies in this SR assessed balance through multidimensional balance outcome measures, which refer to functional balance tests and assessment of balance impairment consequences in real environments during the performance of specific tasks, that resemble the ADL (Horak, 1987). Examples of these multidimensional balance outcome measures include: the Berg Balance Scale (BBS) and the Continuous-Scale Physical Function Performance Test 10 (CS-PFP10), as utilised in four of the cited studies (Dougherty et al., 2011; Kosse et al., 2011; Hande et al., 2014; Smee et al., 2014). Moderate effect of WB training was achieved by utilising these previous measures, (BBS or CS-PFP10), as indicated by a weighted average improvement in performance of 4.4% and increased effect size (ES) ranging from 0.35 (Dougherty et al., 2011) to 0.96 (Hande et al., 2014), as illustrated in the forest plot (see Figure 8). Additionally, overall moderate effect of WB training on the BBS (or similar), as indicated by an average ES of 0.61. This result reflects those of Dougherty et al. (2011) and Smee et al. (2014), who demonstrated improvement between 1.6% and 6.3% respectively, although specifically improved element/s cannot be determined, due to the multi-dimensional nature of the balance outcome measures and insufficiently detailed reporting.

Regarding static balance studies, two studies did not achieve improvement in postural sway post-WB training (Kosse et al., 2011; Ogaya et al., 2011). This might be explained because WB training does not specifically target the physiological measures which impact postural sway performance. Further explanation might be due to difficulty to respond to an inherently derived postural challenge, while remaining “relatively” still (Haines et al., 2007). This contrasts with the externally produced perturbation of the WB; possibly explaining why WB training does not affect postural sway. Final explanation might be due to considering balance as being a high task specificity (Kümmel et al., 2016), therefore, it is recommended to include tasks that are trained in as part of tests, used both in the pre- and post-training period (Giboin et al., 2015) (as discussed in chapter two).

Finally, in this SR, the period of WB training programmes that participants instructed to perform the prescribed WB exercises was ranging between 6 and 30 mins, two-three times per week, as shown in Table 4. However, the justification for the selected period was not provided.

3.4 Conclusion, limitations, clinical implications and future studies of study one

In summary, after WB training, balance is likely to show significant improvement when assessed during functional balance tests that assess multi-modal balance outcome measures, such as BBS. However, it is yet unknown whether this improvement exceeds beyond natural variability. This change in BBS after WB training can be expected to have a relatively moderate ES and small ES in TUG. However, WB training does not seem to have any effect on postural sway. Prescribing effective WB training with large ES can be achieved by motivation of focus and attention on the WB tilt, as well as training sessions with a duration up to 30 mins.

Therefore, it is recommended that future studies integrate dual tasks during WB training, with larger sample sizes. A further recommendation is to investigate whether carrying out specific types of cognitive task during WB training can enhance balance and thereby, reduce falls in the elderly. Thus, future studies are recommended to concentrate on specific manipulations in intervention to fully comprehend the optimal WB prescription in other populations who are at risk of falling, such as individuals with DPN. As such, this researcher planned to implement progressive WB training aiming to improve balance in those individuals, which is conducted in Study 3. However, before proceeding to implement an optimal WB intervention, there is a need to understand how to assess WB performance and investigate the factors that affect WB considered in the literature. Therefore, the next chapter (Chapter 4) will explore in detail the baseline characteristics that affect static balance assessment and WB performance.

Chapter 4: Study two: Observational study to investigate the impact of baseline characteristics including, biological sex, anthropometrics, footwear, dual tasking (DT) and physical activity level on static balance assessment and wobble board (WB) performance in healthy adults.

Chapter two provided evidence supporting the potential value and importance of wobble board (WB) balance training programme for improving balance among elderly. However, there is a lack of agreement in the literature regarding the real impact of biological sex, anthropometrics, footwear, dual tasking (DT) and physical activity on static balance and dynamic balance, defined as WB. Therefore, this study had two aims, as follows:

Aim 1: To explore the impact of previous factors, such as biological sex, anthropometrics, footwear, DT and physical activity level on static balance assessment using the stabilometric assessment device (Prokin 252) with healthy participants.

Aim 2: To explore the impact of previous factors, such as biological sex, anthropometrics, footwear, DT and physical activity level on WB performance, using the Prokin (252) with healthy participants.

This chapter is divided into three sections. Firstly, the methods and methodology utilised in this study will be explained. Second the results and findings of this second study will be investigated. Finally, those findings will be discussed related to the literature about the effect of those factors in comprehensive manner on both static balance and WB performance.

4.1 Methods and methodology of study two

4.1.1 Study design

The study employed an observational design; to minimise observer bias, the participants were unaware of research aims. Furthermore, there was a structured standardised protocol to be used with all participants.

4.1.2 Participants

The participants consisted of eighty-six healthy adult students, of whom forty-four were female (mean age 22.2±1, height 1.60±0.59 meter (m), weight 62.5±12.3 kilogram (Kg) and body mass index (BMI) 24.4±4.2 Kg/m^2) and forty-two were male (mean age 22.0±1.2, height 1.74±0.83 m, weight 78.3±23.8 Kg and BMI 25.8±7.6 Kg/m^2). Recruitment was undertaken by means of media advertisements at the following three universities: (1) The college of health and rehabilitation sciences and college of medical science at Princess Nourah bint Abdulrahman University; (2) Prince Sattam bin Abdulaziz University: and (3) King Saud University, Saudi Arabia.

Justification for choosing healthy participants, is due to a need to determine 'normal responses' prior to a balance assessment by testing the apparatus (Cook and Horak, 1986). Additionally, since the aim of the study was to determine the factors that might affect balance it was considered beneficial to assess safety with healthy students first. Data collected from healthy individuals provides a baseline regarding the factors affecting balance, which can be applied when investigating vulnerable to falling PWD and DPN.

4.1.3 Sample size

Based on data from Puszczalowska-Lizis et al. (2018) the predicted impact of effect size (ES), which describes the ratio of change to standard deviation (SD) and it is calculated using a statistical method for calculating the ES called Cohen's d=0.85, with an alpha level of 0.004 and a beta of 0.008, necessitated the selection of forty-one participants per group, to ensure a sufficient ES, which could then be calculated with G power software, which is a statistical software utilised to calculate the sample size and other statistical tests (Faul et al., 2007). Bonferroni corrections were applied, because this is statistical adjustment used to reduce the chance of obtaining type I error (false-positive result), which applies, when there are multiple comparisons to determine the criterion of significance value (Field, 2017). Thus, these corrections were applied in this study in response to repeated pairwise comparisons, reducing alpha to 0.004, which was obtained by dividing 0.05 by the number of pairwise comparisons, which were 12 comparisons, these were the following tasks; double leg stance eyes open shod (DLSEOS), double leg stance eyes closed shod (DLSECS), single leg stance shod (SLSS), double leg stance eyes open unshod (DLSEOUS), double leg stance eyes closed unshod (DLSECUS), single leg stance unshod (SLSUS), double leg stance eyes open dual tasking shod (DLSEODTS), double leg stance eyes closed dual tasking shod (DLSECDTS), single leg stance dual tasking shod (SLSDTS), double leg stance eyes open dual tasking unshod (DLSEODTUS), double leg stance eyes closed dual tasking unshod (DLSECDTUS) and single leg stance dual tasking unshod (SLSDTUS), for 2 outcome variables (perimeter and ellipse area), as this formula: 0.05/12 = 0.004. For the comparison between with footwear, as opposed to without footwear and single versus DT analyses, the alpha was reduced to 0.008, obtained by dividing 0.05 by the number of pairwise comparisons, which were 6 comparisons, which were the following tasks with footwear versus without footwear; DLSEOS, DLSEOUS, DLSECS, DLSECUS, SLSS, SLSUS and the following single tasks versus DT; DLSEO, DLSEODT, DLSEC, DLSECDT, SLS and SLSDT, for 2 outcome variables (perimeter and ellipse area) as this formula: 0.05/6 = 0.008.

4.1.4 Ethical approval

All of the participants in this study were required to sign a written informed consent form prior to experimentation, according to the Declaration of Helsinki, approved through the Princess Nourah bint Abdulrahman University Institutional Human Ethics Committee. This ethical approval can be found in Appendix 2.

4.1.5 Inclusion and exclusion criteria

Participants were excluded from this study if they were subject to the following conditions:

- Lower limb injury, lower limb pain, or lower back pain, as lower limb injury or pain might impact balance performance or place the participant at risk of further injury, (in accordance with Hrysomallis, 2007). This is due to the fact that any impairment in underlying systems that affect balance, which are the musculoskeletal and nervous system in this case, will result in constraint in the balance ability (Cook and Woollacott, 2016).
- A history of surgery.
- Vestibular conditions or visual problems having a potential impact on balance within the previous twelve months.

- Rheumatological or neurological disorders capable of impacting balance within the previous twelve months.
- Self-declaring of current pregnancy.
- Acutely unwell at the time of testing.

4.1.6 Application and justification of the stabilometric assessment device (Prokin, 252)

The Prokin 252 device, as previously discussed in chapters one and two (Prokin 252, TecnoBody, 2021), was selected for the assessment of static balance and WB performance, due to its relatively high levels of reliability and validity of the assessment of static balance (Wang et al., 2011) and the minimisation of rater error and bias, due to capturing data through the measuring system, rather than the examiner (Brenton-Rule et al., 2012). Recently, high reliability and moderate validity were reported during static and dynamic balance assessments for incomplete spinal cord injury (Jain et al., 2023). Furthermore, it acts as a stabilometer for assessing static balance and consists of four strain gauges (force-transducers) underneath the Prokin (252) the device resembles a 55 cm diameter WB, its tilt sensitivity is 0.1° (Prosperini et al., 2013) and the sampling frequency is 40 Hertz (Hz) (Arcuria et al., 2020). This sensitivity indicates high Prokin's precise ability to detect very small tilt angles or inclinations to a resolution of one-tenth of a degree (Prokin 252 software, 2015). Response signals are computed for analysis of the CoP, after detecting the platform displacement position. Furthermore, it has 50 levels of instability that can be useful when planning a progressive training programme. Additionally, a major concern when using a balance device is safety and the Prokin (252) is equipped with a surrounding handrail to assist in case of imbalance (ProKin 252, TecnoBody, 2021) (see Figure 9). Finally, this device can function as both FP and instrumented WB to assess balance statically and dynamically.

Figure 9. The Prokin (252) device. Adopted from Prokin 252 software, 2015.

1) Touch Screen display 17” with 1024x768 pixel resolution, 2) Adjustable display height, 3) Dynamic platform with 55-centimetre (cm) diameter, 4) Support platform and assistance 110x110 cm ground elevation of 21 cm., 5) Trunk sensor and 6) Safety handrails.

4.1.6.1 Static balance

Static balance assessment can be performed by tracking the postural sway of the centre of pressure (COP) during a Romberg test, which requires performing a double leg stance (DLS) task with eyes open and closed and a SLS by selecting the static stability assessment option in the Prokin (252), as depicted in Figure 10. The arrow represents the postural sway of the CoP in both axes, which are X-axis and Y axis. In this study, the recorded static balance parameters were perimeter and ellipse area. Those parameters were chosen, since the perimeter (measured in mm), represents the CoP path length, which measures the total distance of CoP displacement travelled in both axes, which are X axis and Y axis and it has been shown to demonstrate good validity in many populations (Paillard and Noé, 2015).

Furthermore, the ellipse area (measured in mm^2), represents 90-95% of the total area covered in both directions, which are AP and ML directions and it is considered as an indicator of overall postural performance (Paillard and Noé, 2015). Additionally, small perimeter and ellipse area values, indicate better static balance performance (Paillard and Noé, 2015). Finally, a good reliability of both perimeter and ellipse area parameters have been established in physically active participants (Mauch and Kälin, 2011). Therefore, these two parameters have been chosen to assess static balance in both observational and experimental studies.

The static balance was assessed by this device using the static balance assessment test, where the platform remains static. Firstly, the tests were explained to the participants, who were then permitted three minutes (mins) to familiarise themselves with the specific task and the Prokin (252), as required for this study. The device was then calibrated, according to each participant's age, height, weight and BMI. Following this, the participants were assessed by the performance of a DLS, both with eyes open and closed, as well as SLS during static balance, where the force platform was positioned at the lowest challenging level, to confirm that the platform was static. The participants stood on the platform, both with their own training shoes and without shoes, in a standardised position according to the X axis and Y axis and was requested to look straight at the computer screen and keep his/her arms at their sides, without any visual feedback. Each task took thirty seconds and was completed three times. Once the task had been completed, the participant was given as much rest as required (a minimum of sixty seconds), before the next task. Additionally, a V-Shaped marker was positioned between both feet to ensure a standardised standing position. To assess postural stability during SLS, the participant was instructed to stand unassisted on their dominant leg, while the other leg was flexed off the floor, this was undertaken both with and without footwear. The dominant leg was determined as the preferred leg to kick a ball with. The participant completed three tests, each of thirty seconds, on both their dominant and non-dominant leg.

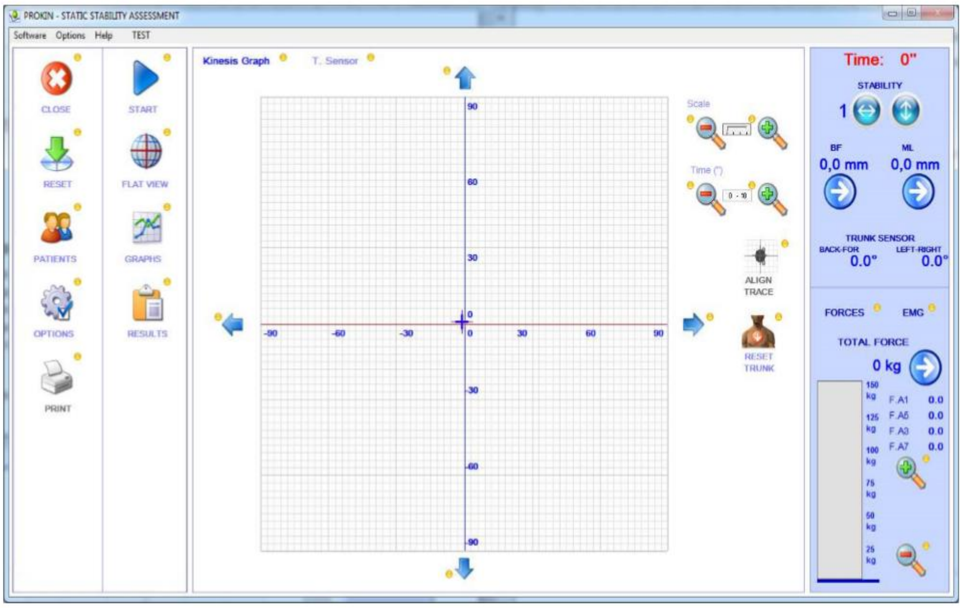


Figure 10. Static balance assessment, conducted by Prokin (252).

Adopted from Prokin (252) software, 2015. The arrow represents the postural sway of COP in both axes, which are X axis and Y axis.

4.1.6.2 Dynamic balance assessment (WB performance)

The dynamic balance was assessed by the Prokin (252), where the platform is unrestrained in all directions and with an instability degree of zero, indicating a level with high degree of instability, resembling a WB. As shown in Figure 11, the dynamic balance assessment was performed by selecting the equilibrium management option in the Prokin (252) to measure the inclination angle of the movable force platform, during both a DLS, with eyes open and closed and SLS tasks. Additionally, the time that the platform occupied one of five zones of inclination (tilt bandings), (named A, B, C, D and out) was calculated as a percentage of total time. Good balance ability was indicated by a greater time spent in zones A and B, called inner zone and calculated as the sum of the percentage time spent in A and B zones, indicating that the participant was able to remain within the centre of the force platform. By contrast, poor balance was shown by a greater percentage of time being spent within the C, D and out zones, called outer zone because the participant would be at the edge of the force platform.

The following parameters of dynamic balance assessment were assessed by the device as shown in Figure 11 as follows:

- Stability Index (°): This measures the dispersion around the weighted value, composed by the reference axis (Prokin (252) software, 2015). It represents the tilt angle behavior of the freely tilting center of the force platform.
- Time spent in A, B, C, D and out zones or tilt banding: these represent the percentage of time spent in each circle (zone), calculated in seconds (Prokin (252) software, 2015). The time spent in an inner zone, the sum of both A and B zones, represents the tilt angles (bandings) between 0 º and 6º absolute tilt. The time spent in outer zone, the sum of C, D and out zones, represents the tilt angles (bandings) being >6º of absolute tilt.

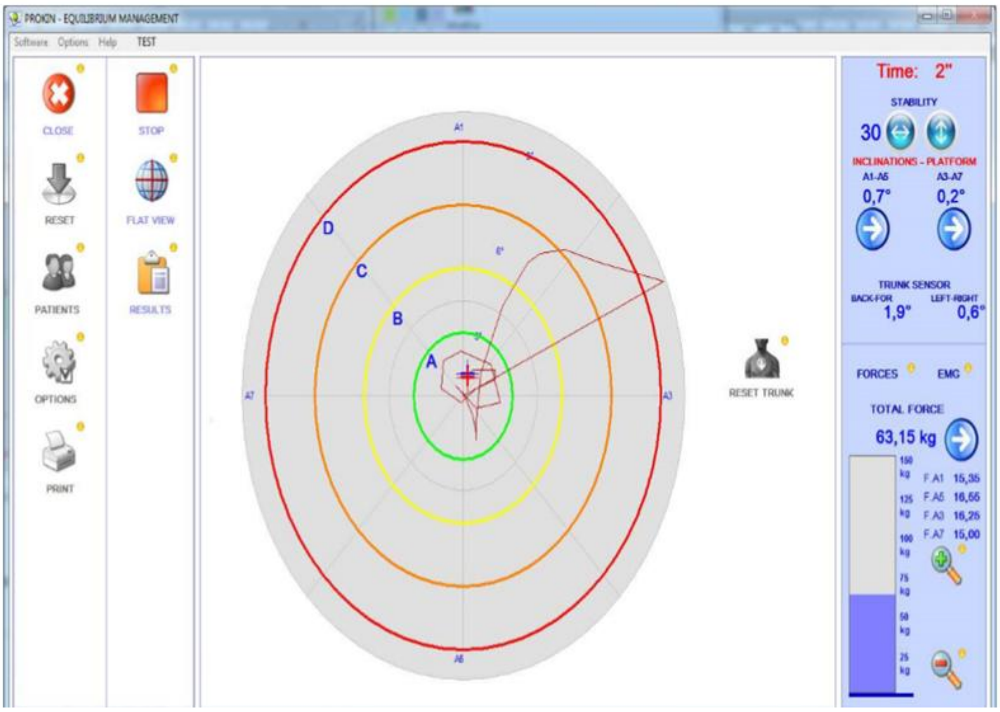


Figure 11. Dynamic balance assessment, provided by the Prokin (252) software, 2015.

All previous static and dynamic balance assessments were repeated with dual tasks (DT), with participants requested, in addition to their balance task, to count down from 100, subtracting 7, over 30 seconds. Calculation is commonly used as a DT to be performed simultaneously during postural task assessment (Paillard and Noé, 2015).

The order of the tasks with and without footwear, as well as with and without DT, was randomised using a random number generator (www.random.org), to minimise the learning effect.

4.1.7 Additional measurement

Anthropometric measures were collected during standing with a tape measurement, comprising of the following: hip circumference (which was around the greater trochanters); chest circumference (which was around the nipples), waist circumference (which was around the mid-point between the ilium and the umbilicus); shoulder circumference (which was inferior to the acromion process) (Acevedo et al., 2011). Based on the measurements obtained, the shoulder/waist ratio (SWR) was calculated by dividing the shoulder circumference by the waist circumference, while the shoulder/hip ratio (SHR) was determined by dividing the shoulder circumference by the hip circumference (Tovée, 2012). All previous anthropometrics were collected by the author (a physiotherapist with more than 10 years of experience). Habitual physical activity was measured using the Baecke questionnaire, which was previously validated in the literature (Baecke et al., 1982), as mentioned in chapter two. This questionnaire is based on the Likert scale and considered as a five-point scale, that represents energy consumption during work, sport and leisure time (Baecke et al., 1982). This questionnaire was chosen, due to its advantages of being short and simple to complete, therefore, reducing participant burden. Furthermore, this questionnaire was selected because it is valid and reliable among adults with medium to high levels of education (Tebar et al., 2022). This may be considered as an advantage because the level of education for the participants' study conducted for this thesis is the same, which was medium to high. Additionally, this questionnaire was translated into Arabic and this Arabic version was the same as that employed by Gillani et al. (2018).

During this experiment, the participants were offered no verbal or visual feedback or coaching. The level of pain was assessed using a VAS after each task. Each participant was asked to mark his/her perceived level of pain on a 10-cm VAS, where 0 indicated 'no pain' and 10 'unbearable pain' (see Figure 12).

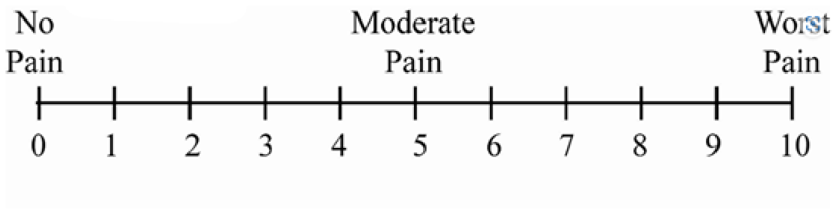


Figure 12. Visual Analogue Scale (VAS).

4.1.8 Data analysis

Static balance data and WB performance data were captured by the Prokin (252) software, representing the sway trace of the CoP used to generate both the ellipse area of the sway trace and the perimeter measurement of the sway trace length. The ellipse area represents the best fit for 95% of the sway trace area (in mm^2), while the perimeter determines the length of the sway trace (in mm).

The Prokin (252) software captured the WB performance data, representing the tilt angle behavior of the freely tilting center of the Prokin's force platform. This was used to produce both a stability index and the percentage of the time spent at various tilt angles within the bandings. The stability index, the average absolute tilt angle, was normalised for time, in both the AP axis and ML axis. The tilt angles (bandings or zones) were between 0^o and 6^o absolute tilt (defined as the inner zone) and $>6^o$ of absolute tilt (defined as the outer zone) and the percentage of the time in each zone was calculated.

4.1.9 Statistical analysis

The data were analysed by the statistical analysis software package SPSS version 26 (SPSS, Version 26.0. Armonk, NY: IBM Corp). Data were tested for normality and homogeneity of variance (the Shapiro-Wilk test). The effects of participant biological sex were analysed using the Mann-Whitney U tests because the majority of the data were found to be non-normally distributed. Furthermore, to determine if any differences across the biological sexes were due to height, balance scores were normalised for height and between sex comparisons were repeated. In addition, the Wilcoxon test was applied to examine the differing outcomes between wearing footwear and not wearing footwear and differences between single and DT and Spearman's rho correlations (R), which is a statistical test used to measure the strength of relationship between two variables, especially if the data were non-parametric (Field, 2017), thus, this test is selected in the present study, to determine the relationships between baseline characteristics and static balance performance, as well as between baseline characteristics and WB performance. Furthermore, Bonferroni corrections were applied, because this is statistical adjustment used to reduce the chance of obtaining type I error (false-positive result), which applies, when there are multiple comparisons to determine the criterion of significance value (Field, 2017). Thus, these corrections were applied in this study in response to repeated pairwise comparisons, reducing alpha to 0.004 between biological sex analysis and correlational analysis. Alpha was obtained by dividing 0.05 by the number of pairwise comparisons, which were 12 comparisons for 2 outcome variables (perimeter and ellipse area), as this formula: 0.05/12 = 0.004. For the comparison between with footwear, as opposed to without footwear and single versus DT analyses, the alpha was 0.008, obtained by dividing 0.05 by the number of pairwise comparisons, which were 6 comparisons for 2 outcome variables (perimeter and ellipse area) as this formula: 0.05/6 = 0.008. Finally, the ES was calculated according to the method outlined in Ricca and Blaine (2020) for non-parametric data, with ≥0.8 considered to be large (Sullivan and Feinn, 2012). Ricca and Blaine (2020) suggested a formula to calculate the ES, aiming to explore the treatment effects or effects due to group differences. This method is applicable when the data are non-parametric and it depends on the median absolute deviation (MAD), which is better than the commonly used method of Cohen's d, which depends on mean and standard deviation (SD) and is applicable for normally distributed data only (Ricca and Blaine, 2020). The formula used in this study, based on Ricca and Blaine's (2020) study, is displayed below (equation 1):

$$\Delta MAD = Median(S1) - Median\ (S2) / \ MAD\ pooled$$

Where, $MAD\ pooled\ = ((n1-1)\ MAD\ (S1)\ +\ (n2-1)\ MAD(S2))/n1 + n2 - 2$ (1)

Where, S1 and S2, are two independent samples, and n1 and n2 are data points respectively.

4.2 Results and findings of study two

Whilst conducting a broad literature review and SR it became evident that there is a lack of consensus regarding those factors that may influence both static and dynamic balance (defined as WB) performance). Thus, a study was designed and conducted to investigate those significant factors that may affect balance performance, as follows:

Firstly, to establish whether biological sex influences static balance assessment and WB performance. Secondly, to determine whether the assessment of static balance and WB performance is influenced by relative participant anthropometrics. Thirdly, to determine whether the wearing of footwear influences static balance and or WB performance. Fourthly, to identify the impact of dual tasking (DT) on static balance assessment and or WB performance. Finally, to investigate the effect of physical activity level on static balance assessment and or WB performance.

The results for each of these objectives are discussed in the section below.

4.2.1 Static balance assessment

The following sections examine the impact of biological sex, anthropometry, physical activity level, with footwear versus without footwear and single task versus DT on static balance.

4.2.1.1 Static balance assessment and biological sex

Static balance performance was assessed by the Prokin in both sexes, as illustrated in Table 5, during double leg stance with eyes open (DLSEO), double leg stance with eyes closed (DLSEC) and SLS with footwear and without footwear, as well as during single and dual taskings (DT). Overall, the data indicates that females were more stable than males, as indicated by reduced static balance parameters, which are perimeter of sway trace and ellipse area during all previous tasks and conditions. Additionally, closing eyes worsening the static balance performance for all static balance tasks, regardless of performing the static balance task with footwear and without footwear, single tasks or DT. Furthermore, adding a dual task worsened the static balance performance also, in all previous tasks. For example, static balance performance during DT with eyes closed was doubled (50%) worser than with eyes open tasks. Regarding footwear, static balance performance during DLSEC task without footwear was better than with footwear in females and males. However, males static balance performance with footwear was better than without footwear during SLS. Finally, the worst static balance performance was the SLS, regardless of with footwear and without footwear, single tasks or DT (see Table 5).

This study identified several significant differences between females and males during static balance assessments, with females consistently demonstrating a higher level of performance for all static balance tasks. Significant differences ($p \leq 0.004$) in perimeter of sway trace were observed during both with and without footwear, as well as single and DT with large effect size (ES) ≥ 0.9 for perimeter across all single balance tasks, along with some DTs both with and without footwear (see Table 5). There were also significant differences between females and males after normalisation of balance scores regarding height, for SLS and DLSEC without footwear, however, only the perimeter outcome measure reached statistical significance (P-value≤0.001) (Table 6). Large ES were also observed for the differences between females and males, following normalisation for height for the perimeter outcomes across SLS with footwear (Table 6).

Table 5. Results of static balance assessment as measured by perimeter and ellipse area and statistical testing determining if biological sex affects static balance performance with footwear (shod) and without footwear (unshod) conditions during single and dual tasks (median and interquartile range).

	Female Perimeter (mm)		**Male Perimeter (mm)**				**Female Ellipse Area (mm^2)**		**Male Ellipse Area (mm^2)**			
Task	**Med**	**IQR**	**Med**	**IQR**	**P-value**	**ES**	**Med**	**IQR**	**Med**	**IQR**	**P-value**	**ES**
With footwear												
DLSEOS	262	87	329	153	**0.001***	**0.94**$_{\varphi}$	121	115	155	204	0.056	0.53
DLSECS	367	147	480	204	**<0.001***	**1.03** $_{\varphi}$	212	207	311	283	0.040	0.75
SLSS	819	258	1019	331	**<0.001***	**1.15** $_{\varphi}$	401	217	558	384	0.005	**0.91** $_{\varphi}$
Without footwear												
DLSEOUS	240	97	297	120	**0.003***	**0.91** $_{\varphi}$	110	137	121	199	0.171	0.18
DLSECUS	323	98	407	165	**<0.001***	**0.99** $_{\varphi}$	149	212	237	221	0.011	**0.80** $_{\varphi}$
SLSUS	850	260	1122	433	**<0.001***	**1.09** $_{\varphi}$	450	357	546	271	0.037	0.55
Dual task												
DLSEODTS	296	162	350	188	0.026	0.62	172	195	197	230	0.286	0.27
DLSECDTS	406	165	539	235	**<0.001***	**1.04** $_{\varphi}$	222	258	322	395	0.035	0.65
SLSDTS	863	384	1057	317	**0.001***	**1.08** $_{\varphi}$	536	301	612	256	0.051	0.54
DLSEODTUS	276	174	317	115	0.616	0.55	168	383	138	148	0.314	-0.39
DLSECDTUS	346	129	400	235	0.030	0.63	148	291	219	198	0.412	0.66

	Female Perimeter (mm)		Male Perimeter (mm)				Female Ellipse Area (mm^2)		Male Ellipse Area (mm^2)			
SLSDTUS	870	421	1083	298	**0.001***	1.69 φ	505	300	568	297	0.074	0.39

DLSEOS; double leg stance eyes open shod, which refers to with footwear, DLSECS; double leg stance eyes closed shod, SLSS; single leg stance shod, DLSEOUS; double leg stance eyes open unshod, that refers to without footwear, DLSECUS; double leg stance eyes closed unshod, SLSUS; single leg stance unshod, DLSEODTS; double leg stance eyes open dual tasking shod, DLSEODTUS; double leg stance eyes open dual tasking unshod, DLSECDTS; double leg stance eyes closed dual tasking shod, DLSECDTUS; double leg stance eyes closed dual tasking unshod, SLSDTS; single leg stance dual tasking shod, SLSDTUS; single leg stance dual tasking unshod, * significant at $p \leq 0.004$, ES; effect size, φ Effect size ≥0.9, Med: median, IQR; interquartile range.

Table 6. Results of static balance performance as measured by perimeter and ellipse area normalisation by height and statistical testing determining if biological sex affects static balance performance with footwear (shod), without footwear (unshod) conditions during single and dual tasks (median and interquartile range).

	Female Perimeter/height (mm/cm)		**Male Perimeter/height (mm/cm)**				**Female Ellipse Area/height (mm^2/cm)**		**Male Ellipse Area/height (mm^2/cm)**			
Task	**Med/ Mean**	**IQR/SD**	**Med/Mean**	**IQR/SD**	**P-value**	**ES**	**Med**	**IQR**	**Med**	**IQR**	**P-value**	**ES**
Shod												
DLSEOS	1.65	0.52	1.90	0.86	0.020	0.62	0.76	0.70	0.88	1.16	0.201	0. 32
DLSECS	2.33[a]	0.63[b]	2.76[a]	0.74[b]	0.005[c]	0.07[d]	1.36	1.18	1.74	1.57	0.132	0.56
SLSS	5.01	1.69	6.05	1.64	0.014	**1.06 φ**	2.57	1.36	3.23	1.87	0.041	0.77
Unshod												
DLSEOUS	1.50	0.66	1.70	0.78	0.068	0.52	0.67	0.86	0.70	1.10	0.439	0.10
DLSECUS	1.97	0.57	2.34	1.09	**<0.001***	0.77	0.96	1.20	1.37	1.36	0.045	0.61
SLSUS	5.26	1.86	6.49	2.66	**0.001***	0.88	2.82	2.34	3.12	1.69	0.220	0.30
Dual task												
DLSEODTS	1.83	1.07	1.98	1.05	0.179	0.30	1.06	1.23	1.15	1.28	0.489	0.14
DLSECDTS	2.63[a]	0.81[b]	3.08[a]	0.87[b]	0.016[c]	0.23[d]	1.34	1.51	1.88	2.02	0.089	0.62
SLSDTS	5.39	2.33	6.02	1.93	0.075	0.60	3.27	1.86	3.53	1.52	0.303	0.29
DLSEDTUS	1.71	1.11	1.77	0.58	0.598	0.17	1.02	2.37	0.80	0.81	0.175	-0.48

	Female Perimeter/height (mm/cm)		Male Perimeter/height (mm/cm)				Female Ellipse Area/height (mm^2/cm)		Male Ellipse Area/height (mm^2/cm)			
Task	**Med/ Mean**	**IQR/SD**	**Med/Mean**	**IQR/SD**	**P-value**	**ES**	**Med**	**IQR**	**Med**	**IQR**	**P-value**	**ES**
DLSECDTUS	2.12	0.90	2.35	1.20	0.282	0.44	0.89	1.85	1.22	1.20	0.710	0.53
SLSDTUS	5.62	2.53	6.26	1.92	0.033	0.62	3.05	1.92	3.33	1.56	0.429	0.31

DLSEOS; double leg stance eyes open shod, which refers to with footwear, DLSECS; double leg stance eyes closed shod, SLSS; single leg stance shod, DLSEOUS; double leg stance eyes open unshod, that refers to without footwear, DLSECUS; double leg stance eyes closed unshod, SLSUS; single leg stance unshod, DLSEODTS; double leg stance eyes open dual tasking shod, DLSEODTUS; double leg stance eyes open dual tasking unshod, DLSECDTS; double leg stance eyes closed dual tasking shod, DLSECDTUS; double leg stance eyes closed dual tasking unshod, SLSDTS; single leg stance dual tasking shod, SLSDTUS; single leg stance dual tasking unshod, ES; effect size, IQR; interquartile range, Med; median, * significant at $p \leq 0.004$ level, $_{\varphi}$ Effect size ≥0.9, [a] Mean, [b] Standard deviation, [c] P-value of independent sample t-test, [d] Effect size calculated for parametric variables as mean/SD.

4.2.1.2 Static balance assessment and anthropometry and physical activity level

The mean for males' participants aged 22.0 ± 1.2 years, height 1.74 ± 0.083 m, weight 78.3 ± 0.023 kg and BMI (body mass index) 25.8 ± 7.6 kg/m2; and for females' participants' mean age 22.2 ± 1.8 years, height 1.60 ± 0.059 m, weight 62.5 ± 0.012 kg and BMI 24.4 ± 4.2 kg/m2. Static balance performance during DLSEO, DLSEC and SLS with footwear and without footwear, as well as during single and dual tasking (DT) were assessed to determine if there are any correlations between static balance variables and height, weight and anthropometric measurements, which were shoulder, waist, hip circumferences, shoulder/waist and shoulder/hip ratios and between physical activity level, as illustrated in Table 7 and appendix 9. Overall, height, weight, shoulder and waist circumference were correlated with all previous tasks during single and DT conditions. However, shoulder/waist ratio was correlated with simple tasks that performed all double leg stance (DLS), with single task condition, and this correlation was observed also during DT with DLSEC with footwear conditions and SLS without footwear condition. Physical activity level, shoulder/hip ratio and static balance variables were not correlated.

This study found a significant correlation between height, weight, shoulder and waist circumference and almost all double leg stance (DLS) and single leg stance (SLS), in both single and DT conditions. However, the degree of correlation was, at best, moderate, ranging between 0.308 – 0.487 (see Table 7 and appendix 9).

In addition, there was a significant correlation (P-value ≤ 0.004) between shoulder/waist ratio and almost all DLS balance variables (both with and without footwear) and single tasks, as shown in Table 7 and appendix 9. However, the magnitude of the correlation was found to be moderate, ranging between (-0.315 – -0.374). In DT, there was significant, moderate correlation between shoulder/waist ratio with two tasks: (1) double leg stance with eyes closed (DLSEC) with footwear (r=-0.341, -0.348 for perimeter and ellipse area respectively) and (2) SLS without footwear (r=-0. 330)(see Table 7 and appendix 9).

The directions of these correlations all suggest that the greater the height and weight, as well as shoulder and waist circumference, the poorer the static balance performance (see Table 7). However, no significant correlations were identified between physical activity level and static balance variables (see appendix 9).

Table 7. Spearman's rho **r** correlation between static balance assessment and anthropometric characteristics.

Confounding factor	Task/parameter	Correlation coefficient
Height (r)	**Shod**	
	DLSEOS (Perimeter)	**0.398***
	DLSEOS (Ellipse Area)	**0.359***
	DLSECS (Perimeter)	**0.436***
	DLSECS (Ellipse Area)	**0.373***
	SLSS (Ellipse Area)	**0.412***
	Unshod	
	DLSECUS (Perimeter)	**0.487***
	DLSECUS (Ellipse Area)	**0.385***
	SLSUS (Perimeter)	**0.344***
	Dual task	
	DLSECDTS (Perimeter)	**0.380***
	DLSECDTS (Ellipse Area)	**0.320***
	SLSDTS (Perimeter)	**0.325***
	SLSDTUS (Perimeter)	**0.370***
	SLSDTUS (Ellipse Area)	**0.313***
Weight (r)	**Shod**	
	DLSEOS (Perimeter)	**0.317***
	DLSEOS (Ellipse Area)	**0.394***
	DLSECS (Perimeter)	**0.339***
	DLSECS (Ellipse Area)	**0.341***
	Unshod	
	DLSEOUS (Perimeter)	**0.338***
	DLSEOUS (Ellipse Area)	**0.427***
	DLSECUS (Perimeter)	**0.414***
	DLSECUS (Ellipse Area)	**0.347***
	Dual task	

Confounding factor	Task/parameter	Correlation coefficient
	DLSECDTS (Perimeter)	**0.331***
	DLSECDTS (Ellipse Area)	**0.350***
	SLSDTUS (Ellipse Area)	**0.381***
Shoulder circumference (r)	**Shod**	
	DLSEOS (Perimeter)	**0.338***
	DLSEOS (Ellipse Area)	**0.320***
	DLSECS (Perimeter)	**0.368***
	Unshod	
	DLSEOUS (Perimeter)	**0.398***
	DLSECUS (Perimeter)	**0.320***
	DLSEOUS (Ellipse Area)	**0.477***
	DLSECUS (Ellipse Area)	**0.328***
	SLSUS (Perimeter)	**0.309***
	Dual task	
	DLSECDTS (Perimeter)	**0.363***
	SLSDTUS (Perimeter)	**0.322***
	SLSDTUS (Ellipse Area)	**0.308***
Waist circumference (r)	**Shod**	
	DLSEOS (Perimeter)	**0.392***
	DLSEOS (Ellipse Area)	**0.370***
	DLSECS (Perimeter)	**0.416***
	Unshod	
	DLSEOUS (Perimeter)	**0.380***
	DLSEOUS (Ellipse Area)	**0.368***
	DLSECUS (Perimeter)	**0.480***
	DLSECUS (Ellipse Area)	**0.355***
	Dual task	
	DLSECDTS (Perimeter)	**0.404***
	DLSECDTS (Ellipse Area)	**0.357***
	SLSDTUS (Perimeter)	**0.340***
	SLSDTUS (Ellipse Area)	**0.377***
Hip circumference (r)	**Shod**	
	DLSEOS (Ellipse Area)	**0.326***

Confounding factor	Task/parameter	Correlation coefficient
	Unshod	
	DLSEOUS (Ellipse Area)	**0.358***
Shoulder-Waist Ratio (r)	**Shod**	
	DLSEOS (Perimeter)	**-0.333***
	DLSEOS (Ellipse Area)	**-0.315***
	DLSECS (Perimeter)	**-0.374***
	Unshod	
	DLSEOUS (Perimeter)	**-0.356***
	DLSEOUS (Ellipse Area)	**-0.338***
	DLSECUS (Perimeter)	**-0.361***
	Dual task	
	DLSECDTS (Perimeter)	**-0.341***
	DLSECDTS (Ellipse Area)	**-0.348***
	SLSDTUS(Ellipse Area)	**-0.330***

r; spearman's rho correlation, DLSEOS; double leg stance eyes open shod, which refers to with footwear, DLSECS; double leg stance eyes closed shod, SLSS; single leg stance shod, DLSEOUS; double leg stance eyes open unshod, that refers to without footwear, DLSECUS; double leg stance eyes closed unshod, SLSUS; single leg stance unshod, DLSEODTS; double leg stance eyes open dual tasking shod, DLSEODTUS; double leg stance eyes open dual tasking unshod, DLSECDTS; double leg stance eyes closed dual tasking shod, DLSECDTUS; double leg stance eyes closed dual tasking unshod, SLSDTS; single leg stance dual tasking shod, SLSDTUS; single leg stance dual tasking unshod, * significant at $p \leq 0.004$.

4.2.1.3 Static balance assessment and with footwear versus without footwear

The static balance assessment and with footwear versus without footwear study demonstrated that balance during DLSEC was better without footwear than with footwear in females and males (significant P-values <0.001, 0.006 and 0.007) for female's perimeter and male's both perimeter and ellipse area respectively), but performance with footwear was better than without footwear for males during SLS with significant P-value=0.004, (see Table 8). Despite this, no large effect sizes were observed for any tasks. No further differences were observed across other tasks or variables in females or male.

Table 8. Results of significance testing and effect size calculation for the effect of being with footwear (shod) or without footwear (unshod) on static balance assessment.

	DLSEO with footwear vs without footwear		**DLSEC with footwear vs without footwear**		**SLS with footwear vs without footwear**	
	P-value	**ES**	**P-value**	**ES**	**P-value**	**ES**
Female						
Perimeter (mm)	0.091	-0.44	**<0.001***	-0.70	0.890	0.25
Ellipse Area (mm^2)	0.111	-0.25	0.009	-0.75	0.433	0.39
Male						
Perimeter (mm)	0.019	-0.56	**0.006***	-0.77	**0.004***	0.58
Ellipse Area (mm^2)	0.016	-0.63	**0.007***	-0.70	0.57	-0.08

DLSEO; double leg stance eyes open, DLSEC; double leg stance eyes closed, SLS; single leg stance, * significant at $p \leq 0.008$ level, ES; effect size, vs; versus.

4.2.1.4 Static balance assessment and single versus dual tasking

The static balance assessment and single versus dual tasking study demonstrated that balance during DLSEC task was better with a single task than dual tasks during DLSEC with footwear for both sexes and without footwear in females only; as measured by perimeter (significant P-values= 0.003, 0.001 and 0.004 in females and males respectively). Additionally, this study demonstrated that balance during DLSEO was better with single task than dual tasking for females only during DLS without footwear, with large effect size (ES) ≥ 0.9, for ellipse area across both DLSEO without footwear and SLS with footwear in females only (see Table 9).

Despite this, no large effect sizes were observed for any tasks in males. No further differences were observed across other tasks or variables in females or males.

Table 9. Results of significance testing and effect size calculation for the effect of single and dual tasking on static balance assessment.

	With footwear single task vs dual task						Without footwear single task vs dual task					
	DLSEO		**DLSEC**		**SLS**		**DLSEO**		**DLSEC**		**SLS**	
	P-value	**ES**	**P-value**	**ES**	**P-value**	**ES**	**P-value**	**ES**	**P-value**	**ES**	**P-value**	**ES**
Female												
Perimeter (mm)	0.016	-0.60	**0.003***	-0.47	0.360	-0.32	**<0.001***	-0.73	**0.001***	-0.41	0.427	-0.12
Ellipse Area (mm^2)	0.024	-0.78	0.340	-0.10	0.019	-1.23 $_{\varphi}$	**0.002***	-0.92 $_{\varphi}$	0.116	0.01	0.068	-0.41
Male												
Perimeter (mm)	0.075	-0.29	**0.004***	-0.53	0.423	-0.25	0.684	-0.38	0.159	0.085	0.247	0.22
Ellipse Area (mm^2)	0.129	-0.55	0.925	-0.08	0.179	-0.34	0.375	-0.30	0.764	0.17	0.406	-0.16

DLSEO; double leg stance eyes open, DLSEC; double leg stance eyes closed, SLS; single leg stance, * significant at $p \leq 0.008$ level. ES; effect size, $_{\varphi}$; Effect size ≥0.8, vs; versus.

4.2.2 Wobble board (WB) performance

4.2.2.1 WB performance and biological sex

WB performance was assessed by the Prokin in both sexes, as illustrated in Table 10, during DLSEO, DLSEC and SLS with footwear and without footwear, as well as during single and dual tasking (DT). Overall, females were more stable during WB testing than males, as indicated by reduced WB performance parameters, which were the stability indices during all previous tasks and conditions. Furthermore, adding a DT worsened the WB performance during all previous tasks. Closing the eyes worsened the WB performance for all WB tasks, regardless of task performance, with footwear and without footwear, single tasks or DT. For example, WB performance during eyes closed tasks were 50% worse than with eyes open tasks. Males outperformed females, as measured by percentage of time in each tilt banding or inclination zones, during SLS without footwear DT (see Table 11).

The study found statistically significant differences between males and females, with females demonstrating a better WB performance across all tests, as measured by stability indices. This was evidenced during DLSEC for (both with and without footwear), for both anteroposterior stability index (APSI) with significant P-value = 0.001 and mediolateral stability index (MLSI) with significant P-value < 0.001, DLSECDT (without footwear) for AP stability index only P-value < 0.001, DLSECDT (both with and without footwear) for ML stability index significant P-values = 0.001 and 0.004, respectively and DLSEO (without footwear) for AP stability index only with P-value = 0.003 (see Table 10), with large effect size (ES) ≥0.8. No statistically significant differences were identified between males and females regarding the percentage of time spent in each tilt angle bandings or inclination zones, both with and without footwear, for single or DT. The exception was SLS without footwear DT (see Table 11), when males demonstrated better performance, as significant P-value = 0.001. However, females were found to perform better than males during DLSEC, with footwear, single task and without footwear DT, where large ES ≥0.8 were observed.

Table 10. Results of wobble board (WB) performance as measured by stability indices and statistical testing determining if biological sex affects WB performance with footwear (shod) and without footwear (unshod) conditions during single and dual tasks (median and interquartile range).

	Female APSI (°)		Male APSI (°)				Female MLSI (°)		Male MLSI (°)			
Task	**Med**	**IQR**	**Med**	**IQR**	**P-value**	**ES**	**Med**	**IQR**	**Med**	**IQR**	**P-value**	**ES**
With footwear												
DLSEOS	3.80	2.17	4.36	2.82	0.113	0.51	5.19	2.67	5.82	3.82	0.406	0.35
DLSECS	7.81	3.06	9.96	2.35	**0.001***	**1.34** φ	7.65	2.68	9.94	2.09	**<0.001***	**1.40** φ
SLSS	3.66	1.84	4.11	2.64	0.045	0.42	4.99	2.49	5.36	3.33	0.178	0.25
Without footwear												
DLSEOUS	3.78	1.91	5.38	2.92	**0.003***	**0.91** φ	4.75	2.68	5.68	4.01	0.090	0.56
DLSECUS	8.22	2.84	10.12	3.06	**0.001***	**1.10** φ	8.13	2.72	9.78	2.26	**<0.001***	**1.15** φ
SLSUS	3.83	2.01	4.19	1.80	0.110	0.37	4.89	3.17	5.38	2.70	0.417	0.33
Dual task												
DLSEODTS	4.05	1.97	5.21	3.40	0.013	0.76	5.53	2.83	7.18	4.04	0.245	**0.81** φ
DLSECDTS	8.21	2.54	9.45	2.94	0.005	**0.96** φ	7.83	2.51	9.78	2.79	**0.001***	**1.31** φ
SLSDTS	4.34	1.88	4.53	2.41	0.061	0.19	5.46	2.00	6.55	3.97	0.082	0.61
DLSEODTUS	4.43	2.09	5.04	4.02	0.020	0.42	5.77	2.85	6.73	4.14	0.276	0.54
DLSECDTUS	8.06	3.14	10.13	2.97	**<0.001***	**1.19** φ	8.39	2.25	9.51	2.25	**0.004***	**0.90** φ

	Female APSI (°)		Male APSI (°)				Female MLSI (°)		Male MLSI (°)			
Task	**Med**	**IQR**	**Med**	**IQR**	**P-value**	**ES**	**Med**	**IQR**	**Med**	**IQR**	**P-value**	**ES**
SLSDTUS	4.12	2.01	4.24	2.41	0.188	0.12	4.98	2.42	5.51	3.40	0.344	0.35

Med; Median, IQR; interquartile range, APSI; anteroposterior stability index, MLSI; mediolateral stability index, IQR; interquartile range, DLSEOS; Double leg stance eyes open shod, DLSECS; Double leg stance eyes closed shod, SLSS; Single leg stance shod, DLSEOUS; Double leg stance eyes open unshod, DLSECUS; Double leg stance eyes closed unshod, SLSUS; Single leg stance unshod, DLSEODTS; double leg stance eyes open dual tasking shod, DLSECDTS; double leg stance eyes closed dual tasking shod, SLSDTS; Single leg stance dual tasking shod, DLSEODTUS; double leg stance eyes open dual tasking unshod, DLSECDTUS; double leg stance eyes closed dual tasking unshod, SLSDTUS; Single leg stance dual tasking unshod, * significant at $p<0.004$ level, ES; effect size, $_{\varphi}$ effect size ≥0.8.

Table 11. Results of wobble board (WB) performance as measured by percentages of time in inner and outer zones and statistical testing determining if biological sex affects WB performance with footwear (shod) and without footwear (unshod) conditions during single and dual tasks (median and interquartile range).

	Female		**Male**				**Female**		**Male**			
	% time inner zone		**% time inner zone**				**% time outer zone**		**% time outer zone**			
Task	**Median**	**IQR**	**Median**	**IQR**	**P-value**	**ES**	**Median**	**IQR**	**Median**	**IQR**	**P-value**	**ES**
With footwear												
DLSEOS	16	23	19	26	0.151	0.29	85	22	81	25	0.123	-0.33
DLSECS	3	6	2	3	0.058	**-1.00** φ	97	5	99	4	0.082	**1.00** φ
SLSS	9	23	14	18	0.134	0.39	92	23	87	18	0.145	-0.48
Without footwear												
DLSEOUS	17	23	17	28	0.762	0.00	83	22	84	28	0.762	0.11
DLSECUS	4	6	2	6	0.135	-0.75	97	6	98	5	0.299	0.50
SLSUS	12	26	19	19	0.181	0.59	89	26	82	20	0.192	-0.54
Dual tasking												
DLSEODTS	9	12	10	21	0.259	0.19	91	13	91	21	0.309	-0.07
DLSECDTS	2	5	2	4	0.546	0.00	98	5	98	3	0.580	0.00
SLSDTS	6	15	9	18	0.122	0.41	95	15	92	18	0.144	-0.44
DLSEODTUS	9	11	14	23	0.303	0.56	92	10	87	24	0.278	-0.59

	Female		Male				Female		Male			
	% time inner zone		% time inner zone				% time outer zone		% time outer zone			
Task	**Median**	**IQR**	**Median**	**IQR**	**P-value**	**ES**	**Median**	**IQR**	**Median**	**IQR**	**P-value**	**ES**
DLSECDTUS	3	4	1	4	0.416	**-1.32 φ**	98	3	99	4	0.384	**0.99 φ**
SLSDTUS	6	13	16	21	**0.001***	**0.97 φ**	95	13	84	20	**0.001***	**-1.02 φ**

Med; Median, IQR; interquartile range, % time inner zone; percentage of time tilt in inner zone, % time outer zone; percentage of time tilt in outer zone, DLSEOS; Double leg stance eyes open shod, DLSECS; Double leg stance eyes closed shod, SLSS; Single leg stance shod, DLSEOUS; Double leg stance eyes open unshod, DLSECUS; Double leg stance eyes closed unshod, SLSUS; Single leg stance unshod, DLSEODTS; double leg stance eyes open dual tasking shod, DLSECDTS; double leg stance eyes closed dual tasking shod, SLSDTS; Single leg stance dual tasking shod, DLSEODTUS; double leg stance eyes open dual tasking unshod, DLSECDTUS; double leg stance eyes closed dual tasking unshod, SLSDTUS; single leg stance dual tasking unshod, * significant at $p<0.004$ level, ES; effect size, φ effect size ≥0.8.

4.2.2.2 WB performance and anthropometry and physical activity level

WB performance was assessed during DLSEO, DLSEC and SLS with footwear and without footwear, as well as during single and dual taskings (DT) to determine if there are any correlations between WB performance variables and height, weight, anthropometric measurements, which were shoulder, waist, hip circumferences, shoulder/waist and shoulder/hip ratios and between physical activity level, as illustrated in Tables 12, 13 and appendices 10 and 11. Overall, height, weight, shoulder, waist, hip circumferences, shoulder-waist ratio and shoulder-hip ratio were correlated with all previous tasks during single and DT conditions. However, shoulder/hip ratio was correlated with simple task that performed during double leg stance (DLS), with footwear and with eyes open condition only. Physical activity level and WB performance variables were not correlated.

The study found significant moderate correlations (ranging between 0.306 - 0.678) between WB performance (as measured by stability indices across all tasks) and weight and height, along with waist, shoulder and hip circumferences, and shoulder-waist ratio, (with P-value<0.004). The strongest correlations were observed for weight, with the majority being greater than 0.55 (see Table 12 and appendix 10).

Similar findings were also identified regarding the percentage time in various tilt angle bandings or inclination zones, with weight and hip circumference showing moderate correlations (ranging between 0.304 - 0.584), with almost all tasks and again weight demonstrating the strongest correlation (see Table 13 and appendix 11).

However, no significant correlations were determined between physical activity level and WB performance variables.

Table 12. Spearman's rho **r** correlation between wobble board (WB) performance (stability indices) and anthropometric characteristics.

	Height (r)	**Weight (r)**	**Shoulder circumference (r)**	**Waist circumference (r)**	**Hip circumference (r)**	**Shoulder-Waist Ratio (r)**
Shod						
DLSEOS (APSI)	**.367***	.678*	.529*	.560*	.579*	**-.486***
DLSEOS (MLSI)	**.326***	.639*	**.391***	**.496***	.590*	-.501*
DLSEOUS (APSI)	.522*	.667*	**.586***	.591*	**.469***	**-.477***
DLSEOUS (MLSI)	**.445***	.641*	**.472***	.552*	**.493***	-.500*
DLSECS (APSI)	**.484***	.625*	.560*	.570*	**.517***	**-.491***
DLSECS (MLSI)	.557*	.615*	.585*	.586*	**.401***	**-.446***
Unshod						
DLSECUS (APSI)	**.458***	.659*	.556*	.621*	**.504***	-.557*
DLSECUS (MLSI)	**.464***	.595*	.551*	.554*	**.421***	**-.450***
SLSS (APSI)	.287	.561*	**.410***	**.431***	**.441***	**-.354***
SLSS (MLSI)	.281	.528*	**.390***	**.428***	.502*	**-.381***
SLSUS (APSI)	**.311***	.652*	**.465***	.514*	.532*	**-.442***
SLSUS (MLSI)	.235	**.406***	.292	**.377***	**.340***	**-.360***
Dual task						
DLSEODTS (APSI)	**.409***	**.602***	**.510***	**539***	**.563***	**-.439***
DLSEODTS (MLSI)	**.327***	**.577***	**.426***	**.429***	**.525***	**-.373**

	Height (r)	Weight (r)	Shoulder circumference (r)	Waist circumference (r)	Hip circumference (r)	Shoulder-Waist Ratio (r)
DLSEODTUS (APSI)	**.415***	**.572***	**.507***	**.546***	**.480***	**-.453***
DLSEODTUS (MLSI)	**.312***	**.562***	**.460***	**.428***	**.473***	**-.306***
DLSECDTS (APSI)	**.369***	**.649***	**.550***	**.629***	**.570***	**-.569***
DLSECDTS (MLSI)	**.497***	**.591***	**.609***	**.534***	**.426***	**-.358***
DLSECDTUS (APSI)	**.465***	**.665***	**.612***	**.665***	**.554***	**-.581***
DLSECDTUS (MLSI)	**.479***	**.597***	**.489***	**.535***	**.411***	**-.488***
SLSDTS (APSI)	.285	**.557**	**.454***	**.406***	**.521***	-.270
SLSDTS (MLSI)	**.357***	**.476***	**.369***	**.350***	**.374***	-.280
SLSDTUS (APSI)	**.342***	**.456***	**.310***	**.309***	**.358***	-.264
SLSDTUS (MLSI)	.269	**.558***	**.378***	**.477***	**.496***	**-.459***

APSI; Anteroposterior stability index, MLSI; Mediolateral stability index, r; spearman's rho correlation, DLSEOS; double leg stance eyes open shod, DLSEODTS; double leg stance eyes open dual tasking shod, DLSECS; double leg stance eyes closed shod, DLSECDTS; double leg stance eyes closed dual tasking shod, SLSS; single leg stance shod, SLSDTS; single leg stance dual tasking shod, SLSUS; single leg stance unshod, SLSDTUS; single leg stance dual tasking unshod, DLSEOUS; double leg stance eyes open unshod, DLSEODTUS; double leg stance eyes open dual tasking unshod, DLSECUS; double leg stance eyes closed unshod, DLSECDTUS; double leg stance eyes closed dual tasking unshod, * significant at p≤0.004 level.

Table 13. Spearman's rho **r** correlation between wobble board (WB) performance (percentages of time in inner and outer zones) and anthropometric characteristics

	Height (r)	**Weight (r)**	**Shoulder circumference (r)**	**Waist circumference (r)**	**Hip circumference (r)**	**Shoulder-Waist Ratio (r)**	**Shoulder-Hip Ratio (r)**
Shod							
DLSEOS % time inner zone	-.104	**-.499***	-.202	**-.329***	-.**549***	**.385***	**.388***
DLSEOS % time outer zone	.089	**.489***	.193	**.320***	.**545***	**-.377***	**-.395***
DLSECS % time inner zone	**-.407***	-.**576***	**-.463***	**-.491***	**-.485***	**.422***	.073
DLSECS % time outer zone	**.386***	.**584***	**.475***	**.476***	.**512***	**-.391***	-.083
SLSS % time inner zone	-.041	-.297	-.092	-.104	**-.340***	.122	.268
SLSS % time outer zone	.047	.282	.077	.092	**.314***	-.114	-.257
Unshod							
DLSEOUS % time inner zone	**-.309***	-.**543***	**-.355***	**-.434***	**-.458***	**.399***	.120
DLSEOUS % time outer zone	**.304***	.**539***	**.349***	**.435***	**.452***	**-.408***	-.122

	Height (r)	**Weight (r)**	**Shoulder circumference (r)**	**Waist circumference (r)**	**Hip circumference (r)**	**Shoulder-Waist Ratio (r)**	**Shoulder-Hip Ratio (r)**
DLSECUS % time inner zone	-.242	**-.464***	**-.319***	**-.407***	**-.427***	**.425***	.125
DLSECUS % time outer zone	.197	**.439***	.275	**.358***	**.437***	**-.389***	-.180
SLSUS % time inner zone	-.070	**-.389***	-.178	-.270	**-.405***	.272	.247
SLSUS % time outer zone	.075	**.390***	.173	.273	**.406***	-.280	-.250
Dual task							
DLSEODTS % time inner zone	-.117	**-.353***	-.160	-.165	**-.422***	.144	.274
DLSEODTS % time outer zone	.125	**.356***	.165	.165	**.417**	-.140	-.261
DLSECDTS % time inner zone	-.210	**-.458***	**-.337***	**-.385***	**-.481***	**.350***	.210
DLSECDTS % time outer zone	.191	**.451***	**.347***	**.345***	**.489***	-.278	-.214
SLSDTS % time inner zone	-.012	-.291	-.097	-.053	**-.314***	.025	.208
SLSDTS % time outer zone	.020	.290	.108	.060	**.311***	-.027	-.196

	Height (r)	Weight (r)	Shoulder circumference (r)	Waist circumference (r)	Hip circumference (r)	Shoulder-Waist Ratio (r)	Shoulder-Hip Ratio (r)
DLSEODTUS % time inner zone	-.101	**-.410***	-.272	-.232	**-.414***	.140	.146
DLSEODTUS % time outer zone	.104	**.410***	.271	.235	**.409***	-.142	-.137
DLSECDTUS % time inner zone	-.230	**-.546***	**-.370***	**-.414***	**-.512***	**.382***	.194
DLSECDTUS % time outer zone	.255	**.561***	**.383***	**.438***	**.517***	**-.401***	-.184
SLSDTUS % time inner zone	.103	-.178	.081	.044	-.263	.008	**.325***
SLSDTUS % time outer zone	-.104	.156	-.094	-.064	.232	.016	**-.308***

% time inner zone; percentage of time tilt in inner zone, % time outer zone; percentage of time tilt in outer zone, r; spearman's rho correlation, DLSEOS; double leg stance eyes open shod, DLSEODTS; double leg stance eyes open dual tasking shod, DLSECS; double leg stance eyes closed shod, DLSECDTS; double leg stance eyes closed dual tasking shod, SLSS; single leg stance shod, SLSDTS; single leg stance dual tasking shod, SLSUS; single leg stance unshod, SLSDTUS; single leg stance dual tasking unshod, DLSEOUS; double leg stance eyes open unshod, DLSEODTUS; double leg stance eyes open dual tasking unshod, DLSECUS; double leg stance eyes closed unshod, DLSECDTUS; double leg stance eyes closed dual tasking unshod, * significant at $p \leq 0.004$ level.

4.2.2.3 WB performance and with footwear versus without footwear

There were no significant differences identified in WB performance with and without footwear in either females or males, regardless of the task or metric, apart from SLS for AP stability indices in males with P-value = 0.005, with footwear (median (Med) = 4.11°) better than without footwear (Med = 4.19°). In addition, the study observed no large ES (see Table 14).

Table 14. Results of significance testing and effect size calculation for the effect of being with footwear (shod) or without footwear (unshod) on WB performance.

	DLSEO with footwear vs without footwear		**DLSEC with footwear vs without footwear**		**SLS with footwear vs without footwear**	
	P-value	**Effect size**	**P-value**	**Effect size**	**P-value**	**Effect size**
Female						
APSI (°)	0.530	-0.03	0.852	0.30	0.360	0.17
MLSI (°)	0.111	-0.34	0.958	0.39	0.843	-0.07
% time inner zone	0.084	0.10	0.435	0.20	0.346	0.18
% time outer zone	0.088	-0.15	0.504	0.00	0.335	-0.27
Male						
APSI (°)	0.035	0.60	0.626	0.12	**0.005***	0.07
MLSI (°)	0.970	-0.07	0.970	-0.15	0.150	0.02
% time inner zone	0.300	-0.23	0.792	0.33	0.187	0.51
% time outer zone	0.255	0.34	0.917	-0.33	0.178	-0.44

DLSEO; double leg stance eyes open, DLSEC; double leg stance eyes closed, SLS; single leg stance, APSI; anteroposterior stability index, MLSI; mediolateral stability index, %inner time; percentage of time tilt in inner zone, %outer time; percentage of time tilt in outer zone, * significant at p≤0.008 level, $_{\varphi}$ Effect size ≥0.8.

4.2.2.4 WB performance and single versus dual task (DT)

This study found that, in females, double leg eyes open (DLSEO) tasks were significantly ($p \leq 0.008$) worse when performed with an additional dual task (DT) across all metrics, with the exception of AP stability indices. However, only two large effect sizes (ES) ≥ 0.8 were determined for DLSEO without footwear, which were percentages of time spent in inner and outer zones (see Table 15). By contrast, no significant differences (or large ES) were established for double leg eyes closed (DLSEC). During single leg stance (SLS), a significant difference (P-values =0.003 and 0.004) was found when it came to percentages of time spent in tilt angle bandings or inclination zones, but not for stability indices. However, no large ES were observed.

In males, all metrics for DLSEO with footwear were significantly (P-value ≤ 0.001) worse during DT. However, no large ES was determined. Additionally, ML indices for DLSEO without footwear (P-value = 0.008), along with AP stability indices for SLS without footwear, proved significantly (P-value = 0.004) worse during DT, although no large ES were determined (see Table 15). Moreover, the percentage of time spent in the inner and outer tilt angle bands for DLSEO and SLS with footwear were significantly (P-values < 0.001, =0.002 and 0.003, respectively) worse during DT (see Table 15).

Table 15. Results of significance testing and effect size calculation for the effect of single and dual tasking on WB performance.

	With footwear single task vs dual task						Without footwear single task vs dual task					
	DLSEO		**DLSEC**		**SLS**		**DLSEO**		**DLSEC**		**SLS**	
	P-value	**Effect size**	**P-value**	**Effect size**	**P-value**	**Effect size**	**P-value**	**Effect size**	**P-value**	**Effect size**	**P-value**	**Effect size**
Female												
APSI (°)	0.163	-0.27	0.713	-0.27	0.014	-0.66	0.154	-0.69	0.762	0.11	0.066	-0.30
MLSI (°)	**<0.001***	-0.26	0.093	-0.13	0.092	-0.41	**0.001***	-0.86	0.140	-0.22	0.762	-0.06
% time inner zone	**<0.001***	0.64	0.475	0.50	0.016	0.46	**<0.001***	**0.91** φ	0.073	0.20	**0.004***	0.59
% time outer zone	**<0.001***	-0.60	0.623	-0.50	0.021	-0.44	**<0.001***	**-0.89** φ	0.195	-0.20	**0.003***	-0.63
Male												
APSI (°)	**0.001***	-0.65	0.196	0.47	0.009	-0.33	0.062	0.19	0.371	-0.01	**0.004***	-0.06
MLSI (°)	**<0.001***	-0.75	0.599	0.17	0.038	-0.77	**0.008***	-0.54	0.666	0.24	0.442	-0.09
% time inner zone	**<0.001***	0.71	0.697	-0.33	**0.002***	0.39	0.019	0.31	0.653	0.5	0.240	0.38
% time outer zone	**<0.001***	-0.78	0.696	0.33	**0.003***	-0.58	0.026	-0.23	0.398	-0.5	0.353	-0.19

DLSEO; double leg stance eyes open, DLSEC; double leg stance eyes closed, SLS; single leg stance, APSI; anteroposterior stability index, MLSI; mediolateral stability index, % time inner zone; percentage of time tilt in inner zone, % time outer zone; percentage of time tilt in outer zone, * significant at $p \leq 0.008$ level, $_{\varphi}$ Effect size ≥0.8.

4.3 Discussion of study two

Study one explored the efficiency and efficacy of the WB training. However, there is lack of consensus in the literature about the factors that may impact the optimal assessment for static balance and WB performance. Specifically, there are no studies investigating comprehensively the relationship between range of anthropometric variables and WB performance, as well as static balance assessment. Understanding this relationship is important in determining balance impairments, leading to guide clinicians to select the correct comparison when comparing them with normative databases or clinical norms, as well as to set the rehabilitation goals. Thus, this study aims to investigate the influence of biological sex, anthropometrics, footwear and dual tasking (DT) on static balance assessment and WB performance during quiet standing.

4.3.1 Biological sex

The first hypothesis of the second study proposed that biological sex will not affect static balance assessment or WB performance. However, this hypothesis was rejected because females outperformed males across most of static balance and WB performance tests, as indicated by the significant difference ($p \leq 0.004$) in stability indices, with some very large ES values ≥ 0.9, as depicted in Tables 5 and 10. However, males showed better WB performance than females, with a significant P-value=0.001, during SLS without footwear DT (see Table 11). Previous studies agree with those of the present study, with females performing better than males during static balance (Ekdahl et al., 1989; Maki et al., 1990; Mickle et al., 2011; Puszczalowska-Lizis et al., 2018), as well as during dynamic balance (Maki et al., 1990; Ku et al., 2012).

Furthermore, it was apparent that static balance performance was worsened as the task became more challenging, such as performing tasks with closed eyes, regardless of whether the task were performed as single tasks or DT, or as with footwear or without footwear, as shown in Table 5. This might be explained due to the requirement of the visual cues for postural orientation to arrange the body part in relation to the surrounding environment (Mancini et al., 2020). However, this does not seem to be the case when complex tasks were added, such as navigation task or visual biofeedback training associating with WB training, where males showed better balance performance than females (Bulut and Erdeniz, 2021; De Maio et al., 2021). Further detail about the DT effect on static balance and WB performance will be explained in section 4.3.4. The justification for these biological sex differences during static balance and WB performance are unknown. It is possible that anthropometric factors play a role, which will be discussed in the below section.

4.3.2 Anthropometry and physical activity level

It has been proposed that anthropometric factors play a role in biological sex difference findings during static balance and WB performance, for example, height (Bryant et al., 2005), since being taller suggests the presence of a higher centre of mass (COM). However, a difference still existed after height normalisation, as illustrated in Table 6. This may provide explanation for the current study findings about modest correlations, ranging between 0.313 - 0.487 between height and weight during static balance, as depicted in Table 7; indicates the lower weight and height, the better static balance during quiet standing. However, greater correlations, ranging between 0.304 - 0.678, as depicted in Tables 12 and 13, were found between WB performance and weight and upper torso 'size'. Further explanation might be provided by this modest correlation, since females have greater mass concentrated in the lower bodies, while men typically have a larger upper body (Farenc et al., 2003; Menegoni et al., 2009). Regarding static balance, there were moderate corrections between static balance and circumferential measurements of the waist (which ranged between 58 and 137 cm) and shoulders (which ranged between 87 and 136 cm) indicated a moderate impact on static balancing performance, ranging between 0.308 and 0.480, as illustrated in Table 7. Indicating that the greater the 'size' of the upper body including the waist, the poorer the static balance performance across DLS tasks. This larger upper body size effect also inhibits control of sway, raises the CoM and potentially contributes to greater sway. Furthermore, in the current study, there was significant correlation between static balance parameter (perimeter and ellipse area) and shoulder circumferential measures, which range between 0.308 and 0.477. This was particularly in evidence with DLS tasks. Such anthropometric relationships may manifest during simpler static balance tests, as SLS tasks were generally not substantially correlated with body size, as demonstrated in Appendix 9.

Additionally, the most significant associations in WB performance were observed with weight, shoulder, waist, and hip circumferential measurements. To the author's knowledge, this finding, has not existed before in the literature. This finding may be justified by several possible biomechanical explanations. As previously indicated, a higher COM could be the biomechanical explanation for this, but the moment functioning around the WB's "joint" is another possibility. Because of the function of mass multiplied by distance, for example, if two individuals of equal height but different weights were requested to sway their bodies by the same distance, the heavier individuals would generate a larger moment around the "WB joint." Additional biomechanical explanations for poor WB performance might include impaired muscle strength (Tomlinson et al., 2016), increased fatiguability (Pajoutan et al., 2016) and anterior shift of the CoM, generated by larger waist circumferences and greater body weight (Corbeil et al., 2001), leading to proprioception challenges (Wang et al., 2008).

Regarding physical activity, in the current study, there was no relationship between physical activity and static balance or WB performance. Thus, advising an individual to increase their physical activity is likely to have a minimal effect on static balance and WB performance. Similarly, in a cross-sectional study conducted by Maitre and Paillard (2016) that assessed static and dynamic balance, which was foam surface, there were no significant differences between physically active and non-active participants, regardless of their age (both young and old).

4.3.3 Footwear versus without footwear

According to the author's knowledge, no previous study explores the effect of footwear on WB performance in healthy adults under multiple tasks and conditions, thus this adds novelty to this study. Overall, there were no differences in performance during static balance and WB performance due to footwear because the P-value ≥ 0.008, as shown in Tables 8 and 14, for static balance and WB performance, respectively. This confirms the second hypothesis of the second study, which proposed that footwear will not affect static balance assessment or WB performance. Two exceptions were found: (i) during DLSEC task wearing shoes worsened performance in both females (P-value <0.001) and males (P-value$=0.006$) during static balance only and (ii) wearing shoes resulted in better balance performance for males under the SLS condition both during static balance (P-value=0.004) and WB performance (P-value=0.005), as shown in Tables 8 and 14. However, the ES was very small (0.07) during WB performance only, as shown in Table 14. Regarding static balance, moving across the plantar foot surface distribution seems to be translated into movement around the CoM, which may affect static balance performance and provide possible explanation for the finding. According to previous literature, biofeedback loop involved in maintaining balance is required for this plantar foot surface sensation (McKeon et al., 2015).

The current study provides a substantial contribution to the current understanding because there is a surprising lack of direct comparisons between the conditions with and without footwear in the literature. The impact of footwear on static balance has been the subject of conflicting research in the past (Germano et al., 2012), with similar results for SLS showing that CoP excursion was higher in the barefoot condition. Smith et al. (2015), on the other hand, showed that balance improved with footwear for both overall and AP CoP sway during DLSEC. Although the cause of these contradictory results is unclear, static balance performance was assessed using the angular displacement of CoP rather than the sway trace's perimeter length (Smith et al., 2015).

Although this is not the case during WB performance, the mechanism previously described regarding the movements of the CoM during balancing on a stable surface is likely to translate into distributed movement of the plantar foot surface pressure, where it may affect the balance performance. This may be explained because any change in the foot surface contact is probably will have minimal effect because the forces created by CoM movements disrupt the board's balance.

4.3.4 Single versus dual task (DT)

The present study did not find any significant differences (P-value≥0.008) between single and dual tasking (DT) during static balance performance, except during the DLSEC task, as shown in Table 9. This confirms the fourth hypothesis of the second study, which proposed that DT will not affect static balance or WB performance. During DLSEC task, there were significant differences (significant P-values <0.001, and 0.003) between single and DT with footwear and without footwear conditions, indicating poorer static balance performance during DT, as shown in Table 9. This might be explained because the young participants in this present study were young who are capable to execute a cognitive activity with little “cost” to the physical effort, this probably reflects the individuals’ age. Previous literature on static balance performances in young individuals revealed no significant changes between single and DT, as assessed by total CoP displacement, ellipse area and CoP velocity in the force plate (FP) (Lüder et al., 2018).

Therefore, for young and healthy individuals, it would be doubtful that the DT provides any additional benefit over single task balance testing. The basal ganglia-cortical network controls the “conscious” aspects of postural stability (Boisgontier et al., 2013). According to previous studies conducted by Raftopoulos (2005) and Boisgontier et al. (2013), posture is controlled by both lower “automatic” and higher “controlled” levels of processing. This suggests that brainstem synergies are involved in lower-level processing (Honeycutt et al., 2009) and the basal ganglia-cortical loop is involved in higher-level processing (Jacobs and Horak, 2007). According to previous literature, any decrease in the conscious regulation of attention towards postural control may raise the risk of stability and coordination problems due to movement-specific reinvestment (Masters, 1992; Masters and Maxwell, 2008).

Regarding WB performance, there were significant differences ($p \leq 0.008$) between single and DT mainly for double leg stance with eyes open (DLSEO) amongst the footwear and without footwear conditions, indicating poorer WB performance when performing DTs, as depicted in Table 15. Direct comparison to the WB literature was not feasible because this study was the first to examine the impact of DT on WB performance. However, it has been demonstrated that DT, like counting out loud affects balance on movable surfaces (Yardley et al., 1999). Even if DT had little to no impact on other WB performances, it is still unclear why some tasks were impacted while others were not. Furthermore, as shown in Table 15, this unstable surface is obviously different from the Prokin used in this study, and altogether, a minor ES ≤0.8 for DT cost was found.

4.4 Conclusion, limitations, clinical implications and future studies of study two

In conclusion, the results of the static balance and WB study represent the first thorough evaluation of how biological sex, footwear and DT affect the assessment of static balance and WB performance. Therefore, this study successful met its objective of providing a deeper understanding of the impact of these factors and aiming to design the best approach to static balance assessment and intervention, as well as WB assessment and training, which are all crucial in physiotherapy and clinical practice. Overall, females performed better than males across a variety of tasks during static balance assessment and WB performance, regardless of footwear or DT conditions. However, biological sex differences were observed in both sexes, in both conditions, with and without footwear as well as in single tasks and DTs, in both static balance assessment and WB performance. Similarly, WB performance while wearing footwear did not differ from that without footwear except during SLS. Additionally, single task during WB performance was not significantly differ from DT, except in double leg stance eyes open though the ESs were moderate to small. Thus, it seems that the footwear and DT effect were task specific. Thus, future research may compare various footwears and different DTs. Regarding anthropometry factors, moderate correlations were found between static balance, WB performance and height, weight and upper body size. The data indicates that the taller, heavier individuals or those with a larger upper torso were correlated with poorer static balance and WB performance. While clinicians may encourage individuals to increase their physical activity, but it seems to have a minimal impact on balance performance, due to observing to be no significant correlation between physical activity and balance performance. These findings are critical for guiding author and physiotherapist, in designing an intervention with a WB and assessing its performance, alongside static balance performance, leading to enhance confidence in clinical decision-making regarding the actual impact of the considered factors. The final recommendation for future studies is to enrol diverse populations, particularly those who are vulnerable to falling or have balance impairments, and apply a similar study design to this one, to determine if the responses observed in healthy adults are applicable to these group.

Thus, the next chapter (Chapter 5), will build on these findings to develop a progressive WB training programme for people with diabetes (PWD) and individuals with DPN, who are vulnerable to falling, aiming to improve balance. Taking into consideration the forementioned findings, the impact of this WB training programme will be investigated and the relationship between static balance, WB performance and baseline characteristics will be examined.

Chapter 5: Study three: Determining the effect of a progressive six-week WB training programme on balance in people with diabetes mellitus (PWD) diabetic peripheral neuropathy (DPN).

This study describes an experimental trial exploring the efficacy of a progressive six-week WB training programme, for improving the balance among PWD and DPN. Due to the proven effectiveness of WB training in the elderly population, established by the SR conducted by the author in the first study, this study was proposed, since like the elderly, PWD and DPN are vulnerable to falling. WB training measures include balance and other variables that were affected in PWD and DPN and which might contribute to poor balance, such as proprioception, foot sensation, neuropathic pain, severity of neuropathy, physical activity level and muscle strength.

Therefore, this study had two aims, as follows:

Aim 1: To plan a WB training programme and investigate its impact on previous variables, such as static balance, WB performance, ankle muscle strength, neuropathic pain, severity of neuropathy, balance confidence and physical activity level utilising the stabilometric assessment device (Prokin 252) among PWD and individuals with DPN.

Aim 2: To explore the relationship of age, anthropometrics, duration of DM, neuropathic pain, severity of neuropathy, balance confidence, ankle muscle strength and physical activity level on both static balance and WB performance, using the Prokin (252) with healthy participants.

This chapter is divided into three sections. Firstly, the methods and methodology utilised in this study will be described. Second the results and findings of this third study will be analysed. Finally, those findings will be discussed related to the literature about the impact of the planned WB training programme and the relation between the baseline characteristics and both static balance and WB performance.

5.1 Methods and methodology of study three

5.1.1 Study design

This was an experimental intervention study, in which thirty-six participants with diabetes mellitus (DM) and DPN (mild, moderate and severe), received a WB intervention programme, designed to influence balance. The primary aim of this study was to explore the efficacy of the intervention for improving balance in PWD and DPN. The secondary aim of this study was to investigate the mechanism behind such changes.

An experimental design was chosen rather than a randomised controlled trial (RCT), because the aim was to expose every participant to the intervention, regardless of the severity of their DPN. Therefore, to investigate the efficacy of this WB intervention it was necessary to extend every participant an equal opportunity to take part.

5.1.2 Participants

The study was conducted at the King Abdullah bin Abdulaziz University hospital in Riyadh, Saudi Arabia. The target group consisted of PWD, either with or without DPN. All participants were included, regardless of the severity of DPN. This was because the participants were identified and recruited from various diabetic centres in Riyadh by means of the following:

- Advertisements on social media.
- Flyers placed in diabetic centres.
- Contacting previous researchers in the field in Saudi Arabia.

Baseline and follow-up (wash out) testing, along with all rehabilitation, was conducted within the university hospital, following instruction from the principal investigator (the author), with over 10 years of clinical practice experience in the field of physiotherapy.

5.1.3 Sample size

Based on first study, which was the SR conducted for this thesis (Chapter 3), that yielded a weighted effect size of 0.5, and using an alpha (significance threshold) of

0.02 (reduced for repeated pairwise comparisons because there were two comparisons double leg stance (DLS) with eyes open and closed, as well as DLS with a wide base of support and a narrow base of support and a power of 80%, 36 participants were required. This was calculated using G-power software.

5.1.4 Ethical approval

Prior to conducting this experiment, the author obtained written informed consent from all the participants, according to the Declaration of Helsinki, as approved by Princess Nourah bint Abdulrahman University Institutional Human Ethics Committee (see Appendix 3). Furthermore, the Saudi Food and Drug Authority (SFDA) provided approval to register this clinical trial in Saudi Arabia (see Appendix 4). Whilst introducing delay to the conducting of this study, credit is obtained by being registered with this authority and completing the study within the planned time. An audit was carried out by the ethical committee before, during and after completing the study and congratulations were afforded to the author for completing it within the planned time, whereas other studies took longer.

5.1.5 Inclusion and exclusion criteria

To be enrolled in this study, those with DM were required to satisfy the following criteria.

5.1.5.1 Inclusion criteria

Inclusion criteria are based on recommendations taken from the most recent standard of care (2023) document published by the ADA (Elsayed et al. 2023a), as the following:

- Formal physician-led diagnosis of Type II DM, as determined from the individual’s medical notes.
- Aged eighteen or over.
- Able to walk independently for twenty minutes (mins) without assistive walking aids (self-assessment).
- Verbal agreement to attend rehabilitation sessions.

5.1.5.2 Exclusion criteria

- Self-declared postural hypotension or vestibular disorders.
- Evidence of significant neurological disorder from the medical files, such as a previous stroke or multiple sclerosis.
- Self-declared musculoskeletal disorders impacting the ability to complete the planned rehabilitation programme.
- Current ulcers or other unhealed wounds on the foot.
- Partial or total amputations.

5.1.6 Dynamic balance assessment and intervention by Prokin (252)

To ensure the appropriate level of WB training, a sequential dynamic balance test was employed to determine the current level of dynamic balance ability. Each participant was asked to complete fifteen seconds of balancing on the stabilometric assessment device (Prokin 252), resembling the WB without footwear, which was progressed sequentially through increasing levels of difficultly (see Table 16), until the occurrence of failure. Failure was defined as contacting the support handrails, moving their stance foot or putting their other foot down. Participants were offered two attempts, with no further tasks completed once failure had been reached. In addition, thirty seconds rest was provided between each attempt. Table 16 demonstrates the fifteen levels of WB difficulty according of tilt angle of the WB and the task performed. The order of the testing (and subsequent training) was based on clinical judgement and experience of WB training, in additional to drawing on findings from the previous study. Examples of such findings include greater scores for dynamic balance with eyes closed compared to eyes open, illustrating this to be more challenging, and single leg as more challenging than double leg.

Once established, this level of dynamic balance was used to prescribe the WB balance exercises (see Table 17). Therefore, the specific nature of this novel intervention was tailored to a participant’s baseline assessment of balance performance, which was measured using the Prokin (ProKin 252, TecnoBody, 2021).

The balance rehabilitation exercises were based on the initial assessment levels. For example, if a participant achieved level 4, but failed level 5 (see Table 17), then the study utilised WB exercises at this level. Table 17 demonstrates a guide to exercise decision making. All balance rehabilitation was completed without footwear.

Table 16. Sequential fifteen levels of WB difficulty balance challenge.

Level of WB difficulty	Description of WB tilt angle	Task
1	Maximum WB tilt angle = 5º	Double leg stance wide, eyes open
2	Maximum WB tilt angle = 5º	Double leg stance narrow, eyes open
3	Maximum WB tilt angle = 10º	Double leg stance wide, eyes open
4	Maximum WB tilt angle = 10º	Double leg stance narrow, eyes open
5	Maximum WB tilt angle = 15º	Double leg stance wide, eyes open
6	Maximum WB tilt angle = 15º	Double leg stance narrow, eyes open
7	Maximum WB tilt angle = 5º	Double leg stance wide, eyes closed
8	Maximum WB tilt angle = 5º	Double leg stance narrow, eyes closed
9	Maximum WB tilt angle = 10º	Double leg stance wide, eyes closed
10	Maximum WB tilt angle = 10º	Double leg stance narrow, eyes closed
11	Maximum WB tilt angle = 15º	Double leg stance wide, eyes closed
12	Maximum WB tilt angle = 15º	Double leg stance narrow, eyes closed
13	Maximum WB tilt angle = 5º	Single leg stance, eyes open
14	Maximum WB tilt angle = 10º	Single leg stance, eyes open
15	Maximum WB tilt angle = 15º	Single leg stance, eyes open

Table 17. Example of WB exercises used based on the level of failure during the assessment.

Level of WB failure	Description of WB exercises
1	Board set to 5º. Double leg stance (DLS) wide, eyes open with bilateral or unilateral palm-up light touch on support bars.
2	Board set to 5º. DLS wide, eyes open, progressing to gradually narrowing stance. Double leg stance narrow, eyes open, with bilateral progressing to unilateral palm-up light touch on support bars.

Level of WB failure	Description of WB exercises
3	Board set to 10º. DLS wide, eyes open with bilateral or unilateral palm-up light touch on support bars.
4	Board set to 10º. DLS wide, eyes open, progressing to gradually narrowing stance. Double leg stance narrow, eyes open, with bilateral progressing to unilateral palm-up light touch on support bars.
5	Board set to 15º. DLS wide, eyes open with bilateral or unilateral palm-up light touch on support bars.
6	Board set to 15º. DLS wide, eyes open, progressing to gradually narrowing stance. Double leg stance narrow, eyes open, with bilateral progressing to unilateral palm-up light touch on support bars.
7	Board set to 5º. DLS wide, eyes closed, with bilateral, progressing to unilateral, palm-up light touch on support bars. Double leg stance wide, eyes roaming. Double leg stance wide, single eye closed.
8	Board set to 5º. DLS narrow, eyes closed, with bilateral, progressing to unilateral, palm-up light touch on support bars. Double leg stance narrow, eyes roaming. Double leg stance narrow, single eye closed.
9	Board set to 10º. DLS wide, eyes closed, with bilateral, progressing to unilateral, palm-up light touch on support bars. Double leg stance wide, eyes roaming. Double leg stance wide, single eye closed.
10	Board set to 10º. DLS narrow, eyes closed, with bilateral, progressing to unilateral, palm-up light touch on support bars. Double leg stance narrow, eyes roaming. Double leg stance narrow, single eye closed.
11	Board set to 15º. DLS wide, eyes closed, with bilateral, progressing to unilateral, palm-up light touch on support bars. Double leg stance wide, eyes roaming. Double leg stance wide, single eye closed.
12	Board set to 15º. DLS narrow, eyes closed, with bilateral, progressing to unilateral, palm-up light touch on support bars. Double leg stance narrow, eyes roaming. Double leg stance narrow, single eye closed.
13	Board set to 5º. Single leg stance (SLS) with bilateral, progressing to unilateral, palm-up light touch on support bars. Single leg stance with high box foot support.

Level of WB failure	Description of WB exercises
14	Board set to 10º. SLS with bilateral, progressing to unilateral, palm-up light touch on support bars. Single leg stance with high box foot support.
15	Board set to 15º. SLS with bilateral, progressing to unilateral, palm-up light touch on support bars. Single leg stance with high box foot support.

Double leg stance (DLS) and single leg stance (SLS).

All of the participants attended the university hospital for rehabilitation sessions, consisting of exercises similar, as described to those shown in Table 17, which were completed over a period of ten and fifteen mins. There was no feedback (visual or verbal) provided during training. The participants were requested to attend the sessions twice a week for six weeks, on non-consecutive days. This training was subsequently paused for two weeks, a period called washing out, with the participants then returning for the purposes of reassessment.

5.1.6.1 Plan on identification, reporting and managing adverse events during the WB intervention.

The following guidelines were employed in this study to minimise the risk of harm:

- All participants were secured with a chest-belt safety harness (h/p/cosmos, Germany) attached to an overhead frame, preventing them from falling to the floor, as recommended by the ethical committee. Appendix 5 demonstrates one of the participants in this study wearing the safety harness. This photo was captured after obtaining permission.
- A safety foam mat was placed on the floor surrounding the device.
- A first aid staff/nurse was informed about the study and remained accessible during the data collection sessions.
- The programme was progressively challenging, using the external support offered by the parallel bar and the least resistance of the dynamic force platform, that is starting with tilt angle of 5°, progressing to a tilt angle of 10° and then 15°. Participants who experienced failure during the assessment level were not permitted to proceed to more challenging or difficult levels. This ensured the

balance intervention was tailored at the same level of participant’s tolerance during the balance assessment, therefore, ensuring a sense of safety and protection.

- If the participant fell during the session, the principal investigator (author), was able to contact the ER and occurrence variance reporting (OVR) was completed and sent to the quality and safety department. In addition, the session was immediately terminated, and the participant was removed from the study, with a report of the fall added to his/her profile.
- Protecting human research participants online training was attended virtually. It was one of the requirements prior to the ethical approval application. It provided all protections and cautions required to conduct research on humans (see Appendix 6 for the certificate of this training).

5.1.7 Main outcome and additional measurements

All the measures in this study were undertaken at the baseline and at periods of two, four, six and eight weeks and were assessed against the following outcome measures.

5.1.7.1 Static balance assessment

The primary outcome of this study was static balance. It was assessed using the integrated static force platform within the Prokin during double leg stance (DLS) with eyes open (EO) and closed (EC) with both a wide base of support (DLSW) and a narrow base of support (DLSN), as well as single leg stance (SLS) with eyes open (EO) (dominant leg only) for 15 seconds. Each task was completed for fifteen seconds, with failure defined as movement of the feet. Two failed attempts at each task were permitted. Successful balance tests (>15 seconds) were measured through the centre of pressure (CoP) trace from the Prokin software. Two metrics quantify sway behaviour of the CoP, the length of the sway trace (perimeter) and the 95% area of best fit of the sway trace (ellipse area).

Training commenced every week, the static balance was assessed every two weeks, first at time point zero (T0), which was the baseline measurement and then subsequently at T1 (two weeks), then at time T2 (four weeks), then at time T3 (six weeks) and finally after two weeks of pausing this intervention, the wash out period, there was a follow-up assessment at T4 (eight weeks).

5.1.7.2 Dynamic balance assessment (WB performance)

The second primary outcome of this study was the dynamic balance, which is referred to as WB performance in this thesis. WB training was assessed using the progressive level of difficulty noted in Table 17, by utilising the movable force platform of the Prokin. Similar successfully completed tasks were compared by the parameters provided by the Prokin software. Two parameters were utilised to quantify WB performance, which are the average absolute tilt angle, which is called the stability index and the percentage time spent during the tilt angle, which is called the percentage of time in inner and outer zones.

The WB performance was performed at the same time points, as the static balance assessments, which was baseline (T0) and every two weeks (T1, T2, T3), as well as following two weeks of pausing the intervention, the washing out period at T4.

To further quantify improvement in dynamic balance, performance on the WB was tracked throughout the experiment. For example, if a participant failed at WB level 5 at baseline but at WB level 13 on completion of the study their progress can be quantified as an improvement in 8 levels. Therefore, the participants were categorised according to their personal baseline level and tracked by how many levels they progressed. Mean, standard deviation (SD) and 95% confidence interval corridor were calculated by using this formula (equation 2):

$$CI = \bar{X} \pm z\frac{s}{\sqrt{n}} \qquad (2)$$

Where, CI= Confidence interval, $\bar{x}$= sample mean, s= sample standard deviation and n= sample size.

5.1.7.3 Demographic profile

Demographic profiles of age, biological sex, weight and height, were measured. Height was measured using a fixed stadiometer (Seca274, Seca, Germany) to the nearest 0.5 cm, weight was measured using stand-on digital scales (Seca274, Seca, Germany) to the nearest 0.1 Kg. These collective measurements were used to calculate BMI (in Kg/m^2). Anthropometric measures were collected during standing with tape measurement, comprising of the following: hip circumference (which was around the greater trochanters); chest circumference (which was around the nipples), waist circumference (which was around the mid-point between the ilium and the umbilicus); shoulder circumference (which was inferior to the acromion process) (Acevedo et al., 2011). Based on the measurements obtained, the shoulder/waist ratio (SWR) was calculated by dividing the shoulder circumference by the waist circumference, while the shoulder/hip ratio (SHR) was determined by dividing the shoulder circumference by the hip circumference (Tovée, 2012).

5.1.7.4 Duration of diabetes mellitus (DM)

All participants were asked about the number of years they had experienced DM and diabetic peripheral neuropathy (DPN), which was confirmed by checking their medical notes. It should be noted that this information was easily established, due to the principal investigator, (the author) being given access to medical files for all participants.

5.1.7.5 Severity of DPN assessment

The Toronto clinical neuropathy scale (TCNS) was used for this study, due to its ability to classify the severity of DPN (Ahmad et al., 2020). The scale is out of a maximum of 19; 0-5 (no neuropathy); 6-8 (mild DPN); 9-11 (moderate DPN) and ≥ 12 (severe neuropathy) (Ahmad et al., 2020). As shown in Table 18, the scale includes the following.

- Subjective information: asking about symptoms, such as foot pain, numbness, tingling, weakness, ataxia and upper limb symptoms.
- Objective information regarding sensation: performing sensory tests, such as pinprick, temperature, light touch, vibration and position sense.
- Objective information regarding reflexes: performing reflexes test by testing deep tendons of the knee and ankle, using a medical hammer (see appendix 7).

Scores were graded as follows:

- Symptom scores were graded as: 0=absent and 1 =present.

- Sensory test scores as: 0=normal and 1=abnormal.
- Reflexes grades: 0=normal, 1=reduced and 2=absent.

The study recorded the TCNS accomplished at the time point, same as the previous balance assessments, at the baseline (T0), every two weeks (T1, T2, T3) and after two weeks, a washing out period (T4).

Table 18. Components of the TCNS, adopted from Bril et al. 2009.

Symptoms scores	Sensory scores	Reflex scores
Foot pain	Pinprick	Knee reflexes
Numbness	Temperature	Ankle reflexes
Tingling	Light touch	Reflexes graded as;
Weakness	Vibration	0= normal
Ataxia	Position sense	1= reduced
Upper limb symptoms	Sensory scores graded as;	2= abnormal
Symptoms scores graded as;	0= normal	
0= absent	1= abnormal	
1= present		

5.1.7.4 Pressure foot sensation assessment and pain

A Semmes-Weinstein nylon monofilament (10 gram) was used to assess pressure perception on the dorsum of the foot. The filament was pressed perpendicular to the skin until it buckled, forming the letter C, for one second (Singh et al., 2005).

An inability to perceive the 10g of this monofilament, applied to four sites of the foot, was associated with clinically significant large-fibre neuropathy (Armstrong, 2000; Perkins et al., 2001). As shown in Figure 13 the four sites on the dorsum of the foot were tested, including the hallux and metatarsal heads 1, 3, and 5 (Mayfield, 2000; Perkins and Bril, 2003). In addition, Figure 13 demonstrates how (and where) the monofilament should be applied at the four sites of pressure foot sensation, as indicated by blue dots.

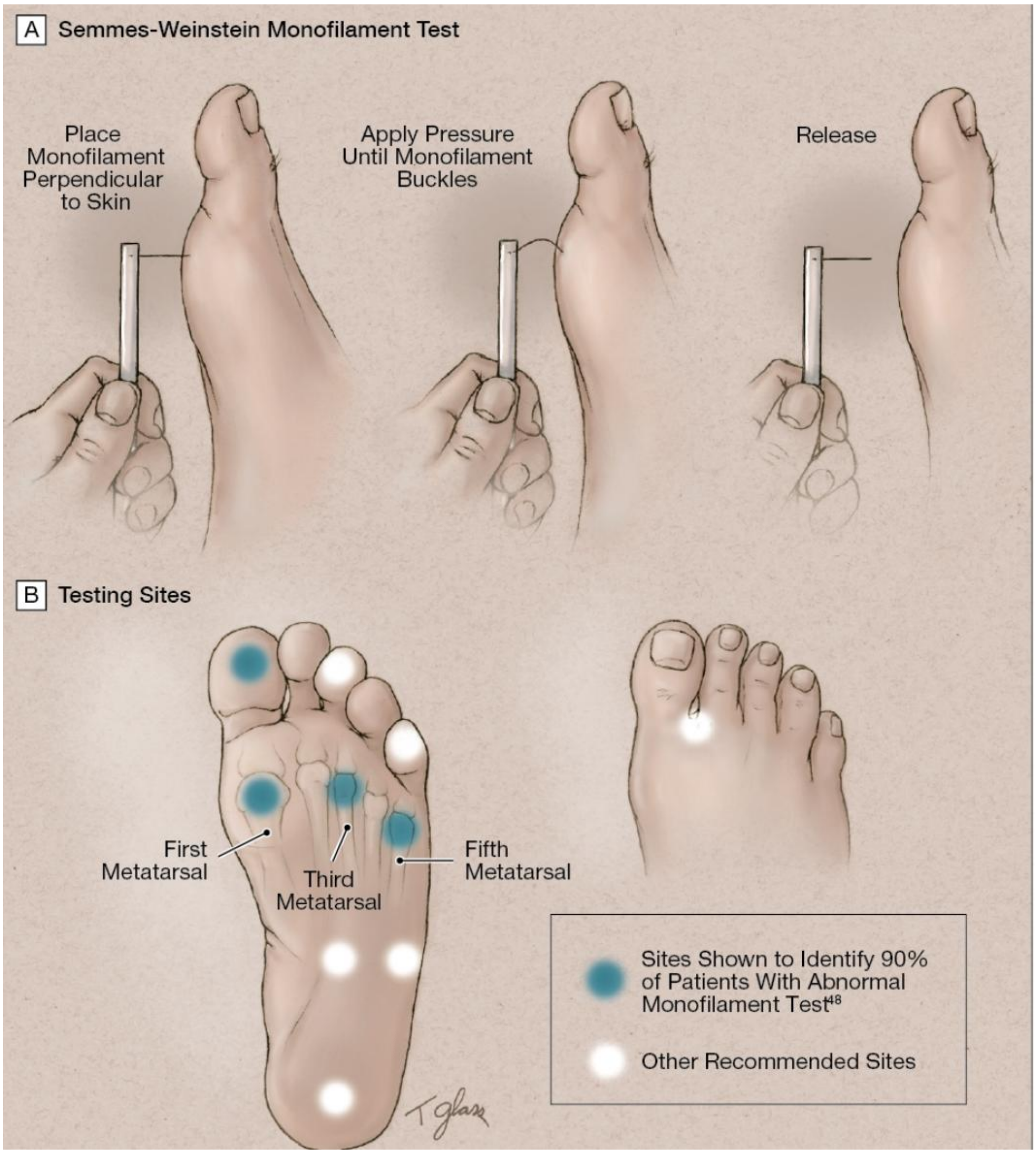


Figure 13. Semmes-Weinstein monofilament test and the four sites on the foot of application derived from Singh et al. 2005, p.219.

The level of pain was assessed using a visual analogue scale (VAS), as explained earlier (see section 4.1.7 and Figure 12). Each participant was asked to mark his/her perceived level of pain on a 10-cm VAS, where 0 indicated ‘no pain’ and 10 ‘unbearable pain’.

The pressure foot sensation and pain were undertaken at the same time as the previous balance and severity of DPN assessment, which was at the baseline (T0) and every two weeks at T1, T2, T3 and T4.

5.1.7.5 Peak force measurement of ankle muscles

Manual muscle testing (MMT) was conducted in concordance with Beld et al. (2006). Briefly, MMT was completed in non-weight bearing, including dorsiflexor, plantar flexor, evertor and invertor muscle groups. Strength was quantified using 'make test' repeated three times, with the mean force then calculated in Newtons (N). MMT was completed using the digital handheld dynamometer (MicroFET®2, Hoggan Health Industries) (see Figure 14). The interrater reliability has been previously established in older adults ($ICC_{3,1}$ = 0.78–0.94) (Spink et. al 2010). Additionally, the use of a hand-held dynamometer to measure ankle dorsiflexor strength because of hemiparesis, secondary to a CVA, has been found to demonstrate a high interrater reliability (Bohannon and Andrews, 1987). Finally, hand-held dynamometry has been used previously in DPN studies to measure muscle strength (Simoneau et al.,1994; Corriveau et al., 2000; Kruse et al., 2010).

Again, the ankle muscle strength was completed at the same time as the previous balance assessments, severity of DPN assessment and pressure foot sensation assessment.

Figure 14. Digital handheld dynamometer (MicroFET ®2, Hoggan health industries, Draper, USA).

5.1.7.6 Physical activity level assessment

A Baecke questionnaire was employed to assess the participants' habitual physical activity (Baecke et al., 1982), as mentioned in detail in section 4.1.7. The Baecke questionnaire was completed at the baseline (T0) and after two weeks of pausing the intervention (washing out period T4).

5.1.7.7 Balance confidence assessment

An Activities Specific Balance Confidence (ABC) questionnaire was used to assess balance confidence, which has been demonstrated as reliable and valid in the Arabic version of the scale (A-ABC) (Alghwiri et al., 2016). The ABC scale lists sixteen activities, for example walking up and down stairs, with individuals describing their degree of confidence in performing each activity on a scale from 0% (no confidence) to 100% (complete confidence) (Richardson et al., 2001). The summary of the percentage scores of these sixteen questions yielded a single ABC score for the data analysis, ranging from 0 to 100% (Powell and Myers, 1995). This indicated that the higher the score, the more confidence was demonstrated by an individual in his or her ability to balance. The ABC confidence scales were completed at each assessment period.

A flow chart detailing how the participants were processed throughout this experiment is demonstrated in the Appendix 8.

5.1.8 Data analysis

The static balance assessment data and WB performance data were captured by the Prokin software, representing the sway trace of the COP, which was used to generate both the ellipse area of the sway trace and the perimeter measurement of the sway trace length. The ellipse area represents the best fit for 95% of the sway trace area (mm^2) and the perimeter represents the length of the sway trace (mm). Percentage change scores were calculated as the change between baseline and the end of the study, divided by the baseline value and multiplied by 100, to yield the percentage change. On the occasion where two values were not available (due to failed tasks) the participant's change could not be calculated. There were some missing values, where the participants had failed to perform the task for 15 seconds; in these cases, data comparison was not possible, therefore the values were disregarded. This applied to more challenging tasks, such as SLS or with eyes closed tasks, where some participants were unable to complete 15 seconds in the first two weeks of the assessment but were able by week three. This meant that there was no data for comparison, as the criteria set for success each time was 15 seconds.

The WB performance data were captured by the Prokin software, representing the tilt angle behavior of the freely tilting center of the Prokin's force platform. These were used to produce both a stability index and the percentage time spent at various tilt angles within bandings or inclination zones. The stability index and the average absolute tilt angle were normalised for time, in both the AP axis and ML axis. The tilt angles (bandings or zones) were between 0^{o} and 6^{o} absolute tilt, defined as the inner zone and $>6^{o}$ of absolute tilt as the outer zone, with the percentage time in each zone calculated. Regarding outliers, they were detected in order to confirm real/true values and not error by applying two rules. The first rule is called interquartile rule, which implies any score>upper quartile plus 1.5 times the interquartile is considered as an extreme value (Field, 2017). The second rule is called the outlier labelling rule outlier labelling rule (Hoaglin et al., 1986), which used formula:

$$upper\ quartile\ -\ lower\ quartile\ *\ 1.5 \qquad (3)$$

Then, the same participant's performance scores were checked and tracked across other tasks and tests. Furthermore, all notes have made during the data collection, were checked. Any false/error values were removed.

5.1.9 Statistical analysis

The data were analysed through SPSS version 26 (SPSS, Version 26.0. Armonk, NY: IBM Corp). First, the normality of the data was assessed through Shapiro-Wilk tests, followed by descriptive statistics being presented for all baseline outcome data to investigate means and standard deviations. Changes in dependant variables were explored through the calculation of the effect size (ES), as well as paired t-tests (or non-parametric equivalent, which is called Wilcoxon test) at each time point.

ES were calculated by dividing the mean of change by the SD of change. The ES were calculated with a value of ≥ 0.8, considered as a large ES (Sullivan and Feinn, 2012). Most of the data were non-normally distributed, therefore, non-parametric tests were conducted. Furthermore, Spearman's rho correlation (R) was calculated to determine the relationship between the initial performance scores of static balance and change in static balance, as well as WB performance. Finally, both correlations, which were Spearman's rho and Pearson's correlations, were calculated to determine the relationships between baseline characteristics and static balance performance, as well as between baseline characteristics and WB performance.

5.2 Results and findings of study three

This experimental trial aims to determine the impact of a six-week progressive programme of WB training on balance and other variables among PWD and DPN, since they are suspectable to falling. Balance training is known to reduce the risks of falling, especially with WB training, which was selected to be method for training, due to its efficacy and efficiency for improving balance among the elderly, this knowledge was achieved by the SR conducted by the author, to investigate its applicability to improving balance in PWD and DPN. Poor balance in PWD and DPN might be a result of one or combination of poor proprioception, reduced foot sensation and low muscle strength. Therefore, balance is the primary aim of this study, whereas the secondary aim of this study was to investigate the mechanism behind such changes by examining other variables, such as the proprioception, foot sensation, muscle strength, neuropathic severity and pain. The final aim is to correlate the baseline characteristics to balance parameters. Thus, results of this study are divided into two sections: the impact of the intervention and the baseline relationship.

5.2.1 The impact of the intervention

The following section discusses the impact of a six-week progressive WB balance training intervention on primary outcome measures.

5.2.1.1 Static balance

The mean and standard deviation (SD) scores for static balance during DLSEOW, DLSECW, DLSEON, DLSECN and SLS are presented in Table 19, along with the mean change, the SD of the change and percentage change, including the effect sizes (ES) for WB performance across the intervention period, which is six weeks of progressive WB balance training programme. Regarding outliers, there were two perimeter outliers identified during DLSEOW, DLSECW, DLSECN and SLS, four during DLSEON. Regarding ellipses area, there were one outlier during DLSEOW, two outliers during DLSECN, three outliers during DLSEON and DLSECW and four outliers during SLS. Initially, face validity was applied to ensure true values, then interquartile rule and the outlier labelling rule were applied, as was described earlier.

Table 19. Mean, standard deviation (SD), mean of change, SD of change, percentage of change and effect sizes (ES) for static balance for all assessment weeks (which were T0, T1, T2, T3 and T4).

Task	Parameter	Week of assessment	Mean	SD	Mean of change	SD of change	Percentage of change	Effect size
DLSEOW	Perimeter	T0 Baseline	187.35 mm	61.83 mm				
		T1	150.37 mm	43.77 mm	-36.81 mm	39.40 mm	-19.65%	-0.93 φ
		T2	128.81 mm	34.92 mm	-21.73 mm	19.36 mm	-14.43%	-1.12 φ
		T3	104.76 mm	32.35 mm	-24.05 mm	19.48 mm	-18.67%	-1.23 φ
		T4 (Wash-out)	135.89 mm	39.40 mm	30.58 mm	26.37 mm	29.19%	1.16 φ
	Ellipse area	T0 Baseline	178.92 mm²	109.26 mm²				
		T1	100.51 mm²	52.21 mm²	-78.41 mm²	83.11 mm²	-43.82%	-0.94 φ
		T2	73.54 mm²	42.45 mm²	-26.97 mm²	28.73 mm²	-26.84%	-0.94 φ
		T3	43.97 mm²	31.57 mm²	-29.57 mm²	22.68 mm²	-40.21%	-1.30 φ
		T4 (Wash-out)	85.78 mm²	52.83 mm²	41.28 mm²	40.35 mm²	93.87%	1.02 φ
DLSECW	Perimeter	T0 Baseline	251.60 mm	86.07 mm				
		T1	228.16 mm	118.49 mm	-9.84 mm	154.01 mm	-3.91%	-0.06
		T2	184.81 mm	68.84 mm	-43.35 mm	64.15 mm	-19.00%	-0.68
		T3	156.84 mm	56.00 mm	-27.97 mm	28.87 mm	-15.14%	-0.97 φ
		T4 (Wash-out)	195.36 mm	73.28 mm	38.61 mm	33.10 mm	24.62%	1.17 φ
	Ellipse area	T0 Baseline	249.46 mm²	162.94 mm²				
		T1	190.08 mm²	141.23 mm²	-45.89 mm²	-28.54 mm²	-18.40%	-0.29

Task	Parameter	Week of assessment	Mean	SD	Mean of change	SD of change	Percentage of change	Effect size
		T2	134.27 mm²	92.38 mm²	-55.81 mm²	-25.02 mm²	-29.36%	-0.87 φ
		T3	88.57 mm²	66.64 mm²	-45.70 mm²	-33.02 mm²	-34.04%	-1.06 φ
		T4 (Wash-out)	130.75 mm²	80.69 mm²	41.39 mm²	68.16 mm²	46.73%	0.98 φ
DLSEON	Perimeter	T0 Baseline	251.32 mm	81.61 mm				
		T1	216.30 mm	69.56mm	-35.03 mm	26.85 mm	-13.94%	-1.30 φ
		T2	184.70 mm	57.92 mm	-31.59 mm	31.72 mm	-14.61%	-1.00 φ
		T3	158.89 mm	46.97 mm	-25.81 mm	30.35 mm	-13.97%	-0.85 φ
		T4 (Wash-out)	191.03mm	47.18 mm	33.78 mm	26.68 mm	21.26%	1.27 φ
	Ellipse area	T0 Baseline	308.19 mm²	146.32 mm²				
		T1	220.62 mm²	92.93 mm²	-87.57 mm²	79.98 mm²	-28.41%	-1.09 φ
		T2	166.41 mm²	76.53 mm²	-54.22 mm²	46.38 mm²	-24.57%	-1.17 φ
		T3	113.16 mm²	60.02 mm²	-53.24 mm²	44.03 mm²	-32.00%	-1.21 φ
		T4 (Wash-out)	182.03 mm²	95.82 mm²	68.53 mm	58.36	60.56%	1.17 φ
DLSECN	Perimeter	T0 Baseline	386.89 mm	105.29 mm				
		T1	329.97 mm	94.91 mm	-64.67 mm	62.27 mm	-16.71%	-1.04 φ
		T2	318.54 mm	114.74 mm	-44.47 mm	35.75 mm	-13.48%	-1.24 φ
		T3	255.14 mm	70.46 mm	-63.41 mm	67.85 mm	-19.90%	-0.93 φ
		T4 (Wash-out)	325.40 mm	107.84 mm	70.60 mm	54.90 mm	27.67%	1.29 φ
	Ellipse area	T0 Baseline	615.33mm²	249.31 mm²				
		T1	534.83 mm²	245.85 mm²	-110.44 mm²	90.32 mm²	-17.95%	-1.22 φ

Task	Parameter	Week of assessment	Mean	SD	Mean of change	SD of change	Percentage of change	Effect size
		T2	484.32 mm²	253.91 mm²	-134.63 mm²	143.88 mm²	-25.17%	-0.94 φ
		T3	300.30 mm²	139.72 mm²	-184.03 mm²	175.46 mm²	-38.00%	-1.05 φ
		T4 (Wash-out)	445.14 mm²	210.60 mm²	146.29 mm²	136.49 mm²	48.71%	1.07 φ
SLS	Perimeter	T0 Baseline	633.86 mm	169.86 mm				
		T1	551.55 mm	157.09 mm	-114.32 mm	116.15 mm	-18.04%	-0.98 φ
		T2	511.22 mm	145.15 mm	-60.18 mm	70.85 mm	-10.91%	-0.85 φ
		T3	454.81 mm	163.10 mm	-69.81 mm	95.20 mm	-13.65%	-0.73
		T4 (Wash-out)	501.86 mm	136.50 mm	91.48 mm	64.14 mm	20.11%	1.43 φ
	Ellipse area	T0 Baseline	605.00 mm²	173.64 mm²				
		T1	515.55 mm²	174.34 mm²	-121.00 mm²	85.94 mm²	-20.00%	-1.41 φ
		T2	443.75 mm²	167.07 mm²	-90.55 mm²	64.03 mm²	-17.56%	-1.41 φ
		T3	381.35 mm²	179.78 mm²	-75.47 mm²	107.51 mm²	-17.01%	-0.70
		T4 (Wash-out)	443.00 mm²	147.03 mm²	117.90 mm²	100.97 mm²	30.92%	1.17 φ

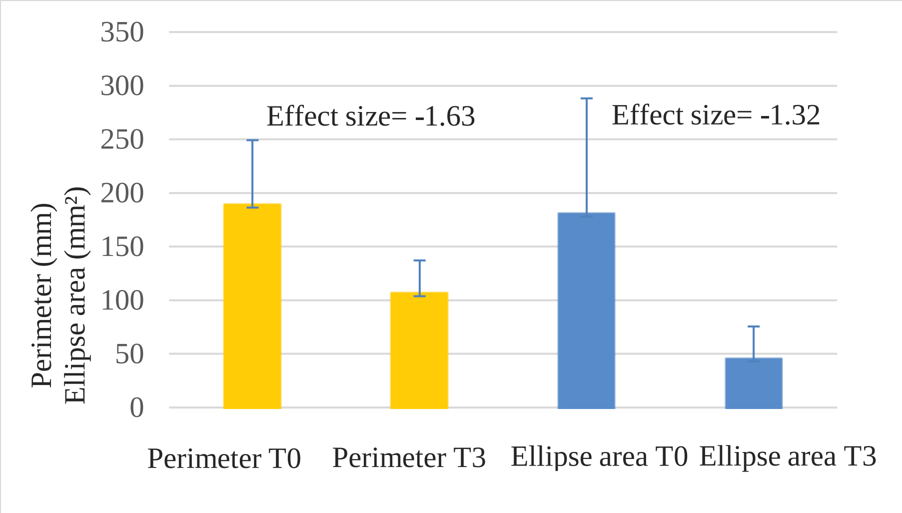
DLSEOW; double leg stance wide base of support with eyes open, DLSECW; double leg stance wide base of support with eyes closed, DLSEON; double leg stance narrow base of support with eyes open, DLSECN; double leg stance narrow base of support with eyes closed, SLS; single leg stance, SD; standard deviation, φ Effect size ≥0.8 or ≤ -0.8..

5.2.1.1.1 End of intervention compared to baseline

The six-week progressive WB balance training programme resulted in a number of statistically significant (P-value < 0.001) improvements in balance during double leg stance wide base of support with eyes open (DLSEOW), double leg stance wide base of support with eyes closed (DLSECW), double leg stance narrow base of support with eyes open (DLSEON), double leg stance narrow base of support with eyes closed (DLSECN) and single leg stance (SLS), as shown in Figures 15, 16, 17, 18 and 19 respectively. Furthermore, large ES ≥0.8 or ≤ -0.8 were also found across most tasks and metrics (Table 19).

5.2.1.1.2 Rate of change in static balance

In this study, statistically significant improvements were noted during each period of measurement (P-value≤0.001). This indicated gradual and consistent improvements in static balance performance, which was also mirrored in the magnitude of the ES ≥0.8 or ≤ -0.8 (Figures 15, 16, 17, 18 and 19 and Table 19).



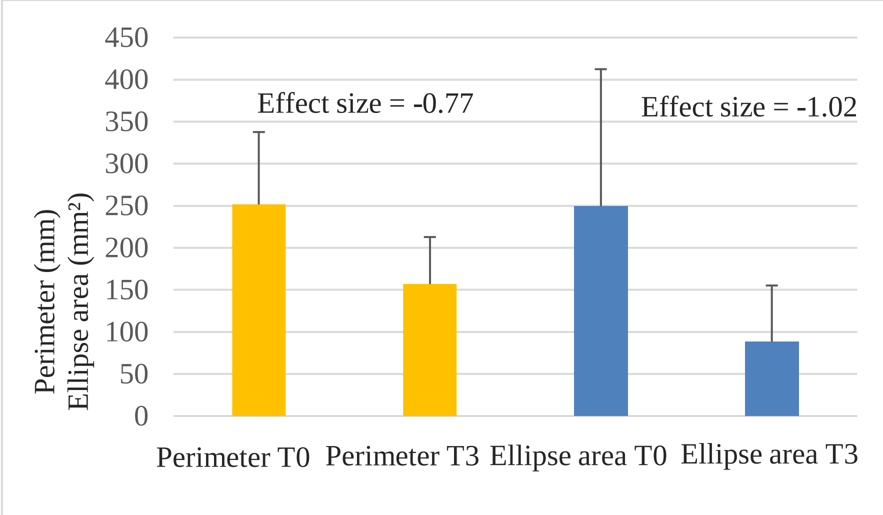
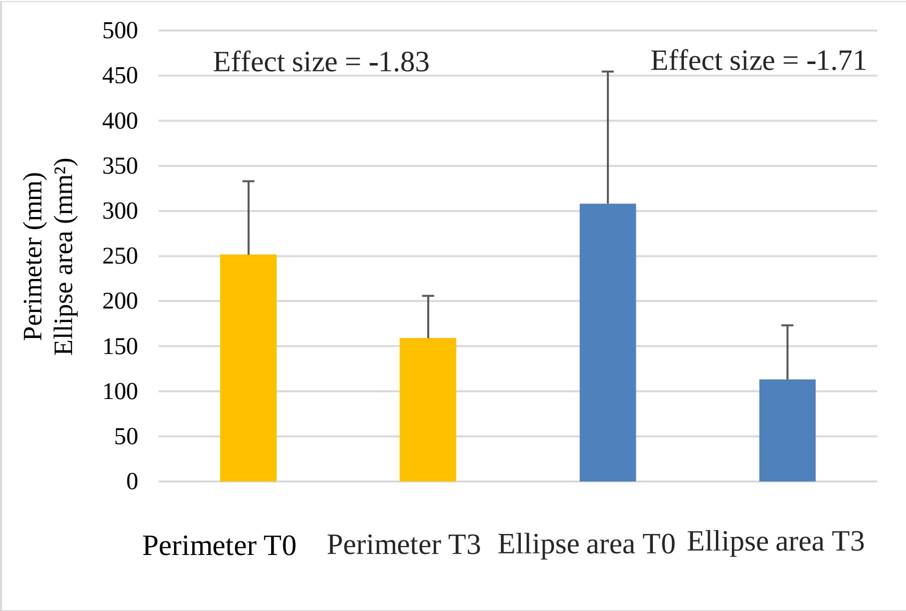


Figure 15. Pre and post six-week WB training effect on static balance during DLSEOW.

DLSEOW; double leg stance wide base of support with eyes open, T0; assessment at baseline, T3; assessment post six-week WB training.

Figure 16. Pre and post six-week WB training effect on static balance during DLSECW.

DLSECW; double leg stance wide base of support with eyes closed, T0; assessment at baseline, T3; assessment post six-week WB training.



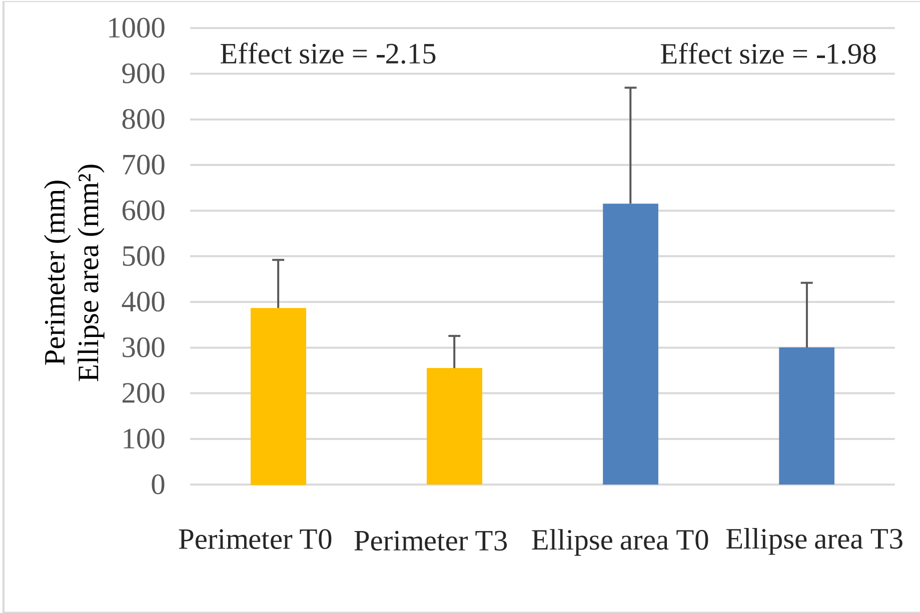


Figure 17. Pre and post six-week WB training effect on static balance during DLSEON.

DLSEON; double leg stance narrow base of support with eyes open, T0; assessment at baseline, T3; assessment post six-week WB training.

Figure 18. Pre and post six-week WB training effect on static balance during DLSECN.

DLSECN; double leg stance narrow base of support with eyes closed, T0; assessment at baseline, T3; assessment post six-week WB training.

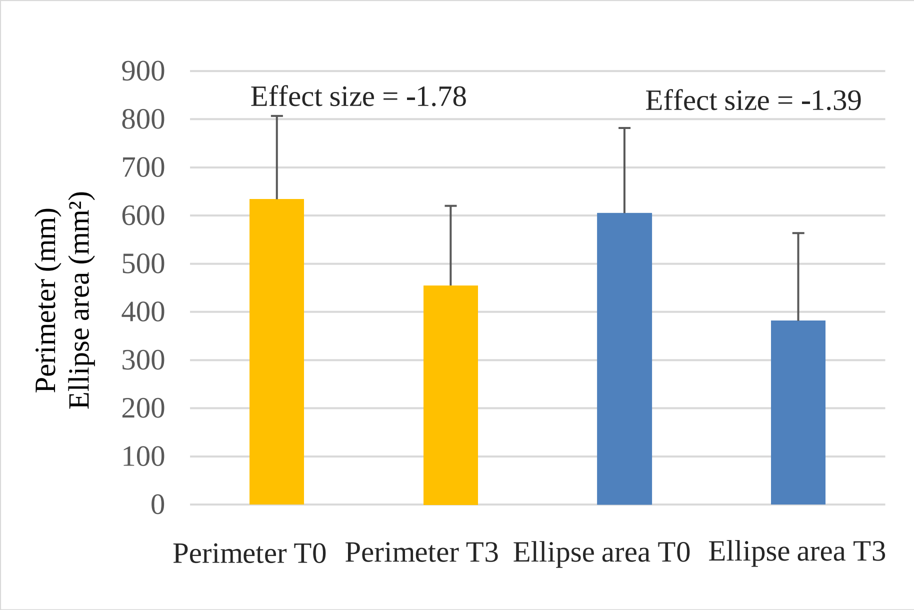
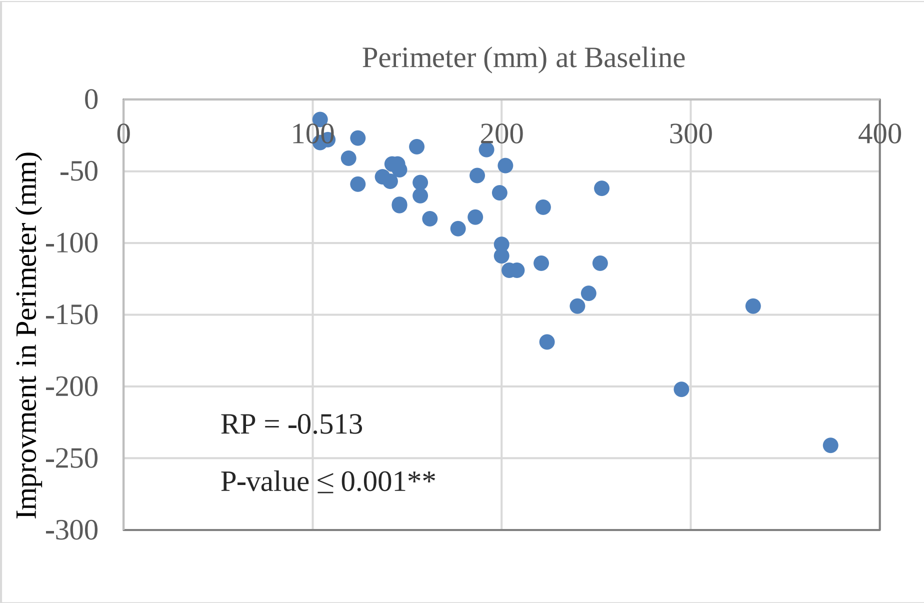


Figure 19. Pre and post six-week WB training effect on static balance during SLS.

SLS; single leg stance T0; assessment at baseline, T3; assessment post six-week WB training.

5.2.1.1.3 Relationship between change in static balance and baseline static balance score

Improvements in most static balance scores were statistically significantly (P-values=0.004, 0.005 and 0.023) correlated to the T0 baseline score, which was the initial balance performance. Therefore, as demonstrated by Figures 20, 21, 22, 24, 28 and 29, the poorer the balance during the initial performance (high positive value), the greater the improvements (or gains) in static balance (high negative value). Overall, the correlations were moderate (-0.428 to -0.531) and statistically significant correlated to T0 baseline, that is at initial balance performance in some tasks. As demonstrated by Figures 22, 24, 28 and 29, these consisted of DLSECW, DLSEON (perimeter area only) and SLS (both perimeter and ellipse area). However, there were non-statistically significant correlations between the T0 baseline score and improvement in static balance during DLSECW, DLSEON (ellipse areas only) and DLSECN (both perimeter and ellipse area), as shown in Figures 23, 25, 26 and 27.



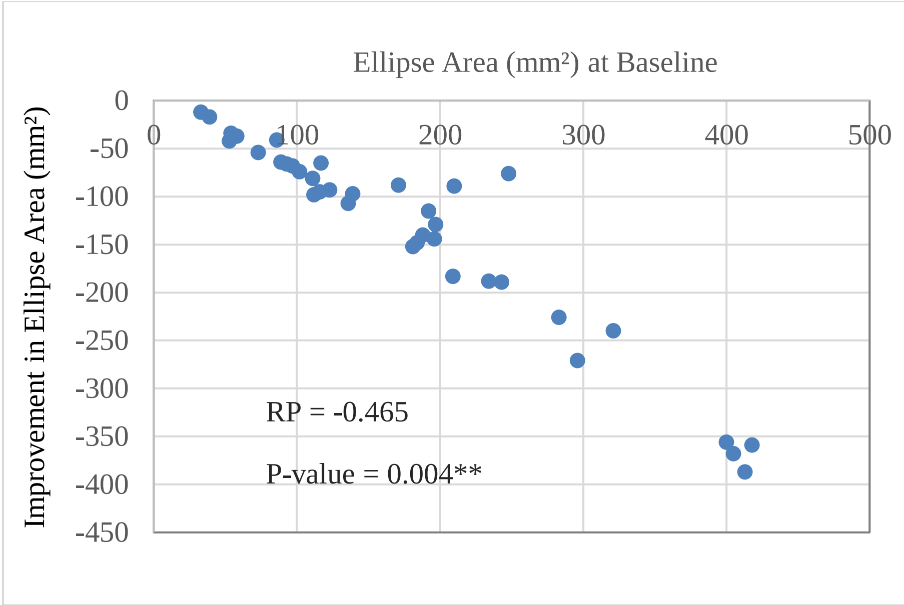


Figure 20. Correlation between baseline and change (improvement) after six weeks during DLSEOW (Perimeter).

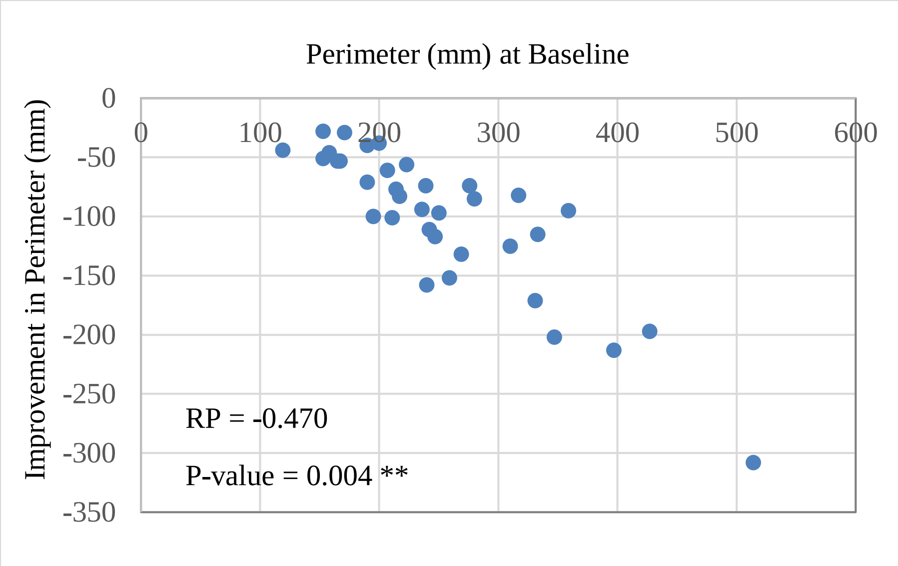
RP; Correlation coefficient of Pearson's correlation test.

**; Correlation is significant at 0.01 level (2-tailed).

Figure 21. Correlation between baseline and change (improvement) after six weeks during DLSEOW (Ellipse area).

RP; Correlation coefficient of Pearson's correlation test.

**; Correlation is significant at 0.01 level (2-tailed).



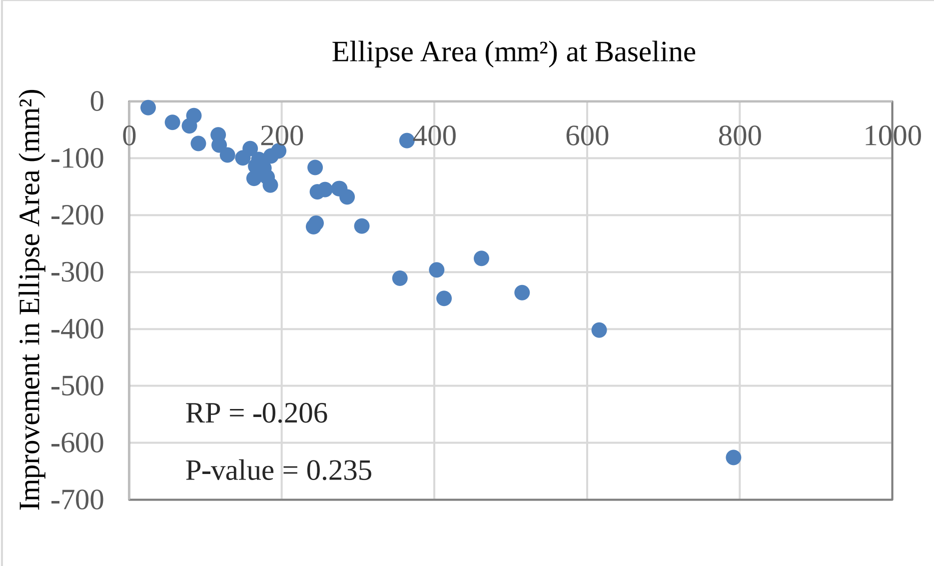


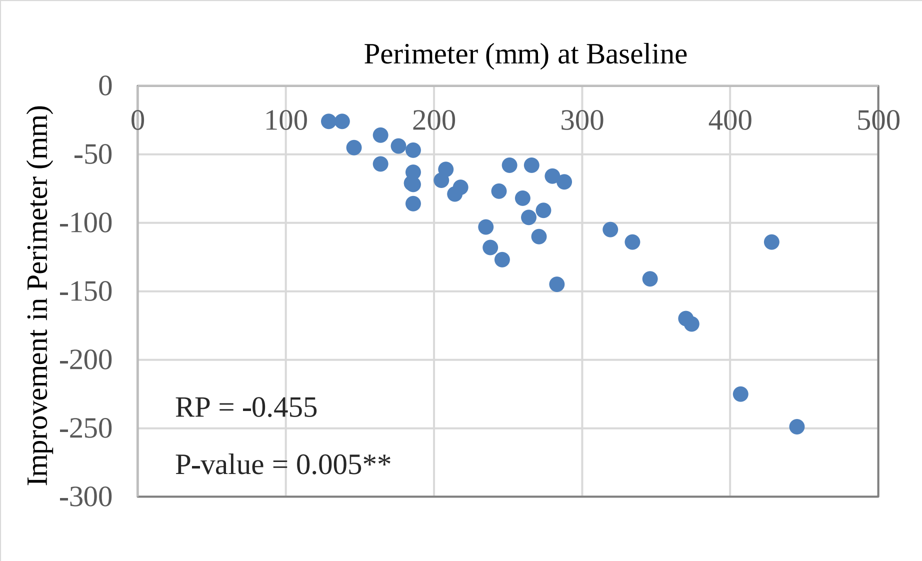
Figure 22. Correlation between baseline and change (improvement) after six weeks during DLSECW (Perimeter).

RP; Correlation coefficient of Pearson's correlation test.

**; Correlation is significant at 0.01 level (2-tailed).

Figure 23. Correlation between baseline and change (improvement) after six weeks during DLSECW (Ellipse area).

RP; Correlation coefficient of Pearson's correlation test.



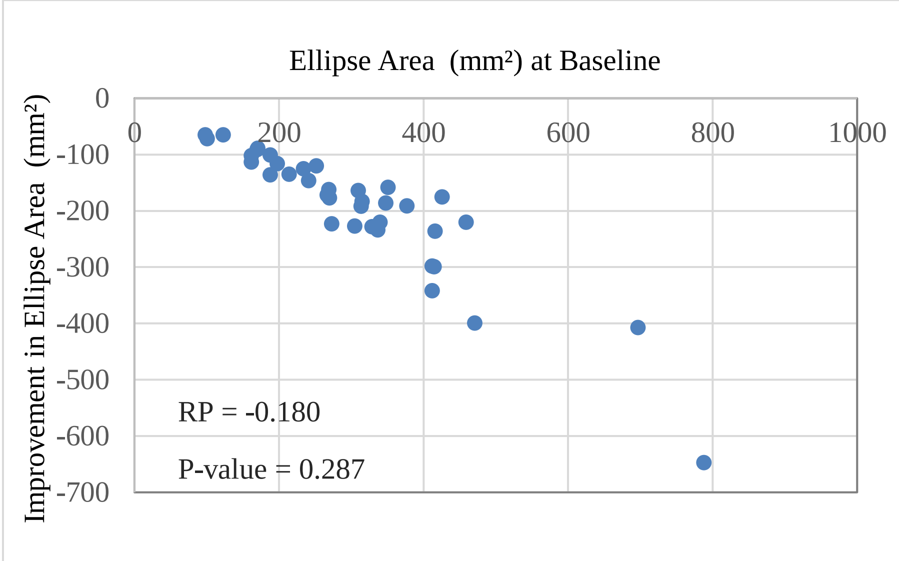


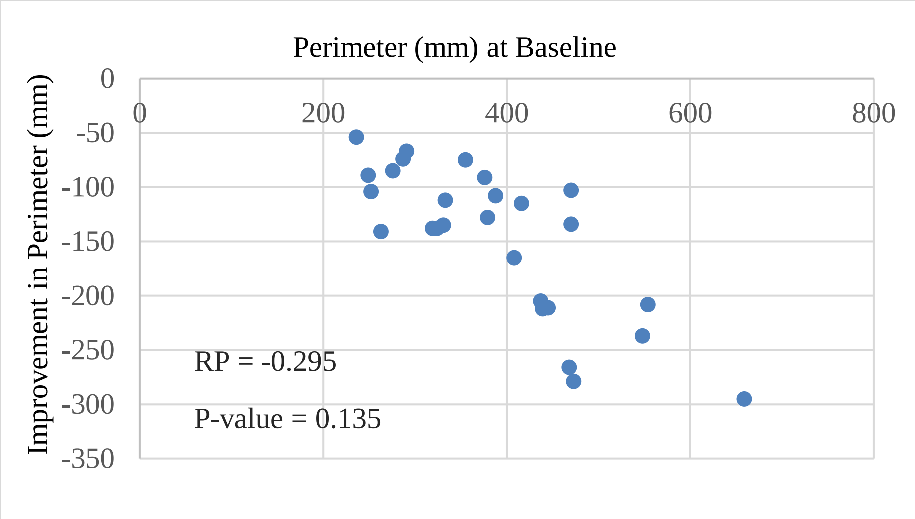
Figure 24. Correlation between baseline and change (improvement) after six weeks during DLSEON (Perimeter).

RP; Correlation coefficient of Pearson's correlation test.

**; Correlation is significant at 0.01 level (2-tailed).

Figure 25. Correlation between baseline and change (improvement) after six weeks during DLSEON (Ellipse area).

RP; Correlation coefficient of Pearson's correlation test.



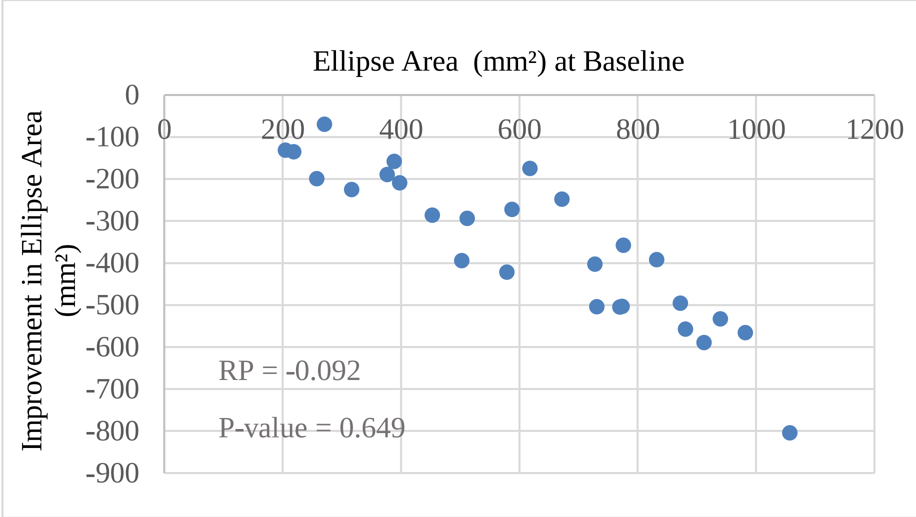
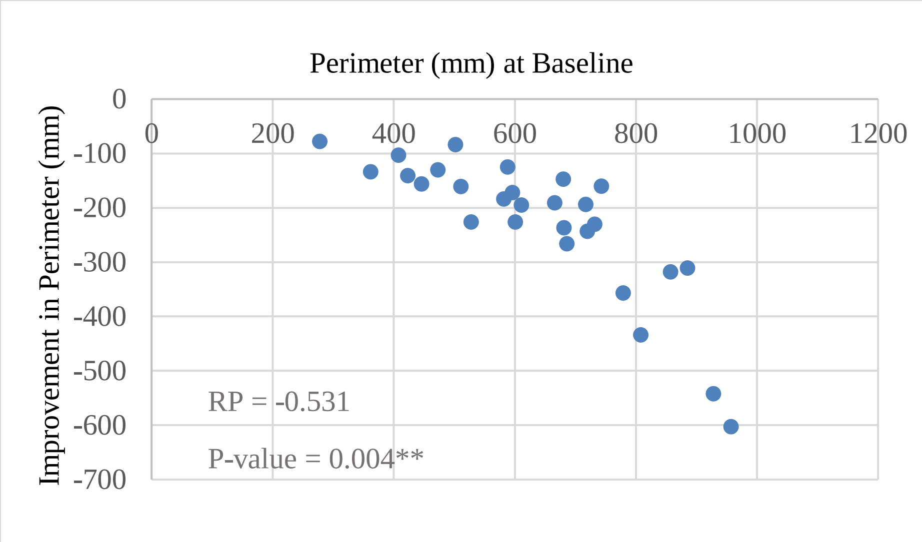


Figure 26. Correlation between baseline and change (improvement) after six weeks during DLSECN (Perimeter).

RP; Correlation coefficient of Pearson's correlation test.

Figure 27. Correlation between baseline and change (improvement) after six weeks during DLSECN (Ellipse area).

RP; Correlation coefficient of Pearson's correlation test.



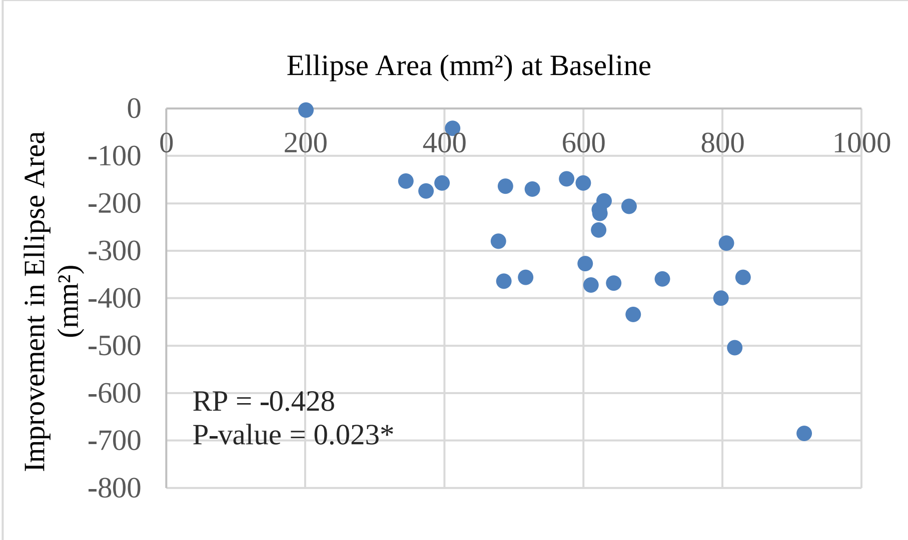


Figure 28. Correlation between baseline and change (improvement) after six weeks during SLS (Perimeter).

RP; Correlation coefficient of Pearson's correlation test.

**; Correlation is significant at 0.01 level (2-tailed).

Figure 29. Correlation between baseline and change (improvement) after six weeks during SLS (Ellipse area)

RP; Correlation coefficient of Pearson's correlation test.

*; Correlation is significant at 0.05 level (2-tailed).

5.2.1.1.4 At follow up

The influence of the wash out period was explored in two ways. Firstly, the balance score at the end of the study (T3) was compared to that following the wash-out period (T4). Secondly, the balance score at the beginning of the study (T0) was compared to that after the wash-out period (T4).

This study observed a statistically significant reduction in balance between T3 and T4, demonstrating a ‘detraining’ or wash-out effect (P-value ≤0.001) ranging from 20.11% to 93.87%. However, the overall improvement in balance retained at T4 was statistically significant in comparison to the baseline, that was ranging from -50.24% to -15.92% (see Table 20).

In addition, a reduction in static balance performance was observed during the wash-out period (follow up) at T4, as shown in Table 20, which demonstrates a reduction in static balance performance in period T4-T3 and an improvement in period T4-T0. Most of the effect sizes (ES) values in Table 20 were ≥ 0.8 or ≤ -0.8, which were considered large ES.

Table 20. Mean of change, standard deviation (SD) of change, percentage of change, effect sizes and P-values for static balance performance during wash-out period.

Task	Parameter	Difference weeks of assessment	Mean of change (mm)	SD of change (mm)	Percentage of change (%)	Effect size	P-value
DLSEOW	**Perimeter**	**T4-T3**	30.58	26.37	29.19	1.16 φ	≤ 0.001
		T4-T0	-51.00	42.22	-27.22	-1.21 φ	≤ 0.001
	Ellipse Area	**Difference weeks of assessment**	**Mean of change (mm²)**	**SD of change (mm²)**	**Percentage of change (%)**	**Effect size**	**P-value**
		T4-T3	41.28	40.35	93.87	1.02 φ	≤ 0.001
		T4-T0	-89.89	101.53	-50.24	-0.89	≤ 0.001
DLSECW	**Perimeter**	**Difference weeks of assessment**	**Mean of change (mm)**	**SD of change (mm)**	**Percentage of change (%)**	**Effect size**	**P-value**
		T4-T3	38.61	33.10	24.62	1.17 φ	≤ 0.001
		T4-T0	-40.06	119.57	-15.92	-0.33	≤ 0.001
		Difference weeks of assessment	**Mean of change (mm²)**	**SD of change (mm²)**	**Percentage of change (%)**	**Effect size**	**P-value**
	Ellipse Area	**T4-T3**	41.39	42.02	46.73	0.98 φ	≤ 0.001
		T4-T0	-106.86	139.21	-42.84	-0.77	≤ 0.001

Task	Parameter	Difference weeks of assessment	Mean of change (mm)	SD of change (mm)	Percentage of change (%)	Effect size	P-value
DLSEON	**Perimeter**	**Difference weeks of assessment**	**Mean of change (mm)**	**SD of change (mm)**	**Percentage of change (%)**	**Effect size**	**P-value**
		T4-T3	33.78	26.68	21.26	1.27 φ	≤ 0.001
		T4-T0	-59.28	55.95	-23.59%	-1.06 φ	≤ 0.001
	Ellipse Area	**Difference weeks of assessment**	**Mean of change (mm^2)**	**SD of change (mm^2)**	**Percentage of change (%)**	**Effect size**	**P-value**
		T4-T3	68.53	58.36	60.56	1.17 φ	≤ 0.001
		T4-T0	-125.58	91.24	-40.75	-1.38 φ	≤ 0.001
DLSECN	**Perimeter**	**Difference weeks of assessment**	**Mean of change (mm)**	**SD of change (mm)**	**Percentage of change (%)**	**Effect size**	**P-value**
		T4-T3	70.60	54.90	27.67	1.29 φ	≤ 0.001
		T4-T0	-89.42	73.10	-23.11	-1.22 φ	≤ 0.001
	Ellipse Area	**Difference weeks of assessment**	**Mean of change (mm^2)**	**SD of change (mm^2)**	**Percentage of change (%)**	**Effect size**	**P-value**
		T4-T3	146.29	136.49	48.71	1.07 φ	≤ 0.001
		T4-T0	-231.92	199.90	-37.69	-1.16 φ	≤ 0.001

Task	Parameter	Difference weeks of assessment	Mean of change (mm)	SD of change (mm)	Percentage of change (%)	Effect size	P-value
SLS	**Perimeter**	**Difference weeks of assessment**	**Mean of change (mm)**	**SD of change (mm)**	**Percentage of change (%)**	**Effect size**	**P-value**
		T4-T3	91.48	64.14	20.11	1.43 φ	≤ 0.001
		T4-T0	-129.92	108.83	-20.50	-1.19 φ	≤ 0.001
	Ellipse Area	**Difference weeks of assessment**	**Mean of change (mm²)**	**SD of change (mm²)**	**Percentage of change (%)**	**Effect size**	**P-value**
		T4-T3	117.90	100.97	30.92	1.17 φ	≤ 0.001
		T4-T0	-173.42	143.06	-28.66	-1.21 φ	≤ 0.001

DLSEOW; double leg stance wide base of support with eyes open, DLSECW; double leg stance wide base of support with eyes closed, DLSEON; double leg stance narrow base of support with eyes open, DLSECN; double leg stance narrow base of support with eyes closed, SLS; single leg stance, SD; standard deviation, φ; Effect size ≥0.8 or ≤ -0.8.

5.2.1.2 Wobble board (WB) performance

The mean and SD scores for WB performance during double leg stance wide base of support with eyes open (DLSEOW) at tilt angle 5° are presented in Table 21, along with the mean change, the SD of the change and percentage of change, including the effect sizes (ES) for WB performance across the intervention period, which is six weeks of progressive WB balance training programme. No outliers were identified.

5.2.1.2.1 End of intervention compared to baseline

This six-week progressive WB balance training programme resulted in a number of significant (P-value ≤ 0.001) improvements in WB performance, as indicated by scores of anteroposterior stability index (APSI) more than scores of mediolateral stability index (MLSI), as well as improvement in percentages of time spent in both inner and outer zones, during DLSEOW at tilt angle 5°, as shown in Figures 30 and 31 respectively. Furthermore, large ES (≥ 0.8 or ≤ -0.8) were also found across APSI and MLSI, with exception of percentages of time spent in inner and outer zones (Table 21).

5.2.1.2.2 Rate of change in WB performance

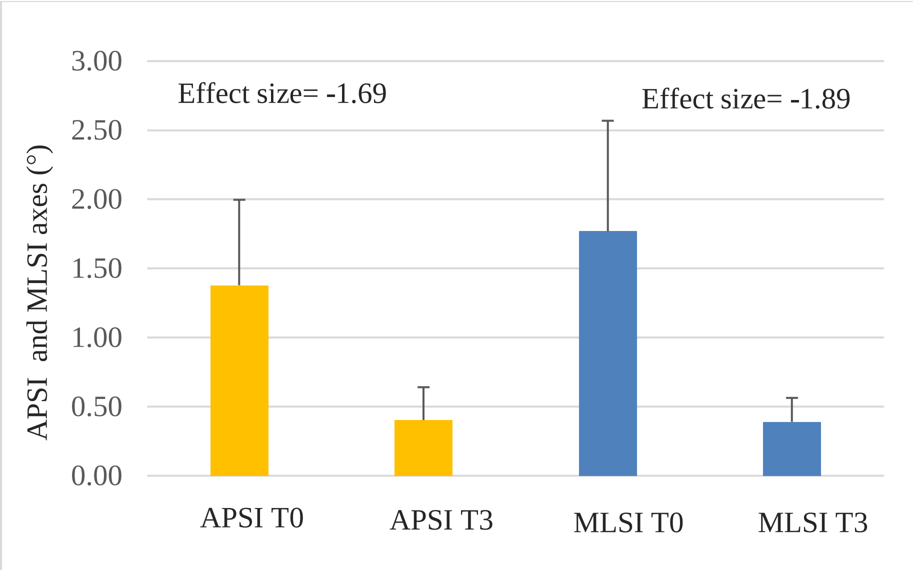
With respect to the rate of change in WB performance, significant improvements were noted during each period of measurement (P-value≤0.001) for APSI and MLSI, as well as during T0 and T1 only for percentages of time spent in inner and outer zones, with the exception of percentages of time spent in inner and outer zones across other weeks. This indicated gradual and consistent improvements in WB performance during DLSEOW 5°, which was also mirrored in the magnitude of the ES (≥ 0.8 or ≤ -0.8) in both APSI and MLSI, with exception of percentages of time spent in inner and outer zones (Table 21).

Table 21. Mean, standard deviation (SD), mean of change, SD of change, percentage of change, effect sizes and P-values for WB performance during DLSEOW 5° for all assessment weeks (which were T0, T1, T2, T3 and T4).

Task	Parameter	Week of assessment	Mean (°)	SD (°)	Mean of change (°)	SD of change (°)	Percentage of change (%)	Effect size	P-value
DLSEOW 5°	APSI	T0 Baseline	1.38	0.62					
		T1	0.86	0.37	-0.51	0.49	-37.24	-1.04 φ	≤0.0001
		T2	0.65	0.33	-0.21	0.17	-24.84	-1.27 φ	≤0.0001
		T3	0.40	0.24	-0.25	0.18	-37.96	-1.38 φ	≤0.0001
		T4 (Wash-out)	0.62	0.34	0.22	0.23	53.32	0.95 φ	≤0.0001
	MLSI	T0 Baseline	1.77	0.80					
		T1	1.17	0.53	-0.60	0.55	-34.12	-1.10 φ	≤0.0001
		T2	0.79	0.47	-0.38	0.30	-32.52	-1.27 φ	≤0.0001
		T3	0.39	0.17	-0.40	0.37	-50.36	-1.07 φ	≤0.0001
		T4 (Wash-out)	0.79	0.47	0.40	0.41	102.07	0.97 φ	≤0.0001
	Percentage of time in inner zone	**Week of assessment**	**Mean (%)**	**SD (%)**	**Mean of change (%)**	**SD of change (%)**	**Percentage of change (%)**	**Effect size**	**P-value**
		T0 Baseline	93.08	13.91					
		T1	99.54	1.37	6.46	13.74	6.94	0.47	≤0.0001
		T2	100.00	0.00	0.46	1.37	0.46	0.34	0.043
		T3	100.00	0.00	0.00	0.00	0.00	NA	1.000

Task	Parameter	Week of assessment	Mean (°)	SD (°)	Mean of change (°)	SD of change (°)	Percentage of change (%)	Effect size	P-value
		T4 (Wash-out)	99.50	1.76	-0.50	1.76	-0.50	-0.28	0.042
	Percentage of time in outer zone	T0 Baseline	6.92	13.91					
		T1	0.46	1.37	-6.46	13.74	-93.36	-0.47	≤0.0001
		T2	0.00	0.00	-0.46	1.37%	-100.00	-0.34	0.043
		T3	0.00	0.00	0.00	0.00	NA	NA	1.000
		T4 (Wash-out)	0.47	1.75	0.47	1.75	6.83	0.27	0.042

APSI; anteroposterior stability index, MLSI; mediolateral stability index, DLSEOW; double leg stance wide base of support with eyes open, SD; standard deviation, $_{\varphi}$ Effect size ≥ 0.8 or ≤ -0.8.



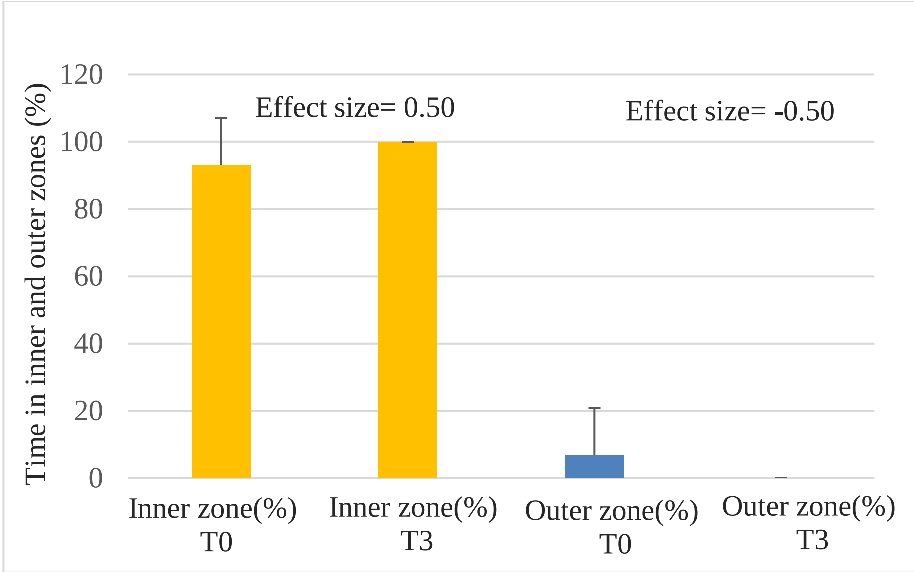


Figure 30. Pre and post six-week WB training effect on WB performance (APSI and MLSI) during DLSEOW 5°.

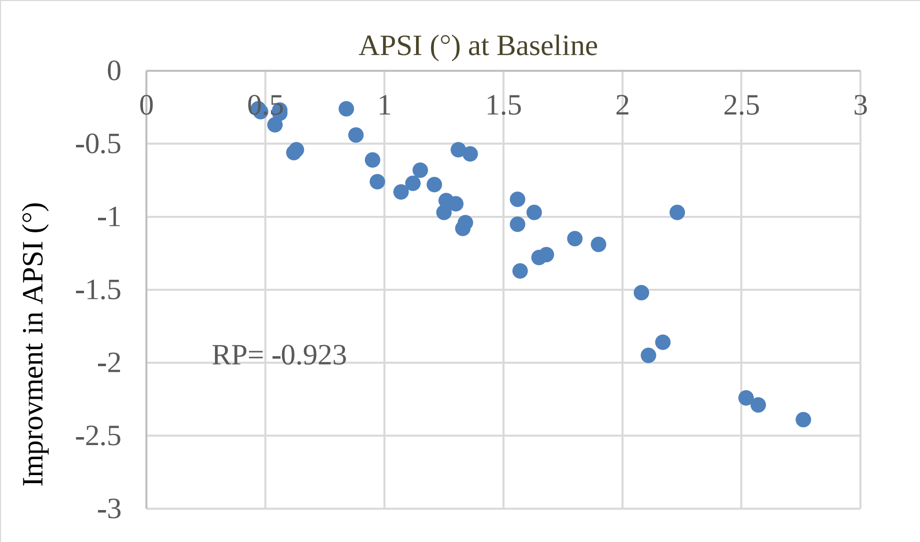
DLSEOW; double leg stance wide base of support with eyes open, APSI; anteroposterior stability index, MLSI; mediolateral stability index, T0; assessment at baseline, T3; assessment post six-week WB training.

Figure 31. Pre and post six-week WB training effect on WB performance (percentages of time spent in inner and outer zones) during DLSEOW 5°.

DLSEOW; double leg stance wide base of support with eyes open, T0; assessment at baseline, T3; assessment post six-week WB training.

5.2.1.2.3 Relationship between change in dynamic balance and baseline WB performance score

The relationship between the change in dynamic balance and baseline WB performance score improved during most WB performances scores were statistically significantly (P-value≤0.001) correlated to the T0 baseline, which was at initial WB performance. Therefore, as demonstrated by Figures 32, 33, 34 and 35, the poorer the WB performance, during the initial performance (high positive value), the greater the improvements (or gains) in WB performance (high negative value) during DLSEOW 5° in all WB performance parameters, which are APSI, MLSI and percentage of time spent in the outer zone, with the exception of percentage of time spent in the inner zone. Percentage of time spent in the inner zone, as demonstrated by Figure 34, the poorer the WB performance during the initial performance (low positive value), the greater the improvements (or gains) in WB performance (high positive value) during DLSEOW 5°. Overall, the correlations were very high negative correlations (-0.923 to -1), as demonstrated in Figures 32, 33, 34 and 35.



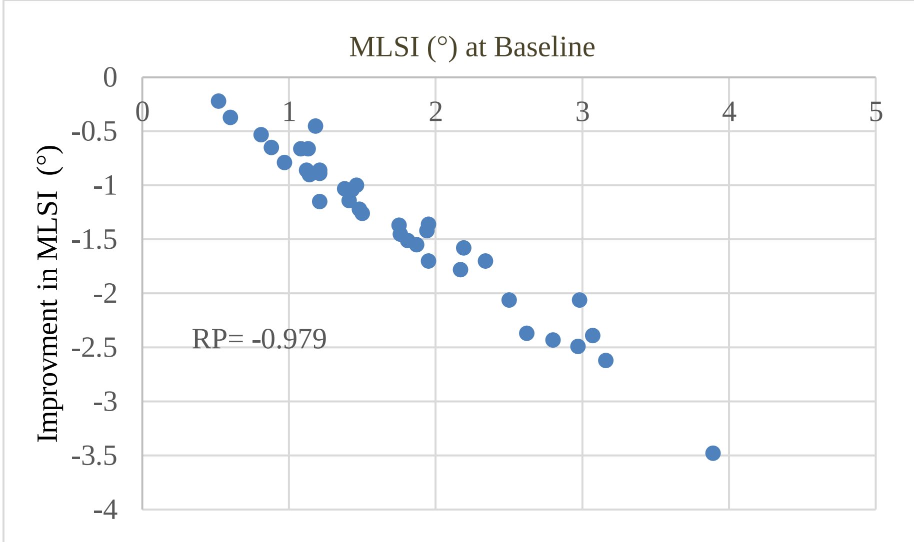
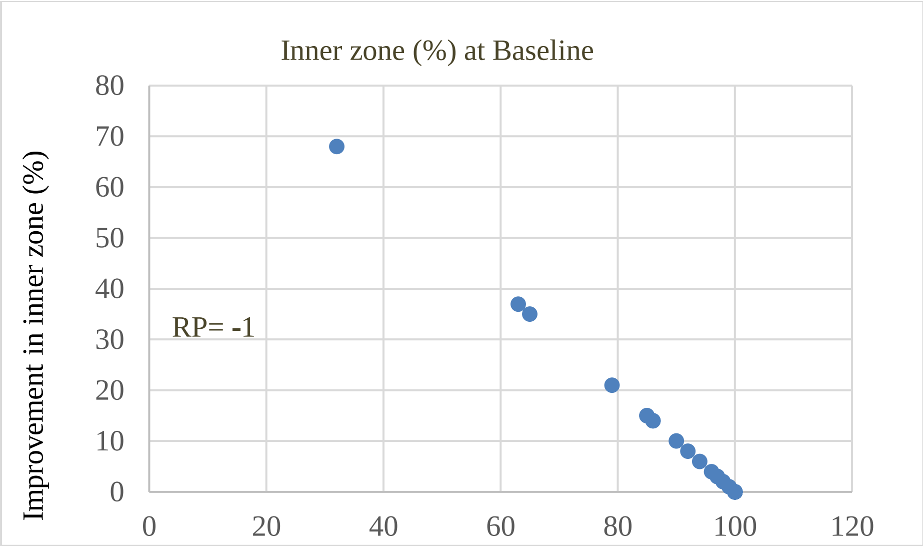


Figure 32. Correlation between baseline and change after six weeks during DLSEOW 5° (APSI).

RP; Correlation coefficient of Pearson's correlation test, APSI; anteroposterior stability index.

Figure 33. Correlation between baseline and change after six weeks during DLSEOW 5° (MLSI).

RP; Correlation coefficient of Pearson's correlation test, MLSI; mediolateral stability index.



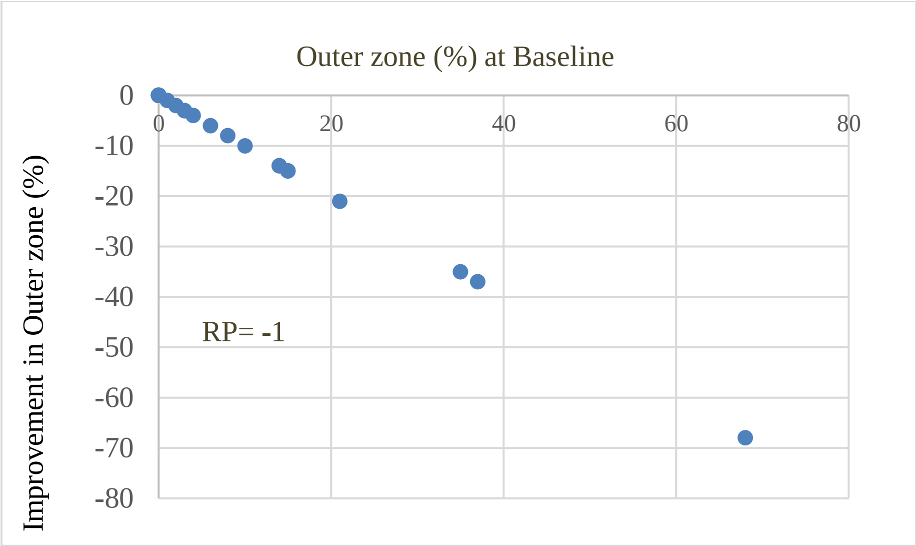


Figure 34. Correlation between baseline and change after six weeks during DLSEOW 5° (percentage of time in inner zone).

RP; Correlation coefficient of Pearson’s correlation test.

Figure 35. Correlation between baseline and change after six weeks during DLSEOW 5° (percentage of time in outer zone).

RP; Correlation coefficient of Pearson’s correlation test.

5.2.1.2.4 At follow up

The effect of the wash-out period was explored in two ways. First, the WB performance scores, during DLSEOW 5° at the end of the study (T3), was compared to the WB performance scores after the wash out period (T4). Next the WB performance scores at the beginning of the study (T0) was compared to the WB performance scores after the wash-out period (T4).

A statistically significant (P-value ≤0.001) reduction in WB performance (APSI and MLSI only, with the exception of percentages of time spent in the inner and outer zones) was noted between T3 and T4. However, the overall improvement in WB performance retained at T4 was statistically significant (APSI, MLSI, percentages of time spent in the inner and outer zones) compared to baseline (see Table 22).

During the wash-out period (follow up) at T4, a reduction in WB performance was observed. Table 22 demonstrates the reduction in WB performance during the period T4-T3 and improvement in period T4-T0. Most of the effect size values in Table 22 were ES ≥ 0.8 or ≤ -0.8, which are considered large effect sizes for APSI and MLSI, with the exception of percentages of time spent in the inner and outer zones.

Table 22. Mean of change, standard deviation (SD) of change, percentage of change, effect sizes and P-values for WB performance during DLSEOW 5° for wash-out period.

Task	Parameter	Difference weeks of assessment	Mean of change	SD of change	Percentage of change	Effect size	p-value
DLSEOW 5°	APSI	**T4-T3**	0.22°	0.23°	53.32%	0.95 φ	≤0.001
		T4-T0	-0.72°	0.51°	-52.49%	-1.43 φ	≤0.001
	MLSI	**T4-T3**	0.40°	0.41°	102.07%	0.97 φ	≤0.001
		T4-T0	-0.98°	0.67°	-55.14%	-1.45 φ	≤0.001
	Inner time	**T4-T3**	-0.50%	1.76%	-0.50%	-0.28	0.042
		T4-T0	6.03%	12.64%	6.48%	0.48	≤0.001
	Outer time	**T4-T3**	0.47%	1.75%	6.83%	0.27	0.042
		T4-T0	-6.06%	12.62%	-87.52%	-0.48	≤0.001

DLSEOW; double leg stance wide base of support with eyes open, SD; standard deviation, APSI; anteroposterior stability index, MLSI; mediolateral stability index, %inner time; percentage of time in inner zone, %outer time; percentage of time in outer zone φ; Effect size ≥ 0.8 or ≤ -0.8

5.2.1.2.5 Level of success prior to failure

The mean, SD and 95% confidence interval corridor for every level of success prior to failure were depicted in Table 23 and Figure 36. The mean and SD show the participants progressed up the WB levels over time but that their levels declined when training ceased. Figure 36 shows the 95% confidence interval corridors demonstrating the expected improvement across the training period and after cessation.

Table 23. Mean, SD and 95% confidence interval corridors for every progression level prior to failure.

Parameter	Change in level of WB success T1-T0	Change in level of WB success T2-T1	Change in level of WB success T3-T2	Change in level of WB success T4-T3
Mean	1.76	2.08	2.38	-3.17
SD	0.86	0.86	1.21	2.16
Confidence interval corridor	0.28	0.28	0.39	0.70

WB; wobble board, SD; standard deviation.

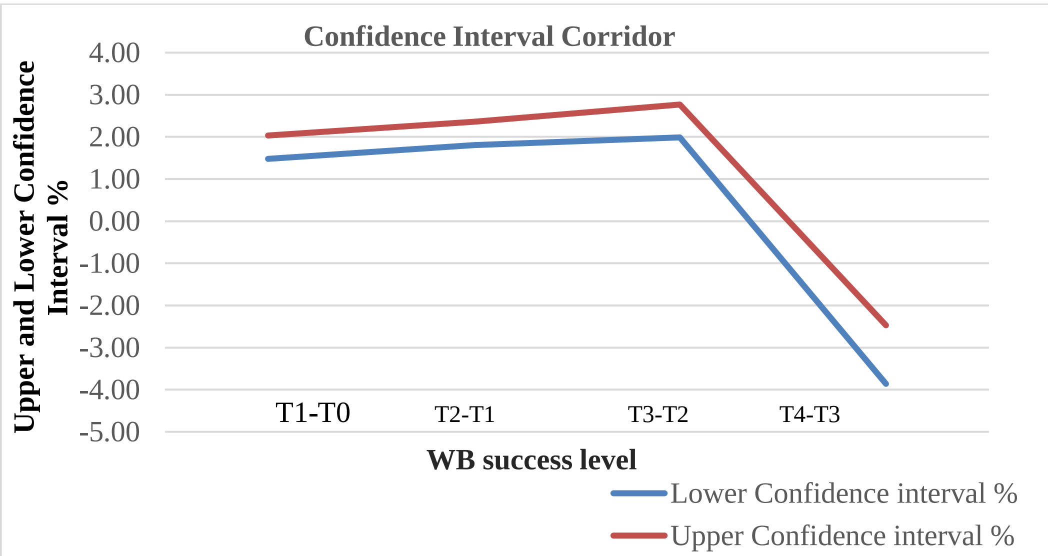


Figure 36. Confidence Interval Corridor.

WB; Wobble board, SD; standard deviation.

5.2.1.3 Muscle Strength

The mean and SD scores for ankle muscle strength, along with the mean change, SD of the change and percentage change, including the effect sizes (ES) on ankle muscle strength across the intervention period, which is six weeks of progressive WB balance training programme is shown in Appendix 12.

5.2.1.3.1 End of intervention compared to baseline

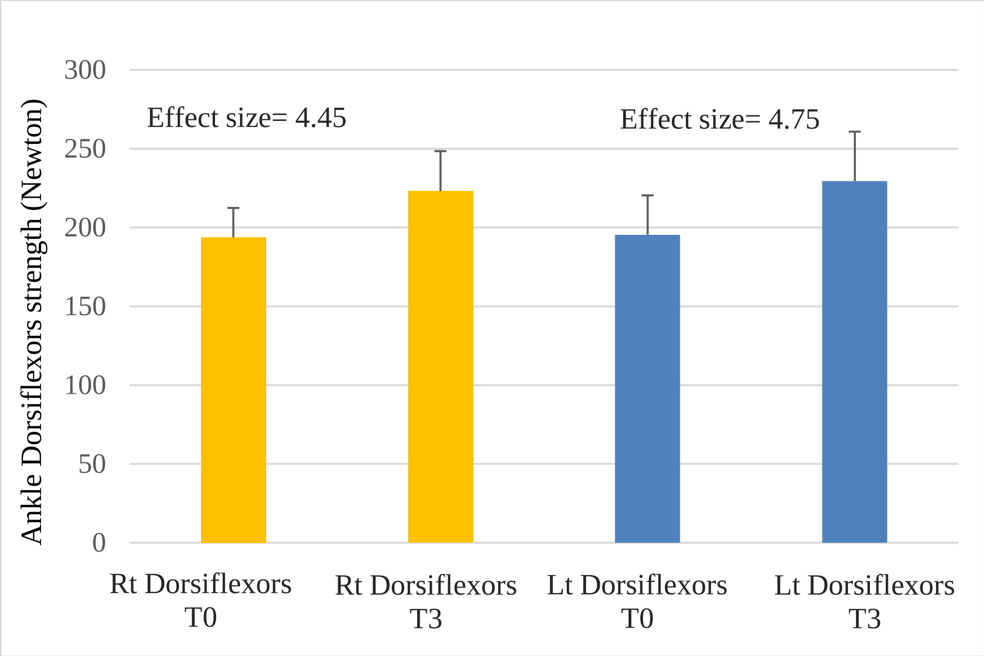
The six-week progressive WB balance training programme resulted in a number of statistically significant (P-value ≤0.001) gains in ankle muscles strength, which are dorsiflexors, plantar flexors, invertors and evertors for both right (Rt) and left (Lt) sides, as shown in Figures 37, 38, 39 and 40, respectively. Furthermore, a considerable improvement was identified across all ankle muscles in both Rt and Lt sides.

5.2.1.3.2 Rate of change in muscle strength

In addition, significant improvements were noted during each measurement period (P-value≤0.001), so demonstrating gradual and consistent gains in the strength of all ankle muscles, which was also mirrored in the magnitude of the ES ≥0.8 or ≤ -0.8 (Appendix 12).

5.2.1.3.3 Relationship between change in muscle strength and baseline muscle strength score

Improvements in muscle strength were found to be statistically significant (P-value≤0.001), when correlated to the T0 baseline, which is at initial ankle muscle strength scores. Therefore, as demonstrated by Figures 41, 42, 43, 44, 45, 46, 47 and 48 the weaker the ankle muscles were found to be during the initial muscle strength measurements (low positive value) the greater their improvements or strength (high positive value), those ankle muscles were dorsiflexors, plantar flexors, invertors and evertors. Overall, the study revealed very high positive correlations (0.706 - 0.860), except for Lt dorsiflexor, which proved moderately positive (0.623).



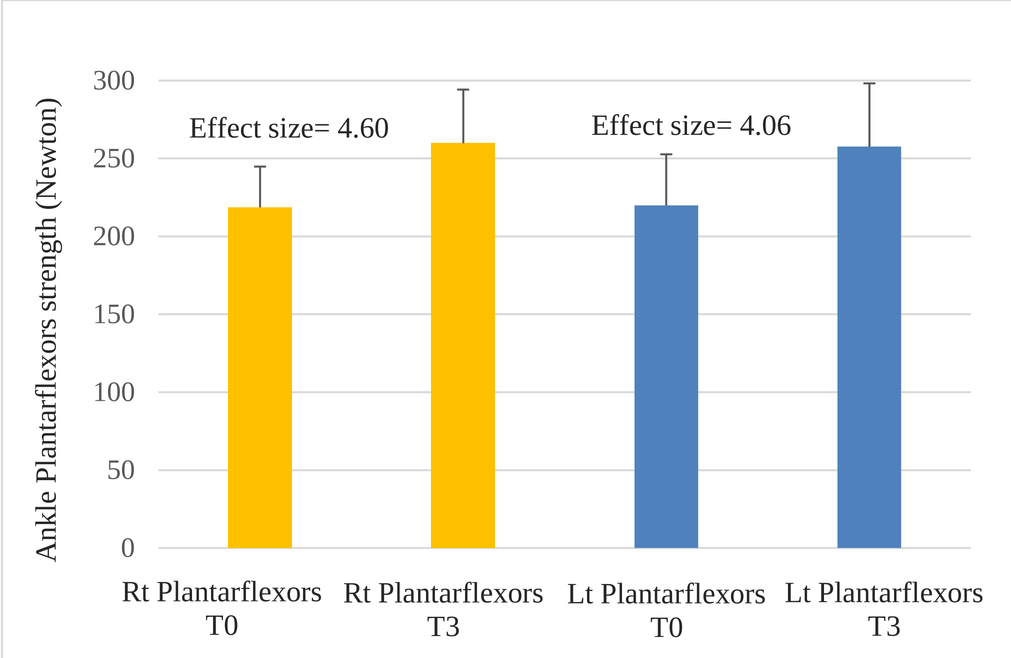
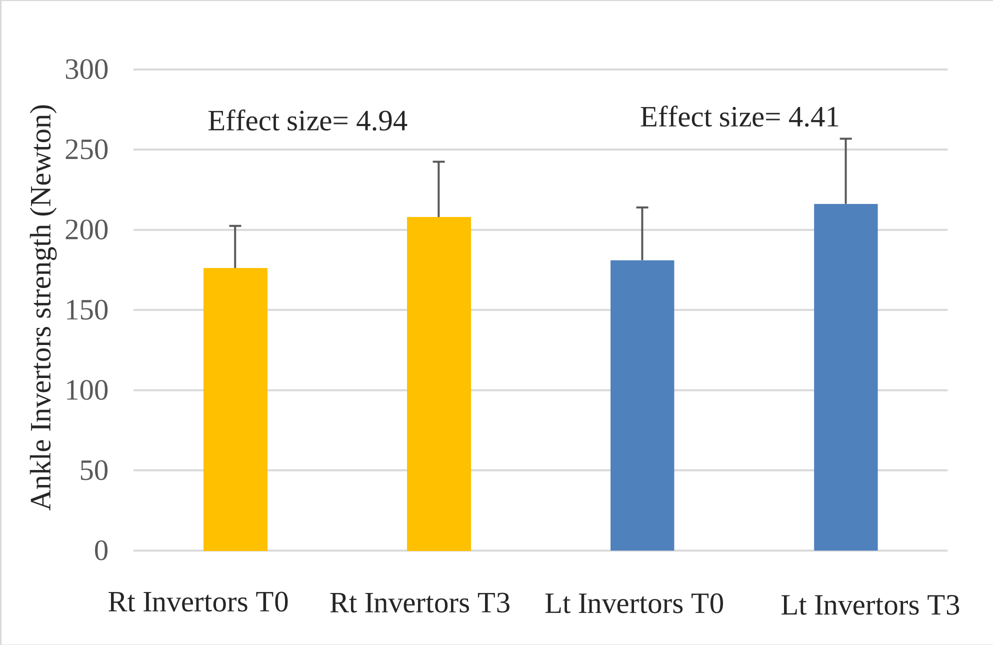


Figure 37. Pre and post six-week WB training effect on strength of ankle Dorsiflexors.

Figure 38. Pre and post six-week WB training effect on strength of ankle Planar flexors.



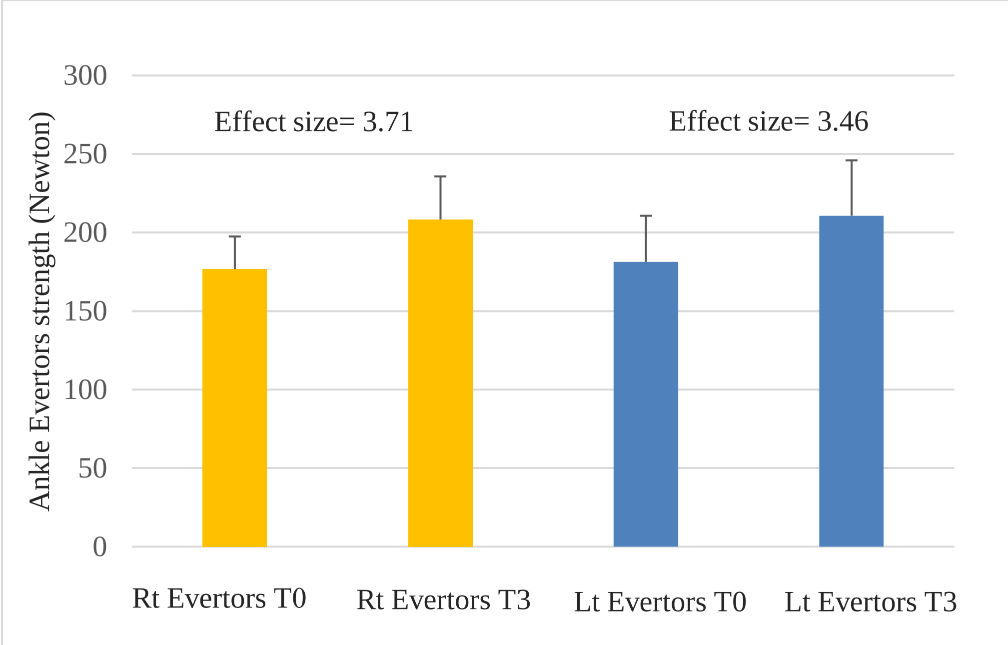
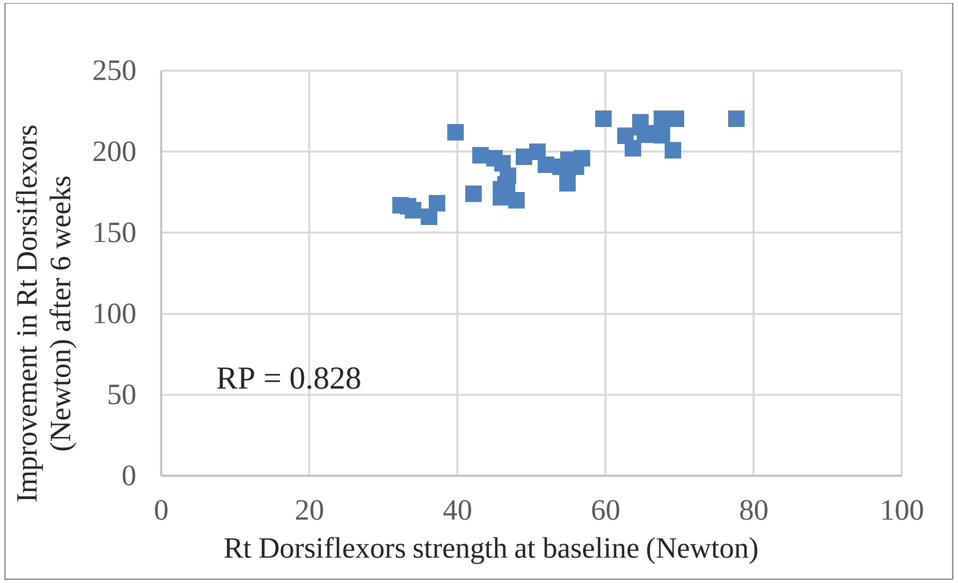


Figure 39. Pre and post six-week WB training effect on strength of ankle Invertors.

Figure 40. Pre and post six-week WB training effect on strength of ankle Evertors.



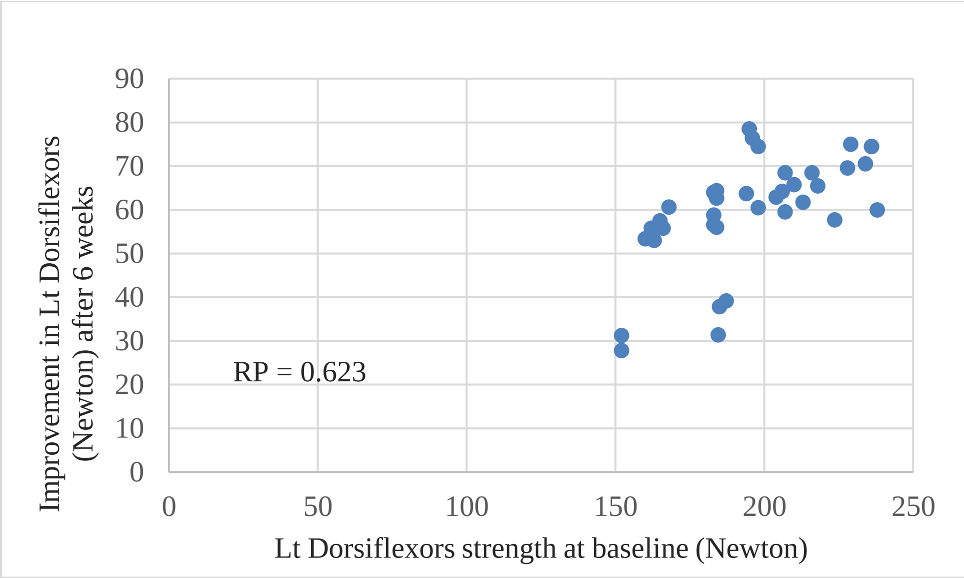
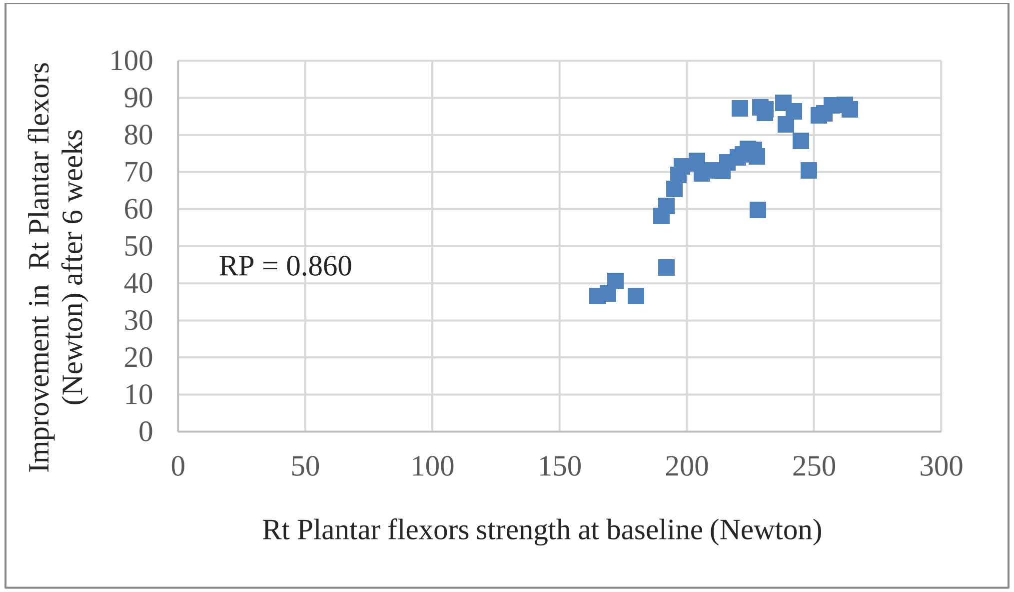


Figure 41. Correlation between baseline and change after six weeks for Rt Dorsiflexors strength.

RP; Correlation coefficient of Pearson's correlation test, Rt.; Right.

Figure 42. Correlation between baseline and change after six weeks for Lt Dorsiflexors strength.

RP; Correlation coefficient of Pearson's correlation test, Lt.; Left.



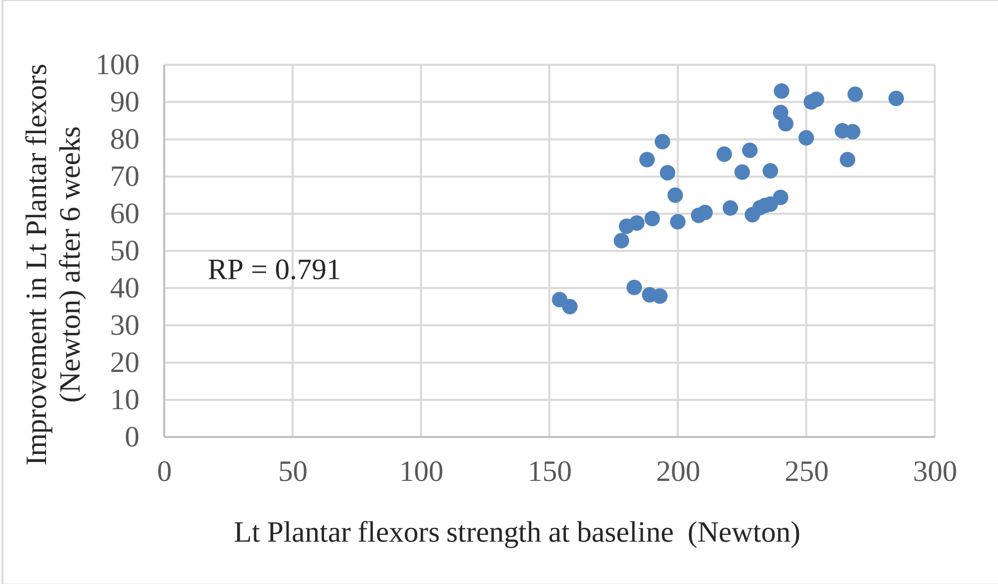
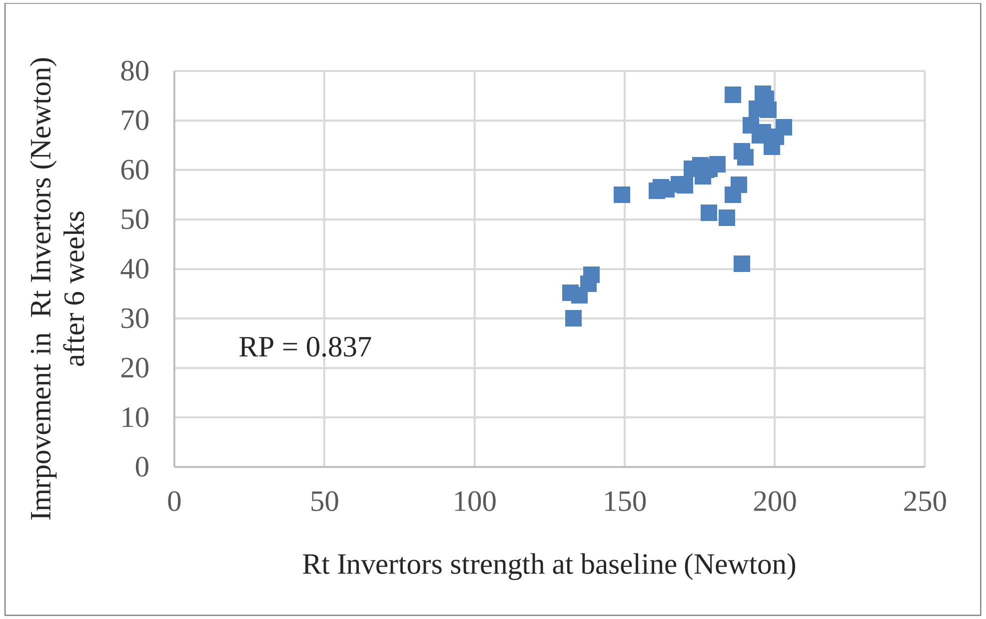


Figure 43. Correlation between baseline and change after six weeks for Rt Plantar flexors strength.

RP; Correlation coefficient of Pearson's correlation test, Rt.; Right.

Figure 44. Correlation between baseline and change after six weeks for Lt Plantar flexors strength.

RP; Correlation coefficient of Pearson's correlation test, Lt.; Left.



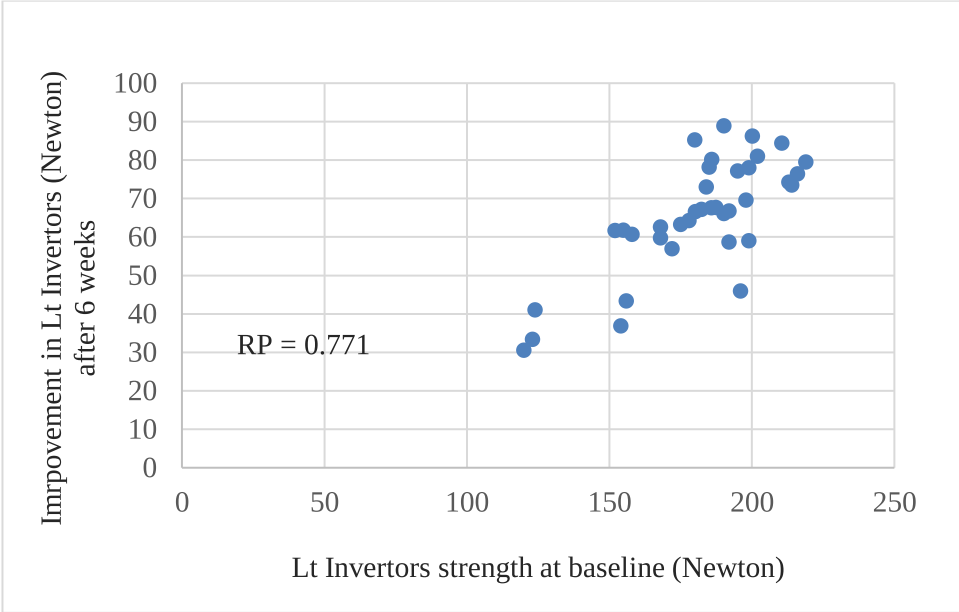
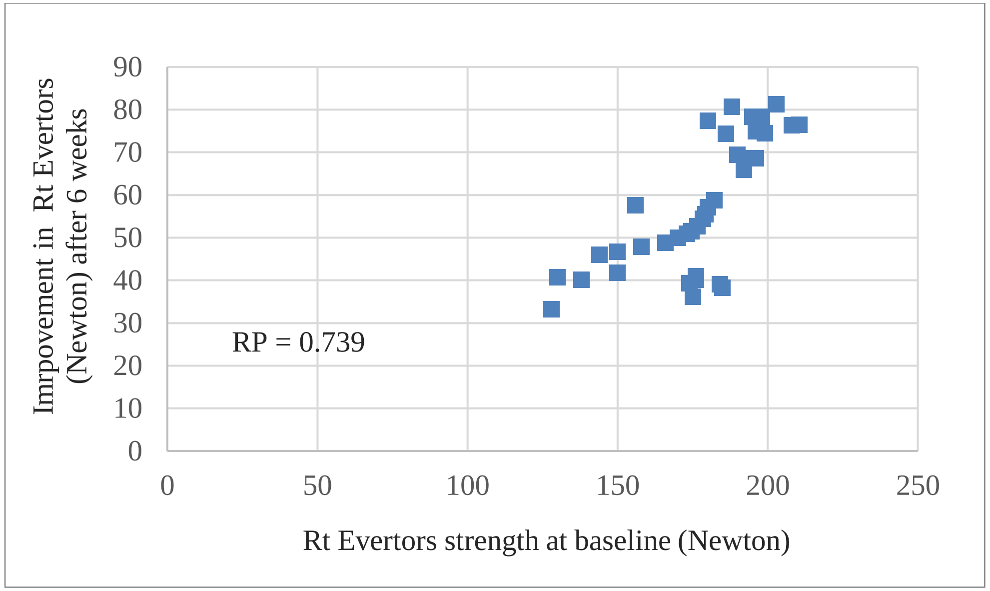


Figure 45. Correlation between baseline and change after six weeks for Rt Invertors strength.

RP; Correlation coefficient of Pearson's correlation test, Rt.; Right.

Figure 46. Correlation between baseline and change after six weeks for Lt Invertors strength.

RP; Correlation coefficient of Pearson's correlation test, Lt.; Left.



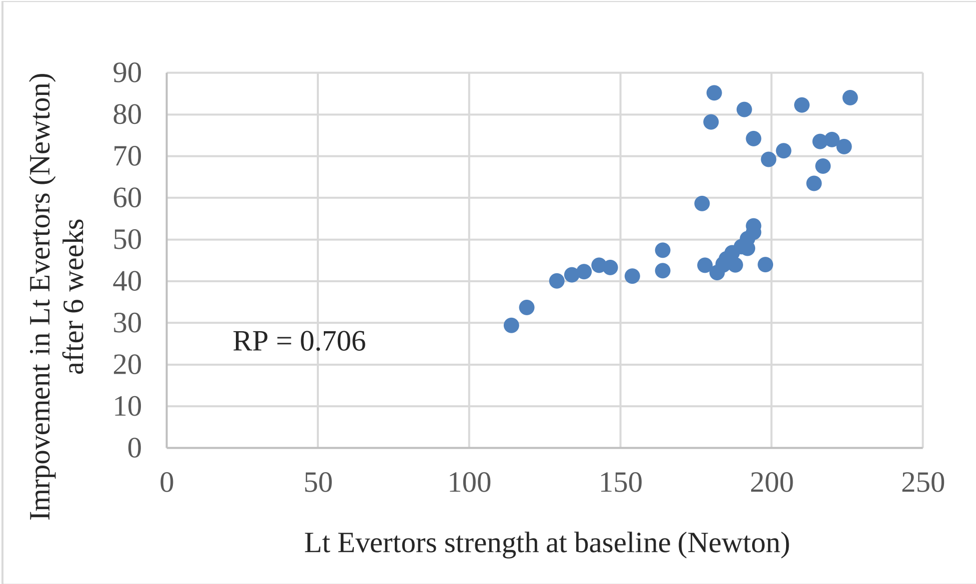


Figure 47. Correlation between baseline and change after six weeks for Rt Evertors strength.

RP; Correlation coefficient of Pearson's correlation test, Rt.; Right.

Figure 48. Correlation between baseline and change after six weeks for Lt Evertors strength.

RP; Correlation coefficient of Pearson's correlation test, Lt.; Left.

5.2.1.3.4 At follow up

The influence of the wash-out period was explored in two ways. Firstly, the muscle strength scores at the end of the study (T3) were compared to those following the wash-out period (T4). Secondly, the muscle strength score at the beginning of the study (T0) was compared to that after the wash-out period (T4).

The study identified a significant reduction in muscle strength between T3 and T4, demonstrating a 'detraining' or wash-out effect (P-value ≤0.001), ranging from -10.85% to -17.39%. However, a comparison to the baseline found a significant overall improvement in muscle strength retained at T4, ranging between 13.31% and 19.25% (see Table 24).

Moreover, a reduction in ankle muscle strength was observed during the wash-out period (follow up) at T4, as shown in Table 24, which demonstrates a reduction in period T4-T3 and improvement in period T4-T0. The majority of the effect size (ES) values in Table 24 were ES ≥ 0.8 or ≤ -0.8, and therefore, considered to represent a large ES.

Table 24. Mean of change, standard deviation (SD) of change, percentage of change, effect sizes and p-values for ankle muscle strength during wash-out period.

Muscle being tests	**Side of the muscle**	**Difference weeks of assessment**	**Mean of change (N)**	**SD of change (N)**	**Percentage of change (%)**	**Effect size**	**p-value**
Dorsiflexors	Right	**T4-T3**	-26.88	8.49	-12.27	-3.16 φ	≤0.001
		T4-T0	25.88	10.43	13.31	2.47 φ	≤0.001
	Left	**T4-T3**	-24.93	8.47	-10.85	-2.94 φ	≤0.001
		T4-T0	35.08	11.87	17.95	2.95 φ	≤0.001
Plantar flexors	Right	**T4-T3**	-29.09	10.57	-11.17	-2.57 φ	≤0.001
		T4-T0	42.09	17.59	19.25	2.39 φ	≤0.001
	Left	**T4-T3**	-33.35	5.11	-13.20	-6.53 φ	≤0.001
		T4-T0	33.41	15.02	15.20	2.22 φ	≤0.001
Invertors	Right	**T4-T3**	-26.81	5.66	-12.95	-4.73 φ	≤0.001

Muscle being tests	Side of the muscle	Difference weeks of assessment	Mean of change (N)	SD of change (N)	Percentage of change (%)	Effect size	p-value
		T4-T0	31.16	12.20	17.68	2.55 $_{\varphi}$	≤0.001
	Left	**T4-T3**	-37.10	10.66	-17.39	-3.48$_{\varphi}$	≤0.001
		T4-T0	32.79	12.45	18.55	2.63 $_{\varphi}$	≤0.001
Evertors	Right	**T4-T3**	-29.36	13.39	-14.44	-2.19 $_{\varphi}$	≤0.001
		T4-T0	27.16	9.30	15.37	2.92 $_{\varphi}$	≤0.001
	Left	**T4-T3**	-28.04	9.79	-13.55	-2.87 $_{\varphi}$	≤0.001
		T4-T0	26.49	9.16	14.62	2.89	≤0.001

SD; standard deviation, N; Newton, $_{\varphi}$; Effect size ≥0.8 or ≤ -0.8.

5.2.1.4 Balance confidence

The mean and SD for balance confidence scores is presented in Table 25, along with the mean of change, the SD of change and the percentage of change. This also includes the effect size (ES) on balance confidence scores across the intervention period, which is six weeks of progressive WB balance training programme.

5.2.1.4.1 End of intervention compared to baseline

This six-week progressive WB balance training programme was found to result in statistically significant (P-value≤0.001) improvements in balance confidence scores, as shown in Figure 49. Furthermore, a large ES was confirmed across all balance confidence scores (Table 25).

5.2.1.4.2 Rate of change in balance confidence

This study noted significant improvements for every measurement period (P-value≤0.001), demonstrating gradual and consistent gains in balance confidence scores. These were also mirrored in the magnitude of the ES ≥ 0.8 or ≤ -0.8 (Table 25).

Table 25. Mean, standard deviation (SD), mean of change, SD of change, percentage of change and effect sizes for balance confidence scores for all assessment weeks (which were at T0, T1, T2, T3 and T4).

Balance confidence	**Week of assessment**	**Mean (%)**	**SD (%)**	**Mean of change (%)**	**SD of change (%)**	**Percentage of change (%)**	**Effect size**
	T0 Baseline	75.41	14.53				
	T1	79.05	13.62	3.65	1.42	4.84	2.57 $_{\varphi}$
	T2	83.14	12.20	4.08	2.14	5.16	1.91 $_{\varphi}$
	T3	86.54	11.35	3.41	1.76	4.10	1.94 $_{\varphi}$
	T4 (Wash-out)	81.69	12.64	-4.97	3.62	-5.75	-1.37 $_{\varphi}$

SD; standard deviation, $_{\varphi}$; Effect size ≥0.8 or ≤ -0.8.

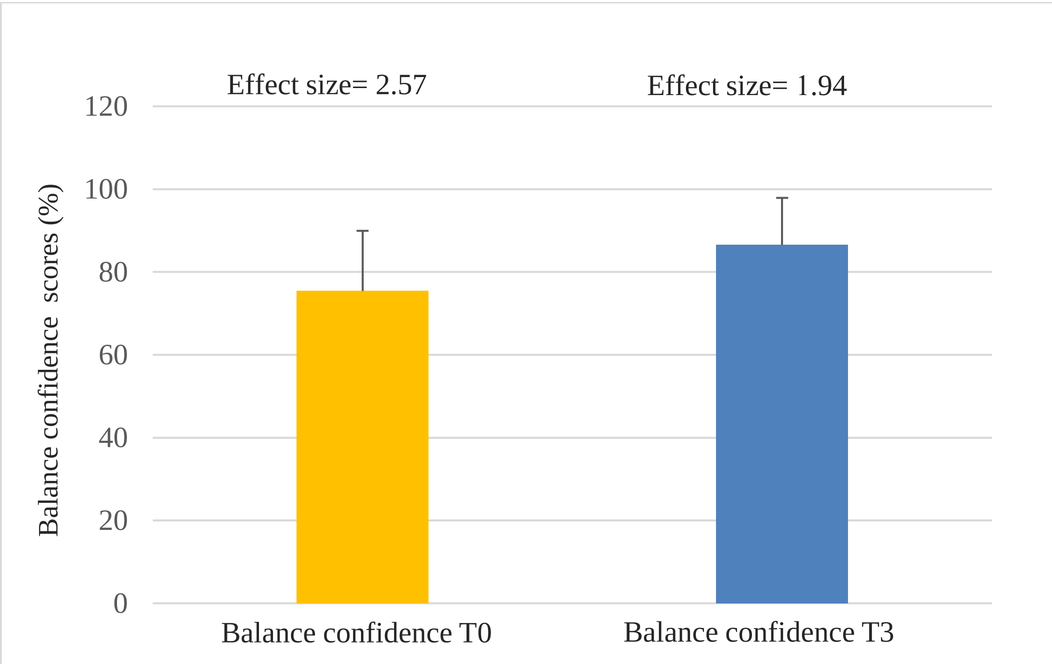


Figure 49. Pre and post six-week progressive WB training effect on balance confidence scores.

5.2.1.4.3 Relationship between change in balance confidence and baseline balance confidence score

Improvements in balance confidence scores were statistically significant when correlated to the T0 baseline, which was at initial balance confidence scores. Therefore, as shown by Figure 50, the lower the balance confidence scores at the initial assessment (low positive value), the greater the improvements in balance confidence scores after the six-week progressive WB balance training programme (high positive value). Therefore, overall, this study determined very high negative correlations (-0.802).

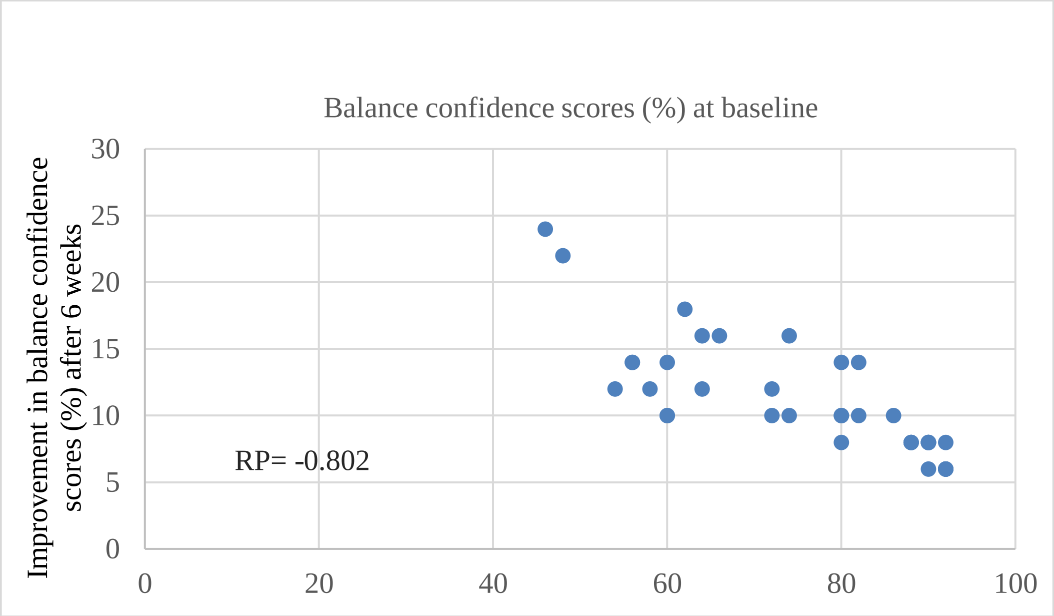


Figure 50. Correlation between baseline and change after six weeks for balance confidence scores.

RP; Correlation coefficient of Pearson's correlation test.

5.2.1.4.4 At follow up

The impact of the wash-out period was explored in two ways. Firstly, the balance confidence scores at the end of the study (T3) were compared to those following the wash-out period (T4). Secondly the balance confidence scores at the beginning of the study (T0) were compared to those after the wash out period (T4).

These identified a significant reduction in balance confidence between T3 and T4, demonstrating a 'detraining' or wash-out effect (P-value ≤0.001), (-5.75%).

However, the overall improvement in balance confidence retained at T4 was found to be significant in comparison to the baseline (7.99%) (see Table 26).

Furthermore, this study observed a reduction in balance confidence during the follow up wash-out period at T4, as shown in Table 26, which demonstrates the reduction in balance confidence scores in period T4-T3 and improvement in period T4-T0. The majority of the ES in Table 26 were ≥ 0.8 or ≤ -0.8, which is considered large.

Table 26. Mean of change, standard deviation (SD) of change, percentage of change, effect sizes and P-values for balance confidence scores during wash-out period

Balance confidence	Difference weeks of assessment	Mean of change (%)	SD of change (%)	Percentage of change (%)	Effect size	P-value
	T4-T3	-4.97	3.62	-5.75	-1.37 φ	≤ 0.001
	T4-T0	6.03	3.47	7.99	1.74 φ	≤ 0.001

SD; standard deviation, φ; Effect size ≥0.8 or ≤ -0.8.

5.2.1.5 Severity of neuropathic scores

The mean and SD for severity of neuropathic scores are presented in Table 27, along with the mean of change, the SD of change and the percentage of change. This includes the effect size (ES) as measured in the severity of neuropathic scores across the intervention period, which is six weeks of progressive WB balance training programme.

5.2.1.5.1 End of intervention compared to baseline

This six-week progressive WB balance training programme resulted in significant improvements (P-value≤0.001), in the severity of neuropathic scores, as shown in Figure 51. Furthermore, a large ES was found across the severity of neuropathic scores (Table 27).

5.2.1.5.2 Rate of change in severity of neuropathic scores

This study noted significant improvements during each measurement period (P-value≤0.001), demonstrating gradual and consistent gains in the severity of the neuropathic scores, which were also mirrored in the magnitude of the ES ≥ 0.8 or ≤ -0.8 (Table 27).

Table 27. Mean, standard deviation (SD), mean of change, SD of change, percentage of change and effect sizes for severity of neuropathic scores for all assessment weeks (which were at T0, T1, T2, T3 and T4).

Neuropathic severity Scores	**Week of assessment**	**Mean**	**SD**	**Mean of change**	**SD of change**	**Percentage of change (%)**	**Effect size**
	T0 Baseline	8.86	3.29				
	T1	8.00	3.33	-0.86	0.48	-9.76 [a]	-1.80 φ
	T2	7.05	3.42	-0.95	0.33	-11.82[a]	-2.88 φ
	T3	6.24	3.50	-0.81	0.40	-11.49 [a]	-2.04 φ
	T4 (Wash-out)	7.81	3.41	1.44	0.69	23.14[b]	2.08 φ

SD; standard deviation, φ Effect size ≥0.8 or ≤ -0.8, [a] negative change means decreasing of severity of DPN measured by Toronto clinical neuropathy scale (TCNS), [b] positive change means increasing of severity of DPN measured by TCNS.

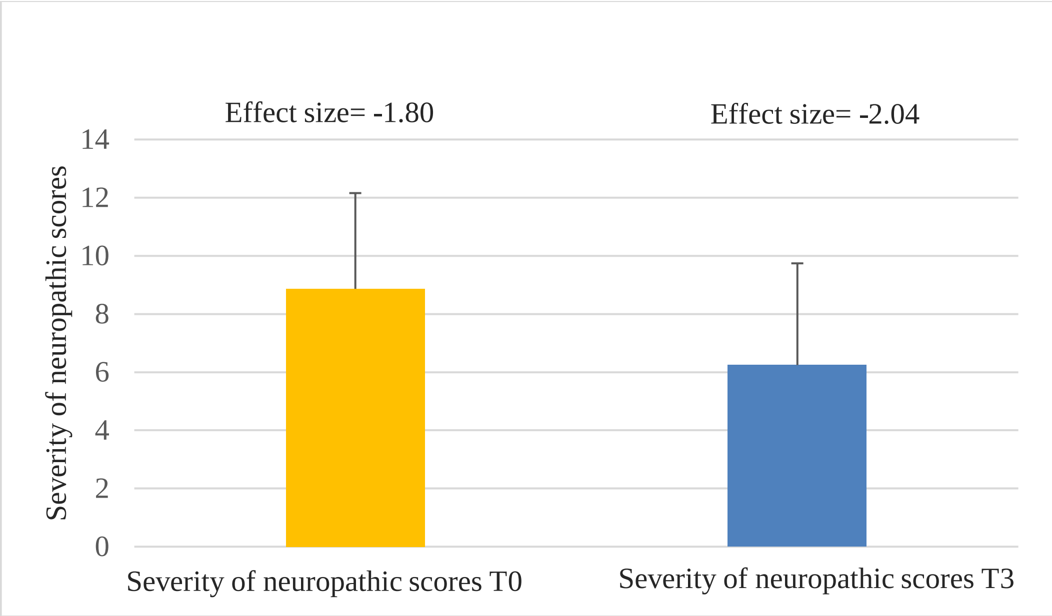


Figure 51. Pre and post six-week progressive WB training effect on severity of neuropathic scores.

5.2.1.5.3 Relationship between change in severity of neuropathy and baseline severity of neuropathic scores

No significant correlations were observed between baseline score and change in severity of neuropathic score.

5.2.1.5.4 At follow up

The influence of the wash-out period was explored in two ways. Firstly, the severity of neuropathic scores at the end of the study (T3) was compared to those following the wash-out period (T4). Secondly, the severity of neuropathic scores at the beginning of the study (T0) was compared to those after the wash-out period (T4).

A significant increase in the severity of neuropathic scores were observed between T3 and T4, therefore, demonstrating a ‘detraining’ or wash-out effect (P-value ≤0.001), (23.14%). However, the overall improvement in severity of neuropathic scores retained at T4 was found to be significant when compared to the baseline (-13.16%) (see Table 28). The majority of the values of the effect size (ES) (as shown in Table 28) were ≥ 0.8 or ≤ -0.8, which is considered large.

Table 28. Mean of change, standard deviation (SD) of change, percentage of change, effect sizes and p-value for severity of neuropathic scores during wash-out period

Neuropathic scores	Difference weeks of assessment	Mean of change	SD of change	Percentage of change (%)	Effect size	P-value
	T4-T3	1.44	0.69	23.14 [a]	2.08 φ	≤ 0.001
	T4-T0	-1.17	0.81	-13.16[b]	-1.44 φ	≤ 0.001

SD; standard deviation, φ; Effect size ≥0.8 or ≤ -0.8, [a]; positive change means increasing of severity of DPN measured by Toronto clinical neuropathy scale (TCNS), [b]; negative change means decreasing of severity of DPN measured by TCNS.

5.2.1.6 Neuropathic pain scores

The mean and SD for neuropathic pain is presented in Table 29, along with the mean, SD and percentage of change, including the effect size (ES) for neuropathic pain scores across the intervention period, which is six weeks of progressive WB balance training.

5.2.1.6.1 End of intervention compared to baseline

Overall, the six-week progressive WB balance training programme resulted in non-significant differences in neuropathic pain scores, but there were only five participants who had pain at baseline and it was relieved at T3, which was after the intervention. Figure 52 shows the five participants at baseline and after six-weeks of the WB balance training along with non-parametric descriptive statistics, such as the median (Med) and interquartile range (IQR). However, large ES were not identified for neuropathic pain scores (Table 29).

5.2.1.6.2 Rate of change in neuropathic pain scores

Overall, the study noted non-significant differences at each measurement period (Table 29). However, regarding the five participants, the pain persisted during baseline, T1, T2 and T4 but were relieved by T3.

Table 29. Mean, standard deviation (SD), mean of change, SD of change, percentage of change and effect sizes for neuropathic pain scores for all assessment weeks (which were at T0, T1, T2, T3 and T4).

Neuropathic pain Scores	Side	Week of assessment	Mean	SD	Mean of change	SD of change	Percentage of change (%)	Effect size
	Right side	T0 Baseline	0.14	0.35				
		T1	0.14	0.35	0.00	0.00	0.00	NA
		T2	0.14	0.35	0.00	0.00	0.00	NA
		T3	0.00	0.00	-0.14	0.35	-100.00	-0.39
		T4 (Wash-out)	0.14	0.35	0.14	0.36	NA	0.39
	Left side	T0 Baseline	0.14	0.35				
		T1	0.14	0.35	0.00	0.00	0.00	NA
		T2	0.14	0.35	0.00	0.00	0.00	NA
		T3	0.00	0.00	-0.14	0.35	-100.00	-0.39
		T4 (Wash-out)	0.14	0.35	0.14	0.36	NA	0.39

SD; standard deviation

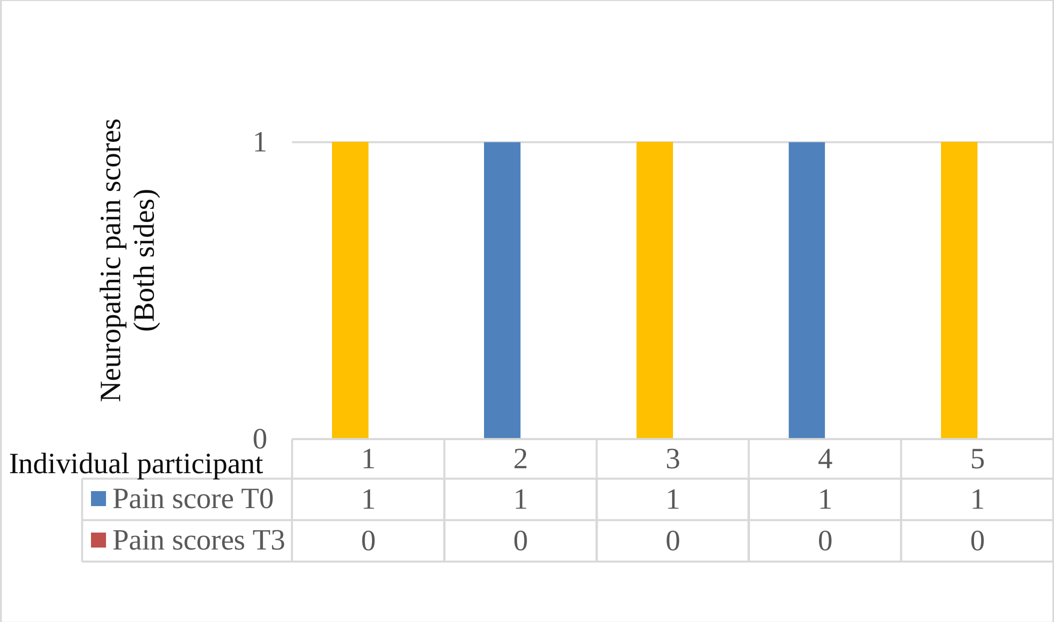


Figure 52. Pre and post six-week progressive WB training effect on neuropathic pain scores for five participants only (both sides).

5.2.1.6.3 At follow up

The influence of the wash-out period was explored in two ways. Firstly, the neuropathic pain scores at the end of the study (T3) were compared to those following the wash out period (T4). Secondly, the neuropathic pain scores at the beginning of the study (T0) were compared to those after the wash-out period (T4).

This study noted no significant difference in neuropathic pain scores between T3 and T4 and T4 and T0, as shown in Table 30.

However, regarding the five participants, pain was relieved during the period between T3 and T4 but again appeared during the period T4 and T0 (Table 30).

Table 30. Mean of change, standard deviation (SD) of change, percentage of change, effect sizes and p-values for neuropathic pain scores during wash-out period.

Neuropathic pain scores	Side	Difference weeks of assessment	Mean of change	SD of change	Percentage of change	Effect size	P-value
	Right side	**T4-T3**	0.14	0.36	NA	0.39	0.025
		T4-T0	0.00	0.00	0.00	NA	1.00
	Left side	**T4-T3**	0.14	0.36	NA	0.39	0.025
		T4-T0	0.00	0.00	0.00	NA	1.00

SD; standard deviation.

5.2.1.7 Physical activity level

Table 31 shows the mean and SD for physical activity level scores, along with the mean of change, the SD of change and the percentage of change, including the ES for physical activity level scores, involving three indices of physical activity level which are work, sport and leisure time.

5.2.1.7.1 End of intervention compared to baseline

The end of the intervention compared to baseline study showed that, as shown in Figure 53, the six-week progressive WB balance training programme resulted in non-significant differences in physical activity scores. Furthermore, large ES were not found across the physical activity scores (Table 31).

Figure 53. Pre and post six-week progressive WB training effect on physical activity level.

Table 31. Mean, standard deviation (SD), mean of change, SD of change, percentage of change and effect sizes for physical activity level scores for two assessment weeks (which were at T0 and T4).

Physical activity level	Week of assessment	Mean	SD	Mean of change	SD of change	Percentage of change	Effect size
Work index	T0 Baseline	2.52	0.53				
	T4 (Wash-out)	2.47	0.57	-0.05	0.35	-2.16%	-0.15
Sport Index	T0 Baseline	2.62	1.38				
	T4 (Wash-out)	2.48	1.30	-0.17	1.28	-6.50%	-0.13
Leisure time index	T0 Baseline	2.45	0.82				
	T4 (Wash-out)	2.59	0.75	0.15	0.50	6.25%	0.31

SD; standard deviation.

5.2.2 Baseline relationship

As mentioned previously in chapter two, balance might be affected by internal and external factors. Therefore, it is worth investigating the relationship between balance and baseline characteristics. Baseline characteristics include, age, height, weight, physical activity level, anthropometry, duration of diabetes mellitus (DM), severity of diabetic peripheral neuropathy (DPN), neuropathic pain, balance confidence and ankle muscle strength. Each of the characteristics are examined for any correlation with both static balance parameters at baseline and WB performance parameters.

5.2.2.1 Age

5.2.2.1.1 Age correlation with static balance

There was a statistically significant positive correlation between age and static balance parameter (perimeter) during double leg stance with narrow base of support and eyes open (DLSEON) at baseline (T0) and was moderate (r=0.478) with a p value= 0.01, as shown in table 32. This means the older the individual, the higher the perimeter, as indicated by poor balance performance during DLSEON. There were no statistically significant correlations between age and ellipse area for any of the tasks, (Appendix 13).

Table 32. Pearson's **r** correlation between static balance performance (perimeter) and age.

Confounding factor	Task/parameter	Correlation coefficient
Age (r)	DLSEON (Perimeter)	**0.478****

DLSEON; double leg stance eyes open narrow base of support, **; Correlation is significant at the 0.01 level (2-tailed).

5.2.2.1.2 Age correlation with WB performance

There were two statistically significant positive correlations between age, with the anteroposterior stability index (APSI) during double leg stance at 5° with a narrow base of support (DLSEON) during both eyes open (low r=0.342) and closed (very high r=0.881), as depicted in Table 33 and Appendix 14. This means, the older the individual, the poorer the WB performance in the APSI during DLSEON 5° and DLSECN 5°, when the WB tilt angle is 5° with a narrow base of support and with eyes both open and closed.

There were two statistically significantly low correlations between age, with respect to the percentages of time spent in the inner (negative r=-0.375) and outer zones (positive r=0.375) during double leg stance at 10° with a wide base of support and eyes open (DLSEOW), as shown in Table 33 and Appendix 15. This means the older the individual, the poorer the WB performance in the percentages of time spent in inner and outer zones during DLSEOW 10°, which indicates that the WB performance will be poor when the WB tilt angle is 10° with a wide base of support and eyes open.

Table 33. Pearson's **r** correlation between WB performance (stability index and percentages of time in inner and outer zones) and age.

Confounding factor	Task/parameter	Correlation coefficient
Age (r)	DLSEON 5° (APSI)	**0.342***
	DLSECN 5° (APSI)°	**0.881***
	DLSEOW 10° (% time inner zone)	**-0.375***
	DLSEOW 10° (% time outer zone)	**0.375***

DLSEOW; double leg stance wide base of support with eyes open, DLSEON; double leg stance narrow base of support with eyes open, DLSECN; double leg stance narrow base of support with eyes closed, APSI; anteroposterior stability index, MLSI; mediolateral stability index, % time inner zone; percentage of time spent in inner zone, % time outer zone; percentage of time spent in outer zone, *Correlation is significant at the 0.05 level (2-tailed).

5.2.2.2 Height

5.2.2.2.1 Height correlation with static balance

There was no statistically significant correlation between height and static balance in either of the parameters or tasks (Appendix 13).

5.2.2.2.2 Height correlation with WB performance

There was no statistically significant correlation between height and WB performance, except during double leg stance with wide base of support and eyes closed (DLSECW) 10° along the MLSI (very high positive r=0.959), as shown in Table 34 and Appendix 14. Therefore, the taller the individual, the poorer the WB performance along the MLSI during DLSECW 10°, which indicates that the WB performance will be poor when the WB the tilt angle is 10° with a wide base of support and eyes closed.

Table 34. Pearson's **r** correlation between WB performance (stability index) and height.

Confounding factor	Task/parameter	Correlation coefficient
Height (r)	DLSECW 10° (MLSI)	**0.959***

DLSECW; double leg stance wide base of support with eyes closed, MLSI; mediolateral stability index, *Correlation is significant at the 0.05 level (2-tailed).

5.2.2.3 Weight

5.2.2.3.1 Weight correlation with static balance

With respect to a correlation between weight and static balance, there was no statistically significant correlation between weight and static balance in either parameter or task because the P-value did not reach the significant level at 0.05 or 0.01 (Appendix 13).

5.2.2.3.2 *Weight correlation with WB performance*

Between weight and WB performance, there were statistically significant correlations during DLSECW 5° in APSI, MLSI, as well as in percentages of time spent in both inner and outer zones (very high positive, r=0.896, 0.904, 0.891) respectively, except in inner zone, there was very high negative (r=-0.891), statistically significant correlation, as shown in Table 35 and Appendices 14 and 15. This means the greater the weight of the individual, the poorer the WB performance in APSI, MLSI, percentages of time spent in inner and outer zones during DLSECW 5°, which indicates that the WB performance will be poor when the WB tilt angle is at 5° with a wide base of support and eyes closed. Additionally, there were statistically significant moderate (r=0.559) positive correlations between weight and WB performance during DLSEOW 15° and statistically significant high (r=0.748) positive correlation double leg stance with narrow base of support and eyes open (DLSEON) at tilt angle 15° in MLSI, as shown in Table 35 and Appendix 14. This suggests that the greater the weight of the individual, the poorer the WB performance along the MLSI during DLSEOW 15° and DLSEON 15°, which indicates that the WB performance will be poor when the WB tilt angle is at 15° with a wide and a narrow base of support during eyes open conditions. Furthermore, there were statistically significant low (r=-0.365 - 0.365) correlations between weight and WB performance during DLSEON 5° in the percentages of time spent in the inner and outer zones, as shown in Table 35 and appendix 15. This suggests that the greater the weight of the individual, the poorer the WB performance in the percentages of time spent in inner and outer zones during DLSEON 5°, which indicates that the WB performance will be poor when the WB tilt angle is at 5° with a narrow base of support and eyes open.

Table 35. Pearson's **r** and Spearman's rho correlation between WB performance (stability indices and percentages of time in inner and outer zones) and weight.

Confounding factor	Task/parameter	Correlation coefficient
Weight (r)	DLSECW 5° (APSI)	**0.896****
	DLSEOW 15° (MLSI)	**0.559***
	DLSEON 15°	**0.748***

Confounding factor	Task/parameter	Correlation coefficient
	(MLSI)	
	DLSECW 5° (MLSI)	**0.904**[**]
	DLSEON 5° (% time inner zone)	**-0.365**[*a]
	DLSEON 5° (% time outer zone)	**0.365**[*a]
	DLSECW 5° (% time inner zone)	**-0.891**[**]
	DLSECW 5° (% time outer zone)	**0.891**[**]

DLSECW; double leg stance wide base of support with eyes closed, DLSEOW; double leg stance wide base of support with eyes open, DLSEON; double leg stance narrow base of support with eyes open, DLSECN; double leg stance narrow base of support with eyes closed, APSI; anteroposterior stability index, MLSI; mediolateral stability index, [a]: Spearman's rho correlation*Correlation is significant at the 0.05 level (2-tailed), **; Correlation is significant at the 0.01 level (2-tailed), % time inner zone; percentage of time spent in inner zone, % time outer zone; percentage of time spent in outer zone.

5.2.2.4 Physical activity level

5.2.2.4.1 Physical activity level correlation with static balance

There was a statistically significant negative correlation between physical activity level and static balance parameter (ellipse areas), during single leg stance (SLS) at baseline (T0) and a moderate correlation (r=-0.434), as shown in Table 36. This suggests that the less physically active an individual is, the greater the ellipse, the poorer the static balance performance will be during SLS.

Table 36. Spearman's rho correlation between static balance performance (ellipse area) and physical activity level.

Confounding factor	Task/parameter	Correlation coefficient
Physical activity (r)	SLS (Ellipse area)	**-0.434***[a]

SLS; single leg stance, [a]; Spearman's rho (r) Correlation, *Correlation is significant at the 0.05 level (2-tailed).

5.2.2.4.2 Physical activity correlation with WB performance.

There was a very high (-0.900 - 0.900) significant correlation between physical activity and percentages of time spent in the inner and outer zones during DLSECN 5°, as shown in Table 37 and Appendix 15. That suggests that the less active the individual is physically, the lower the percentages of time spent in the inner zone and the greater the percentages of time spent in the outer zone and the poorer the WB performance will be during the DLSECN 5°.

Table 37. Spearman's rho correlation between WB performance (percentages of time in inner and outer zones) and physical activity level.

Confounding factor	Task/parameter	Correlation coefficient
Physical activity (r)	DLSECN 5° (% time inner zone)	**-0.900***[a]
	DLSECN 5° (% time outer zone)	**0.900***[a]

DLSECN; double leg stance narrow base of support with eyes closed, *Correlation is significant at the 0.05 level (2-tailed), [a]: Spearman's rho correlation, % time inner zone; percentage of time spent in inner zone, % time outer zone; percentage of time spent in outer zone.

5.2.2.5 Anthropometry

5.2.2.5.1 Anthropometry correlation with static balance

There were no statistically significant correlations between the anthropometry of an individual and static balance in any of the parameters or tasks because the P-value did not reach the significant level at 0.05 or 0.01, as shown in appendix 13.

5.2.2.5.2 Anthropometry correlation with WB performance

Correlations between WB performance and circumferential measurements, which are shoulder, chest, waist and hip are explored and correlations between WB performance and ratios of shoulder-waist and shoulder-hip are investigated.

5.2.2.5.2.1 Shoulder circumference correlation with WB performance

There were statistically moderate (r=0.569-0.541) positive significant correlations between shoulder circumference and WB performance during DLSEOW 15° in APSI, MLSI and high a positive (r=0.703) correlation during DLSEON 15° in MLSI, as shown in Table 38 and appendix 14. Suggesting that the greater the shoulder circumference, the poorer the WB performance during DLSEOW 15° and DLSEON 15°. Additionally, there were statistically significant low (r=-0.335 - 0.335) and very high (-0.938 - 0.938) correlations between shoulder circumference and WB performance during DLSEON 5° and DLSECN 5° respectively, in the percentages of time spent in the inner (negative) and outer (positive) zones, as shown in Table 39 and appendix 15. Suggesting that the greater the shoulder circumference, the poorer the WB performance is during DLSEON 5° and DLSECN 5°.

5.2.2.5.2.2 Chest circumference correlation with WB performance

There were statistically moderate (r=0.544) and high (r=0.803) positive significant correlations between chest circumference and WB performance during DLSEOW 15° and DLSEON 15° along the MLSI respectively, as shown in Table 38 and appendix 14. Furthermore, there was a moderate (r=0.417) positive correlation during DLSEON 10° along the APSI, as shown in Table 38 and appendix 14. Indicating that the greater the chest circumference, the poorer the WB performance during DLSEOW 15° DLSEON 15°, and DLSEON 10°. Additionally, there was a low (r=-0.387 – 0.387) statistically significant correlation between chest circumference and WB performance during DLSEOW 5° in the percentages of time spent in the inner and outer zones, as shown in Table 39 and appendix 15. Suggesting that the greater the chest circumference, the poorer the WB performance during DLSEOW 5°.

5.2.2.5.2.3 Waist circumference correlation with WB performance

There were statistically moderate (r=-0.431 – 0.431, -0.691 – 0.691) and very high (r=-0.918 – 0.918) significant correlations between waist circumference and WB performance in the percentages of time spent in the inner (negative) and outer (positive) zones during DLSEON 5°, DLSEOW 15° and DLSECN 5°, respectively, as shown in Table 39 and appendix 15. Suggesting that the greater the waist circumference, the poorer the WB performance during DLSEON 5°, DLSECN 5° and DLSEOW 15°.

5.2.2.5.2.4 Hip circumference correlation with WB performance

There were statistically very high (-1.000 - 1.000) significant correlations between hip circumference and WB performance during DLSECW 10° in APSI, MLSI, percentages of time spent in the inner and outer zones, as well as a significant moderate (-0.611 – 0.611) correlation during DLSEOW 15° percentage of time spent in the inner and outer zones, as shown in Tables 38, 39 and appendices 14 and 15. Thus, there is a suggestion that the greater the hip circumference, the poorer the WB performance during DLSECW 10° and DLSEOW 15°.

5.2.2.5.2.5 Shoulder-waist ratio correlation with WB performance

There were no statistically significant correlations between shoulder-waist ratio and static balance or WB performance for either parameter or any of the tasks because the P-value did not reach the significant level at 0.05 or 0.01.

5.2.2.5.2.6 Shoulder-hip ratio correlation with WB performance

There was low (r=0.356) positive significant correlation between shoulder-hip ratio and WB performance during DLSEON 5° along the MLSI, as shown in Table 38 and appendix 14. This shows, the greater the shoulder-hip ratio, the poorer the WB performance during DLSEON 5°.

Table 38. Pearson's **r** and Spearman's rho correlation between WB performance (stability indices) and anthropometric characteristics.

Confounding factor	Task/parameter	Correlation coefficient
Shoulder circumference (r)	DLSEOW 15° (APSI)	**0.569***
	DLSEOW 15° (MLSI)	**0.541***
	DLSEON 15° (MLSI)	**0.703***
Chest circumference (r)	DLSEON 10° (APSI)	**0.417***
	DLSEOW 15° (MLSI)	**0.544***
	DLSEON 15° (MLSI)	**0.803****
Hip circumference (r)	DLSECW 10° (APSI)	**1.000****[a]
	DLSECW 10° (MLSI)	**1.000****[a]
Shoulder-Hip Ratio (r)	DLSEON 5° (MLSI)	**0.356***[a]

DLSEOW; double leg stance wide base of support with eyes open, DLSECW; double leg stance wide base of support with eyes closed, DLSEON; double leg stance narrow base of support with eyes open, APSI; anteroposterior stability index, MLSI; mediolateral stability index, [a]: Spearman's rho correlation, *Correlation is significant at the 0.05 level (2-tailed), **; Correlation is significant at the 0.01 level (2-tailed).

Table 39. Pearson's **r** and Spearman's rho correlation between WB performance (percentages of time in inner and outer zones) and anthropometric characteristics.

Confounding factor	Task/parameter	Correlation coefficient
Shoulder circumference (r)	DLSEON 5° (% time inner zone)	**-0.335**[*a]
	DLSEON 5° (% time outer zone)	**0.335**[*a]
	DLSECN 5° (% time inner zone)	**-0.938**[*]
	DLSECN 5° (% time outer zone)	**0.938**[*]
Chest circumference (r)	DLSEOW 5° (% time inner zone)	**-0.387**[*]
	DLSEOW 5° (% time outer zone)	**0.387**[*]
Waist Circumference (r)	DLSEON 5° (% time inner zone)	**-0.431**[**a]
	DLSEON 5° (% time outer zone)	**0.431**[**a]
	DLSEOW 15° (% time inner zone)	**-0.691**[**]
	DLSEOW 15° (% time outer zone)	**0.691**[**]
	DLSECN 5° (% time inner zone)	**-0.918**[*]
	DLSECN 5° (% time outer zone)	**0.918**[*]
Hip circumference (r)	DLSEOW 15° (% time inner zone)	**-0.611**[*a]
	DLSEOW 15° (% time outer zone)	**0.611**[*a]
	DLSECW 10° (% time inner zone)	**-1.000**[**a]
	DLSECW 10° (% time outer zone)	**1.000**[**a]

DLSEOW; double leg stance wide base of support with eyes open, DLSECW; double leg stance wide base of support with eyes closed, DLSEON; double leg stance narrow base of support with eyes open, DLSECN; double leg stance narrow base of support with eyes closed, % time inner zone; percentage of time spent in inner zone, % time outer zone; percentage of time spent in outer zone, [a]: Spearman's rho correlation, *Correlation is significant at the 0.05 level (2-tailed), **; Correlation is significant at the 0.01 level (2-tailed).

5.2.2.6 Duration of diabetes mellitus (DM) and balance performance

5.2.2.6.1 Duration of diabetes mellitus (DM) correlation with static balance

With respect to the duration of diabetes mellitus (DM) correlation with static balance, there was a low (r=0.374 – 0.460) positive statistically significant correlation between duration of DM and the perimeter during double leg stance with narrow base of support and eyes open (DLSEON) and the ellipse area during SLS, as shown in Table 40. The longer the individual has had DM, the poorer was the static balance performance at the perimeter during DLSEON and the ellipse area during SLS.

5.2.2.6.2 Duration of diabetes mellitus (DM) correlation with WB performance

There were low positive (r=0.398 – 0.425) statistically significant correlations between the duration of DM and the APSI and the percentages of time spent in inner and outer zones, except in inner zone, there was low negative (r=-0.425) statistically significant correlation, during double leg stance with wide base of support and eyes open (DLSEOW) 10°, as shown in Tables 41 and 42. The longer the individual has had DM, the poorer was the WB performance in the APSI, time spent in inner and outer zones during DLSEOW 10°.

5.2.2.7 Severity of diabetic peripheral neuropathy (DPN)

5.2.2.7.1 Severity of DPN correlation with static balance

There were low positive (r=0.446, 0.338, 0.379) statistically significant correlations between the severity of DPN and the perimeter and ellipse area during DLSEON and ellipse area during SLS only, as shown in Table 40. The more severe the individual's DPN, the poorer was their static balance performance in perimeter and ellipse area during DLSEON and the ellipse area during SLS only.

5.2.2.7.2 Severity of DPN correlation with WB performance

There were low positive (r=0.382) statistically significant correlations between the severity of DPN and percentages of time spent in inner and outer zones, except in the inner zone, there was low negative (r=-0.382) statistically significant correlation during DLSEOW 10°, as shown in Table 42. The more severe the individual’s DPN, the poorer was their WB performance in percentages of time spent in the inner and outer zones during DLSEOW 10°.

5.2.2.8 Neuropathic pain

5.2.2.8.1 Neuropathic pain correlation with static balance

There were low positive (r=0.382 – 0.415) statistically significant correlations between neuropathic pain and perimeter and ellipse area during DLSEON, as shown in Table 40. The more severe the individual’s neuropathic pain, the poorer was their static balance performance in the perimeter and ellipse area during DLSEON.

5.2.2.8.2 Neuropathic pain correlation with WB performance

There were low positive (r=0.491) statistically significant correlations between neuropathic pain and percentages of time spent in the inner and outer zones, except in the inner zone, there was low negative (r=-0.491) statistically significant correlation during DLSEON 5°, as shown in Table 42. The more severe the individual’s neuropathic pain, the poorer was their WB performance in percentages of time spent in the inner and outer zones during DLSEON 5°.

5.2.2.9 Balance confidence

5.2.2.9.1 Balance confidence correlation with static balance

There were low negative (r=-0.471) statistically significant correlations between balance confidence and perimeter during DLSEON, as shown in Table 40. The lower the individual’s confidence balancing, the poorer was the static balance performance at the perimeter during DLSEON.

5.2.2.9.2 *Balance confidence correlation with WB performance*

There were low negative (r=-0.421, -0.471) statistically significant correlations between balance confidence and the APSI, percentages of time spent in the inner and outer zones, except in the inner zone, there was low positive (r=0.471) statistically significant correlation during DLSEON 5°, as shown in Tables 41 and 42. The lower the individual's confidence with balance, the poorer was their WB performance in APSI, percentages of time spent in the inner and outer zones during DLSEON 5°. Additionally, there was very high negative (r=-0.957) statistically significant correlations between balance confidence and the MLSI during DLSECW 10°, as shown in Table 41. Suggesting that the less confident the individual is regarding their balance, the poorer was the WB performance along the MLSI during DLSECW 10°.

Table 40. Spearman's rho **r** correlation between static balance performance (perimeter and ellipse area) and duration of DM, severity of DPN, neuropathic pain and balance confidence.

	Duration of DM	**Severity of DPN**	**Neuropathic pain**	**Balance Confidence**
Perimeter				
DLSEOW	-0.018	0.076	0.144	-0.058
DLSECW	0.137	0.168	0.040	-0.152[b]
DLSEON	**0.374***	**0.446****	**0.382***	**-0.471****[b]
DLSECN	0.181	0.179	-0.036	-0.135[b]
SLS	0.081	-0.006	-0.226	-0.113[b]
Ellipse Area				
DLSEOW	-0.048	0.108	0.118	-0.046
DLSECW	0.165	0.291	0.240	0.006
DLSEON	0.243	**0.338***	**0.415***	-0.284[b]
DLSECN	0.138	0.147	0.272	-0.034[b]
SLS	**0.460***	**0.379***	0.155	-0.124[b]

[b]; Pearson's Correlation, *; Correlation is significant at the 0.05 level (2-tailed), **; Correlation is significant at the 0.01 level (2-tailed).

Table 41. Spearman's rho **r** correlation between WB performance (stability indices) and duration of DM, severity of DPN, neuropathic pain and balance confidence.

	Duration of DM	Severity of DPN	Neuropathic pain	Balance Confidence
APSI				
DLSEOW 5°	0.232	0.222	0.167	-0.247[b]
DLSEON 5°	0.283	0.222	0.232	**-0.421**[*b]
DLSEOW 10°	**0.398**[*]	0.238	-	-0.172[b]
DLSEON 10°	0.115	0.129	-	-0.328[b]
DLSEOW 15°	-0.033	0.076	**-**	-0.247[b]
DLSEON 15°	0.184	0.315	**-**	-0.554[b]
DLSECW 5°	-0.294	-0.217	**-**	-0.038[b]
DLSECN 5°	-0.707	-0.707	**-**	-0.577[b]
DLSECW 10°	-0.775	-0.775	**-**	-0.823[b]
MLSI				
DLSEOW 5°	0.185	0.242	0.267	-0.196[b]
DLSEON 5°	0.034	0.039	0.329	-0.160[b]
DLSEOW 10°	0.099	0.110	-	-0.203[b]
DLSEON 10°	0.051	-0.008	-	-0.225[b]
DLSEOW 15°	0.035	0.076	-	-0.235[b]
DLSEON 15°	-0.306	-0.175	-	-0.408[b]
DLSECW 5°	-0.128	-0.051	-	0.096[b]
DLSECN 5°	0.000	0.000	-	-0.784[b]
DLSECW 10°	-0. 775	-0.775	-	**-0.957**[*b]

[b]; Pearson's Correlation, *; Correlation is significant at the 0.05 level (2-tailed).

Table 42. Spearman's rho **r** correlation between WB performance (percentages of time in inner and outer zones) and duration of DM, severity of DPN, neuropathic pain and balance confidence.

	Duration of DM	**Severity of DPN**	**Neuropathic pain**	**Balance Confidence**
Inner zone %				
DLSEOW 5°	-0.195	-0.272	-0.287	0.261[b]
DLSEON 5°	-0.274	-0.219	**-0.491****	**0.471****
DLSEOW 10°	**-0.425***	**-0.382***		0.141[b]
DLSEON 10°	-0.284	-0.287		0.193[b]
DLSEOW 15°	-0.217	-0.267		-0.265[b]
DLSEON 15°	0.240	0.107		0.500[b]
DLSECW 5°	0.263	0.148		0.070[b]
DLSECN 5°	0.707	0.707		0.145[b]
DLSECW 10°	0.775	0.775		0.735[b]
Outer zone %				
DLSEOW 5°	0.195	0.272	0.287	-0.261[b]
DLSEON 5°	0.274	0.219	**0.491****	**-0.471****
DLSEOW 10°	**0.425***	**0.382***	-	-0.141[b]
DLSEON 10°	0.284	0.287	-	-0.193[b]
DLSEOW 15°	0.217	0.267	-	0.265[b]
DLSEON 15°	-0.240	-0.107	-	-0.500[b]
DLSECW 5°	-0.263	-0.148	-	-0.070[b]
DLSECN 5°	-0.707	-0.707	-	-0.145[b]
DLSECW 10°	-0.775	-0.775	-	-0.735[b]

%inner time; percentage of time tilt in inner zone, %outer time; percentage of time tilt in outer zone [b]; Pearson's Correlation, *; Correlation is significant at the 0.05 level (2-tailed), **; Correlation is significant at the 0.01 level (2-tailed).

5.2.2.10 Ankle muscle strength

5.2.2.10.1 Ankle muscle strength correlation with static balance

There were statistically low (r=-0.396) to moderate (r=-0.504, -0.425, -0.472, -0.457) negative significant correlations between both sides, which are right (Rt) and left (Lt) of ankle plantar flexors, evertors and Lt side only of the invertors and static balance (perimeter), although only during double leg stance with narrow base of support and eyes open (DLSEON), as shown in Table 43. Suggesting that the weaker the ankle muscle strength at baseline, the poorer the static balance performance during DLSEON. Additionally, there were statistically low negative (r=-0.352) significant correlations between plantar flexors and static balance (ellipse area) during double leg stance with wide base of support and eyes closed (DLSECW) in Lt side only and DLSEON in Rt side only (r=-0.355), as shown in Table 43. Thus, the weaker the plantar flexors were at baseline, the poorer the static balance performance was during DLSECW and DLSEON.

5.2.2.10.2 Ankle muscle strength correlation with WB performance

There was a statistically low negative (r=-0.415, -0.414, -0.397) significant correlations between the Rt plantar flexors and Rt and Lt invertors and WB performance (APSI) during DLSEON 5°, as shown in Table 44. Suggesting that the weaker the plantar flexors and invertors were at baseline, the poorer the WB performance was along APSI during DLSEON 5°.

Regarding percentages of time spent in the inner zone, there were statistically low negative (r=-0.405) correlations between the Rt plantar flexors and Rt invertors and WB performance (percentage of time spent in the inner zone) during DLSEON 10°, as shown in Table 45. Indicating that the weaker the plantar flexors and invertors were at baseline, the poorer the WB performance was in percentages of time spent in the inner zone during DLSEON 10°.

Additionally, there were statistically high negative (r=-0.903 - -0.880) significant correlations between Lt dorsiflexors and Lt invertors and WB performance (percentage of time spent in the inner zone) during DLSECN 5°, as well as a statistically high negative (r=-0.964) significant correlation between Lt evertors and WB performance (percentage of time spent in the inner zone) during DLSECW 10°, as shown in Table 45. Suggesting that the weaker the dorsiflexors, invertors and evertors were at baseline, the poorer the WB performance was in percentage of time spent in the inner zone during DLSECN 5° and DLSECW 10°, respectively.

Furthermore, regarding the percentage of time spent in the outer zone, there were statistically low positive (r=0.405) significant correlations between the Rt plantar flexors and Rt invertors and WB performance (percentage of time spent in the outer zone) during DLSEON 10°, as shown in Table 45. Suggesting that the weaker the plantar flexors and invertors were at baseline, the poorer the WB performance in percentage of time spent in the outer zone was during DLSEON 10°.

Finally, there were statistically high positive (r=0.903 - 0.880) significant correlations between the Lt dorsiflexors and Lt invertors and WB performance (percentage of time spent in the outer zone) during DLSECN 5°, as well as there was a statistically high positive (r=0.964) significant correlation between the Lt evertors and WB performance (percentage of time spent in the outer zone) during DLSECW 10°, as shown in Table 45. Indicating that the weaker the dorsiflexors, invertors and evertors were at baseline, the poorer the WB performance was in percentage of time spent in both inner and outer zones during DLSECN 5° and DLSECW 10° respectively.

Table 43. Pearson's **r** correlation between static balance performance (perimeter and ellipse area) and ankle muscle strength.

	Muscle strength Rt Dorsiflexors	**Muscle strength Lt Dorsiflexors**	**Muscle strength Rt Plantar flexors**	**Muscle strength Lt Plantar flexors**	**Muscle strength Rt Invertors**	**Muscle strength Lt Invertors**	**Muscle strength Rt Evertors**	**Muscle strength Lt Evertors**
Perimeter								
DLSEOW	-0.044[a]	-0.119[a]	-0.071[a]	-0.104[a]	-0.002[aa]	0.005[a]	-0.073[aa]	-0.071[aa]
DLSECW	-0.117[a]	-0.102	-0.131	-0.161	-0.148[a]	-0.019	-0.090	-0.097
DLSEON	-0.320[a]	-0.314	**-0.504****	**-0.396***	-0.322[a]	**-0.425****	**-0.472****	**-0.457****
DLSECN	-0.227[a]	-0.332	-0.243	-0.212	-0.186[a]	-0.251	-0.249	-0.255
SLS	-0.074[a]	-0.073	-0.051	0.035	-0.022[a]	0.098	-0.002	0.027
Ellipse Area								
DLSEOW	-0.009[a]	0.189[a]	-0.062[aa]	-0.176[aa]	-0.057[a]	-0.106[a]	-0.010[a]	-0.121[a]
DLSECW	-0.182[a]	-0.245 -0.178	-0.276	**-0.352***	-0.171[a]	-0.224	-0.208	-0.294
DLSEON	-0.189[a]	-0.178	**-0.355***	-0.236	-0.191[a]	-0.248	-0.257	-0.314
DLSECN	-0.184[a]	-0.216	-0.193	-0.149	-0.078[a]	-0.268	-0.258	-0.325
SLS	-0.338[a]	-0.230	-0.279	-0.121	-0.320[a]	-0.078	-0.273	-0.210

DLSEOW; double leg stance wide base of support with eyes open, DLSECW; double leg stance wide base of support with eyes closed, DLSEON; double leg stance narrow base of support with eyes open, DLSECN; double leg stance narrow base of support with eyes closed, SLS; single leg stance, Rt; right, Lt; left, [a]; Spearman's rho correlation, *; Correlation is significant at the 0.05 level (2-tailed), **; Correlation is significant at the 0.01 level (2-tailed).

Table 44. Pearson's **r** correlation between WB performance (stability indices) and ankle muscle strength.

	Muscle strength Rt Dorsiflexors	**Muscle strength Lt Dorsiflexors**	**Muscle strength Rt Plantar flexors**	**Muscle strength Lt Plantar flexors**	**Muscle strength Rt Invertors**	**Muscle strength Lt Invertors**	**Muscle strength Rt Evertors**	**Muscle strength Lt Evertors**
APSI								
DLSEOW 5°	-0.254[a]	-0.195	-0.285	-0.168	-0.321[a]	-0.253	-0.155	-0.139
DLSEON 5°	-0.293[a]	-0.208	**-0.415***	-0.171	**-0.414*[a]**	**-0.397***	-0.318	-0.273
DLSEOW 10°	-0.290[a]	-0.071	-0.249	-0.115	-0.282[a]	-0.033	-0.162	0.044
DLSEON 10°	-0.195[a]	-0.013	-0.195	0.020	-0.134[a]	0.045	-0.018	0.077
DLSEOW 15°	-0.095[a]	0.222	-0.319	-0.012	-0.247[a]	0.107	0.036	0.318
DLSEON 15°	-0.314[a]	-0.004	-0.188	-0.086	-0.137[a]	0.142	-0.070	0.061
DLSECW 5°	-0.036[a]	0.438	0.067	0.301	-0.252[a]	0.378	0.201	0.287
DLSECN 5°	-0.600[a]	0.840	-0.483	0.212	-0.600[a]	0.755	-0.444	0.728
DLSECW 10°	-0.400[a]	0.918	-0.609	0.168	-0.800[a]	0.745	-0.497	0.906
MLSI								
DLSEOW 5°	-0.230[a]	-0.050	-0.174	-0.148	-0.206[a]	-0.202	-0.166	-0.196
DLSEON 5°	-0.114[a]	-0.134	-0.257	-0.175	-0.119[a]	-0.262	-0.230	-0.230
DLSEOW 10°	-0.227[a]	0.139	-0.185	-0.004	-0.140[a]	-0.082	0.035	0.160
DLSEON 10°	-0.036[a]	0.159	-0.157	0.021	-0.140[a]	0.005	0.141	0.210
DLSEOW 15°	-0.238[a]	0.151	-0.326	-0.050	-0.462[a]	-0.401	0.025	0.260
DLSEON 15°	-0.192[a]	0.421	-0.082	0.097	-0.444[a]	-0.223	0.060	0.320

	Muscle strength Rt Dorsiflexors	Muscle strength Lt Dorsiflexors	Muscle strength Rt Plantar flexors	Muscle strength Lt Plantar flexors	Muscle strength Rt Invertors	Muscle strength Lt Invertors	Muscle strength Rt Evertors	Muscle strength Lt Evertors
DLSECW 5°	0.072[a]	0.525	0.350	0.515	-0.108[a]	0.190	0.460	0.376
DLSECN 5°	-0.600[a]	0.295	-0.807	-0.365	-0.400[a]	-0.805	-0.195	0.374
DLSECW 10°	-0.400[a]	0.760	-0.656	-0.129	-0.800[a]	-0.837	-0.279	0.741

DLSEOW; double leg stance wide base of support with eyes open, DLSECW; double leg stance wide base of support with eyes closed, DLSEON; double leg stance narrow base of support with eyes open, DLSECN; double leg stance narrow base of support with eyes closed, Rt; right, Lt; left, APSI; anteroposterior stability index, MLSI; mediolateral stability index [a]; Spearman's rho correlation, *; Correlation is significant at the 0.05 level (2-tailed), APSI; anteroposterior stability index, MLSI; mediolateral stability index.

Table 45. Pearson's **r** correlation between WB performance (percentages of time in inner and outer zones) and ankle muscle strength.

	Muscle strength Rt Dorsiflexors	**Muscle strength Lt Dorsiflexors**	**Muscle strength Rt Plantar flexors**	**Muscle strength Lt Plantar flexors**	**Muscle strength Rt Invertors**	**Muscle strength Lt Invertors**	**Muscle strength Rt Evertors**	**Muscle strength Lt Evertors**
Inner zone %								
DLSEOW 5°	0.247[a]	-0.079	0.074	0.063	0.287[a]	0.104	0.051	0.064
DLSEON 5°	0.180[a]	0.145[a]	0.239[a]	0.224[a]	0.225[a]	0.213[a]	0.165[a]	0.239[a]
DLSEOW 10°	0.318[a]	0.058	0.360	0.160	0.336[a]	0.071	0.244	-0.033
DLSEON 10°	0.213[a]	0.134	**-0.405**[*]	0.109	**-0.405**[*a]	0.242	0.148	0.018
DLSEOW 15°	0.214[a]	0.057	0.049	-0.035	0.332[a]	-0.027	0.122	-0.081
DLSEON 15°	0.170[a]	-0.316	0.348	-0.038	0.332[a]	-0.396	0.034	-0.428
DLSECW 5°	0.030[a]	-0.492	-0.109	-0.302	0.277[a]	-0.377	-0.163	-0.252
DLSECN 5°	0.300[a]	**-0.903**[*]	0.029	-0.609	0.200[a]	**-0.880**[*]	0.208	-0.787
DLSECW 10°	0.400[a]	-0.926	0.684	-0.241	0.800[a]	-0.840	0.669	**-0.964**[*]
Outer zone %								
DLSEOW 5°	-0.247[a]	0.079	-0.074	-0.063	-0.287[a]	-0.104	-0.051	-0.064
DLSEON 5°	-0.180[a]	-0.145[a]	-0.239[a]	-0.224[a]	-0.225[a]	-0.213[a]	-0.165[a]	-0.239[a]
DLSEOW 10°	-0.318[a]	-0.058	-0.360	-0.160	-0.336[a]	-0.071	-0.244	0.033
DLSEON 10°	-0.213[a]	-0.134	**0.405**[*]	-0.109	**0.405**[*a]	-0.242	-0.148	-0.018
DLSEOW 15°	-0.214[a]	-0.057	-0.049	0.035	-0.332[a]	0.027	-0.122	0.081
DLSEON 15°	-0.170[a]	0.316	-0.348	0.038	-0.332[a]	0.396	-0.034	0.428

	Muscle strength Rt Dorsiflexors	Muscle strength Lt Dorsiflexors	Muscle strength Rt Plantar flexors	Muscle strength Lt Plantar flexors	Muscle strength Rt Invertors	Muscle strength Lt Invertors	Muscle strength Rt Evertors	Muscle strength Lt Evertors
DLSECW 5°	-0.030[a]	0.492	0.109	0.302	-0.277[a]	0.377	0.163	0.252
DLSECN 5°	-0.300[a]	**0.903***	-0.029	0.609	-0.200[a]	**0.880***	-0.208	0.787
DLSECW 10°	-0.400[a]	0.926	-0.684	0.241	-0.800[a]	0.840	-0.669	**0.964***

DLSEOW; double leg stance wide base of support with eyes open, DLSECW; double leg stance wide base of support with eyes closed, DLSEON; double leg stance narrow base of support with eyes open, DLSECN; double leg stance narrow base of support with eyes closed, Rt; right, Lt; left, %inner time; percentage of time tilt in inner zone, %outer time; percentage of time tilt in outer zone [a]; Spearman's rho correlation, *; Correlation is significant at the 0.05 level (2-tailed).

5.3 Discussion of study three

The primary aim of this study is to investigate the efficacy of a six-week progressive programme that used WB training to improve balance among people with diabetes mellitus (PWD) and diabetic peripheral neuropathy (DPN). The secondary aim is to explore the mechanisms underlying any changes resulting from the programme by understanding the relationship between baseline characteristics and static balance, as well as WB performance.

Therefore, various outcomes related to the primary aim will be discussed in the below sections. The primary outcomes are as follows.

5.3.1 Impact of intervention

5.3.1.1 Static balance

This study found significant improvements in static balance during all tasks (double leg stance eyes open wide base of support (DLSEOW), double leg stance eyes closed wide base of support (DLSECW), double leg stance eyes open narrow base of support (DLSEON), double leg stance eyes closed narrow base of support (DLSECN) and SLS following a six-week progressive WB balance training programme, with large effect sizes (ESs) ≥ 0.8 or ≤ 0.8, as shown in Figures 15, 16, 17, 18 and 19 and Table 19. This confirms the first hypothesis of the third study, which proposed that this WB training will result in static balance improvement for PWD and individuals with DPN.

Previous literature has demonstrated significant differences in static balance post-WB training or training with a movable surface in older adults (Balogun et al., 1992; Morioka et al., 2011; Salsabili et al., 2011; Song et al., 2011), who shared similarities in symptoms associated with both elderly and DPN patients, such as deconditioning, muscle weakness, reduced proprioception and decreased joint mobility (Kutty and Majida, 2013), it is worth reviewing the literature on the elderly population to support previous findings. Overall, these studies demonstrated that post-WB training achieved positive static balance performance results, therefore, indicating an improvement in at least one of the outcome measures relating to static balance.

The more difficult a postural task, the more cognitive processing is required to maintain balance during quiet standing, especially with neurological impaired individuals who have limited cognitive processing (Horak, 2006). Although the training in third study is considered dynamic training, the improvement discussed here is with regard to static balance. This is in agreement with previous research that suggests that the type of balance training is not a significant variable with regard to gaining improvements in balance (DiStefano et al., 2009). Additionally, progressive training was embedded into the third study's training programme based on each participant's balance ability, that may provide explanation for static balance improvement. The progressive nature of our training might challenge the sensorimotor system by requiring stabilisation on an unstable surface (DiStefano et al., 2009), which could result in enhancing proprioception post WB training (Waddington and Adams, 2004). Foot proprioception, muscle mechanoreceptors, joint receptors, ligaments and tendons that are considered components of the somatosensory system, are reported to be facilitated post unstable training (Mohammadian et al., 2019). Triggering the sensory information, since DPN affects the re-weighting of sensory information (Horak, 2006) underpinning balance control during exercise, might result in static balance improvement in elderly patients (Hu and Woollacott, 1994).

Regarding the deterioration that was seen in static balance during the wash out period in this study, which was accompanied by a decline in muscle strength, this confirmed the previous suggestion that neural adaptation happens first, then muscle strength changes post WB training. Comparison of this finding with those of other studies proves that static balance is associated with a slight increase in the duration of SLS, however, this did not reach a significant level (Kruse et al. 2010). Additionally, this agrees with a previous study that corrects the widely held belief about irreversibility of muscle weakness and joint limitations post prescribed exercise regimens for individuals with DPN (Sacco and Sartor, 2016).

5.3.1.2 Dynamic balance

The diabetic study demonstrated significant improvements in all dynamic balance (WB) parameters, which were the AP axis, ML axis, inner and outer times during DLSEOW 5°, which was the lowest level that was accomplished by all participants in the study, with large ESs ≥ 0.8 or ≤ 0.8, as shown in Figures 30 and 31 and Table 21. This result supports the second hypothesis, which proposed that this WB training will result in WB performance enhancement for PWD and individuals with DPN. However, not every participant started with the DLSEOW 5° task. Therefore, it was proposed to track each participant's level of success prior to failure. This tracking revealed a progression of WB performance levels, which manifested in means of 1.8, 2.1, and 2.4 every two weeks for the six-week training period, as explored in Table 23. This result indicates that, as WB training progresses, the performance of WB improves; however, it deteriorated among PWD and DPN individuals when training was paused for two weeks, which supports the third hypothesis of third study.

Similar to previous studies, though using a stability trainer instead of WB training, a quasi-experimental study design was conducted in individuals with DPN, where participants were divided into two groups: an experimental group that received the conventional physiotherapeutic exercises and balance training with a stability trainer and a control group that received the conventional physiotherapeutic exercises, twice per week for 8 weeks (Ajitha and Roopalokesh, 2020). The experimental group showed a clinically significant increase in Berg Balance Scale (BBS) compared to the control group (Ajitha and Roopalokesh, 2020). BBS was selected because Horak (2010) recommend utilising it due to its high reliability to evaluate the efficacy of intervention.

Two further studies that agree with previous results were conducted in individuals with DPN to compare the efficacy of WB training with a stability disc to improve balance (Jannu et al., 2017; Maruboyina et al., 2018). Both groups showed improvement in BBS and TUG scores (Jannu et al., 2017; Maruboyina et al., 2018).

Additional supporting literature from Akbari et al.'s (2012) study, who found significant improvement in AP stability index during DLSEO and DLSEC, as well as the AP axis during DLSEC, DPN individuals' scores after training with WB and Biodex balance training in comparison with their pre-training scores. Another study, conducted by El-Wishy (2012), showed significant greater improvement in an intervention group for both AP and ML stability indices during DLSEC assessed using the Biodex stability system, as part of a post-proprioceptive training programme (including balance board training) to enhance later balance reactions, compared to a control group who received a conventional PT programme.

One explanation for these results might be due to task transferability in balance training, rather than considering balance as a general ability (Giboin et al., 2015). Previous authors have investigated the transferability of balance performance in non-trained balance tasks after balance training and demonstrated that balance training had an effect only on the trained tasks, even if the non-trained tasks were performed on the same balance device but with a different direction of perturbation, or with the same direction of perturbation but on a different balance device in healthy adults (Giboin et al., 2015). Additionally, Kümmel et al. (2016) confirmed that healthy adults can improve their balance performance in a trained task with no effect on a non-trained task and recommended that physiotherapists include a task that requires training in the balance assessment or battery test in healthy adults. This is in line with the current study, which confirmed that, even in an unhealthy population such as PWD and DPN individuals, the improvement in dynamic balance was limited to the already-trained task and progressed to the subsequent level after 2 weeks of training at the same level. This explained why, when the follow-up assessment was performed, most of the participants showed progression to the next level (except for four participants only) due to severe DPN.

A final explanation, for the improvement in WB training over time might be due to the neural adaptation that occurs during the short period of the intervention, rather than muscle hypertrophy (Balogun et al., 1992; Schoenfeld, 2010) but muscles, especially in lower limbs, gained the strength required to improve balance after WB training (Waddington et al., 1999).

Regarding the deterioration that was seen in dynamic balance measures during the wash out period in the current study, this was accompanied by a decline in muscle strength, confirming the previous suggestion that neural adaptation happens first, then muscle increases in strength post WB training. A similar study utilised both BBS and TUG to assess dynamic balance post 3 months' strengthening and balance training for diabetic and individuals with DPN and did not achieve any statistically significant differences between the intervention and control groups after 6 and after 12 months (follow-up period) (Kruse et al., 2010). However, a recent SR and meta-analysis conducted by de Oliveira Lima et al. (2021) of three studies (Kruse et al., 2010; Song et al., 2011; Lee et al., 2013) highlighted that no significant differences were achieved in either measure (BBS or TUG), providing low-certainty evidence.

5.3.1.3 Muscle strength

The six-week of progressive WB training in PWD and individuals with DPN led to significant strength gains in all ankle muscles (dorsiflexors, plantarflexors, invertors and evertors) on both Rt and Lt sides, with large effect sizes (ESs) ≥ 0.8 or ≤ 0.8, as depicted in Figures 37, 38, 39 and 40. This confirms the fourth hypothesis of the third study, which proposed that WB training will result in strength gain of ankle muscles for PWD and individuals with DPN.

There is support from the literature on the elderly population, who might have significant declines in overall muscle strength and function similar to type II diabetic elderly individuals (Hewston and Deshpande, 2016). Although no correlation was found between lower-extremity strength and balance in the elderly (Muehlbauer et al., 2012), significant ankle movement (inversion) was achieved following 5 weeks of daily WB training in elderly individuals wearing shoes, compared to a barefoot control group (Waddington and Adams, 2004). The mechanism behind this improvement might be the effect of WB training on the ankle motor control process that occurs below the level of conscious attention (Waddington and Adams, 2004). Then, unstable training might enhance the somatosensory system, which is responsible for achieving balance through activation of the mechanoreceptors, joints, ligaments and tendons (Mohammadian et al., 2019). Additionally, muscle co-contraction between the soleus and tibialis anterior muscles can be achieved, though not after one balance training session – it required ten training sessions to increase the duration of this co-contraction in an elderly population (Alizadehsaravi et al., 2022). This increased the duration of antagonistic muscle co-contraction, which has been shown to result in facilitation of joint stiffness and enhancement of quick corrective response to unexpected disturbances, e.g., slips in challenging tasks, leading to the prevention of falls in the elderly (Chambers and Cham, 2007).

There are other possible explanations for the improvement of dynamic balance post WB training. One might be due to the nature of the training, which was progressive based on dynamic systems theory (McKeon, 2009). This theory suggests that the sensorimotor system, which plays a vital role in maintaining balance, alters coordination to self-organise, in response to environmental constraints, progressing to create greater demands at a higher difficulty level, leading to a more significant improvements in achieving the movement goal (Mancini et al., 2020). This is true, that achieving significant improvement in balance, demonstrated by gaining ankle muscles strength, due to changing the sensorimotor coordination to achieve the movement goal, which is in the present study progressed to a higher level of WB balance performance, that required more ankle muscle strength.

The final explanation for gaining ankle muscle strength is the utilisation of the ankle strategy for maintaining balance and control of quick CoM perturbations, which put greater demands on the balance systems and require a quicker and stronger muscle response to maintain balance (Hewston and Deshpande, 2016). The ankle strategy is a postural strategy that results in primary activation of the ankle muscles, then sequentially, the thigh and trunk muscles (Horak and Nashner, 1986). Therefore, the participants in the diabetic study may utilise the ankle strategy to gain balance, as demonstrated by higher scores of ankle muscle strength gained after six-weeks of WB training, which were notably, initially weak at baseline assessment. The improvement in ankle muscle strength (which was calculated as ankle muscle strength scores at T3–T0) were observed by the statistically significant correlation (P-value≤0.001), to the T0 baseline, as shown by Figures 41, 42, 43, 44, 45, 46, 47 and 48. These findings indicate that the weaker the ankle muscles during the initial muscle strength measurements (low positive value), the greater the relative improvements in strength (high positive value) measured in the ankle muscles.

Regarding the wash-out period results, the present study showed a significant (P-value ≤0.001), reduction in muscle strength for all ankle muscles, ranging between -10.85% to -17.39%, two weeks after pausing the WB training, corresponding to the period between T3 and T4, in PWD and individuals with DPN. In comparison, the previous literature showed that ankle plantar flexors did not show any significant differences in muscle strength after 6 months of cessation of the intervention (Allet et al., 2010). However, this study had a limitation that it did not extend the follow-up period, which may be taken into consideration in any future study.

5.3.1.4 Balance confidence

The six-week of progressive WB training resulted in significant improvements in balance confidence scores, with large ESs = 1.94, as illustrated in Figure 49 and Table 25, which is in line with the fifth hypothesis, which proposed that WB training will result in enhancement of balance confidence. Balance confidence in the present study was assessed using the Activities Specific Balance Confidence (ABC) scale, whereby participants indicated their level of confidence in performing various activities without losing their balance, using a scale from 0% (no confidence) to 100% (completely confident). Higher scores indicate greater balance confidence in daily living activities and decreased fall risk. There is a significant association between a high ABC scale score (greater than 80) and a lower fall risk (Mak and Pang, 2009). Additionally, ABC scores are indicative of the level of functioning; for example, an ABC score above 50 and lower than 80 indicates a moderate level of functioning, characteristic of the elderly population and individuals with chronic health conditions, while ABC scores above 80 are indicative of high functioning in the physically active elderly population (Myers et al. ,1998). The present study baseline mean value was 75.41%, which fell in the range between >50 and <80 that indicates a moderate level of functioning.

Only two studies with conflicting findings have examined the impact of WB training on balance confidence, as determined by the ABC questionnaire. One of these studies did not report any actual values (Dougherty et al., 2011). However, Schilling et al. (2009) reported small magnitude improvements in ABC scores: pre-intervention ABC of 92.8 ± 4.3% and a post-intervention ABC of 96.6 ± 3.6%, showing just a 3.8% change, though this was arguably due to the MDC of 15 (Wang et al., 2018). Similarly, the present study results, despite the intervention differences, because in Schilling et al.’s (2009) study, the participants were elderly (60–68 years old) and trained balance exercises on VersaDisc and CorDisc devices, three times per week for 5 weeks. The air volume of these devices was kept constant for the 5-week intervention, to ensure that the support surface was the same for all training sessions. However, in the present study, most of the participants were middle aged, though a few were elderly with DM and different DPN scores; they trained with a WB three times per week for 6 weeks in a progressive pattern. An 11.13% increase in ABC questionnaire score was reported after this WB training programme (the pre-intervention ABC mean was 75.41% and the post-intervention ABC mean was 86.54%) but a 5.75% reduction in ABC scores after a two-week wash out period. This suggests a beneficial effect of this progressive WB training programme for PWD and individuals with DPN in enhancing their balance confidence. Furthermore, 13 out of 44 participants initially scored <67%, indicating an increased fall risk; however, after the intervention, only one participant scored <67%. This provides an indication that this intervention indirectly decreased the risk of falling by increasing balance confidence scores.

5.3.1.5 Severity of neuropathic scores

The six-week of progressive WB training demonstrated a significant improvement in the severity of neuropathy, as assessed by the TCNS, as shown in Figure 51; this supports the sixth hypothesis of the third study, which proposed that this WB training will result in a reduction of the severity of neuropathic scores for PWD and individuals with DPN. Additionally, this improvement was gradual and consistent throughout the 6-week of training program, with large ESs ≥ 0.8 or ≤ 0.8, as shown in Table 27.

Similarly, a RCT proved that practising foot ankle exercises for 12 weeks significantly decreased DPN severity, as measured by the Michigan Neuropathy Screening Instrument (MNSI), in both intervention and control groups, with the intervention group reporting fewer symptoms than the control group (Monteiro et al., 2020). This is in agreement with other RCT conducted by Sartor et al. (2014), the intervention group received gait training and ankle/foot exercises for 12 weeks, followed by a 24-week washout period. Both assessments (at 12 weeks and 24 weeks) showed a significant reduction in MNSI score of 2 points (33.3%) with a medium ES. Similarly, the present study showed significant deterioration by a reduction of TCNS scores during the wash out period (-13.16%) (see Table 28).

An additional RCT study utilised treadmill exercises at moderate intensity, in addition to foot education and usual care for 8 weeks; the study showed a significant reduction in MNSI in both the control group (7.5%) and the intervention group (44.1%) (Dixit et al., 2014). Recently, a study conducted among type II diabetics with moderate neuropathy, who received WB training for 10 consecutive days, showed a significant reduction in MNSI and Valk scores that were maintained for two weeks (Ravand et al., 2021).

The present study is consistent with the previous RCT studies, though the severity of DPN was measured using the TCNS and this intervention was with WB only, which proved again its ability to reduce TCNS for mild and moderate DPN by 2 points, with large ESs. However, for individuals with severe DPN, their severity was reduced by just 1 point.

Overall, achieving this neurological adaptation, because of mechanical control mechanisms post WB training, confirmed that WB training not only improves muscle strength but it suggests that these adaptations, as a result of WB training, are achieved at the subcortical integration areas, such as the basal ganglia and cerebellum (Silva et al., 2016; Silva et al., 2018). Additional explanation might be because of training with an unstable surface leading to improved proprioception, via mechanoreceptor stimulation, which are located in muscle spindles, joint receptors, ligaments and tendons (Mohammadian et al., 2019).

5.3.1.6 Neuropathic pain scores

The seventh hypothesis was that pain would be relieved, post six-week of progressive WB training, in PWD and individuals with DPN. However, this hypothesis was rejected, due to finding non-significant improvements in pain, post six-week of this WB training, except for five participants.

Neuropathic pain was assessed via the VAS (see Figure 12). This scale was utilised in a RCT study, which applied balance and aerobic training exercises for individuals with DPN (Toth et al., 2014). However, after 6 months, the intervention group did not show significant changes in neuropathic pain, compared to the education only (control) group (Toth et al., 2014). This might be due to the small sample size of this study and the high dropout rates. Similarly, the current study failed to achieve significant differences in neuropathic pain, for similar reasons as stated previously; only the five participants > 60 years were complaining of pain at baseline but this pain was relieved at the third week of assessment (T3), indicating that WB training relieved their pain, even if the P-value did not reach a significant level (see Figure 52 and Table 29). Although the P-value might be non-significant, the result may be considered clinically significant (Sharma, 2021), when applying this parameter.

It is critical to comprehend the effect of specific exercise mechanisms, since those underpinning mechanisms might be applied to other neurological diseases (Streckmann et al., 2021). It is suggested, in a recent meta-analysis, that the therapeutic exercises might have the potential to reduce nociceptive responses to mechanical and thermal tests, compared to control groups without exercise; this has been shown in animal models of peripheral nerve injury (Guo et al., 2019). Another suggested mechanism is that neuropathic pain might be reduced by exercise through normalising microglia activation, balancing pro- and anti-inflammatory responses and producing alterations in neurotransmitter and neuro-modulatory systems (Leitzelar and Koltyn, 2021). However, individuals with DPN, who complained of chronic pain might spend less time exercising than those individuals without chronic pain (Butchart et al., 2009). Yet, these results indicated that therapeutic exercises or physical activity might play a role in pain management such that the affected individuals are unaware of it (Butchart et al., 2009). Thus, there is a demand to enhance individuals' awareness of the role of exercise in managing pain and improving overall health (Butchart et al., 2009). Consequently, it is recommended that physical activity be improved in DPN individuals; this will be discussed in the section below.

5.3.1.7 Physical activity level

The eighth hypothesis was that the level of physical activity would be improved post six-week progressive WB training in PWD and individuals with DPN. However, this hypothesis was partially rejected, due to non- significant differences found in the work index, which is one of the physical activity indices. This might be explained by the fact that most of the participants were working in offices and most of the time, would be seated in the work environment and their scores at baseline were lower in comparison with the normative value of the same index in healthy adults (Baecke et al., 1982). On the other hand, there were significant differences in other indices, such as sport and leisure time indices, following this WB training programme (see Figure 53 and Table 31 in chapter five).

These finding were consistent with previous studies, that achieved significant improvements in physical activity after different training programmes (Dougherty et al., 2011; Kempf and Martin, 2013; Smee et al., 2014; Mi et al., 2020). Achieving these improvements might be explained by two reasons, which will be discussed in the below section.

First, utilising different methods of assessing physical activities, for example, the patient neurotoxicity questionnaire, which was utilised in Mi et al.'s (2020). A further example is the Continuous Scale-Physical Functional Performance 10 (SCS-PEP10), which was utilised in Smee et al. (2014) and Kempf and Martin (2013). It is arguable that these previous physical activity assessment methods were all subjective, due to using questionnaire rather than quantitative objective tools, such as wearable sensors (AlShorman et al., 2021). Therefore, more clinical tests might provide stronger indications than these subjective questionnaires, such as the BBS, which was utilised in Dougherty et al's (2011) study.

A second reason for achieving improvements in physical activity, was that the nature of those exercise programmes, that include balance training with a balance board, such as standard WB or Wii Fit, which the latter has multi-axial fulcrum and utilises the IndoFLO ® Balance Cushion and ankle range of motion (Dougherty et al., 2011; Kempf and Martin, 2013; Smee et al., 2014; Mi et al., 2020). There are two strengths of these previous studies, the first being that the study design, conducted by Mi et al. (2020), was a RCT with the beneficial impact of ankle range of motion exercises, as demonstrated by increasing the range of motion, which is required to perform ADL (Mi et al., 2020). The second, strength for the other previous study, conducted by Dougherty et al. (2011), is that the effect of Wi Fit training was observed in the improvement scores of BBS and ABC questionnaire. This is in accordance with the present study findings, that a six-week progressive WB training program achieved proprioception enhancement, ankle muscle strengthening and balance confidence promotion. Consequently, proprioception improvement and ankle muscle strength training can lead to improved gait speed, balance enhancement and the restoration of balance confidence (Kutty and Majida, 2013). All these previous elements are required to perform the ADL and increase participation in activity, which consequently resulted in improving the SF36 questionnaire (Myers et al., 2013) and Baecke questionnaire, as in this present study.

5.3.1.8 Conclusion

This study set out to assess the effect of six-week progressive WB training among PWD and individuals with DPN. Therefore, this study confirms that this WB training alone is able to improve static balance, WB performance, muscle strength, balance confidence and neuropathy severity scores but they deteriorated after a washing out period. Additionally, this study investigates the mechanism underpinning achieving this improvement, such as neural adaptation, task specificity and utilisation of the ankle strategy and the progressive pattern of WB training. The novelty of this study lies in the fact that no previous study has used solely WB training in PWD and individuals with DPN, as well as the progressive nature of the training, which is based on balance assessment. Those findings can help guide clinicians on how to improve balance for PWD and individuals with DPN. Future studies might be conducted on other populations who are at risk of falling. Therefore, it is recommended to utilise this progressive pattern of WB training by tailoring it individually to each participant, taking into consideration the safety measures and the confounding factors. Examples of these factors are the patient's age, height, weight, anthropometrics, severity of neuropathy, neuropathic pain, duration of DM, physical activity level and balance confidence. Therefore, all of these previous factors, will be discussed in the following section regarding if there is any relationship between them and static balance, as well as WB performance.

5.3.2 Baseline characteristics

The secondary aim of this study is to explore the mechanisms underlying any changes resulting from the programme by understanding the relationship between baseline characteristics and static balance, as well as WB performance. Therefore, the below section investigates comprehensively the relationship between baseline characteristics, such as aging, anthropometrics, duration of DM, severity of DPN, balance confidence, physical activity, ankle muscle strength and static balance, as well as WB performance in PWD and individuals with DPN.

5.3.2.1 Age

The present study found significant (P-value= 0.01) moderate positive correlations (r=0.478), as depicted in Table 32, indicating that the older the individual, the poorer their static balance (perimeter) during the double leg stance eyes open with narrow (DLSEON) task. This resulted in the rejection of the nineth hypothesis, which proposed that age will not affect static balance in PWD and individuals with DPN.

This previous significant correlation might be explained by the requirement for maintaining static balance during DLSEON, which is sufficient sensory information provided by intact somatosensory and visual systems (Horak, 2006). Additionally, narrow base of support is known to be more difficult than a wide base of support, because the CoM is moving in a small base of support and required to establish equilibrium for avoiding falls by activating ankle-hip muscles, namely the 'hip strategy', especially in the elderly, while ankle muscle activity, which is called 'ankle strategy' is sufficient for controlling balance in young adults (Amiridis et al., 2003). However, despite its simplicity, it is difficult maintain in elderly individuals, who are above 80 years, due to motor dysfunction (Masdeu et al., 1997). The elderly and individuals with DPN, are known to experience impaired balance, which might arise from multiple sources, such as deconditioning, muscle weakness, reduced proprioception and decreased joint mobility (Kutty and Majida, 2013). Certainly, decreased foot sole sensation (FSS) might disturb the mechanoreceptors, consequently resulting in balance impairment in both the elderly and PWD (Santos et al., 2008). Decreased proprioception and weakness in the lower limbs might prove to be a strong predictor of falls in PWD, individuals with DPN and the elderly (Timar et al., 2016; Chatzistergos et al., 2020).

Thus, age and DPN are accompanied by a reduction in the complexity of the physiological or behavioural control system, which can alter the neuromechanical mechanism underpinning static balance (Vaillancourt and Newell, 2002), resulting in an increased risk of falling (Morrison et al., 2012).

Regarding WB performance, there were significant correlations between most of the previous age-related factors and WB performance. The degree of correlation increased as the WB task became more complex. For example, the correlations between age and WB performance were low during simple tasks, such as those with eyes open, wide base of support and 10° tilt angle but when the task became more challenging by closing eyes, increasing the tile angle and narrowing the base of support, the correlations became higher with WB performance. This led to the rejection of the nineth hypothesis, which was that age will not affect WB performance in PWD and individuals with DPN.

This is consistent with the with previous study that found a negative correlation between age and dynamic balance, indicating that the older the participant the less stable, when they were on a rubber foam surface with both eyes open and eyes closed (Di Nardo et al., 1999). Furthermore, elderly individuals with DPN were found to sway with eyes open in a manner equal to those in the age-matched population who performed the same task but without vision (Simoneau et al., 1994). This might be explainable because the elderly depend on exteroceptive information and prioritise the use of vision to maintain balance (Hatzitaki et al., 2009). Standing on a compliant foam surface might reduce the effectiveness to produce of ankle torque, which is required for postural stabilisation on such surfaces (Horak and Hlavacka, 2001). Producing this ankle torque required strong ankle muscles, which appear to decline in the elderly, causing an inability to produce sufficient torque, leading to an increased AP axis in the elderly with DM (Lee et al., 2018a). The AP axis was more significantly displaced in diabetic older adults than young and healthy non-diabetic older adults (Lee et al., 2018a), which is similar to the present study's finding.

5.3.2.2 Height, weight and

5.3.2.3 Anthropometric measures

The present study failed to find any correlation between height, weight, BMI, anthropometric measures and static balance in either of the parameters or tasks. Similarly, previous literature reported no correlation between height, BMI and static balance in asymptomatic type II DM without DPN (Razzak and Hussein, 2016). This confirms the tenth hypothesis of the third study, which proposed that anthropometric measures will not affect static balance in PWD and individuals with DPN, though this was rejected regarding WB performance, as will be discussed in the below section.

The present study found a correlation between WB performance and anthropometrics. It is possible that this may be due to height (Bryant et al., 2005).

The present study found a significant very high positive correlation (r=0.959) between height and WB performance during DLSECW 10°, along the mediolateral stability index (MLSI), as depicted in Table 34 and Appendix 14. Being tall, posing a higher center of mass (COM) distance from the base of support, potentially produces greater instability (Bryant et al., 2005). Thus, the present study established greater correlations for height, weight and upper torso 'size' and WB performance. Specifically, height, weight, shoulder, waist and hip circumferential measures demonstrate the strongest correlations with WB performance. For example, there was correlation between weight and WB performance along the percentages of time spent in the inner and outer regions, which ranged from low (r=-0.365 - 0.365) to high (r=-0.891 - 0.891), depending on the complexity of the task. Thus, the harder and more challenging the task on the WB (greater inclination, narrow base of support and eyes closed) the greater the correlation, as depicted in Table 35. Further, there was a significant correlation between anthropometric measures (shoulder, chest, hip circumferential measures and shoulder-hip ratio) and WB performance (APSI, MLSI, percentages of time spent in inner and outer zones) ranged from low (r=0.335 – 0.387) to moderate (r= 0.417 – 0.691), high (r=0.803 – 0.918) and very high (r= 0.938 – 1.000), as shown in Tables 38 and 39. These degrees of correlation increased again, according to the complexity of the task; suggesting that the harder and more challenging the task on the WB (greater inclination, narrow base of support and eyes closed), the greater the correlation. This is consistent with previous literature, which reports a very high negative correlation between BMI and the mean scores for BBS in individuals with DPN, although no correlations were found among healthy, aged and sex matched individuals (Fahmy, 2014). There has been no previous study that investigated the correlation between WB performance and anthropometric baseline characteristics in PWD and individuals with DPN.

These findings might be explained due to the outcome of the moment functioning around the WB's "joint". Because of the function of mass times distance, the heavier subject would acquire a greater moment around the "WB joint" if two people of same height but different weights were to be swaying their bodies by the same amount. Furthermore, a heavier body weight with larger waist circumference causes the COM position to shift anteriorly (Corbeil et al., 2001), which can be challenging for proprioception (Wang et al., 2008), and when combined with a decline in muscle strength (Tomlinson et al., 2016) and an increase in fatiguability (De Souza et al., 2005; Pajoutan et al., 2016), especially in PWD and individuals with DPN (Hilton et al., 2008), which consequently can lead to a potential reduction in WB performance. This anterior shift of COM in obese individuals was represented by modelling the human body using a 15-segment mathematical humanoid to identify the relationship between obesity and postural control (Corbeil et al., 2001). This model confirmed the anterior shift of the COM in obese individuals was caused by abdominal obesity and may restrict the range of stability at the boundaries (Corbeil et al., 2001). Consequently, greater ankle torque will be required for balance during perturbations (Corbeil et al., 2001). If insufficient torque is produced, then the obese person is more susceptible to loss of balance and falling (Corbeil et al., 2001).

5.3.2.4 Physical activity

This present study failed to find a correlation between the majority of the tasks during both static balance and WB performance and physical activity (PA). This confirmed the eleventh hypothesis of this study, that PA will not affect static balance or WB performance. This is similar to a previous study, that failed to establish any correlation between the total PA index, when measured using the Baecke questionnaire and DM (Sakaue et al., 2020). The normative data from the Baecke questionnaire (Baecke et al., 1982), which was used to assess PA in the present study, was for healthy adults only but no normative data for the Baecke questionnaire exists for these populations in the literature. However, individuals with DPN might experience an impact on their daily activities, due to neurological impairments arising from muscle weakness and sensory disturbances (Hoffman et al., 2015).

Therefore, in the present study, there were two exceptions in terms of correlations between PA and static balance (ellipse area, r=-0.434) during SLS, as well as between PA and WB performance (percentage of time spent in inner and outer zones r=-0.900 – 0.900), during DLSECN 5°, as shown in Tables 36 and 37, respectively. These correlations might be explained due to the nature of tasks and complexity requiring greater muscle coordination and certain strategies to maintain balance. Specifically, during SLS and DLSECN, the CoG can move within the BoS in a smaller distance than wide base of support tasks, where there is a wider distance to move CoG within the BoS (Alonso et al., 2012). Additionally, hip strategy is adopted to adjust the hip-joint moments of the stance leg, which is utilised for the changing of the ground reaction force's horizontal component, leading the CoM moving over the support surface (Richardson et al., 1996; Amiridis et al., 2003).

5.3.2.5 Duration of diabetes mellitus (DM)

This present study, achieved a significant positive low correlation between the duration of DM and static balance during DLSEON and SLS, as shown in Table 40. This led to the rejection of the twelfth hypothesis of the third study, that duration of DM will not affect static balance. Similarly, a previous study achieved a significant low positive correlation between the duration of DM and static balance parameters (Giacomini et al., 1996). This might be explained because of the effect of having DM for a protracted duration, which can lead to the development of DPN, that in turn can result in significant skeletal muscle deficits, such as neurogenic muscle atrophy, loss of muscle strength, power and endurance, depending on the severity of the disease (Andreassen et al., 2006). This might provide an explanation for the significant correlation between the duration of DM and WB performance during DLSEOW 10°; which are the APSI, the percentage of time spent in the outer zone, although the inner time was negatively correlated (r=-0.425), as shown in Tables 41 and 42. This led again to the rejection of the twelfth hypothesis of the third study, that duration of DM will not affect WB performance. This finding corresponds with the previous study, which found a positive moderate correlation between duration of DM and dynamic balance; which was sway on foam with eyes open, after controlling for age (Lord et al., 1993).

Thus, a long duration of DM leads to a decline in the somatosensory and musculoskeletal systems required to maintain balance. Consequently, a protracted period of DM will increase the risk of developing DPN with increasing severity, which in turn is required to be assessed. Therefore, the severity of DPN will be discussed in the below section.

5.3.2.6 Severity of diabetic peripheral neuropathy (DPN)

The current study found a low positive (r=0.446, 0.338, 0.379) correlation between severity of DPN and static balance, during DLSEON (perimeter and ellipse area), as well as during SLS (ellipse area) as shown in Table 40. This led to the rejection of the thirteenth hypothesis of the third study, that the severity of neuropathy will not affect static balance. This may be a result of a non-intact somatosensory system in individuals with DPN, since, this system is required to be intact for the maintaining of balance, specifically during narrow base of support tasks (Horak, 2006). Similarly, static balance was correlated with the severity of neuropathy in four studies (Boucher et al., 1995; Giacomini et al., 1996; Uccioli et al., 1997; Fortaleza et al., 2005; Palma et al., 2013). These studies utilised various assessment instruments for evaluating the severity of DPN, such as nerve conduction velocity (Giacomini et al., 1996; Uccioli et al., 1997), clinical tests, such as Valk (Boucher et al., 1995), Diabetic Neuropathy Examination Score (DNES) (Palma et al., 2013) and MNSI (Fortaleza et al., 2013). Despite the variety of tests and different age ranges (from 35 years old (Giacomini et al., 1996; Uccioli et al., 1997) to 70 years old) (Fortaleza et al., 2013), static balance was correlated with the severity of the neuropathy.

Additionally, the present study found a significant correlation between severity of DPN and WB performance during DLSEOW 10°. This led to rejection of the thirteenth hypothesis of the third study, that the severity of neuropathy will not affect WB performance. Due to novelty of this study, direct comparison from the literature is impossible, however, there are other dynamic balance tests, such as BBS, which was also used as a dynamic balance test and found to be significantly correlated with severity of DPN in the two studies (Ghanavati et al., 2012; Timar et al., 2016). This might be explained due to the nature of this task when conducted using a WB, since this method necessitates a quick response from the muscles to return CoM with the BoS. However, in individuals with DPN, there are signs and symptoms, such as ankle muscles weakness, impairment of the small afferent fibres, long latency and reduced ankle torque, all of which are required to maintain balance during perturbation (Nardone and Schieppati, 2004; Andreassen et al., 2006; Salsabili et al., 2011; Li et al., 2019).

A final explanation is that neuropathic individuals might experience limitations when re-weighting sensory information based on the sensory context, which might lead to an increased vulnerability of falling in specific sensory contexts (Horak, 2006). Eventually, prolonged reweighting might be a consequence of neuroplastic changes to the CNS, caused by chronic impairments in DPN (Li et al., 2019). DPN demonstrated a significantly increased touch pressure sensation threshold and significantly increased the passive joint motion perception threshold, compared to the controls (Corriveau et al., 2000; Lafond et al., 2004).

5.3.2.7 Neuropathic pain

The findings of the current study revealed the more severe an individual's neuropathic pain, the poorer their static balance (perimeter and ellipse area) during DLSEON (low positive correlation r=0.382 – 0.415) and WB performance (percentages of time spent in inner and outer zones) during DLSEON 5° (low positive and negative correlations r=0.491 - -0.491), as shown in Tables 40 and 42. Three studies agreed with this observation (Boucher et al., 1995; Daousi et al., 2004; Fortaleza et al., 2013). This concluded in the rejection of the fourteenth hypothesis of the third study, that neuropathic pain will not affect static balance or WB performance. However, pain in the present study was assessed subjectively by the VAS.

The previous studies, utilised various methods for assessing pain, such as VAS, the pain disability index, Valk score and MNSI (Boucher et al., 1995; Daousi et al., 2004; Fortaleza et al., 2013). MNSI was used to assess the severity of DPN, with a score ≥ 8 considered as abnormal and pain was assessed within this scale (Feldman et al., 1994). This pain was chronic and could interfere with various ADL (Boucher et al., 1995; Daousi et al., 2004; Fortaleza et al., 2013). This indicates that the more severe the neuropathic pain, the more severe the disruption experienced by PWD when engaging in activities, compared to individuals without chronic neuropathic pain (Daousi et al., 2004). Additionally, there was a linear correlation between neuropathic pain and static balance (Boucher et al., 1995; Fortaleza et al., 2013). This might be explained by the nature of the pain phenomenon, which is multi-dimensional and includes cognitive, emotional and physical components (Lee, 1985). Considering the physical components, such as muscle weakness and loss of proprioception, these might provide further explanation for the correlation between the neuropathic pain and balance. Regarding the emotional component, lack of balance confidence due to pain, can result in activity avoidance. Therefore, balance confidence will be explored in the below section.

5.3.2.8 Balance confidence

The present study used the ABC-16 version to assess balance confidence. The results showed significant correlations between static balance, WB performance and balance confidence. That, the lower an individual's balance confidence, the poorer their static balance and WB performance during DLSEON and DLSEON 5° respectively, as depicted in Tables 40, 41 and 42. The degree of correlation was low negative (r=-0.471) between balance confidence and the static balance parameter (perimeter) during DLSEON, as shown in Table 40. Furthermore, the degree of correlation was low negative (r=-0.421, -0.471) between balance confidence and the WB performance parameters (APSI, percentage of time spent in the inner and outer zones), except in the inner zone, there was low positive (r=0.471) statistically significant correlation during DLSEON 5°, as depicted in Tables 41 and 42. This led to the rejection of the fifteenth hypothesis of the third study, that balance confidence will not affect static balance or WB performance.

These previous findings correspond with two studies, which used the same ABC-16 version (Cho et al., 2004; Schepens et al., 2010). Balance was assessed by the SLS and TUG tests. These correlations were significant, indicating that the higher the balance confidence, the better the balance performance (Cho et al., 2004; Schepens et al., 2010).

This might be explained by the fact that the requirement to successfully perform these tasks (narrowing base of support and SLS) is the presence of intact somatosensory and visual systems, which in turn are required to produce sufficient sensory information (Horak, 2006). However, diabetic individuals and those with DPN may have non-intact somatosensory and visual systems, thus might result in poorer balance, especially in the elderly rather than young adults (Nagy et al., 2007). Additionally, narrowing the base of support leads to a relative increase in the distance from the CoG to the BoS, because there is a small distance within which the CoG can move, which may be close to the edge of the BoS (Alonso et al., 2012) and requires more ankle-hip muscle activation than a wide base of support to control balance in the elderly. While ankle muscle activity alone was only sufficient for controlling balance in young adults (Amiridis et al., 2003), as was explained previously in this chapter. Due to the previous explanation of narrowing base of support, this might justify the low confidence among the participants in this present study during DLSEON 5°. Similarly, the same significant correlation was found between balance confidence and dynamic balance test, i.e. TUG in elderly individuals (Schepens et al., 2010).

Additionally, there were high negative (r=-0.957) correlations between the WB performance parameter (MLSI) and balance confidence during DLSECW 10°, as shown in Table 41. This might be explained by the nature of this task, which required absence of visual cues that are known to be impacted in individuals with DPN, in comparison to age-matched PWD without neuropathy and healthy control subjects without DM, during quiet standing (Simoneau et al., 1994). Furthermore, individuals with DPN are known to be unbalanced during assessment of the MLSI parameter, that can lead to difficulties during performance of tasks that require a shift to the ML direction (Ghanavati et al., 2012). Therefore, balance confidence is a critical factor required to be assessed, due to previous correlations between balance confidence and static balance, as well as WB performance, which may lead indirectly to reduce the risk of falling.

Finally, there are two strong predictors of falls in PWD and individuals with DPN, especially if they are elderly, which are decreased proprioception and weakness in the lower limbs (Timar et al., 2016; Chatzistergos et al., 2020; Maki and McIlroy, 1996; Masdeu et al., 1997). Therefore, muscle strength is an important factor that can be considered when assessing static balance and WB performance, which will be explored in the below section.

5.3.2.9 Ankle muscle strength

In this present study, overall, there were significant low to moderate negative correlations between static balance and most ankle muscles on both sides during DLSEON and SLS, as shown in Table 43. Furthermore, there were correlations between ankle muscle strength and WB performance (APSI) during DLSEON 5° and (inner and outer times) during DLSEON 10°, DLSECN 5° and DLSEOW 10°, as shown in Tables 44 and 45. This led to a rejection of the sixteenth hypothesis of the third study, which proposed that ankle muscle strength will not affect static balance or WB performance. The required ankle muscle strength to produce essential torque required for balancing during WB activity was not sufficient, due to muscular decline in those individuals and as the task became more challenging, it required greater ankle muscle strength and this explains the greater correlation. A further explanation might be due to the decline in peripheral nerve function, with both sensory and motor nerve involvement in PWD and individuals with DPN, which led to muscle atrophy (Andersen et al., 1997; Bus et al., 2002; Greenman et al., 2005), a decline in strength (Andersen et al., 2004; Andreassen et al., 2006) and a reduced ability to generate force (Andersen et al., 2004), which are all required for WB performance. The muscle atrophy and loss of strength have been found to be greater distally in the leg compared to proximally (Andersen et al., 1997; Andersen et al., 2004). Such atrophy might be a consequence of degeneration and demyelination of axons as indicated by the nerve conduction and amplitude reduction shown in electrophysiology studies (Boulton et al., 2005). The rate of decline of strength increases as DM worsens and becomes significantly worse when DPN starts (Le Corre et al., 2023). This was evidenced in the ankle dorsiflexors and plantar flexors, as muscle weakness was associated with neuropathy scores (Andreassen et al., 2006); notably, ankle and toe flexors resulted in impairment throughout the course of the disease (Monteiro et al., 2018).

Distal muscles were weakened due to the greater accumulations of intramuscular fat present, and proximal leg muscles also showed a reduction in muscle volume (Almurdhi et al., 2016). Further examples of proximal muscle impairment was found in the knee extensors among females only, but not males; however, this study did not measure the strength of the ankle muscles, or correlate the findings with weight, DPN or severity of DPN (Lord et al., 1993). Therefore, DPN might not be the sole cause of muscle weakness, although muscle disorders, such as increased intramuscular fat deposits, due to obesity, might contribute to such a weakness, especially in calf muscles that interfere with physical function among obese PWD and individuals with DPN (Hilton et al., 2008). Therefore, ankle muscle strength contributes to a vital role during static balance assessment and WB performance, which requires assessment pre and post any balance training programme.

5.4 Conclusion, limitations, clinical implications and future studies of study three

The previous section discusses the relationship between static balance, WB performance and baseline characteristics, such as age, anthropometric measures, duration of DM, severity of DPN, balance confidence, physical activity level and ankle muscle strength. Overall, there were no correlations between previous baseline characteristics and simple tasks. However, there were some exceptions, such as challenging tasks during DLSEON and SLS. Similarly, WB performance was impacted by most of these baseline characteristics, specifically when the task was more challenging, such as closing eyes, increasing tilt angle and narrowing BoS. The common task for all previous correlations is double leg stance eyes open with narrow base of support (DLSEON). This task required intact somatosensory and visual systems, which are not intact in PWD and individuals with DPN and might provide explanations for these correlations. Therefore, it is recommended to consider these baseline characteristics when plan an effective balance training program to improve balance and reduce the risk of falling, especially during complex tasks, such as DLSEON and SLS. This recommendation should be taken into consideration, regardless of what the static balance and WB performance parameters are. This is study has limitations, similar to most of the other clinical studies which are small sample sizes, limited variations in height and outliers from PROKIN. However, these outliers were removed by using the interquartile rule. Future studies are recommended to include larger sample sizes, with increased participant height and the use of a combination of clinical and quantifiable objective balance tests. Finally, this study provides more confidence in clinical decision making about assessing balance and prescribing WB intervention, due to the gained knowledge about the effect of previous baseline characteristics on static balance and WB performance.

Chapter 6: Discussion of the thesis

Wobble board (WB) assessment and training are popular in clinical practice and sport rehabilitation for improving balance performance but there are elements of WB exposure and physiological response that are not fully understood. Therefore, the potential benefits of WB training exposure, in terms of improving balance in individuals vulnerable to falling, such as the elderly, people with diabetes mellitus, type II (PWD) and those with diabetic peripheral neuropathy (DPN) require consideration. Some studies suggest that improvements in physiological response do occur and that they are due to neuroplasticity (Balogun et al., 1992; Schoenfeld, 2010), while others argue that it is due to hypertrophy of the ankle musculature (Waddington et al., 1999). Thus, the main focus of this present study and thus thesis, is the investigation of those factors that affect static and dynamic balance performance and the potential improvements in balance associated with WB training in PWD and individuals with DPN by experimentation.

The following thesis sections discuss the main findings of this study, which are divided into three sections, a SR of the literature on the potential benefits of WB training in the elderly, an observational study to investigate the factors that impact WB training, and an assessment of a planned progressive WB training programme, designed to improve balance in PWD and individuals with DPN. The findings of the three studies will be compared against relevant literature and the potential effects on the clinical practice of WB assessment and training in the elderly, PWD and individuals with DPN, will be considered.

6.1 Study One: The Systematic Review (SR) of the efficacy and efficiency of wobble board (WB) training in elderly populations

With advancing age, the elderly become increasingly vulnerable to falling, therefore, preventative strategies are required to minimise their risks of slips, trips and falls (American College of Sports Medicine (ACSM), 2021). Preventive programmes of focused balance training are recommended by the American Geriatrics Society (AGS), the British Geriatrics Society (BGS) and the American College of Sports Medicine (ACSM) (AGS and BGS, 2011; ACSM, 2021), (discussed earlier in chapters one and two). Balance training with a WB is associated with a reduced risk of sport-related injury (Emery et al., 2019), enhanced balance rehabilitation (Williams and Bentman, 2014; Fusco et al., 2019), facilitation of neuromuscular function (Webster and Gribble, 2010) and the minimisation of the risk of injury (Hübscher et al., 2010). This SR was the first review conducted to assess WB training efficacy for improving balance in an elderly population and only six articles were found to address this research question. The Downs and Black (1998) checklist was used to assess the methodological quality of theses selected studies, as mentioned in chapter three and listed in Table 3, which will be discussed in greater depth in the section below.

None of the six articles had blinded participants, which threatens validity, since blinding minimises the systematic effects of experimentation and limits participant bias. Providing that the intervention is typically fundamentally different to the control group, performing blinding is difficult in exercise-based studies; nevertheless, because this reflects physical therapy practise, those findings are still highly applicable to clinicians.

Additionally, failure to blind an outcome may lead assessors to an unintentional bias, favouring an intervention and thereby, affecting an outcome. This may be minimised, if the various balance assessment outcomes are calculated automatically, such as using a force plate (FP) with standardised outputs. Thus, this study utilised an integrated static force platform within a Prokin to assess static balance, as discussed earlier in chapter four.

The outcome measures for those articles included in this SR were multidimensional balance outcome measures, referring to functional balance tests and assessing balance impairment consequences in real environments during the performance of specific tasks, that resemble the activities of daily living (ADL) (Horak, 1987), (see section 1.2.1 in chapter one). Examples of these functional balance tests to assess multidimensional balance outcome measures include: the Berg Balance Scale (BBS) and the Continuous-Scale Physical Function Performance Test 10 (CS-PFP10), as utilised in four of the cited studies (Dougherty et al., 2011; Kosse et al., 2011; Hande et al., 2014; Smee et al., 2014). Those studies that utilised these previous outcome measures, (BBS or CS-PFP10), observed a weighted average improvement in performance of 4.4% and increased effect size (ES) ranging from 0.35 (Dougherty et al., 2011) to 0.96 (Hande et al., 2014), as demonstrated in the forest plot (see Figure 8), with an average ES of 0.61, indicating WB training has an overall moderate effect on the BBS (or similar). This result reflects those of Dougherty et al. (2011) and Smee et al. (2014), who demonstrated improvement between 1.6% and 6.3% respectively, although specifically improved element/s cannot be determined, due to the multi-dimensional nature of the balance outcome measures and insufficiently detailed reporting.

The minimal clinically important difference (MCID), which is used in most clinical studies to determine if the smallest amount of change is clinically meaningful or not, due to measurement error (Stratford et al., 1996; Stokes, 2010), as discussed in section 1.3 in chapter one, has unfortunately not been determined in the healthy elderly but values range between 5% and 21% in people with multiple sclerosis and in elderly individuals healing from hip fracture, respectively, as reported in the literature (Gervasoni et al., 2017; Tamura et al., 2022).

There were no significant differences in TUG, as reported in two studies (Schilling et al., 2009; Ogaya et al., 2011). However, both studies indicated that WB training yielded an average weighted improvement in TUG tests of 6.3% and a weighted ES of 0.40. The initial value and distribution value of TUG tests across these two studies are noteworthy, as Schilling et al. (2009) recruited participants with an average baseline TUG time of 5.6 s (Schilling et al., 2009). This might classify TUG performance in the top 5th percentile of performances (Pondal and del Ser, 2008), minimising the possibility of progression, regardless of training.

Moreover, there was high variability across the enrolled participants, as indicated by the reported TUG time's SD (13.6 s) and mean (14.7 s) (Ogaya et al., 2011). However, it is unknown how or if outliers (scores that stands out from the rest of the data (Field, 2017) were detected or handled, which could have a negative impact on the capacity to detect significant changes.

Only one study reported a significant improvement in TUG, with an actual value of 1.7s among healthy elderly individuals (Hande et al., 2014), potentially indicating a meaningful clinical change. For example, by comparison, a difference of 1.4s was considered a clinically meaningful difference in hip osteoarthritic elderly subjects (Wright et al., 2011).

A positive impact of WB training on the BBS and TUG balance outcome measures were reported but the magnitude of change in the BBS was small, with the highest change post-WB training being three points, such as in Hande et al.'s. (2014) study, the pre-BBS score was 48.5 ± 3.1 and the post-BBS score 50.8 ± 1.4, as shown in Table 4 in chapter three. However, it is uncertain if these alterations exceed the normal variation anticipated with repeated measurements, because Dougherty et al. (2011) suggested the MCID in BBS was at four points. Additionally, the assessor bias might affect successful scoring because the performance of ADL (for example, transferring from bed to chair), are evaluated by functional balance testes subjectively.

Additionally, the impact of WB training on the static and dynamic balance components of BBS, remains uncertain. Further explanation of gaining small improvements in BBS might be due to the ceiling effect, where initial scores are near the highest achievable value (56), resulting in a lack of possibility to explain balance improvement. For example, the initial scores for BBS in the included articles in this SR vary from 48.5 to 53, indicating that these achievable scores were near the maximum of 56 (see Table 4 in chapter three).

Despite the similarity between BBS and TUG, it is still not immediately apparent why there were discrepancies in the findings between those two balance assessment tests. Examples of this similarity are the shared components, such as sit to stand and turning, however, TUG test measures the time taken to complete linked tasks, while the BBS measures quality subjectively. Two studies Schilling et al. (2009) and Ogaya et al. (2011) out of the three, Hande et al. (2014), failed to demonstrate a statistically significant difference in TUG but this may have occurred due to the evaluation of a fundamentally different functional construct. BBS performance can account for 22% of TUG variability but 78% remains unexplained, indicating these are primarily independent balance tests (Bennie et al., 2003). This supports the concept that balance training with a WB stimulates different adaptive mechanisms, implying that WB training might not produce improvements universally across all balance measures.

Regarding static balance studies, two failed to show improvement in postural sway post-WB training (Kosse et al., 2011; Ogaya et al., 2011). Ogaya et al. (2011) used a double leg stance (DLS) and calculated the RMS area and duration for single leg stance (SLS) task, but neither metric showed a significant change after training (see Table 4 in chapter three), where the RMS area pre-WB training was 2.9 ± 2.4 cm^2 and post-WB training was 1.7 ± 0.9 cm^2 and the SLS duration pre-WB training was 19.6 ± 30.0 s and post-WB training was 27.0 ± 40.2 s. Similarly, Kosse et al. (2011) indicated a lack of improvement in tandem stance and SLS task duration, as shown in Table 4 in chapter three, although no actual values were reported. These findings indicated that postural sway parameter improvements for static balance measures were not significantly affected by WB training. Consequently, it is concluded that WB training does not specifically target the physiological measures that influence postural sway performance. Examples of the measures that impact postural sway are the integration of the somatosensory system and the inverted pendulum theory during ankle strategy, (see chapter two). These tests have been referred to as static balancing tests, where the difficulty is in responding to an inherently derived postural challenge, while remaining “relatively” still (Haines et al., 2007). This contrasts with the externally generated perturbation of the WB; possibly explaining why WB training does not affect postural sway. Additionally, balance training has a high task specificity (Kümmel et al., 2016), therefore, it is recommended to include tasks that are trained in as part of tests, used both in the pre- and post-training period (Giboin et al., 2015) (as discussed in section 2.6.10.1, in chapter two).

The SR indicated that all WB training programmes included, participants instructed to perform prescribed exercises for a period ranging between 6 and 30 mins, two-three times per week, as shown in Table 4 in chapter three. However, no justification for the choice of these specific parameters was provided. Thus, indicating a lack of evidence in the literature, with regard to what constitutes an optimal WB or balance training regimen. Ideal training programmes, based on a synthesis of evidence were often provided by the positional statements of the ACSM (2018), however, they were unable to provide precise and specific prescriptions of balance exercises beyond the most fundamental of principles.

According to the outcomes of this SR, the studies with WB sessions durations up to 30 mins seem to demonstrate larger ESs, the ceiling included for this review, as shown in Figure 8 and Table 4 in chapter three. These findings agree with the findings of Lesinski et al. (2015b) that represented the relationship between the effectiveness of balance training and the duration of a single training session as an inverse U-shape in older adults. Therefore, they recommended splitting the total duration of weekly balance training into three or more sessions per week, with the shortest duration of a single session being between 21–30 mins (Lesinski et al., 2015b). It can, therefore, be assumed that a single 30-minute session of WB training would significantly influence a variety of mechanisms, which might affect balance. For example, WB training is likely to have an impact on neuromuscular adaptation. This has been supported by previous literature, with two studies providing evidence of improvements, one with regard to proprioception (Waddington and Adams, 2004) and one, latency times (Akhbari et al., 2007). Additionally, Mohammadian et al.'s study (2019) supports the proposition that foot proprioception, muscle mechanoreceptors and other components of the somatosensory system, such as joint receptors, ligaments and tendons, might be enhanced after unstable training.

Furthermore, WB training has been shown to lead to significant gains in lower limb muscle strength (Balogun et al.,1992), although, the largest ESs seem to be associated with shorter training programmes, such as four sessions of 4 mins per week for three weeks in Hande et al.'s (2014) study and three sessions of 10 mins per week for five consecutive weeks in Dougherty et al.'s (2011) study, as illustrated in Figure 8 and Table 4 in chapter three. However, a mechanism underpinning these short training stimuli might be explained in relation to neuromuscular changes, rather than muscle hypertrophy (Balogun et al., 1992; Schoenfeld, 2010). There are three factors that influence muscular hypertrophy, intensity, load and type of muscle contraction, these will be discussed in the following section.

The time spent during a WB training session does not necessarily provide an accurate indicator of exercise intensity (the energy expended per unit of time) and assessing this variable might hinder any attempt to correlate it with balance rehabilitation. For example, performing simple tasks during WB training, such as moving side-to-side and rocking forward backwards and performing cursor matching tasks demonstrates the greatest ES=0.88 (Hande et al., 2014), as shown in Figure 8 and Table 4 in chapter three. In contrast, similar programmes only reported modest ESs. The most complicated training programme, which involved WB based squats, lunges and reaching exercises yielded only a very small ES=0.11 (Schilling et al., 2009), as shown in Figure 8 and Table 4 in chapter three. It is probable that focus or attention played a role in this outcome. Previous literature has observed that individuals perform better when they concentrate on or pay attention to the outcomes of their activities, rather than the specific inputs (movements) (Lohse et al., 2010). Therefore, if individuals divert their attention to perform additional tasks, like squats or lunges, while using a WB, this could potentially distract them from controlling the WB's tilt and consequently lead to poor WB performance that eventually, reduces balance improvement. Hence, it is possible that a high level of complexity is not necessary to achieve the goal of enhancing balance. It is likely that the demand of concentrating, to maintain the board level and adjusting the degree of tilt, either by giving explicit verbal instructions or by tracking the movement of a cursor on a screen, provides sufficient stimulus to enhance balance.

The load acting on the muscles and type of muscle contraction are other essential factors that might be taken into consideration, when discussing muscular hypertrophic adaptation (Nigg and Herzog, 2007). Internal forces, which are the forces that act on the musculoskeletal system, such as ligaments, bones and articular cartilage provide a significant load stimulus on the muscles (Nigg and Herzog, 2007). Calculation of an individual's muscular forces can be obtained by indirect measurement of muscular activation using the electromyography (EMG) (Nigg and Herzog, 2007). Greater muscle activity is required during unstable surface training, particularly from lower limb musculature than the upper limb musculature (Wolburg et al., 2016). Additionally, training with an unstable surface was suggested to cause low intensity contractions, that consequently may lead to activate the slow twitch, type I fibres, which play a significant role in maintaining posture and do not easily fatigue (Paassen and Gramsbergen, 2005; Behm et al., 2013).

An additional factor that may affect the efficiency of WB training is a fear of falling, which may affect performance tasks, involving those within BBS and TUG and may account for up to 90% of the variance in TUG performance (Kumar et al., 2008) and

36–94% of the variance in BBS performance (Kumar et al., 2008; McAuley et al., 1997). The consequences of fear of falling among the elderly might lead to additional restrictions on their activity and alterations in gait, as observed in balance tests that assessed those two consequences, such as BBS and TUG (Kumar et al., 2008). Further consequence for those individuals who are afraid of falling, may be the performance of tasks more slowly, perhaps as a safety measure, to increase their security and lower their risk of falling.

Moving the CoM more quickly could put additional demands on the balance system's equilibrium and necessitate a quicker and stronger muscle response to maintain balance. Consequently, individuals who have a greater fear of falling frequently accomplish activities more slowly. Only two studies, each with conflicting findings, examined the impact of WB training on balance confidence, as assessed by the Activities Specific Balance Confidence (ABC) questionnaire. One study showed non-significant differences or no recorded actual values (Dougherty et al., 2011), as indicated previously in Table 4 in chapter three. Another study reported small improvements on the ABC scale, just 3.8 points (4%) (Schilling et al., 2009), as was pointed out in Table 4 in chapter three, which is arguable, in light of the MCID of 15 (Wang et al., 2018). Fear of falling might, in part, play a role in explaining the mechanism underlying the effect of WB training among the elderly, such that WB training familiarity may desensitise an individual to a fear of falling. Therefore, future studies might consider exercise prescription that specifically address a fear of falling.

6.1.1 Conclusion, limitations, clinical implications and future studies

In conclusion, this SR has provided conflicting evidence regarding how WB training programmes improve balance. Efficient and effective WB training can be achieved by prescribing simple tasks and assessing them using multi-modal balance outcome measures to produce large ESs, such as BBS. The encouragement of concentration and attention on the WB tilt, as well as training sessions with a duration up to 30 mins, produces large ESs and are advised to be considered when prescribing WB training. Successfully conducting this SR fulfilled the first aim of this thesis and answers the first research question, which was: does WB training enhance balance in the elderly population? The answer was found to be yes.

However, there were two limitations in this SR, the small sample size of this review, which included only healthy older adults, may limit the generalisability of the findings; thus, caution must be applied, when interpreting its findings, since the impact of the synthesis and generalisability might be reduced. However, the sample was sufficient to conduct a meta-analysis of the data. Another possible limitation is selection bias, due to only involving studies written in English, as no translation service was available due to the Covid-19 lockdown restrictions. However, the author used databases that index studies in multiple languages (Medline, Scopus, EBSCO, CINAHL, Science Direct and Google Scholar), broadening the search base, despite only including English language studies, as mentioned previously in chapter three.

6.2 Study Two: The impact of baseline characteristics including, biological sex, anthropometrics, footwear, dual tasking (DT) and physical activity level, on static balance assessment and wobble board (WB) performance in healthy adults.

The previous SR study investigated the efficiency and efficacy of the WB training but the optimal assessment for static balance and WB performance by the stabilometric assessment device (Prokin 252) does not exist in the literature and is required to guide researchers, physical therapists and sport trainers. Specifically, there are no studies integrating the assessment of static balance and WB performance to investigate performance and its relationship to a range of anthropometric variables. This comparison is fundamental in identifying balance impairments, leading to enable clinicians to set rehabilitation goals, to select the correct comparison when comparing them with normative databases or clinical norms. Thus, this study was designed due to this previous lack of clarity in the literature, about the influence of biological sex, anthropometrics, footwear and dual tasking (DT) on static balance assessment and WB performance during quiet standing. To assist in planning assessments and training for the subsequent study (study three) in this thesis: a study of balance related performance of people with diabetes (PWD) and individuals with diabetic peripheral neuropathy (DPN). This diabetic study aims to design a WB intervention and assess its efficacy.

The static stability assessment option of the stabilometric assessment device Prokin (252) was applied as a FP, as described previously in section 1.2.1.3 in chapter one to perform static balance tests during a Romberg test, that includes performance of a double leg stance (DLS) task with eyes open and closed and a single leg stance (SLS), as described previously in chapter two and shown in Figure 10 in chapter four. Each task took 30 seconds and was completed three times. Thus, due to the nature of this study, which required repeated tasks (three times), a learning effect of fatigue could occur, which might impact the findings but this is likely to be minimised by the randomisation of the task allocation. In this study, the recorded static balance parameters were perimeter and ellipse area. The perimeter (measured in mm) represents the path length of the displacement of CoP during imbalance, which measures the total distance of CoP displacement travelled in both axes, which are X axis and Y axis, whereas the ellipse area (measured in mm^2), represents 90%-95% of the total area covered in both directions, which are AP and ML directions (Paillard and Noé, 2015), as indicated previously in chapter four. The smaller the perimeter and ellipse area values, the better the static balance performance (Paillard and Noé, 2015). The same Prokin device was utilised to assess dynamic balance, resembling WB performance by altering the platform from static to dynamic in all directions and with an instability degree of zero, indicating a level with a high degree of instability, resembling a WB function, as explained previously in chapter four. The WB performance was achieved by selecting the equilibrium management option to measure the inclination angle of the movable force platform, during both a DLS, with eyes open and closed and SLS tasks, as depicted in Figure 11, in chapter four. An additional parameter for WB performance was the percentage of total time during which the platform occupied one of five zones of inclination, or tilt bandings (named A, B, C, D and out), calculated as described earlier in chapter four. This Prokin was utilised to assess static balance and WB performance in both sexes, to determine if biological sex affects performance, which will be discussed in the below section.

6.2.1 Biological sex

The first hypothesis of the second study was that biological sex will not affect static balance assessment or WB performance. However, this hypothesis was rejected because females outperformed males across most static balance tests, as demonstrated by the significant difference ($p \leq 0.001$) in the perimeter of the sway trace in the static balance parameter, with some very large effect sizes (ES) ≥ 0.9, as shown in Table 5 in chapter four. This was indicated by the lower perimeter's median (Med) values for females of 262 mm, 367 mm, 819 mm, 240 mm, 323 mm, 850 mm, 406 mm,863 mm and 870 mm, compared to the same perimeter's Med values for males at 329 mm, 480 mm, 1019 mm, 297 mm, 407 mm, 1122 mm, 539 mm, 1057 mm, and 1083 mm during DLEOS, DLSECS, SLSS, DLSEOUS, DLSECUS, SLSUS, DLSECDTS, SLSDTS and SLSDTUS tasks, respectively. Similarly, females outperformed males across most WB performance tests, as indicated by the significant difference (p≤0.004) in stability indices, with some very large ES values ≥ 0.9, as depicted in Table 10 in chapter four. This was further demonstrated by the smaller APSI Med values in females of 7.81°, 3.78°, 8.22° and 8.06°, compared to the values in males of 9.96°, 5.38°, 10.12° and 10.13°during DLSECS, DLSEOUS, DLSECUS and DLSECDTUS tasks, respectively. An additional demonstration of a significant difference in stability indices was found in the smaller MLSI Med values in females of 7.65°, 7.83° and 8.39°, compared to the values in males of 9.94°, 9.78° and 9.51° during DLSECS, DLSECDTS and DLSECDTUS tasks, respectively. However, males demonstrated better WB performance than females, with a significant P-value=0.001, during SLS without footwear DT (see Table 11). This was indicated by the mean value for percentage of time spent in the outer zone for males, which was 84%, compared to the value in females, which was 95%. Furthermore, the mean value for percentage of time spent in the inner zone for males was 16%, compared to the value in female, which was 6%. Previous studies mirror those of the current study, with women performing better than men during static balance (Ekdahl et al., 1989; Maki et al., 1990; Mickle et al., 2011; Puszczalowska-Lizis et al., 2018), as well as during dynamic balance (Maki et al., 1990; Ku et al., 2012). However, when the task became more challenging, such as performing tasks with closed eyes, the static balance performance worsened, for all static balance tasks regardless of whether the static balance task was performed with footwear or without footwear, as single tasks or DT, as shown in Table 5. This might be explained because of critical role of visual system in maintaining balance, since visual cues are required for postural orientation, to arrange the body part in relation to the surrounding environment (Mancini et al., 2020), as discussed earlier in chapter two.

Thus, the current study not only compliments the previous literature but demonstrates that this difference is present whether or not shoes are worn and whether single or dual taskings (DTs) are performed during testing. However, this does not appear to be the case when complicated tasks were added, such as navigation task or visual biofeedback training accompanying WB training, where males showed better balance performance than females (Bulut and Erdeniz, 2021; De Maio et al., 2021). Further detail about the DT effect on static balance and WB performance will be discussed in section 6.2.4. The reasons for these sex differences during static balance and WB performance are unknown. It is possible that anthropometric factors play a role, which will be discussed in the below section.

6.2.2 Anthropometry and physical activity level

It has been suggested that anthropometric factors play a role in sex difference outcomes during static balance and WB performance, for example, height (Bryant et al., 2005), since being taller suggests the presence of a higher centre of mass (COM). However, a difference was still found after normalisation for height, as shown in Table 6. This possible explanation was suggested because the current study established modest correlations, ranging between 0.313 - 0.487 between height and weight in healthy adults during static balance, as shown in Table 7 in chapter four; WB performance, suggests a lower weight and height correlates with a better static balance and WB performance during quiet standing. However, greater correlations, ranging between 0.304 - 0.678, as shown in Tables 12 and 13 in chapter four, were found between WB performance and weight and upper torso 'size'. This modest correlation may also explain the results, since males tend to have a relatively larger upper body, whilst in general, females have greater mass concentrated in the lower body (Farenc et al., 2003; Menegoni et al., 2009). Additionally, waist (which ranged between 58 cm and 137 cm) and shoulder circumferential measures (which ranged between 87 cm and 136 cm), showed a modest effect, ranging between 0.308 - 0.480 on static balance performance, as depicted in Table 7 in chapter four. Suggesting the greater the 'size' of the upper body including the waist, the poorer the static balance performance across double leg stance (DLS) tasks. This larger upper body size effect also inhibits control of sway, raises the CoM and potentially contributes to greater sway. In the present study, significant correlational ($p \leq 0.004$) analysis seems to support a correlation between greater upper body size (albeit moderately) and poorer static balance performance, as shown in Table 7, in chapter four. Indicated by the significant correlation between static balance parameter (perimeter and ellipse area) and shoulder circumferential measures, which range between 0.308 and 0.477. This was particularly in evidence with DLS tasks. It is possible that such anthropometric relationships are evident during simpler static balance tasks, as almost universally, SLS tasks were not significantly correlated with body size, as shown in appendix 9. Previous research has demonstrated that DLS moderately correlated with BMI (Ku et al., 2012) and the components of BMI (Chiari et al., 2002), suggesting the significance ($p \leq 0.004$) of anthropometrics is evident in lower complexity tasks, such as DLS with eyes open single tasks, as depicted in Table 7 in chapter four.

Furthermore, the strongest correlations in WB performance were reported with weight, shoulder, waist and hip circumferential measures. This finding, a correlation between WB performance and anthropometric characteristics, has not existed before in the literature. There are several possible explanations for this result. A possible biomechanical explanation for this might be an elevated COM, as mentioned previously but another possible explanation for this is the moment functioning around the ‘joint’ of the WB. For instance, if two individuals having equal height but different weight were asked to sway their body by the same distance, then the heavier individuals would achieve a greater moment around the ‘WB joint’, due to the function of mass multiplied by distance.

Further biomechanical explanations for poor WB performance might include an anterior shift of the CoM, caused by larger waist circumferences and greater body weight (Corbeil et al., 2001), leading to proprioception challenges (Wang et al., 2008), combined with poor muscle strength (Tomlinson et al., 2016) and increased fatiguability (Pajoutan et al., 2016).

Habitual physical activity, as measured via Baecke questionnaire, had no relationship with static balance or WB performance; therefore, advising an individual to increase their physical activity is likely to have a minimal impact on static balance and WB performance. Similarly, there were no significant differences between physically active and non-active participants, whatever their age (both young and old) in a cross-sectional study conducted by Maitre and Paillard (2016) that assessed static and dynamic balance, which is foam surface.

6.2.3 Footwear versus without footwear

To the best of the author's knowledge the current study is the first to investigate the effect of footwear on WB performance in healthy adults under multiple positions and conditions. This information is essential for physiotherapists and clinicians when deciding whether to assess and train balance, especially with WB, with or without footwear. To determine the optimal approach, it was first required to determine if static balance and WB performance differs across these conditions. The findings of the current study demonstrate that overall, there were no differences in performance during static balance and WB performance due to footwear because the P-value ≥0.008, as shown in Tables 8 and 14 in chapter four, for static balance and WB performance, respectively. This confirms the second hypothesis of the second study, as mentioned in chapter one, which was that footwear will not affect static balance assessment or WB performance. Two exceptions were found: (i) during DLSEC task wearing shoes worsened performance in both females (P-value <0.001) and males (P-value=0.006) during static balance only and (ii) wearing shoes resulted in better balance performance for males under the SLS condition both during static balance (P-value=0.004) and WB performance (P-value=0.005), as depicted in Tables 8 and 14 in chapter four. However, the effect size (ES) was very small (0.07) during WB performance only, noted in Table 14 in chapter four. This was indicated by the Med values for the perimeters (of 367 mm in females and 480 mm in males) during DLSEC task while wearing shoes being higher than Med perimeter values when not wearing shoes (323 mm for females and 407 mm for males). However, wearing shoes resulted in better static balance and WB performance in males, as indicated by the larger perimeter's Med value (1122 mm) and APSI's Med value (4.19°) during SLS performed while not wearing shoes than during SLS while wearing shoes (Med values of 1019 mm for perimeter and 4.11° for APSI). A possible explanation for the static balance findings, is that moving across the distribution of the plantar foot surface during static balance appears to be translated into movement around the CoM, which could impact static balance performance. Previous studies have demonstrated that plantar foot surface sensation is a critical contributor to the biofeedback loop involved in maintaining balance (McKeon et al., 2015). Arguably, this may be enhanced during the barefoot condition, as supported by findings in this study for the significant difference (p≤0.008) DLS condition but not the SLS condition. The difference may be explained by visual contribution. Potentially, the double leg stance with eyes closed (DLSEC) condition may have resulted in a re-evaluation of the weighting of the input parameters to the biofeedback loop (Benjuya et al., 2004). However, reliance on plantar pressure feedback with vision present (SLS condition) may be unnecessary, due to the dominance of the visual contribution. Without vision (DLSEC condition) it is possible that attention to the input from the plantar foot pressure is raised, resulting in the difference between both with and without footwear conditions. The current literature is surprisingly sparse regarding direct comparisons between the with and without footwear conditions; therefore, the current study significantly contributes to the current understanding. Previous studies have demonstrated mixed results regarding the effect of footwear on static balance (Germano et al., 2012), demonstrating similar findings for SLS, reporting that CoP excursion was greater in the barefoot condition. In contrast, Smith et al. (2015) demonstrated that balance, whilst wearing shoes was better for CoP sway overall and in the AP direction during DLSEC. The reason for these conflicting findings is not clear; however, angular displacement of CoP was used to determine static balance performance, rather than perimeter length of the sway trace (Smith et al., 2015).

This is contrary to the fact that, foot sensation with footwear is known to be changed, leading to affected proprioception (Robbins et al., 1995; Waddington and Adams, 2004) and postural stability (Maki and McIlroy, 2006; Menant et al., 2008). However, the non-significant difference ($p \geq 0.008$) WB performance with and without footwear in either females or males, regardless of the task or metric of the WB performance, as shown in Table 14 in chapter four, is in agreement with a prior study using a rocker board (single axis WB), in which there was no significant difference between the conditions with and without footwear (Zech et al., 2018). The mechanism, which was described previously, regarding the movements of the CoM during balancing on a stable surface, is likely to be translated into distributed movement of the plantar foot surface pressure, where this may affect the balance performance, but this is not the case during WB performance. This is due to the fact that forces produced by CoM movements disrupt the balance of the board, thus, any alteration in the foot surface contact is likely to have little impact. It is still unknown whether the mechanism utilised to stabilise WB performance with or without footwear versus single or DT are the same, although this analysis is outside the scope of this thesis. Although there is consistency in performance across conditions, the relative contributions from different balancing systems may not be similar but this information, regarding muscle activation and latency are unclear.

6.2.4 Single versus dual task (DT)

The “conscious” components of postural stability are managed by the basal ganglia-cortical network (Boisgontier et al., 2013). This is in line with the studies of Raftopoulos (2005) and Boisgontier et al. (2013), who confirmed that posture is regulated by both higher “controlled” and lower “automatic” levels of processing, suggesting that the basal ganglia-cortical loop is involved in higher level processing (Jacobs and Horak, 2007) and brainstem synergies in lower-level processing (Honeycutt et al., 2009). Studies have indicated that any reduction in the conscious regulation of attention towards postural control may increase the likelihood of interrupting coordination and stability (Wulf et al., 2001; Masters and Maxwell, 2008), as a result of movement-specific reinvestment (Masters, 1992; Masters and Maxwell, 2008).

The theory of reinvestment suggests that directing attention internally to control movement, which is usually automatic, can disrupt its performance (Wulf et al., 2001; Masters and Maxwell, 2008). The theory also suggests that aging (Schaefer et al., 2015) and neurological diseases (Masters and Maxwell, 2008) are common conditions that increase reinvestment (Ghai et al., 2017). Further explanation about older adults, who have relatively less capacity to manage the competing demands of attending to both the cognitive task and the balance task, demonstrate a difference between single and cognitive task, with the later task producing poorer balance (Boisgontier et al., 2013). DT balance testing has increasingly been reported in the literature, since it affords greater discriminatory capacity than single task balance tests (Ruffieux et al., 2015). However, in this present study, while static balance performance was marginally worse with DT, no significant differences (P-value≥0.008) were determined, except during the DLSEC task, as shown in Table 9 in chapter four. This confirms the fourth hypothesis of the second study, which was that DT will not affect static balance or WB performance. The previously highlighted exception is that, during the DLSEC task, there were significant differences (significant P-values <0.001, and 0.003) determined between with footwear and without footwear conditions, demonstrating poorer static balance performance during DT, as depicted in Table 9 in chapter four. This was indicated by the higher perimeter Med value during DLSECDTS (406 mm in females and 539 mm in males), compared to the DLSECS (367 mm in females and 480 mm in males). Additionally, it was demonstrated by the higher Med values for perimeter and ellipse area during DLSEODTUS (276 mm and 168 mm^2 in females), compared to the DLSEOUS task (240 mm and 110 mm^2 in females). This likely reflects the participants' age, since the present study's young participants possess adequate capacity to complete a cognitive task, with little 'cost' to the physical task. Previous studies found no significant differences between single and DT during static balance performances, as measured by total CoP displacement, ellipse area and CoP velocity in the FP in youths (Lüder et al., 2018). Therefore, it seems unlikely that the DT offers additional benefit over single task balance testing for young healthy individuals.

Regarding WB performance, there were significant differences ($p \leq 0.008$) determined mainly for double leg stance with eyes open (DLSEO) amongst the footwear and without footwear conditions, demonstrating poorer performance when conducting DTs, as shown in Table 15 in chapter four. This was indicated by the higher Med value for APSI during DLSEODTS (5.21° in males), compared to DLSEOS (4.36° in males), as well as the higher Med value of MLSI during DLSEODTS (5.53° in females 7.18° in males), compared to the DLSEOS (5.19° in females 5.82° in males). It was further demonstrated by the higher Med value MLSI during DLSEODTUS (5.77°) in females (6.73°) in males, compared to the DLSEOUS (4.75°) in females (5.68°) in males. Additional evidence for the previous significant differences was found in the higher Med values for percentage of time spent in the outer zone (91% in females and males) during the DLSEODTS, compared to (85% in females and 81% in males) during the DLSEOS and lower Med values for percentage of time spent in the inner zone 9% in females and 10% in males) during DLSEODTS, compared to (16% in females and 19% in males) during DLSEOS. Further significant differences were seen in the Med values for percentage of time spent in the outer zone (92% in females) during DLSEODTUS, compared to (83% in females) during the DLSEOUS and the lower Med values for percentage of time spent in the inner zone (9% in females) during DLSEODTUS, compared to (17% in females) during the DLSEOUS. Since this study was the first to investigate how DT affected WB performance, direct comparison to the WB literature was not possible. However, it has been shown that DT, such as counting aloud has an impact on balancing on unstable surfaces (Yardley et al., 1999). An interesting finding by Yardley and colleagues (1999), which challenge the current understanding of DT concept, implies that cognitive function results in DT cost, where attentional demands of voicing the arithmetic prevent the balance task from being attended to in the same manner.

Their study implies the apparent compromise may be related to the dual function of the muscles required for postural control and voicing arithmetic aloud, as no DT cost was observed for the same cognitive task without vocalisation. The WB performance may be affected by such a mechanism but if so, a more universal effect might be anticipated across all WB tasks. However, it is still unknown why some tasks were affected, while others were not, despite the fact that DT had little to no effect on other WB performances. Additionally, this unstable surface clearly differs from the Prokin employed in this investigation and overall, small ES ≤0.8 for DT cost were found, as indicated in Table 15 in chapter four.

6.2.5 Conclusion, clinical implications and future studies

In conclusion, the findings of the static balance and WB study provide the first comprehensive investigation into the impact of biological sex, footwear and DT on static balance assessment and WB performance. Thus, this study was successful in achieving its aim, which was to provide an in-depth understanding of the effect of these factors to design the optimal approach to static balance assessment and intervention, as well as WB assessment and training, which are all are essential in physiotherapy and clinical practice. Overall, females outperformed males across a range of tasks during static balance assessment and WB performance, regardless of whether the wearing of footwear or DT was investigated. However, biological sex differences were noted in both sexes, in both with and without footwear conditions, as well as in single tasks and DTs, during both static balance assessment and WB performance. There were, however, no large ESs reported during with footwear or without footwear conditions, or between single tasks and DTs for static balance assessment. Similarly, WB performance while wearing footwear did not differ from that without footwear except during SLS. Additionally, WB performance during single tasking did not differ from DT, except for double leg stance eyes open but the ESs were moderate to small. Thus, the footwear and DT effect appeared to be task specific. Therefore, future studies are required to determine and comprehend the potential benefits, as well as identify the possible mechanisms underlying DT cost during WB performance. Additionally, future research might compare different footwears and different DTs. With respect to anthropometry, correlations were moderate for static balance, WB performance and height, weight and upper body size. The data suggests that being taller, heavier or having a larger upper torso were associated with poorer static balance and WB performance. This information is important for clinicians or physiotherapists, who may struggle to decide how best to test static balance and WB performance, or in prescribing WB exercises. Clinicians might advise individuals to increase their physical activity but this is likely to have a minimal demonstrable effect on balance performance, due to appearing to be no significant relationship between physical activity and balance performance. These findings are crucial to guide physiotherapist, as well as the author in planning an intervention with a WB and assessing its performance, alongside static balance performance. Thus, allowing greater confidence regarding making clinical decisions about the real effect of the considered factors. The final recommendation for future studies is to recruit different populations, such as those who are vulnerable to falling or have balance impairments, implementing a similar study design to this one, to investigate whether participants show a similar response or effect to that of healthy adults.

Therefore, the next section, which is based on the findings presented here, seeks to establish a progressive WB training programme and applies it to people with diabetes (PWD) and individuals with DPN, who are vulnerable to falling, aiming to improve balance. The effect of this WB training programme will be explored and the relationship between static balance, WB performance and baseline characteristics will be investigated, taking the above findings into account.

6.3 Study three: The effect of a progressive six-week WB training programme on balance in people with diabetes mellitus (PWD) and diabetic peripheral neuropathic (DPN)

Falling is considered the second largest cause of accidental injuries, leading to death in the elderly population (Wang et al., 2014). There is also an increased risk of falling in people with diabetes mellitus (PWD) and associated diabetic peripheral neuropathy (DPN), due to sensory, vestibular and musculoskeletal systems impairment, which are responsible for the maintenance of balance (Deshpande et al., 2017). Therefore, to prevent falls among the older population and individuals with DPN appropriate balance training exercises are recommended by the American College of Sports Medicine (ACSM) (ACSM, 2021; Khan and Andersen, 2022), as discussed in chapter two. Balance training with a WB is widespread in clinical practice and sport rehabilitation, as discussed earlier in this chapter, as well as in chapters one and two. However, the factors affecting the appropriate prescribing of this type of training are not fully understood. As described earlier in this chapter, static balance assessment and WB performance will be conducted via the stabilometric assessment device (Prokin 252). Therefore, this study endeavoured to design a WB training programme based on the literature and applied the studies included in this thesis, which as an aid to memory are the SR study, to explore the efficiency of this type of training among elderly population and the second study, which investigated comprehensively, the factors that affect this WB training. Thus, the primary aim of this present study in this thesis is to investigate the efficacy of a planned WB training programme to improve balance among PWD and individuals with DPN. The secondary aim is to explore the mechanisms underlying any changes resulting from the programme by understanding the relationship between baseline characteristics and both static and dynamic balance, referring the dynamic balance to WB performance and assessed by the Prokin device, as was mentioned earlier in this chapter and in chapter one.

To this end, various outcomes that relate to the primary aim will be discussed in the following sections. The primary outcomes are as follows.

6.3.1 The impact of the intervention

6.3.1.1 Static balance

This study was the first of its kind to take PWD and individuals with DPN and expose them to a progressive WB training programme, therefore, direct comparison with the literature is not possible. However, a comparison is attempted with the literature related to WB training in the elderly more generally, since it may be possible to derive some insights to assist in interpreting the study's findings.

WB training in the elderly is reported to demonstrate only non-significant differences in static balance performance (Schilling et al., 2009; Kosse et al., 2011; Ogaya et al., 2011), this observation could be explained by differences in the outcomes measured, including, sample size, population and/or nature of the intervention. For example, the three studies failing to demonstrate an effect in static balance might have obtained these results due to their relatively small sample size and or the effect size (ES). Indeed, researchers have to consider the sample size and the ES when analysing a study result, think critically and evaluate the result logically and despite having a small size, which in turn can cause non-significant P-values, the results may be considered clinically significant (Sharma, 2021).

A further consideration regarding the discrepancy between the findings, is that one of the three previous studies did not use a FP but a tandem stance and single leg stance (SLS) duration (Kosse et al., 2011). These are clinical balance tests, which are considered as functional tests but lack objectivity, while the FP provides a valid and objective measure for static balance and is considered as a gold standard for static balance assessment (Nardone, 2016; Sandrini et al., 2018), as described earlier in this chapter and chapter two. Therefore, the study conducted for this thesis used an integrated static force platform within the Prokin (Prokin 252, TecnoBody, 2021) to assess static balance.

Moreover, all the populations in the previous studies, which fail to show improvement in static balance post-WB training, were elderly (Schilling et al., 2009; Kosse et al., 2011; Ogaya et al., 2011). Aging is known to affect static balance, displayed by poorer control of the center of pressure (CoP) location, as being closer to the boundaries of base of support (BoS), for longer periods of time compared to young adults, which places the elderly at a higher risk of postural instability (Bugnariu and Sveistrup, 2006). It is, however, important to consider that impaired balance in the elderly might arise from multiple sources. Certainly, a decreased foot sole sensation (FSS) might disturb the mechanoreceptors, consequently resulting in balance impairment in both the elderly and PWD (Santos et al., 2008). Decreased proprioception and weakness in the lower limbs may also explain balance impairments in PWD (Chatzistergos et al., 2020) and the elderly (Vincent and Joseph, 2017). An additional consideration is that the efficacy of the ankle strategy is reduced by aging (Horak et al., 1989). This consequently results in a shift from an ankle to a hip-based strategy in the elderly (Inglin and Woollacott, 1988).

Due to the previously discussed causes of balance impairment in the elderly, WB training might be unable to specifically target a specific physiological underpinning mechanisms that impacts static balance, as indicated by postural sway performance, which required essential elements that do not exist in the elderly, as indicated previously as the result of the SR study, conducted by the author in this thesis. This SR discussed lack of information in the included articles regarding outliers, specifically whether they were detected and how they were handled, which may result in a negative impact on the capacity to detect significant changes. Therefore, in this thesis, the author detected some outliers from the Prokin but these were solved by applying the interquartile rule and the outlier labelling rule, which were explained earlier in chapter five.

Unlike the SR study, the current study resulted in a significant (P-value <0.001) improvement in static balance performance parameters, which are perimeter and ellipse area, post six-week of progressive WB training programme in PWD and individuals with DNP. This significant improvement was noticed during double leg stance wide base of support with eyes open (DLSEOW), double leg stance wide base of support with eyes closed (DLSECW), double leg stance narrow base of support with eyes open (DLSEON), double leg stance narrow base of support with eyes closed (DLSECN) and SLS, as shown in Figures 15, 16, 17, 18 and 19, respectively, in chapter five. Additionally, large ESs ≥ 0.8 or ≤ -0.8 were also found across most tasks and metrics (see previous figures and Table 19 in chapter five). This was indicated by the pre- and post-WB training mean values for perimeter and ellipse area. For example, the pre-WB training perimeter mean values were 187.35 mm, 251.60 mm, 251.32 mm, 386.89 mm and 633.86 mm, compared to post-WB training perimeter mean values of 104.76 mm, 156.84 mm, 158.89 mm, 255.14 mm and 454.81 mm during DLSEOW, DLSECW, DLSEON, DLSECN and SLS, respectively. Furthermore, the pre-WB training ellipse area mean values were 178.92 mm², 249.46 mm², 308.19 mm², 615.33 mm² and 605.00 mm², compared to post-WB training mean ellipse area values of 43.97 mm², 88.57 mm², 113.16 mm², 300.30 mm² and 381.35 mm² during DLSEOW, DLSECW, DLSEON, DLSECN and SLS, respectively. This confirms the first hypothesis of the third study conducted for this thesis, as mentioned in chapter one, which proposed that this WB training programme will result in static balance improvement for PWD and individuals with DPN.

There are seven studies that are in agreement with this finding, including those conducted in healthy older adults (Balogun et al., 1992; Morioka et al., 2011), individuals with DPN (Nardone et al., 2010; Salsabili et al., 2011; Song et al., 2011), older adults with small vessel disease, (Zhao et al., 2019) and individuals who have had a stroke (Zhang et al., 2020). The findings from these studies indicate significant improvements in static balance performance following WB (or similar movable surface) training.

With respect to dynamic balance training, a progressive training programme was recommended for balance training based on the dynamic systems theory (McKeon, 2009). This theory relates to the behaviour of an important system in balance, which is the sensorimotor system (McKeon, 2009). This system changes coordination to self-organise around a certain task, to achieve a movement goal, responding to environmental cues, which progress to create greater demands at higher levels of physical difficulty, reaching the movement goal and resulting in a more significant improvement (McKeon, 2009). As described previously in chapters one and two. Cuğ et al.'s progressive pattern of training was utilised using a BOSU ball, which is a movable surface similar to a WB, in healthy adults and led to a significant improvement in static balance parameters (Cuğ et al., 2016). An additional benefit of progressive sensorimotor training, which involves WB training, started with the unidirectional movement of a WB and progressed to bilateral movement of the WB during double leg stance, then progressed to a SLS increasing ankle muscle activity in individuals with DPN (Ahmad et al., 2020). Additional progressive training was embedded into training programmes in the present study in this thesis, as well as the training programme, which was tailored individually based on each participant's balance ability at baseline, as explained earlier in Tables 16 and 17 in chapter five. The participants' balance ability at baseline was assessed using the Prokin, acting as a WB with fifteen levels of WB difficulty according to the tilt angle of the WB and the task performed, as described in Table 16 in chapter five. Once a certain level of WB performance was successfully achieved, this level was used to prescribe the WB training programme, as indicated in Table 17 in chapter five. This progressive nature of balance training might challenge the sensorimotor system by requiring stabilisation on an unstable surface (Distefano et al., 2009), which could result in the enhancement of proprioception, post-WB training (Waddington and Adams, 2004).

Previous literature has demonstrated significant differences in static balance post-WB training or training with a movable surface in older adults (Balogun et al., 1992; Morioka et al., 2011; Salsabili et al., 2011; Song et al., 2011). Overall, these studies demonstrated that post-WB training achieved positive static balance performance results, therefore, indicating an improvement in at least one of the outcome measures relating to static balance. Furthermore, the collated results revealed conflicting evidence concerning the potential for WB training to improve static balance in older adults (Van Tulder et al., 2003). This was noted because static balance improvement was not evenly distributed across all static balance outcome measures. This is true in the current study conducted for this thesis because the perimeter, which measures the length of the centre of pressure (CoP) was improved after six week of WB training less than, the ellipse area which represents the best fit for 95% of the sway trace area across all tasks performed, which were in balance during DLSEOW, DLSECW, DLSEON, DLSECN and SLS, as illustrated in Figures 15, 16, 17, 18 and 19 and Table 19 in chapter five. This improvement was indicated by a percentage change score, which was calculated as the change between baseline and the end of the study, divided by the baseline value and multiplied by 100, as explained in chapter five. Calculated this way, the percentage change for the perimeter values during DLSEOW, DLSECW, DLSEON, DLSECN and SLS were -18.67%, -15.14%, -13.97%, -19.90% and -13.65%, respectively; these values were less than the percentage change values for the ellipse area during DLSEOW, DLSECW, DLSEON, DLSECN and SLS, which were -40.21%, -34.04%, -32.00%, -38.00% and -17.01%, respectively. Thus, we can see that the ellipse area improved more than the perimeter.

One explanation for the achievement of improved static balance performance, post-WB training, is that during WB training the centre of mass (CoM) is likely to move quickly, which requires rapid response to return it to the base of support, via a quick muscle response. Therefore, this quick movement of the WB caused a fast CoM movement to maintain balance, leading to significant improvements in lower-limb muscle strength because these muscles are being activated by this fast movement (Balogun et al., 1992). Lower limb muscle, particularly ankle plantar flexors/dorsiflexors and the invertors/evertors are required in static balance to counteract the body sway in multiple directions (Kisner and Colby, 2012). This body sway is similar to an inverted pendulum during a postural strategy called an ankle strategy (Winter, 1995b), as indicated in chapter two. This strategy, adopted during WB training to counteract the fast movement of CoM, results in significant (P-value ≤0.001) ankle muscle strength gains in the dorsiflexors, plantar flexors, invertors and evertors for both right (Rt) and left (Lt) sides, as illustrated in Figures 37, 38, 39 and 40 in chapter five. These gains are required for an individual with DPN, since they very often have a weakness in strength in the lower limb, that may lead to balance impairment and an increased risk of falling (Andreassen et al., 2006). Therefore, there is a need to strengthen these muscles, particularly ankle dorsiflexor and plantar flexor muscles, which control ankle torque and ankle strategy, as mentioned previously in chapters one and two, that are utilised via WB training, as shown by Ahmad et al (2020). Therefore, muscle strength improvements, post balance training, might be one of the reasons for static balance improvement in the elderly (Hu and Woollacott, 1994) and can provide an explanation for the significant improvement in static balance achieved in this present study. These gains in ankle muscle strength will be discussed further in section 6.3.1.3.

In addition to the improvements in the musculoskeletal system post unstable training, additional benefits may include improvements in the somatosensory system, such as the foot proprioception, muscle mechanoreceptors, joint receptors and structural adaptations in ligaments and tendons. (Mohammadian et al., 2019). This is in agreement with the findings of the neuropathy severity scores, post six-week progressive WB training in the study conducted for this present study, as indicated by the significant (P-value ≤ 0.001) improvements and by the reduction of theses scores, by 2 points in Figure 51 and Table 27 in chapter five, as assessed by the TCNS, which assesses subjective and objective information, such as sensations, including: vibration, touch and position perception, namely proprioception, as well as knee and ankle reflexes (Carmichael et al., 2021). This severity of neuropathic scores will be discussed further in section 6.3.1.5. This integration of the somatosensory systems accounts for approximately 70% for the ability to stand on a firm or stable surface for maintaining static balance (Mancini et al., 2020), as was pointed out in chapter two. Triggering the sensory information, since DPN affects the re-weighting of sensory information (Horak, 2006) and underpins balance control during training, resulting in static balance improvements in elderly patients (Hu and Woollacott, 1994).

There is, however, an argument that explains why the improvements in performance associated with WB training for short periods of time are likely related to more neuromuscular changes than muscle hypertrophy (Balogun et al., 1992; Schoenfeld, 2010). The more complex the intervention, the longer the time required to enhance this neural adaptation, (Rutherford and Jones, 1986), which may provide a reason why the WB training, conducted in the present study induced improvement in all ankle muscles. The more difficult the postural task, the more cognitive processing is required to maintain balance during quiet standing, especially with neurological impaired individuals, who have limited cognitive processing (Horak, 2006), such as the participants in the present study, when the tasks became more changeable such as SLS and double leg stance eyes closed. Although the training in the current study, is considered dynamic training, the improvement discussed here is with respect to the static balance training.

A further explanation for the achievement of an improvement in static balance performance, post-WB training, is that balance ability is an acquisition skill and not a necessarily a transferable one, according to a SR, which suggests that type of balance training is not specific to the responses gained with regard to gaining improvements in balance (Distefano et al., 2009). This is true as indicated by significant moderated (-0.428 to -0.531) correlation between initial balance performance and static balance improvements post-WB training in most static balance scores, as shown in Figures 20, 21, 22, 24, 28 and 29 in chapter five, indicating the poorer the balance during the initial performance (high positive value), the greater the improvements (or gains) in static balance (high negative value). Despite the fact that the type of training was dynamic (WB) there was a significant improvement (P-value ≤0.001) in static balance parameters, which are the perimeter and ellipse area, particularly if these parameters were assessed initially at baseline and indicated poor static balance.

A further consideration is that the balance mechanism modifies the whole-body angular momentum by segment rotation (Hof, 2007). This seems to be more obvious where there is a decreased base of support, such as in a tandem or single leg stance (SLS), utilised by the central nervous system (Tisserand et al., 2023). The decreased base of support tasks, such as tandem stance and SLS were assessed post-WB or ankle disc training and showed a significant improvement in static balance in adolescents, healthy high school pupils, soccer players and men with functional ankle instability in the studies of (Gauffin et al., 1988; Tropp and Askling, 1988; Hoffman and Payne, 1995; Emery et al., 2005), respectively. This is in agreement with the present study finding and provides an explanation for the static balance significant improvement (P-value<0.001) during SLS post-WB training programme, as depicted in Figure 19 in chapter five.

Therefore, in the study of Holmes and Hastings (2021), balance training was recommended to improve various measures of static and dynamic balance performance and muscle strength, leading to a reduced fall risk, especially in the elderly and more severe DPN cases, making it a more efficient and effective choice of treatment. Furthermore, it was proposed by Nardone et al., (2010), that combining supervised balance exercises and an instrumented oscillating powered platform produced a synergist effect, improving balance assessed by both subjective and objective balance assessment among neuropathic individuals, including individuals with DPN (Nardone et al., 2010). Additionally, from a clinical perspective, it is recommended for PWD and individuals with DPN to assess static balance clinically in conjunction with quantifiable devices, such as faceplate or posturography (Horak, 1987). Therefore, this study utilised the Prokin, acting as force plate (FP), as well as a WB, as mentioned in chapter five. Additionally, the study conducted for this thesis used a clinical scale to assess the severity of DPN, which is TCNS and the training programme was supervised by a senior physiotherapist who had over 10 years' clinical experience in the field, being the author of this thesis. Based on the author's previous experience, to assess the effect of detraining the WB training programme was paused for two weeks, with the participants then returning for the purpose of reassessment, as explained in chapter five; the findings for this wash-out period will be discussed in the following section.

The wash-out period was divided into two periods: (1) the balance score achieved at the end of the study (T3) was compared to that achieved following the wash-out period (T4); (2) the balance score from the beginning of the study (T0) was compared to that after the wash-out period (T4). There were significant (P-value ≤0.001) differences in static balance, as indicated by the percentage change scores. The static balance performance during the period between T4 to T0 showed improvement, whereas the between T4 to T3 showed deterioration. This was indicated by the direction of the percentage change scores in static balance performance during the wash-out period ranging between 20.11% to 93.87%, for the period T4-T3 and -50.24% to -15.92% for the period T4-T0 as shown in Table 20, in chapter five, this was accompanied by a significant (P-value ≤0.001) decline in muscle strength, ranging from -10.85% to -17.39%, as shown in Table 24, in chapter five. Confirming the previous suggestion that neural adaptation happens first and early, then muscle strength changes later and during and post-WB training. Comparison of this significant deterioration finding with those of other studies confirm that static balance performance, as measured by the duration of SLS, was slightly increased but this was not considered statistically significant (Kruse et al., 2010).

It is worth noting that there was a deterioration in static balance performance during the period between T4-T3. This is in agreement with a previous study that corrects the widely held belief about irreversibility of muscle weakness and joint limitations post prescribed exercise regimens for individuals with DPN (Sacco and Sartor, 2016).

In summary, the reported results and mechanisms of all of the above studies were in line with the present study results, where there were significant differences between pre and post-WB training in static balance for all parameters (perimeter and ellipse areas) post six-week progressive WB training in PWD and individuals with DPN in double leg stance conditions with both eyes open and closed, as well as with narrow and wide bases of support and SLS. Therefore, the training programme with the WB is considered successful in improving muscle strength, proprioception and the somatosensory system, which is required to improve static balance, despite being practised on a dynamic surface. No previous literature has shown that WB (unstable surface) training alone can enhance static balance parameters in PWD and individuals with DPN. Improved post-WB training was not only restricted to static balance; there may be other improvements, such as in WB performance, which will be discussed in the below section.

6.3.1.2 Wobble board (WB) performance

Unstable training, including WB and other movable surface training, has been demonstrated to improve dynamic balance (Allet et al., 2010; Salsabili et al., 2011; Song et al., 2011; Akbari et al., 2012; El-Wishy, 2012; Kutty and Majida, 2013; Eftekhar-Sadat et al., 2015; Chaitali, 2016; Alshimy et al., 2017; Elshinnawy et al., 2018; Ahmad et al., 2020; Ajitha and Roopalokesh, 2020; Iram et al., 2021; Jannu et al., 2017; Maruboyina et al., 2018) and is aligned with the diabetic study's results achieved in this thesis.

Whilst the above studies were not conducted on WB training only in PWD or DPN, such that a direct comparison with the literature is not possible, a study was performed to assess whether improvements in dynamic balance could be produced in PWD individuals with DPN by a progressive WB training programme. The literature, which assessed dynamic balance, either by clinical functional balance tests or dynamic posturography post multimodal training, incorporates WB training or other movable surface with the training and may provide additional insights to assist in the interpretation of the study findings.

Previous literature recommended the use of clinical functional balance tests, such as the BBS and TUG, for assessing the efficacy of this type of balance training (Mancini and Horak, 2010), as mentioned previously in chapters one and two. Examples of utilising these recommended clinical functional balance tests, is the TUG test, which produced decreased scores, the BBS scores, which were increased and the overall stability index in the experimental group, compared to non-significant differences in the control group (Eftekhar-Sadat et al., 2015). This previous study utilised both quantitative and functional balance assessments, which are beneficial in determining a balance problem (Horak, 1987), as mentioned previously in chapter one. Further examples of utilising functional balance tests are the use of BBS, functional reach test, TUG and a 10-meter walking time, which all were improved after eight-week of multimodal balance training, including an unstable surface, such as foam and trampoline, among DPN elderly individuals (Song et al., 2011). The same intervention, which was the multimodal balance training was conducted among elderly individuals with DPN and yielded similar results, in terms of dynamic balance improvements, as assessed by BBS and TUG, whereas no significant result was achieved in the control group who received education only (Iram et al., 2021).

However, these previous clinical balance tests have disadvantages, such as a lack of objectivity, validity, particularly for type II diabetic individuals and are unable to involve all aspects of the balance system (Dixon et al., 2017). Therefore, quantitative approaches were recommended to be utilised for identifying the causes of balance impairment by specifying which balance system is affected and aiming to treat it (Horak, 1987), as mentioned previously in chapter one. Thus, the study conducted in this thesis addresses these shortcomings, since it utilised a stabilometric assessment device (Prokin 252) with 0.1° sensitivity (Prosperini et al., 2013), as mentioned previously in chapter five, to assess WB performance, which resulted in significant improvements (P-value ≤ 0.001) in all WB performance parameters, which are the APSI, MLSI, percentage of time spent in inner and outer zones, as illustrated in Figures 30 and 31 in chapter five, rather than using the previous clinical functional balance tests. Thus, supporting the second hypothesis of the third study conducted in this thesis, as mentioned in chapter one, which proposed that WB training programme will result in WB performance improvement for both PWD and individuals with DPN.

Previous studies utilised various assessments and interventions used for the purpose of balance assessment and training (Jannu et al., 2017; Maruboyina et al., 2018; Ajitha and Roopalokesh, 2020). For example, Jannu et al. (2017) and Ajitha and Roopalokesh (2020) used a stability trainer in one group and WB in other group for an intervention period of eight weeks, to improve dynamic balance in individuals with DPN, as indicated by a clinically significant increase in BBS in both groups. BBS was selected because Mancini and Horak (2010) recommend using this scale due to it being considered a highly reliable clinical test to assess the efficacy of training. Another study utilised a stability disc in one group and a WB in another in individuals with DPN (Maruboyina et al., 2018). The stability disc differs from the WB, because it is cushion like and so does not have a stable base or ability to measure tilt degrees. Both groups showed improvements in BBS and TUG scores (Maruboyina et al., 2018), post-WB training, which might be explained by the supported and easy pattern of WB training as manifested by allowing participants to a hold a chair, if desired, during task performance with eyes closed (Jannu et al., 2017; Maruboyina et al., 2018). However, the nature of the training is different to the training programme provided for the PWD and individuals with DPN in this thesis, because the Prokin resembles a WB's function across a wide range of instability, including, 50 levels of instability, a range of tilt angles (maximum tilt angle of 15°) (ProKin 252, TecnoBody, 2021) and a progressive and tailored programme subject to each individual's baseline assessment, as described earlier in Tables 16 and 17 in chapter five. In contrast, no information was provided regarding the WB manufacturer or maximum tilt angle in either of the aforementioned studies. However, despite these differences, WB training was effective in these studies, improving BBS and TUG and proving to be more effective, when compared with a compliant surface (balance pad) training, where both were used for training three times per week for six weeks by individuals with DPN, as measured by TUG and 6-minute walk tests (Chaitali, 2016).

Therefore, the overwhelming literature demonstrates that WB training results in improvements in functional tests; yet the mechanism underpinning its success has yet to be clearly identified. Thus, this thesis assists in providing a consideration of possible explanations for a mechanism or mechanisms. One explanation might be due to balance being task specific, rather than a general ability, especially if this training is on unstable surface (Giboin et al., 2015); the authors demonstrating that balance training had an effect on the trained tasks only, even if the non-trained tasks were performed on the same balance device but with a different direction of perturbation, or with the same direction of perturbation but on a different balance device in healthy adults (Giboin et al., 2015). Additionally, Kümmel et al. (2016) confirmed that healthy adults can improve their balance performance in a trained task with no discernible effect on a non-trained task, recommending that physiotherapists include a task that requires training in the balance assessment or clinical functional test in healthy adults. This is in agreement with the author's current study, which confirmed that, even in an unhealthy population such as PWD and individuals with DPN, the significant (P-value ≤0.001) improvement with large ES (≥ 0.8 or ≤ -0.8), in WB performance as indicated by gradual improvement in the stability indices and the percentage of time spent in inner and outer zones, as depicted in Figures 30 and 31 and Table 21 in chapter five, throughout the intervention period. This intervention was an individually tailored WB programme according to baseline assessments. Tasks in the baseline assessment, which are fifteen sequential levels of WB difficulty balance challenge, as explained in Table 16 in chapter five, might provide an opportunity to train a particular task. WB performance, as defined by level of success, was tracked for each participant's performance to failure, as demonstrated in Table 17 in chapter five, which provided an example of prescribed WB exercises, based on the level of failure during the assessment. This tracking revealed a progression of WB performance levels, which manifested in means of 1.76, 2.08 and 2.38 levels of improvement every two weeks for the six-week training period, as illustrated in Table 23 in chapter five. This level of improvement was explained by the example of WB prescribed exercises in Table 17 in chapter five. This result indicates that as WB training progresses, the balance performance on the WB improves, with a 95% confidence interval corridor illustrating the expected improvement across the training period and after cessation, as shown in Figure 36 in chapter five. This explains why, when a follow-up assessment was performed, most of the participants showed progression to the next level. This result supports the third hypothesis of the third study conducted in this thesis, as mentioned in chapter one, which was that the six-week progressive, WB training involving PWD and individuals with DPN will result in WB performance progression, relative to each participant's initial level of success.

A further explanation, for post-WB training improvement might be due to the neural adaptation that occurs during the short period of the intervention (Balogun et al., 1992; Schoenfeld, 2010). This neural adaptation is suggested to occur post-WB training exposure at subcortical areas, such as cerebellum (Silva et al., 2016; Mancini et al., 2020). This has been shown to be due to reduced cerebellar brain inhibition (CBI), during the initial stage of motor learning, where sensory prediction errors are largest (Spampinato and Celnik, 2021). The mechanism behind this is called the error-based learning process and may explain why the participants may learn from their errors, as they adapt to the task and how they can update their motor command to balance at an advanced level of WB performance. This mechanism explains the highly negative significant correlation (-0.923 to -1), between initial WB performance and WB improvement, as depicted by Figures 32, 33, 34 and 35 in chapter five, indicating the poorer the WB performance during the initial performance (high positive value). The greater the improvements (or gains) in WB performance (high negative value) during DLSEOW 5° in all WB performance parameters, which are AP axis, ML axis and percentages of time spent in outer zone, with the exception of percentage of time spent in inner zone. Regarding the percentage of time spent in the inner zone, the poorer the WB performance during the initial performance (low positive value), the greater the improvements (or gains) in WB performance (high positive value), as shown in Figure 34 in chapter five. The poorer WB performance during the initial performance indicates errors but after six weeks in the programme, these were corrected, as indicated by gains in WB performance.

Additionally, it may be that balancing on an unstable surface triggers brain activity in the supplementary motor area (Thomas et al., 2019), as the greater the complexity of the postural task, the greater the engagement with cognitive processing (Horak, 2006). These higher cognitive engagements occur in the basal ganglia and cerebellum (Mancini et al., 2020), as discussed previously in chapters one and two. The reward-based learning is a motor learning process, whereby individuals learn how to differentiate between successful and unsuccessful results from previous experience (Spampinato and Celnik, 2021). This mechanism appeared to be applied by the participants in the current study, as they avoided the unsuccessful WB performance, as assessed bi-weekly, resulting in significant improvements during each period of assessment (P-value≤0.001) for APSI and MLSI (as well as percentages of time spent in inner and outer zones) and then progressing to the next level of difficulty, in accordance with the progressive pattern of WB training. This indicated gradual and consistent improvements in WB performance during DLSEOW 5°, as was also mirrored in the magnitude of the ES (≥ 0.8 or ≤ -0.8) in both APSI and MLSI (see Table 21).

However, the present study, conducted for this thesis, showed significant (P-value ≤0.001) deterioration, which was seen in WB performance during the wash out period, as indicated by increased values of APSI, MLSI, percentages of time spent in outer zone between T4 to T3, ranging from 6.83% - 102.07%, decreased in time spent in inner zones between T4-T3 (-87.52 – -0.50%), as illustrated in Table 22 in chapter five, was accompanied by a decline in muscle strength, ranging from -10.85% to -17.39%, as shown in Table 24, in chapter five suggesting that neural adaptation happens first, as indicated by the higher percentage change for the severity of neuropathy scores more than percentage change for muscle strength score post-WB training at T1, T2 and T3, as illustrated in Figures 37, 38, 39 and 40 in chapter five and appendix 12. This result corroborates the findings of a great deal of the previous work in PWD and individuals with DPN individuals (Allet et al., 2010). Despite the different training programmes provided in Allet et al. (2010) and various dynamic balance tests, which were assessed by a Biodex system, as indicated by non-significant values of stability index, those authors confirmed that the dynamic balance deteriorated during the wash out period, which was 6 months.

Despite this deterioration, there was significant improvement post-WB training, which may be due to the adoption of an ankle strategy, which is one of the postural strategies. As mentioned previously in chapters one and two, which is known to be utilised during exposure to balance perturbations, such as WB training, indicated by early dorsal ankle muscles activation, followed by activation of dorsal thigh and trunk muscles (Horak and Nashner, 1986). This is in agreement with the findings achieved in the study conducted in this thesis, which demonstrated significant ankle muscle strength gains. This finding will be explored in further detail in section 6.3.1.3. As discussed above, in individuals with DPN, ankle muscles are weak and known to be affected first, which consequently may lead to balance impairment and an increased risk of falling (Andreassen et al., 2006). Additionally, the ankle strategy is reduced by aging (Horak et al., 1989) and the peripheral neuropathy may be present in PWD (Giacomini et al., 1996), due to similar symptoms associated with both the elderly and DPN, such as deconditioning, muscle weakness, reduced proprioception and decreased joint mobility (Kutty and Majida, 2013). This, consequently, resulted in elderly and DPN patients shifting from an ankle to a hip-based strategy (Inglin and Woollacott, 1988; Jyoti, 2016). Thus, strengthening these ankle muscles, particularly ankle dorsiflexor and plantar flexor muscles, via WB training is essential for utilising successfully the ankle strategy, as indicated by Ahmad et al (2020) study.

A final consideration is that long muscle latency, which is a component of activation post perturbation (Mancini et al., 2020), for example, if a task in the training becomes more complex, it might consume a longer time to trigger a neural adaptation and this might explain a training induced improvement in agonist, antagonist, stabiliser and synergistic coordination, rather than muscle activation only (Rutherford and Jones, 1986). However, four-week of WB training was able to reduce the onset of latency in individuals with a functionally unstable ankle (Clark and Burden 2005). Therefore, to clinically impact this present WB training study, this knowledge might be transferable to PWD and individuals with DPN, who are known to have longer latencies (Di Nardo et al., 1999), as well as in the elderly population (Kanekar and Aruin, 2014). These latencies are induced by inputs from muscle proprioception, as well as by the entire loop, including the spinal cord, brain stem and cortical pathways (Mirka and Black, 1990). Proprioception was improved in this present study conducted in this thesis, as indicated by a reduced score (2.62), because the pre WB training mean score was 8.86 and post-WB training mean score was 6.24, as assessed by (TCNS), which assesses the sensation, such as vibration, touch and position perception, namely proprioception (Carmichael et al., 2021), as shown in Table 27 in chapter five. The severity of neuropathy, higher neuropathic scores, will be explored in further detail in section 6.3.1.5. Thus, improvements in proprioception, might infer that the latency is improved in these individuals.

There is however an absence of literature supporting the use of a dynamic stabilometric assessment device (Prokin 252) with PWD and individuals with DPN. Therefore, supporting literature regarding the dynamic balance parameter, such as the APSI and MLSI, will be discussed in the below paragraph, reviewing studies conducted on a dynamic posturography (Biodex system), that includes static and movable boards with adjustable levels of instability, used for both balance assessment and training, though it does not operate as freely as the dynamic stabilometre (Prokin 252). APSI is assessed by the Biodex system measuring the platform displacement in the sagittal plane, whereas the displacement in the frontal plane is assessed by MLSI (Elshinnawy et al., 2018).

There were contradictory findings regarding the improvements in the Biodex system parameters, which are in the APSI and MLSI. Two studies showed greater improvement in the MLSI more than the APSI, following a task-oriented programme for individuals with DPN (Alshimy et al., 2017; Elshinnawy et al., 2018). However, APSI shows improvement but non-significant MLSI improvements in two studies (Akbari et al., 2012; Eftekhar-Sadat et al., 2015). In contrast, improvements for both the APSI and MLSI axes in two other studies (Salsabili et al., 2011; El-Wishy, 2012). This is similar to the present diabetic study, where the APSI and MLSI were both improved during the double leg stance eyes open (DLSEO) task after six weeks of progressive WB training programmes but more improvement was observed in MLSI than APSI, as shown in Figure 30 in chapter five. This was indicated in the pre- and post-WB training mean values for APSI and MLSI, such as the pre-WB training APSI and MLSI mean values of 1.38° and 1.77°, respectively, compared to the post-WB training APSI and MLSI mean values of 0.40° and 0.39°, respectively. These greater improvements, specifically in the APSI, compared to the MLSI observed in the diabetic study conducted in this thesis, can be justified due to many reasons, including a strategy suggested by Nashner and McCollum (1985), in which the nervous system controls the horizontal CoM position in the sagittal plane. Thus, leading to rotational movement around the ankle axes, which generates the angular velocity required to control ankle torque, indicating an inverted pendulum (Smith, 1957). This means that the whole body moves as a single-segment inverted pendulum, which requires ankle strategy repositioning of the CoM through exerting torques at the ankle (Nashner and McCollum, 1985) and this strategy is required to control slow and small CoM movements at low velocity (Cook and Woollacott, 2016). Therefore, it is assumed that APSI is more related to the activation of ankle muscles. These muscles are expected to be more affected by DPN than the proximal muscles

(Akbari et al., 2006), whereas the hip abductor and adductor muscles control the MLSI and are less affected in individuals with DPN (Nashner and McCollum, 1985).

However, the opposite of this strategy is whole-body movement in the form of a double-segment pendulum, necessitating use of the hips, producing counter-phase motion at both the hip and ankle (Cook and Woollacott, 2016). The same authors further suggested that the hip strategy is utilised with an unstable or compliant surface where it is difficult to produce ankle torque (Nashner and McCollum, 1985), where the large movement of CoM is required at higher velocities to be controlled by this strategy (Cook and Woollacott, 2016), such as the unstable surface and foam included in multi-modal training to enhance ankle strategy, especially in elderly individuals with DPN (Song et al., 2011). However, a recent SR and meta-analysis conducted by De Oliveira Lima et al. (2021) highlighted that in Song et al.'s. (2011) study, the magnitude of change in balance was, on the whole, small and of questionable clinical significance, providing low-certainty evidence.

Additional scrutiny of the finding in this literature was observed in the improvement of APSI and MLSI during double leg stance eyes open (DLSEO) task more than double leg stance eyes closed (DLSEC) task. This is similar to the diabetic neuropathy study conducted by Akbari et al. (2012) that provides evidence for insufficient improvement of the MLSI and overall stability index post-WB training and Biodex system training during DLSEC. This difference could be explained by the visual contribution. Potentially, the DLSEC condition may have resulted in a re-evaluation of the weighting of the input parameters to the biofeedback loop (Benjuya et al., 2004). With vision present, reliance on plantar pressure feedback is unnecessary, due to the dominance of the visual contribution. Without vision (DLSEC condition), it is possible that attention to the input from the plantar foot pressure increased, resulting in the difference between APIS and MLSI improvement, although individuals with DPN had reported elevated plantar foot pressure, which might have appeared after 5 years of DM, even if there are no biomechanical factors involved (Falzon et al., 2017). Therefore, that the APSI improved more than the MLSI may be due to eyes closed tasks that require elevated plantar pressure, as well as mentioned previously that CoM movement in APSI, which is controlled by the ankle strategy, which is in turn responsible for controlling the slow movement of CoM at low velocity (Cook and Woollacott, 2016). An additional explanation for the APSI improving more than MLSI relates to the participant’s age, because participants were elderly with DPN (Eftekhar-Sadat et al., 2015). Elderly people with DPN swayed with eyes open in a manner equal to the age-matched population, who performed the same task but without vision (Boucher et al., 1995; Lafond et al., 2004). Additionally, age was negatively correlated with dynamic balance, indicating that the older the participant, the less stable they were on the rubber foam surface with both eyes open and eyes closed (Di Nardo et al., 1999). Use of vision is prioritised in the elderly to control balance, because they depend on exteroceptive information (Hatzitaki et al., 2009). An example of this is the information from the vestibular system or proprioception, which explains an increased postural sway during closed eye tasks among individuals with DPN (Boucher et al., 1995). This is obvious, as the neuropathy severity scores were correlated with the overall stability index and APSI in these individuals (Aly et al., 2007) and this might provide further explanation for the significant (P-value ≤ 0.001) improvement in APSI (percentage change = -37.96%) compared to MLSI (percentage change = -50.36%) in the present study conducted in this thesis, as shown in Figure 30 in chapter five and Table 21. This is the case as indicated by the significant correlation (r=-0.382) between TCNS scores and WB performance parameter, which are the percentage of time spent in inner and outer zones, during DLSEON 5°, as shown in Table 42, in chapter five, this will be discussed in further detail in section 6.3.1.5.

A final possible explanation for WB balance performance improvement, especially during DLSEC, might be the nature of the training programme, which required the administration of progressive balance training at a challenging level, based on an initial balance assessment, that can lead to an enhanced somatosensory integration with visual and vestibular senses (Jyoti, 2016). In turn, this system is allowed to change its coordination, to organise itself during certain tasks by responding to environmental cues, that lead to progress to higher levels of challenge, resulting in improvements in the targeted movement, this theory is called the dynamic systems theory (McKeon, 2009), as discussed above. Example of previous studies that have demonstrated that application of dynamic systems theory in the form of a progressive training programme to individuals with DPN, result in improvements in the dynamic balance, which was assessed using the mini-board, known as the

‘Pedalo ® -Sensamove balance test Pro’, whereby the participants were required to tilt the board to its maximum tilt angle in four directions, namely front, back, Rt and Lt (Ahmad et al., 2020). Other studies have employed similar styles of progressive training programmes to individuals with DPN, with favourable results in dynamic balance tests, which were assessed by the Biodex system (Allet et al., 2010). Thus, a progressive training programme is a successful method of balance training that can be utilised in prescribing WB training in clinical practice, due to the underpinning dynamic system theory, that can improve the WB performance and might lead to a reduced risk of falling in PWD and individual with DPN. This programme was based on recommendation provided by the ADA, that balance training be performed two-three times per week for PWD, especially if they are elderly and each exercise tailored to achieve the specific needs of the individual (Colberg et al., 2016; Harrington and Henson, 2021). Therefore, the study conducted in this thesis has taken into consideration the ADA’s recommendation and tailored WB training according to baseline assessments of WB performance, which was conducted on a bi-weekly basis. Therefore, applying similar programmes in other populations who are at risk of falling and using other dynamic balance tests that specifically assess specifically fall risk is recommended for future studies.

In conclusion, the present diabetic study, reported in this thesis, demonstrated that six- week of progressive WB training alone is able to improve WB performance, as indicated by reduced mean values of APSI, MSI, percentages of time spent in outer zones and increased time percentage of time spent in inner zones in PWD and individuals with DPN. It investigates the possible mechanisms underpinning this improvement, such as neural adaptation, ankle strategy utilisation, task specificity, muscle latency reduction and dynamic systems theory. No previous study has used solely WB training in PWD and individuals with DPN, in combination with a determined baseline, tailored, progressive training programme and bi-weekly performance assessments. These findings can help guide clinicians in prescribing a successful and accurate WB training programme, aimed at improving WB performance for PWD and individuals with DPN, with caution about the detraining effect, which was accompanied with decline in muscle strength. Thus, muscle strength is an important factor that can be improved during and post-WB training, which will be explained in the below section.

6.3.1.3 Muscle strength

Lower limb weakness in individuals with DPN might cause balance impairment and increased risks of falling (Andreassen et al., 2006). This may be explained by reference to the concept that was discussed previously in chapter two, about normal recovery from perturbations requiring a rapid production of sufficient muscle forces to maintain an individuals' CoM within its BoS, specifically the ankle muscles (Hewston and Deshpande, 2016). Thus, improving the tibialis anterior muscle strength is important, since this muscle is highly correlated with trip and fall risk, due to compromised dorsiflexion and may be particularly affected in individuals with DPN (Morrison et al., 2010; Morrison et al., 2012). A risk of a rapid involuntary foot drop is reported in the literature, resulting in a reduced shock absorption of the foot during the initial phase of gait (heel strike) (Kutty and Majida, 2013), as explained in chapter two. Tibialis anterior strength may, in elderly individuals with DPN, mitigate the risks of falling, an investigation was conducted to assess the viability of balance training in improving strength and balance performance among this population (Morrison et al., 2010). This programme resulted, not only in ankle muscle strength gains but also improved balance, proprioception and reaction time, which led to a reduced risk of falls in older individuals with type II DM, regardless of whether they had neuropathy (Morrison et al., 2010). Therefore, it is recommended to perform balance training two to three times per week, which can improve muscular strength in the elderly, with higher intensities of training producing greater gains (Foster and Armstrong, 2018). Examples of this recommended balance training is the performance of dynamic activities from a standing position that are highly challenging (Foster and Armstrong, 2018), such as WB training. The findings with the present study confirm that WB can result in ankle strength gains. These were observed in the dorsiflexors, plantar flexors, invertors and evertors for the Rt and Lt sides (See Figures 37, 38, 39 and 40). These corroborate those of Waddington and Adam's study (2004), whose findings in older adults, also demonstrated significant gains in ankle muscle strength.

Thus, the present diabetic study was conducted to investigate the effect of WB training solely on muscle strength by conducting non-weight bearing, including dorsiflexors, plantar flexors, evertors and invertors muscle groups measurements, utilising a digital handheld dynamometer (MicroFET ®2, Hoggan health industries, Draper, USA), as mentioned earlier. However, the reliability and accuracy of this dynamometer may be limited by the investigator’s ability to hold it stationary and by the fact that participants may overpower the testers. The investigators tried to minimise this problem by ensuring that the same person always carried out the tests (Allet et al., 2010). The current study yielded significant (P-value ≤0.001) improvements in ankle muscle strength, as indicated by percentage of change, ranging between 14.10% - 10.63 % in dorsiflexors, plantar flexors, invertors and evertors for both Rt and Lt sides, as shown in Figures 37, 38, 39 and 40 in chapter five. Additionally, muscle strength mean values, pre-WB training, were 193.81 N, 195.47 N, 218.61N, 219.82 N, 176.25 N, 181.08 N, 176.74 N and 181.26 N for the Rt and Lt sides of the dorsiflexors, plantar flexors, invertors and evertors, respectively. The same muscles demonstrated strength gains post-WB training, as indicated by the muscle strength mean values, which were 246.84 N, 255.41 N, 290.18 N, 287.29 N, 234.35 N, 246.70 N, 233.85 N, and 236.55 N for the Rt and Lt sides of the dorsiflexors, plantar flexors, invertors, and evertors, respectively. Therefore, six-week of progressive WB training in PWD and individuals with DPN led to significant (P-value ≤0.001) strength gains in all ankle muscles (dorsiflexors, plantar flexors, invertors, and evertors) on both Rt and Lt sides, as shown in Figures 37, 38, 39 and 40, earlier in chapter five. Additionally, these significant (P-value≤0.001) improvements were tracked during each assessment period, T1, T2 and T3, indicating gradual and consistent gains in the strength of all ankle muscles, which was also mirrored in the magnitude of the ES ≥0.8 or ≤ -0.8 as shown in Appendix 12. Thus, supporting the fourth hypothesis, proposed in this thesis, as mentioned in chapter one, that a WB training programme can result in ankle muscle strength gains for both PWD and individuals with DPN. These results appear to be consistent with other research, which found that balance training conducted among PWD and individuals with DPN were able to enhance muscle strength (Allet et al., 2010; Song et al., 2011; Morrison et al., 2012; Ahmad et al., 2020). Despite this unified finding, the studies vary with regard to the type of balance exercise and whether they incorporate strength and balance exercises, or only balance training.

There are several possible explanations for this observation. One might be due to the utilisation of a progressive balance training with WB and gait training programmes, which were effective in improving strength of hip, knee and ankle muscles (Allet et al., 2010; Ahmad et al., 2020). However, the nature of the progression, regarding balance training differed, for example, changing from stable to unstable surfaces (WB) was one of the progressions in Allet et al (2010), whereas, in Ahmad et al.'s (2020) study, participants initially trained with a WB in a bidirectional pattern, then a multidirectional pattern was used, progressing from DLS task to SLS task. The nature of conducting this training with the WB was progressive, based on dynamic systems theory (McKeon, 2009), as mentioned previously in the static balance and WB performance sections of this chapter. This theory suggests that the sensorimotor system, which plays a vital role in maintaining balance, alters coordination to self-organise, in response to environmental constraints, progressing to create greater demands at a higher difficulty level, leading to a more significant improvement in achieving the movement goal (Mancini et al., 2020). This is true, that achieving significant improvement in balance, demonstrated by gaining ankle muscles strength, due to changing the sensorimotor coordination to achieve the movement goal, which is in the present study progressed to a higher level of WB balance performance, that required more ankle muscle strength.

An additional explanation for gaining ankle muscle strength is the utilisation of the ankle strategy for maintaining balance and control of quick CoM movements, which put greater demands on the balance systems and require a quicker and stronger muscle response to maintain balance (Hewston and Deshpande, 2016). The ankle strategy is a postural strategy that results in primary activation of the ankle muscles, then sequentially, the thigh and trunk muscles (Horak and Nashner, 1986). This late activation of trunk and hip muscles might be due to not being initially affected by DPN and the highly affected sensations are the light touch and pressure, which are more affected than proprioceptive information from muscles spindles or golgi tendon organ receptors (Horak et al., 2002). Therefore, the participants in the diabetic study conducted in this thesis may utilised the ankle strategy to gain balance, as demonstrated by higher scores of ankle muscle strength gained after six-week of WB training, which were notably initially weak at baseline assessment. The improvement in ankle muscle strength (which was calculated as ankle muscle strength scores at T3–T0) were observed by the statistically significant correlation (P-value≤0.001), to the T0 baseline, as shown by Figures 41, 42, 43, 44, 45, 46, 47 and 48 in chapter five. These findings indicate that the weaker the ankle muscles during the initial muscle strength measurements (low positive value), the greater the relative improvements in strength (high positive value) measured in the ankle muscles. The degree of this correlation was very highly positive (0.706 - 0.860), with the exception of the Lt dorsiflexor, which was moderately positive (0.623), as shown in previous figures in chapter five.

A final explanation might be neuromuscular adaptations producing strength gains as a result of training on unstable surfaces (Behm et al., 2002). However, these might not be immediately activated by complex interventions and may require a longer time, thus, an additional mechanism that explains the greater muscular strength during training is the enhanced coordination between agonist, antagonist, synergist and stabilisers (Rutherford and Jones, 1986; Anderson and Behm, 2005). The more unstable the surface, the greater the required muscle activity, especially from lower limb musculature than the upper limb musculature (Wolburg et al., 2016). This is evident in Ahmad et al.'s 2020 study, which showed increased activation of leg muscles in individuals with DPN post balance training, that included WB training. This is likely to enhance the reactive balance response, to an unexpected balance disturbance, which is reduced in elderly PWD (Lee et al., 2018a). That is true in the present study conducted in this thesis, where individuals with DPN increased ankle muscles strength, as the WB became more challenge throughout the intervention period.

An alternative explanation for this improvement might be the effect of WB training on the ankle motor control process that occurs below the level of conscious attention (Waddington and Adams, 2004). Unstable training might enhance the somatosensory system, which is responsible for achieving balance through the activation of the mechanoreceptors, proprioceptors, joints, ligaments and tendons (Mohammadian et al., 2019). This somatosensory information is diminished in individuals with DPN but training with a WB might enhance it (Horak et al., 2002). However, the present study conducted in this thesis enhanced neuropathic scores, which included examination of sensation and proprioception as examined by TCNS, as demonstrated by significant improvements in the scores of this scale, further details will be provided in section 6.3.1.5.

Additionally, muscle co-contraction between the soleus and tibialis anterior muscles can be achieved, though not after only one balance training session but ten training sessions to increase the duration of this co-contraction in an elderly population (Alizadehsaravi et al., 2022). This increased duration of antagonistic muscles co-contraction, which has been investigated and shown to result in facilitating joint stiffness and enhancing quick corrective responses to unexpected disturbances, such as slips in challenging tasks, leading to the prevention of falls in the elderly (Chambers and Cham, 2007). This mechanism of muscle co-contraction indicated by a low soleus/tibialis anterior EMG ratio is utilised by elderly individuals when the size of their BoS becomes challenged during standing, indicating that healthy elderly individuals do not rely solely on greater sensory information (cutaneous and proprioceptive) that arises during increased sway to replace other sensory inputs but rather maintain their balance by adopting this mechanism (Benjuya et al., 2004). This was not assessed in the present study presented. However, it can be considered in future studies, assuming that the individuals with DPN, who may have sensory deficit, might not rely on the sensory information during an increased WB challenge but may adopt co-contraction in the ankle muscles. Evidence from EMG to examine the soleus/tibialis anterior ratio is required to prove this assumption in the future. Therefore, muscle activity might be assessed by EMG to confirm the assumption of improvement due to muscle co-contraction, which may lead to an enhanced reactive balance response. Additionally, future studies might be conducted in other populations who are at risk of falling, such as the elderly or individuals with neurological conditions, for example stroke or multiple sclerosis, or balance impairment and examine the effect of this training programmes on those individuals. However, safety should be ensured by the addition of a harness and a therapist or assistant standing beside the participants in case of a loss of balance.

Furthermore, there was physiological benefit to soleus muscle exercise, beyond improving balance and gaining strength, since this muscle represents a powerful way to raise the local oxidative metabolism to higher levels for a prolonged period of time without fatigue post-soleus push-up exercises (SPU) after 3 days (Hamilton et al., 2022). The position of this exercise was from standing and the movements were not only plantar flexions but also whole lower-limb muscles activation to gain balance. The period of programme engagement for the present study in this thesis was longer than Hamiton's study, running for six weeks of WB training and was able to strengthen the Rt plantar flexors (soleus and gastrocnemius) up to 11.70%. This percentage change score was yielded by dividing the mean change for the Rt plantar flexors, which was 30.39 N divided by the baseline mean value, which was 259.79 N multiplied by 100. Investigating the physiological benefits of this programme fell beyond the main aim of this thesis. However, it may be considered as a future study, to take into consideration the physiological benefits of WB training for these individuals, such as examining the physiological status pre- and post-WB training. An additional point that should be taken into consideration is the period of detraining, which will be discussed in the below section.

The wash-out period results in this present study showed a significant (P-value ≤0.001), reduction in muscle strength for all ankle muscles, ranging between -10.85% to -17.39%, two weeks after pausing the WB training, corresponding to the period between T3 and T4, in PWD and individuals with DPN. This was indicated by the mean change values during the period T4–T3, which were -26.88 N, -24.93 N, -29.09 N, -33.35 N, -26.81 N, -37.10 N, -29.36 N and -28.04 N for the Rt and Lt sides of the dorsiflexors, plantar flexors, invertors and evertors, respectively (see Table 24). However, a comparison to the baseline showed a significant overall improvement in muscle strength retained at T4, ranging between 13.31% and 19.25% (see Table 24 in chapter five). This was indicated by the mean change values during the period T4–T0, which were 25.88 N, 35.08 N, 42.09 N, 33.41 N, 31.16 N, 32.79 N, 27.16 N and 26.49 N for the Rt and Lt sides of the dorsiflexors, plantar flexors, invertors and evertors, respectively. In comparison to the previous literature, ankle plantar flexors did not show any significant differences in muscle strength after 6 months of cessation of the intervention (Allet et al., 2010). A limitation of this study is that did not provide long-term follow up, which might provide guidance as to how to create a standard for WB training, how to maintain improvement and how to prevent decline. Therefore, future studies should extend the period of follow up and monitor when decline appears or when a ceiling effect is seen, since this study did not find any ceiling effect.

In conclusion, the diabetic study has proved that six-week of WB training, alone, is able to strengthen ankle muscles in PWD and individuals with DPN. There are suggested mechanisms behind these gains, such as progressive pattern of training, ankle strategy adoption, neural adaptation, muscle coordination and physiological benefits. The novelty of this study lies in the fact that no previous study has used solely WB training in PWD and individuals with DPN, as well as the progressive nature of the training and the use of initial balance assessment. The findings can help guide clinicians on how to improve muscle strength, reduce the risk of foot drop and enhance balance in individuals with DPN. Thereby reducing the incidence of falling and the sedentary time. In turn, this promotes activity whilst decreasing the risk of falling. This might require individuals to be confident, thus, balance confidence might play a role in WB performance; this will be discussed in the below section

6.3.1.4 Balance confidence

Performance of certain tasks within some dynamic clinical balance tests, such as BBS and TUG were reported to be affected by a fear of falling among the elderly (Kumar et al., 2008; McAuley et al., 1997). Consequently, those of the elderly population who have a greater fear of falling, frequently accomplishing activities more slowly, possibly as a safety measure to enhance their security and lower their risk of falling. Eventually, fear of falling, may affect balance confidence and result in activity avoidance during feared or more challenging activities (Hewston and Deshpande, 2018), which may alter gait, as appeared clearly in clinical balance tests, that evaluates those two consequences, such as BBS and TUG (Kumar et al., 2008). Similarly, WB training, that requires quick movement of an individual's CoM might challenge the postural control system to provide a quicker and stronger muscle response to maintaining balance (Hewston and Deshpande, 2016). Thus, a fear of falling might lead to lower confidence, which may affect the efficient implementation of WB training. Hence, based on the first study conducted in this thesis (see Chapter three), it was recommended to take this factor into account when prescribing a WB intervention. Therefore, the author assessed balance confidence using the Activities Specific Balance Confidence (ABC) scale, whereby participants indicated their level of confidence in doing sixteen activities without losing their balance, using a scale from 0% (no confidence) to 100% (completely confident) (Richardson et al., 2001). Higher scores indicate greater balance confidence in ADL and decreased fall risk. This scale was chosen because of the significant association between a high ABC scale score (greater than 80) and a lower fall risk (Mak and Pang, 2009). Additionally, ABC scores are indicative of the level of confidence; for example, an ABC score above 50 and lower than 80 indicates a moderate level of balance confidence, characteristic of the elderly population and individuals with chronic health conditions, while ABC scores above 80 are indicative of high balance confidence levels in the physically active elderly population (Myers et al., 1998), as described in chapter five.

The author hypothesised in the third study (fifth hypothesis) in chapter one, that six-week of progressive balance WB training would result in significant improvements in balance confidence scores. This hypothesis was confirmed, as indicated by significant (P-value ≤ 0.001) improvements in scores of ABC scale post this intervention with large ESs = 1.94, as shown in Figure 49 and Table 25 in chapter five. The current study baseline mean value was 75.41%, which fell in the range between >50 and <80 that suggests a moderate level of balance confidence. Similarly, previous literature, considered an ABC value of 71.42% as indicative of a moderate level of physical functioning in older adults with DPN (Alshahrani et al., 2016).

Previous literatures are in line with these findings as there were three studies that reported a significant improvement in ABC scores, although two other studies failed to find any significant improvement in ABC scores (Richardson et al., 2001; Schilling et al., 2009; Dougherty et al., 2011; Londhe and Ferzandi, 2012; Sartor et al., 2014). The interventions vary between these studies but all of them provided balance training. Interpretation of the results of these findings should be treated with caution, since no WB training was conducted in any study that recruited individuals with DPN. The present study achieved a significant improvement in ABC post-WB intervention. This represents a novel finding as no previous studies have measured confidence post WB training. This improvement is in line with the previous literature that achieved a higher magnitude of improvements in ABC scale scores, by 13.00% and 20.45% points were reported post eight-week balance training alone and combining resistance with balance training, respectively, among individuals with DPN but without utilising a WB training in any group (Londhe and Ferzandi, 2012). However, the ABC scale scores in previous studies are based on the MCID of 15 (Wang et al., 2018). This is similar to the present study results, despite the intervention differences, because in Schilling et al.'s (2009) study, the participants were elderly (60–68 years old) and performed balance exercises on VersaDisc and CorDisc devices, three times per week for five weeks. The instability, regulated by air volume (pressure) within these devices, was constant for the five-week intervention, so that the support surface was the same for all training sessions without progression (Schilling et al., 2009). However, in the present study, participants were mostly middle aged, though a few were elderly, with diabetes and different diabetic neuropathy scores; they performed WB training three times per week for six weeks with a progressive increase in WB level of inclination instability, based on assessed balance performance. An 11.13% increase in ABC questionnaire score was reported after six-week of progressive WB training (the pre-intervention ABC mean was 75.41% and the post-intervention ABC mean was 86.54%) but a 5.75% reduction in ABC scores resulted, after a two-weeks cessation of WB training, as shown in Tables 25 and 26. This suggests a beneficial effect of the progressive WB training programme for PWD and individuals with DPN in increasing balance confidence after a six-week progressive WB training programme. Additionally, in this study, 13 out of 36 participants initially scored <67%, indicating increased fall risk; however, after the intervention, only one participant scored <67%. Thus, indicating that this intervention indirectly decreased the risk of falling by increasing balance confidence scores.

However, one study failed to find any significant differences in ABC scale scores following three weeks of strengthening and balance intervention in DPN (Richardson et al., 2001). There might be a consideration that no WB training was included in the intervention. Additionally, this study had several limitations, such as the small sample size, lack of randomisation and matched-control participants (Ites et al., 2011). Failure to blind participants and personnel might cause performance bias, which appeared in another study conducted to identify significant differences in ABC scale scores following 12 weeks of strengthening and balance training. However, improvements in ABC Scale scores, were reported as an increase of 2.4% after 12 weeks of exercise intervention and 6.0% after 24 weeks of follow up (Sartor et al., 2014; De Oliveira Lima et al., 2021). Although the P-value might be non-significant, the results may be considered clinically significant (Sharma, 2021), especially as

Sartor et al. (2014) gained a score of 10 on the Pedro scale, when assessing the methodological quality of this study, indicating a high methodological quality (Matos et al., 2018). The Pedro scale is a reliable 11-item scale to rate the methodological quality of RCTs (Maher et al., 2003). Similar to the current study's result, improvement in balance confidence scores for DPN was observed post 60 mins of yoga intervention for eight weeks, twice per week; scores improved from 68.96 ± 18.41 at baseline to 76.10 ± 17.38 at eight weeks (Willis Boslego et al., 2017), though this was still below the MDC, which was 15 points for ABC scores (Wang et al., 2018). However, a significant (P-value ≤0.001) reduction in balance confidence between T3 and T4, demonstrating a 'detraining' or wash out effect (-5.75%) but the overall improvement in balance confidence retained at T4 was found to be significant in comparison to the baseline (7.99%) in the current study (see Table 26 in chapter five). This indicates that six-week of progressive WB training was able to successfully enhance the participants' balance confidence, however, two weeks of detraining was able to result in a loss of this gained balance confidence.

Therefore, WB training can offer an intervention which increases balance confidence in PWD and individuals with DPN, especially those who scored low at the baseline assessment, as indicated by a statistically significant high negative (-0.802) correlation between the initial balance confidence scores and the improvements in balance confidence scores after the six-week progressive WB balance training programme, as shown by Figure 50, in chapter five. In conclusion, balance confidence can be enhanced post-WB training programme, especially in the individuals who demonstrate the least confidence at baseline. Consequently, increasing balance confidence might lead indirectly to decrease risk of falling and enhance the quality of life in PWD and individuals with DPN. Those individuals with DPN for a long time might have impaired functionality and susceptibility to falling (Callaghan et al., 2015). Thus, there is a need to assess the severity of DPN post-WB training, which will be discussed in the below section.

6.3.1.5 Severity of neuropathic scores

There are various symptoms and signs of severities of DPN, ranging from sensory symptoms (paraesthesia, numbness) in the hands and or feet to severe sensorimotor alteration with both proximal and distal involvement (Hoffman et al., 2015; Sommer et al., 2018; Lehmann et al., 2020). In the long term, DPN can lead to functional impairments, such as increased risk of fall, increased use of walking aids and difficulties with ADL, for example, ascending and descending stairs (Callaghan et al., 2015; Hoffman et al., 2015).

Therefore, it is essential to consider the age and severity of diabetic neuropathy, since these two issues seem to be independent predictors of risks of falling in individuals with DPN (Timar et al., 2016). Further discussion about correlation between age, static balance and WB performance are found in section 6.3.2.1.

The present study achieved significant improvements (P-value≤0.001) in the severity of neuropathic scores, post six-week of progressive WB training programme, as illustrated in Figure 51 in chapter five. The severity of neuropathy was assessed by the TCNS; this supports the sixth hypothesis, which was suggested in chapter one within the third study. The TCNS is graded out of a maximum of 19; 0-5 (no neuropathy); 6-8 (mild DPN); 9-11 (moderate DPN) and ≥ 12 (severe neuropathy) and includes both subjective and objective assessments (Ahmad et al., 2020), as described earlier in chapter five. There was improvement in the severity of neuropathy scores observed in mild and moderate individuals with DPN by 2 points, as indicated by the means of TCNS scores at pre-WB training (T0=8.86) and the mean TCNS scores post-WB training (T3=6.24), with large ES ≥ 0.8 or ≤ -0.8, demonstrating significant (P-value≤0.001) improvement in the severity of neuropathy post six-week of progressive WB training (see Table 27 in chapter five). However, for individuals with severe DPN, the severity was reduced by just 1 point. This improvement was tracked through the intervention period and yielded significant improvements during each assessment period (P-value≤0.001), demonstrating gradual and consistent gains in the TCNS scores, which were also mirrored in the magnitude of the ES ≥ 0.8 or ≤ -0.8 (shown in Table 27 in chapter five).

There are similarities between this finding and previous studies that demonstrated similar improvements in the severity of DPN scores (Kluding et al., 2012; Dixit et al., 2014; Monteiro et al., 2020; Ravand et al., 2021). However, one study did not show any statistically significant improvement in the severity of DPN score (Sartor et al., 2014). Those conflicting findings in the literature, regarding the effect of various training on whether they achieve improvements or not, in the severity of neuropathy

(Kluding et al., 2012; Dixit et al., 2014; Sartor et al., 2014; Monteiro et al., 2020; Ravand et al., 2021). All of these studies utilised the MNSI to assess the severity of neuropathy, which was described earlier in chapter five.

A failure to find any significant improvement in MNSI scores, might be attributable to a lack of blinding of the therapist and a failure to describe the intensity of the intervention (Matos et al., 2018). However, there was a clinical improvement apparent in the experimental group, involving a significant reduction of 2 points in the MNSI scores, with a medium effect size, which remained after 12 weeks follow up, especially in the score for the physical examination of the feet from 4.0 to 4.5 points but not considered statistically significant (Sartor et al., 2014). This is similar to the present study, where 2 points in TCNS were reported among most of the participants, as mentioned earlier. However, there was a significant (P-value ≤0.001) reduction in TCNS scores between T3 and T4, demonstrating a 'detraining' or wash out effect (23.14%). The overall improvement in TCNS scores, retained at T4, was found to be significant when compared to the baseline (-13.16%) (see Table 28 in chapter five).

Achieving small improvements, which are not considered statistically significant is quite frequently seen in a clinical context, where despite the P-value being non-significant, the result might be considered clinically significant (Sharma, 2021). An additional explanation for achieving small improvements is that the period of training might be short and insufficient to alter the structural deformities in individuals with DPN, which are more likely to occur at the somatosensory level (Sartor et al., 2014).

Despite the previous interventions in the four studies finding significant differences in the severity of neuropathy, as demonstrated by the MNSI scores, which were significantly different, indicating improvement in the severity the DPN (Dixit et al., 2014; Kluding et al., 2017a; Monteiro et al., 2020; Ravand et al., 2021). Those interventions vary between strengthening, gait and balance training (Monteiro et al., 2020), treadmill exercises (Dixit et al., 2014), strengthening and aerobic training (Kluding et al., 2017a) and balance board training (Ravand et al., 2021).

The variations in the intervention might be taken into consideration when postulating a mechanism of improvement in the severity of neuropathy scores, as some may argue that aerobic exercises only improve the effects of glycaemic control on nerve fibres and vascular function, leading to improvements in the severity of neuropathy scores; however, other factors might be considered, such as body composition changes or psychological/social factors (Kluding et al., 2012). This is in agreement with a recent SR that explains the mechanism of neuropathy signs and symptom improvement post exercise, which might be due to an increased ability of blood vessels to vasodilate, which leads to increases in blood flow and perfusion of peripheral nerves (Holmes and Hastings, 2021).

A further mechanism behind improvements in the severity of neuropathy scores, post therapeutic exercises, might be due to the effect of pharmaceuticals only, on the severity of the neuropathy scores, causing reduction of this severity by improving signs and symptoms. However, this may not the case because the combination of exercises with drug therapy yields greater benefits than drug therapy alone (Dixit et al., 2014). Therapeutic exercises have proved able to mitigate neuropathic symptoms in PWD and individuals with DPN condition (Akbari et al., 2020). For example, proprioception plays a vital role in postural control as conveyed through larger type I afferent fibres, which was described earlier in chapters one and two, as a type of nerve fibres that is responsible for transmitting feedback from the muscle and proprioception to the CNS (Li et al., 2019). These afferent fibres are impaired, as indicated by a loss of sensory feedback or proprioception in the feet, especially the loss of, or reduction in, ankle joint proprioception, which may affect balance in individuals with DPN (Li et al., 2019; Reeves et al., 2021). Therefore, WB training might aim for proprioception improvement. This was seen to be the case where proprioception, assessed by identifying small differences in the extent of ankle inversion movement, was improved post-WB training in elderly individuals (Waddington and Adams, 2004). Similarly, proprioception was improved in the current study. Proprioception, as indicated by position sense is one of the important components in the TCNS, as depicted in Table 18, in chapter five where the component of TCNS was explained.

A further explanation of a mechanism might be stimulation of the mechanoreceptors located in the muscle spindle, joint capsule and Golgi tendon organs, which are responsible for improving the proprioception inputs from the foot and ankle (Gilman, 2002). The sole of the foot has cutaneous sensation, with sufficient spatial relevance to inform the CNS about the body's position and consequently, induce adapted postural responses (Kavounoudias et al., 1998). Improvement of proprioception might be achieved post unstable training, utilising the same mechanism as previously mentioned (Mohammadian et al., 2019). However, Kiers et al. (2012) argued that ankle proprioception is not targeted during unstable surface training and can be unreliable, so the CNS places more emphasis on other sources of information about the spatial orientation of the body, such as visual and vestibular information, leading to shift postural strategy from ankle to hip (Horak et al., 2002). On the contrary, the present study has proved that proprioception was improved post unstable WB training, as indicated by improvement in the TCNS scores, which include proprioception tests. Regarding neuropathic pain, it is a subjective measure; section 6.3.1.6 will discuss this symptom in more detail.

A final explanation for this improvement in TCNS scores might be due to the ability of WB training to improve ankle muscle activity and enhance neurological adaptation, as a result of mechanical control mechanisms post-WB training, which provides a further mechanism for reducing the neuropathy scores (Silva et al., 2016; Silva et al., 2018). It suggests that these adaptations, as a result of WB training, are achieved at the subcortical integration areas, such as the basal ganglia and cerebellum, as mentioned previously in the static and dynamic balance sections (Silva et al., 2016; Silva et al., 2018).

Although previous literature provided various training programmes to improve the severity of DPN scores, none of them utilised WB training solely among individuals with DPN. Therefore, this study is considered novel due to the results of improving neuropathy scores post six-week of progressive WB training. Caution might be considered that the participants in this study have mild to moderate DPN and not too many severe cases. The mechanisms behind achieving this improvement might be due to a variety of training programmes, stimulation of proprioception, activation of ankle muscles or neural adaptation. Hence, due to these mechanisms, clinicians can consider prescription of WB training for mild to moderate individuals with DPN to reduce symptoms of neuropathy and thereby, improve quality of life and reduce risks of falling. Future study is recommended to include more severe individuals with

DPN, as well as to prescribe WB training in home programmes but ensure safety and commitment throughout this programme.

6.3.1.6 Neuropathic pain scores

Neuropathic pain is commonly associated with most forms of peripheral neuropathy. This elevated pain threshold and reduced pain sensation can lead to complication, such as causing skin breakdown and deformities, such as Charcot's joint destruction (ADA, 2021b), foot ulcers and lower limb amputation (Pop-Busui et al., 2017). Therefore, it is recommended to mitigate this pain with less invasive techniques, such as therapeutic exercises and an exploration of the effect of these exercises for enhancing the magnitude of exercise-induced hypoalgesia, among various populations, especially among the elderly, with a washing period to comprehend how long this effect can last (Song et al., 2023).

The level of pain in this present study was assessed using a VAS, the same as in Toth et al.'s (2014) study. Each participant was asked to mark their perceived level of pain on a 10-cm VAS, where 0 indicated 'no pain' and 10 'unbearable pain', as was described in chapter five (see Figure 12). Therefore, the seventh hypothesis of the third study as mentioned previously in chapter one assumed that pain can be relieved post six-week of progressive WB training in PWD and individuals with DPN. However, this hypothesis was rejected because there was no significant improvement in pain in PWD and individuals DPN, except there were five participants who had pain at baseline and it was relieved at T3, which was after the intervention, as depicted in Figure 52 in chapter five. Relief of pain was tracked throughout the training period and yielded non-significant differences at each assessment period (see Table 29 in chapter five). However, regarding the five participants, the pain persists during baseline, T1, T2 and T4 but is relieved by T3.

Similarly, one study affirmed this result (Toth et al., 2014); however, two SRs found various pain-relieving physiotherapy interventions among PWD and individuals with DPN (Akbari et al., 2020; Nupoor and Sripriya, 2022). The study that did not show significant changes in neuropathic pain, compared to the education only (control) group, assessed neuropathic pain via the usual assessment for pain, which was the VAS and was conducted among individuals with DPN and utilised balance and aerobic training exercises (Toth et al., 2014). Despite this study being a RCT design study, there were some limitations, such as the small sample size, high dropout rates, inappropriateness of exercise programme and unsuitability to generalise findings because the recruitment of the participants were from primary care and tertiary care clinics (Toth et al., 2014). Therefore, future studies might consider having therapists and researchers encourage commitment to completing the whole training programmes.

However, only five participants were complaining of pain and were >60 years at baseline but this pain was relieved at week three of the assessment, indicating that WB training relieved their pain even if the P-value did not reach a significant level, which might explain why significant difference in pain were not achieved. Although the P-value might be non-significant, the result may be considered clinically significant (Sharma, 2021), when applying this parameter.

A further possible explanation is the nature of the pain phenomenon, being multi-dimensional and including cognitive, emotional and physical components (Lee, 1985). These components might be taken into consideration when planning pain treatments. Techniques used to treat chronic pain are based on the gate control theory (Lee, 1985).; these techniques bring about relief by closing a hypothetical “gate” in the spinal cord, which prevents pain signals from reaching the brain (Siegele, 1974). However, this is not the case in individuals with DPN, because they suffer from decreased local blood flow that may lead to reduce oxidative stress and factors that inhibit the passage of nerve signals (Malik et al., 1989). Furthermore, these damaged sensory neurons exhibit hyperexcitability and produce action potentials spontaneously, even in the absence of a stimulus and with altered response (Quiroz-Aldave et al., 2023). Consequently, as more spontaneously activated nociceptors enter the spinal cord in individuals with DPN, synaptic transmission is improved, enhancing nociceptive signalling through a process known as central sensitisation (Quiroz-Aldave et al., 2023). In relation to this process, an epigenetic mechanism was suggested (Polli et al., 2019). Through this mechanism, there was a further explanation of the effect of exercises, such as hypoalgesia at the gene level, as exercises might produce changes at that level, possibly leading to regulation of nociceptive processes (Polli et al., 2019).

Examples of the modalities that are based on this theory and have a proven ability to reduce pain in individuals with DPN are the “transcutaneous electronic nerve stimulator” (TENS), electro-acupuncture, acupuncture, low-level laser, pain relief medications, Thai massage and foot massage (Akbari, et al., 2020; Nupoor and Sripriya, 2022). The foot massage mechanism might enhance circulation and improve the release of endorphins, which consequently results in pain relief among individuals with DPN (Nupoor and Sripriya, 2022). However, despite medication being the primary option to treat neuropathic pain, exercises represent a safe and low-cost option that might attract interest (Leitzelar and Koltyn, 2021). Therefore, it is essential to understand the mechanism of the effect of specific exercises, as those underpinning mechanisms may apply to other neurological diseases (Streckmann et al., 2021).

One mechanism suggested in a recent meta-analysis is that the exercise therapy might have the potential to reduce nociceptive responses to mechanical and thermal tests, compared to control groups without exercise; this has been shown in animal models of peripheral nerve injury (Guo et al., 2019). Another suggested mechanism is that neuropathic pain might be reduced by exercise through normalising microglia activation, balancing pro- and anti-inflammatory responses and producing alterations in neurotransmitter and neuro-modulatory systems (Leitzelar and Koltyn, 2021). Examples of this, in animal studies, include treadmill exercise training in mice being able to improve the regeneration of transected nerves by altering neurotrophic factor expression, which is the nerve growth factor (NGF) (Park and Höke, 2014). Similarly, treadmill training was able to restore levels of neurotrophins and synaptic plasticity through brain-derived neurotrophic factor (BDNF) in the spinal cord (Gómez-Pinilla et al., 2002). Both NGF and BDNF play a role, not only in the axonal regeneration but also during the development of neuropathic pain (Pezet and McMahon, 2006). One of the neuropathic pain symptoms is allodynia, which can be reduced by the same mechanism of BDNF that promotes neuroplasticity, post voluntary exercise for spinal cord injury in rats (Hutchinson et al., 2004). However, it is important to bear in mind that animal models may not fully represent the feelings of pain in human beings (Yezierski and Hansson, 2018). Therefore, studies in human beings have been conducted with various exercises and have shown similar significant reductions in neuropathic pain (Balducci et al., 2006; Kluding et al., 2012;

Hamed and Raoof, 2014). Examples include a study that found that 15 weeks of high-intensity interval training in obese diabetic women with DPN significantly reduced neuropathic pain scores in comparison with those in the moderate aerobic training group (Hamed and Raoof, 2014). Another example of exercise that can reduce neuropathic pain in the form of numbness, burning and tactile sensitivity, is the progressive aerobic and resistance training programme of 10 weeks, as tested in PWD with metabolic syndrome (Kluding et al., 2012). However, DPN individuals with chronic pain might spend less time exercising than those individuals without chronic pain (Butchart et al., 2009). Yet these results indicated that exercise therapy or physical activity might play a role in pain management that the affected individuals are unaware of (Butchart et al., 2009). This is true as indicated in the current study where the pain complained of by the five participants was relieved during the period between T3 and T4 but they again complained during the period T4 and T0 but did not reach a significant level (see Table 30 in chapter five).

Therefore, there is a demand to enhance an individuals' awareness of the role of exercise in managing pain and improving overall health (Butchart et al., 2009). Consequently, it is recommended that physical activity be improved in individuals with DPN (Colberg et al., 2016); this will be discussed in the section 6.3.1.7 below.

In conclusion, although there was statistical non-significant improvement in pain scores, the findings are considered clinically significant. This is because five participants only complained of pain and were >60 years at baseline but this pain was relieved by the week three assessment, indicating that WB training may have relieved their pain, even if the P-value did not reach a significant level. This pain was only for elderly participant, which might indicate other reasons for pain rather than being neuropathic only. Therefore, it is recommended to assess pain objectively, as well as subjectively by health care practitioners among individuals with DPN (Abbott et al., 2011). Overall, despite pain being assessed subjectively, it was alleviated in five participants after the training programmes, indicating that this WB training programme was effective in reducing pain as a clinical symptom complained of by individuals with DPN and might be prescribed for these individuals who complain of neuropathic pain. Future study is recommended to include individuals with different severities of DPN, who complain of neuropathic pain and to assess this pain both subjectively and objectively.

6.3.1.7 Physical activity level

Sedentary lifestyle, due to a lack of physical activity, might be one of the main causes of type II DM among the Saudi Arabian population (Naemi et al., 2015), as mentioned previously in the chapter two of this thesis. Furthermore, sedentary lifestyle behaviours and low activity were reported in individuals with type II DM with and without complications in an analysis of 233,110 UK Biobank participants (Cassidy et al., 2016), as mentioned previously in chapter two. Consequently, low physical activity might contribute to increased morbidity and mortality; thus, there is a demand to motivate participation in physical activity exercise programmes to reduce those complications (Harrington and Henson, 2021). For example, activity for a diabetic polyneuropathy protocol that included balance training was able to enhance quality of life and a shift from a sedentary lifestyle to a more active one (Kluding et al., 2017b). A further complication is that individuals with DPN are at higher risk of falling, especially during descending stairs as a part of ADL, leading to 60 % increase in mortality consequences (Richardson and Hurvitz, 1995; Startzell et al., 2000; Tilling et al., 2006). Hence this thesis assessed physical activity levels via Baecke questionnaire post six-week of progressive WB training in PWD and individuals with DPN. This questionnaire is based on the Likert scale and considered a five-point scale, that represents energy consumption during work, sport and leisure time (Baecke et al., 1982), as indicated in chapter five. This questionnaire has shown a strong inverse correlation between level of physical activity assessed by this questionnaire and type II DM among the Saudi population (Gillani et al. 2018). It was hypothesised in the eighth hypothesis of the study three, as mentioned earlier in chapter one that the physical activity level could be improved post this WB training. However, this hypothesis was partially rejected, due to one of the physical activity indices, work index, being found to show no significant difference following this WB training programme (see Figure 53 and Table 31 in chapter five). This was likely because most of the participants were working in offices and most of the time would be seated in the work environment and their scores at baseline were lower in comparison with the normative value of the same index in healthy adults (Baecke et al., 1982). This comparison might be unfair but no normative value data for this questionnaire was found in the literature.

Regarding other indices, there were significant improvements in the two indices of physical activity, which are sport and leisure time, following this WB training programme in PWD and individuals with DPN. As these indices are performed in the participant’s own time, whereas activity in work was restricted, due to being office work for most of the sample of this study and scoring low at the baseline, explaining the non-significant improvement in the work index.

These finding are in accordance with previous studies, that found significant improvements in physical activity post various training programmes (Dougherty et al., 2011; Kempf and Martin, 2013; Smee et al., 2014; Mi et al., 2020). The explanation for these improvements might vary for several reasons, which will be discussed in the below section.

First, how physical activities were assessed, since there were two different questionnaires in each study, as the patient neurotoxicity questionnaire, which was utilised in Mi et al.’s (2020) and Continuous Scale-Physical Functional Performance 10 (SCS-PEP10), which was utilised in Smee et al. (2014) and Kempf and Martin (2013). However, it is argued that these physical activity assessments were all subjective, due to using questionnaires rather than quantitative objective tools, such as wearable sensors (AlShorman et al., 2021). Therefore, more clinical tests might provide a stronger indication than these subjective questionnaires, such as the BBS, which was utilised in the Dougherty et al. (2011) study. BBS, as mentioned previously in chapter two, was used to assess the physical function by 14 functional activities ranging from sitting to standing to performing postural transitions, rated from 0 to 4 points with a maximum score of 56 (Berg and Norman, 1996). Score of this scale was associated with increased risk of falling with a score of less than 45 (Mancini and Horak, 2010). Although the BBS scores in Dougherty et al. (2011) was improved by 1.6%, this was below the minimal clinically important difference (MCID), which ranged from 5% to 21% in people with multiple sclerosis and in the elderly who were healing from hip fracture, respectively) (Gervasoni et al., 2017; Tamura et al., 2022), as mentioned earlier in chapter three. Unfortunately, MCID in the healthy elderly has not been determined, as mentioned earlier in chapter three, making comparison with this present study difficult.

A second reason for finding improvements in physical activity was the nature of those exercise programmes, that include ankle range of motion, balance training with balance board, such as standard WB or Wii Fit, which the latter has multi-axial fulcrum and utilises the IndoFLO ® Balance Cushion (Dougherty et al., 2011; Kempf and Martin, 2013; Smee et al., 2014; Mi et al., 2020). Despite reporting benefits in physical activity, both studies were limited to small sample sizes (Dougherty et al., 2011; Mi et al., 2020). However, there are two strengths of these previous studies, that the study design conducted by Mi et al. (2020) was a RCT with beneficial impact of ankle range of motion exercise as demonstrated by increasing the range of motion, which is required to perform ADL (Mi et al., 2020). The study conducted by Dougherty et al. (2011) assessed the effect of Wi Fit training in the improvement scores of BBS and ABC questionnaire. This agrees with the findings of this present study, that WB training resulted in enhanced proprioception, strengthening of ankle muscles and improved balance confidence, as was described earlier in chapter five. Consequently, proprioception and ankle muscle strength improvements, can lead to improved gait speed, balance enhancement and regaining of balance confidence (Kutty and Majida, 2013). All these previous elements are required to perform the ADL and increase participation in activity, which consequently result in improving the SF36 questionnaire (Myers et al., 2013) and Baecke questionnaire in the present study. This is highly beneficial for individuals with DPN, because it is manifested by sensory deficits, weakness in lower limb muscle and a fear of falling, which all are relevant to changes in gait (Allet et al., 2010). For example, individuals with DPN prefer to walk at a slow gait speed (Kutty and Majida, 2013). This “cautious” gait pattern is adopted as a compensatory mechanism to ensure safety due to diminished sensation in these individuals (Menz et al., 2004). Poor gait and balance affect the independence of performing physical function (Horak et al., 2023). Gait assessment, however, is outside the scope of this present study.

In summary, a WB training programme enhances physical activity in PWD and individuals with DPN, especially during sport and leisure times. Mechanisms behind this improvement were considered, due to the WBs ability to promote elements, which are required to engage in physical activity, such as proprioception, muscle strength and balance confidence. Hence, training on a movable surface, such as WB might encourage these individuals to participate more in activities, such as sport during leisure time, with more confidence. Therefore, clinicians in the future are advised to add WB prescription to PWD and individuals with DPN, then monitor their physical activity in a more objective updated manner, such as using sensors (Horak et al., 2023) but with low cost and try to convince them about the beneficial effects. Examples of these beneficial effects include a potential reduction in morbidity and mortality, and an improvement in the quality of life among those populations. Indeed, quality of life and gait are recommended to be assessed using digital technology as future study. Utilisation of digital technology has been recommended by the ADA to monitor blood glucose and improve quality of life (American Diabetes Association, 2019) and has proved beneficial, especially during the Covid-19 lockdown period (Elsayed et al., 2023b). Examples of this technology include the use of a wearable sensor (AlShorman et al., 2021). However, there are some limitations and weakness, such as the high cost of continuous monitoring, sensor calibration, energy efficiency and patient acceptance (AlShorman et al., 2021). Therefore, professional medical engineers are required to overcome these complications. An additional source to promote physical activity among PWD is online courses, that have proved to be successful for providing lifestyle counselling to help with weight loss and physical activity motivation (Chao et al., 2019). Finally, other resources for improving activities in PWD might involve the use of an educational booklet (Monteiro et al., 2020).

6.3.1.8 Conclusion, clinical implications and future studies

The above section discusses the effect of a six-week progressive WB training programme among PWD and individuals with DPN. It explores the mechanisms behind the improvements in static balance, WB performance, muscle strength, balance confidence, neuropathy severity scores, neuropathic pain and physical activity level. Thus, the main aim of this thesis, which was to report the investigation of the effect of a planned six-week progressive WB training programme in PWD and individuals with DPN, was successfully achieved. Most of previous factors were improved after six weeks, however, they were observed to deteriorate after exercise withdrawn, a washing out period. Examples of these improvements post-WB training are strength in the ankle muscles and improvement in the sensory system. Consequently, these motor and sensory systems are required to improve balance and thereby, reduce the risk of falling among these individuals. This was achieved by the progressive pattern employed in this study by means of WB training. Balancing an unexpected perturbation, such as produced by a wobbly surface during WB training required reactive balance responses, to combat the quick movement of the WB, which in turn required strong muscles, especially ankle muscles, which are weak in individuals with DPN and might cause drop foot, leading to ulcers, increase risk of falling and being sedentary for long period of time. An additional requirement for balancing on a wobbly surface is adopting the ankle strategy by strengthening the ankle muscles, which was achieved gradually throughout this progressive pattern of training conducted in this study, as being assessed for the ankle muscles strength on bi-weekly basis. Further requirement for balancing on such a surface is proper proprioception, which is reduced in these individuals, however, by training in a progressive pattern, of the type conducted in this study, gradual improvements were noted, via the means of the biweekly assessment for neuropathic severity based on TCNS. All previous improvements post-WB training might contribute to improvements in static balance, WB performance and physical activity level. Therefore, it is recommended to utilise this progressive pattern of WB training, by tailoring it to every individual participant's need, taking into consideration safety measures and the confounding factors. Examples of such factors are the patient's age, height, weight, anthropometrics, severity of neuropathy, neuropathic pain, duration of DM, physical activity level and balance confidence. Some of these factors are already known to affect static balance and WB performance following the previous study conducted in this thesis, such as height, weight and anthropometrics. However, the participants in the previous study were healthy adults and it is not clear whether these findings can be directly transferred to the PWD and individuals with DPN. Therefore, all these factors, height, weight, anthropometrics, severity of neuropathy, neuropathic pain, duration of DM, physical activity level and balance confidence will be discussed in the following section, specifically in terms of if there is any relationship between them and static balance, as well as WB performance.

6.3.2 Baseline relationship

A correlation study is essential in any research to avoid bias and ensure ecological validity and reliability, which indicates that the study's findings produced in the lab can be generalised to the real-world (Field, 2017), which in this context is the clinical environment. An important aspect of this type of validity is ensuring that the findings are not influenced by the research; this is achieved by applying the correlation study method. In applying this method, understanding the baseline characteristics, such as age, height, weight, body mass index (BMI), physical activity level, duration of DM, severity of neuropathy, neuropathic pain and balance confidence relationship assists with fulfilling the aim of investigating the mechanism behind any observed changes. Thus, to ensure ecological validity and reliability of the current study, the below section will discuss the findings of the study conducted in this thesis by investigating the previous baseline relationship to static balance and WB performance to ensure reliability.

6.3.2.1 Age

The elderly are known to experience impaired balance (Maki and McIlroy, 1996). Two different trends were identified, when evaluating static balance, a U-shaped and inverted U-shaped trend for dynamic balance across a person's life span (Granacher et al., 2011a) (see Figure 6). Therefore, it is of worth investigating the effect of age on static balance and WB performance. Initially, the effect of age on general balance will be investigated in the below section, then the aging effect on static balance and WB performance, individually.

It is important to consider that impaired balance in the elderly might arise from multiple sources. Decreased FSS might disturb the mechanoreceptors, consequently resulting in balance impairment in both the elderly and people with diabetes (PWD) (Santos et al., 2008) (see chapter two). Consequently, this will lead to disturbance in the afferent and efferent receptors in the lower extremity, which are apparent in individuals with DPN (Lafond et al., 2004; Kutty and Majida, 2013; Ahmad et al., 2017), especially if individuals are elderly (Maurer et al., 2005), as was pointed out in chapter two. Consequently, decreased proprioception and weakness in the lower limbs might prove to be a strong predictor of falls in PWD (Chatzistergos et al., 2020), individuals with DPN, particularly with type II DM (Timar et al., 2016) and the elderly (Maki and McIlroy, 1996; Masdeu et al., 1997). This reduced proprioception is associated with reduced efficiency of the somatosensory system in elderly and individuals with DPN (Bosch et al., 1995; Gutierrez et al., 2001) (see chapter two).

Balance impairment might also result in the elderly when the CoP location is in a less safe area, at the boundaries of BoS for longer periods of time, compared to young adults, compounding the risk of postural instability (Bugnariu and Sveistrup, 2006)(see chapter two).

An old individual might be suffering from neuropathy, as indicated by a significant increase in the incidence of neuropathy in the elderly (Feldman et al., 2019) (see chapter two). Consequently, these elderly individuals with DPN swayed more with eyes open, compared with a healthy matched age group during static balance assessment, (Corriveau et al., 2000) (see chapter two). Additionally, postural instability might arise due to the similar symptoms associated with both the elderly and DPN, such as deconditioning, muscle weakness, reduced proprioception and decreased joint mobility (Kutty and Majida, 2013), as was explained earlier in chapter five.

However, balance impairment in elderly people with type II DM might not be solely due to DPN but also impairments of other sensory systems, including visual, vestibular and somatosensory systems, due to prolonged hyperglycaemia, which has the potential to cause a gradual deterioration of the sensory nerve fibres within the somatosensory system (Hewston and Deshpande, 2016; Deshpande et al., 2017), or deficits in other systems, as was mentioned earlier in chapters two and five. For example, a muscular and cognitive systems deficit might contribute to balance impairment in elderly people with type II DM (Hewston and Deshpande, 2016; Mustapa et al., 2016). Cognitive and attention impairments play a vital role in difficulties with maintaining balance, because the brain is responsible for providing commands to the muscles in the limbs required for body stabilisation (Mustapa et al., 2016) (see chapter two).

The adoption of the ankle strategy also reduces with age (Horak et al., 1989) and in individuals with DPN (Giacomini et al., 1996). This has resulted in elderly and DPN individuals shifting from an ankle to a hip-based strategy (Inglin and Woollacott, 1988; Jyoti, 2016) (see chapter two). However, this strategy is required, especially during unexpected surface related perturbations, such as balancing on a WB.

Therefore, due to the previous stated reasons, age and disease (which is in this case, DPN) are accompanied by a reduction in the complexity of the physiological or behavioural control systems, which can alter the neuromechanical mechanism underpinning static balance (Vaillancourt and Newell, 2002), resulting in increased falling risk (Morrison et al., 2012). This is true as indicated by finding a significant correlation between age and instability during static balance assessment in a DPN study (Simoneau et al., 1994; Giacomini et al., 1996) and agrees with the author's finding that confirms a significant correlation with the double leg stance eyes open narrow base of support condition (DLSEON). The explanation for this finding is that static balance requires understanding of the physiological systems underlying certain tasks (Horak, 2006). For example, sufficient sensory information by intact somatosensory and visual systems, is essential for maintaining balance during quiet standing with eyes open and a narrow base of support (Horak, 2006). Narrowing the base of support, resulted in a greater postural sway in the elderly than in young adults (Nagy et al., 2007). A narrow base of support is known to be more difficult to maintain than a wide base of support, as ankle-hip muscle activation is required to control balance in the elderly, while ankle muscle activity only was sufficient for controlling balance in young adults (Amiridis et al., 2003). Widening the area of the support base is easier than narrowing the base of support, because with a wide base of support the distance from the centre of gravity to the base will be reduced, subsequently resulting in improved balance (Alonso et al., 2012). Linked to the previous justifications and reasons, these provide an explanation for the findings of the present study conducted in this thesis, as the older the individual, the poorer their static balance (perimeter) during the DLSEON task, as indicated by significant p value= 0.01 moderate positive correlation (r=0.478), as depicted in Table 32, in chapter five. This led to the rejection of the ninth hypothesis, which was that age will not affect static balance in PWD and individuals with DPN.

In terms of WB performance, the present study found a low positive correlation between age and DLSEON at 5° (r=0.342), DLSECN at 5° (very high positive r=0.881) on the APSI only and DLSEOW at 10° in the percentage of time spent in outer zone (low positive r=0.375) and inner zones (low negative r=-0.375), which indicates the older the participants were, the poorer their WB performance was, as shown in Table 33 in chapter five and Appendices 14 and 15. This again led to the rejection of the ninth hypothesis, which was that age will not affect WB performance in PWD and individuals with DPN. To the author's knowledge this is the first study to investigate the relationship between age and WB performance. Thus, comparison with the literature is difficult, unless comparisons are to be made with other movable surface types. One such movable surface is foam rubber (70 cm× 62 cm× 15 cm thick), which was used to assess dynamic balance in DPN participants (Di Nardo et al., 1999).

Age was found to be negatively correlated with dynamic balance, indicating that the older the participant, the less stable they were on a rubber foam surface with both eyes open and eyes closed (Di Nardo et al., 1999). In the absence of, or degradation of visual or vestibular cues, individuals with DPN experienced greater postural instability than aged-matched diabetics without DPN and the control of healthy subjects without DM group during quiet standing (Simoneau et al., 1994). Not only during the absence of visual cues but also with vision, posture may be impaired in individuals with DPN, who exhibited poor posture during quiet standing (Lafond et al., 2004), especially when elderly (Caronni et al., 2016). Furthermore, elderly individuals with DPN were found to sway with eyes open in a manner equal to those in the age-matched population, who performed the same task but without vision (Boucher et al., 1995; Lafond et al., 2004), as was explained earlier in chapters two and five. This might be explained by the fact that the elderly depend on exteroceptive information and prioritise the use of vision to maintain balance (Hatzitaki et al., 2009). Therefore, this might provide an explanation for the high positive correlation (r=0.881) of age with WB performance during DLSECN at 5° in APSI, shown in Table 33 in chapter five and Appendix 14.

Additionally, the finding of a correlation in the APSI in the present study corresponds with the evidence from the literature, where diabetic older adults displace in the AP axis more than young and healthy and non-diabetic older adults (Lee et al., 2018a). This is because the platform in this study was moved backward, requiring a counteracting force to return the participant to an upright position (Lee et al., 2018a). This force was produced by joint torque, which rotated the body forward, by using hip flexors, ankle dorsiflexors and knee extensors (Lee et al., 2018a). All these muscles decline in the elderly, causing an inability to produce sufficient torque and leading to an increased AP axis in the elderly with DM (Lee et al., 2018a). Additional reduction of the effectiveness of ankle torque to achieve postural stabilisation might also result from standing on a compliant foam surface (Horak and Hlavacka, 2001).

However, individuals with DPN showed good postural stability under dynamic conditions (Nardone et al., 2006), such as exposure to unexpected postural perturbations, although the movable surface in this case was a platform producing a horizontal sinusoidal (0.2 Hz) movement (peak-to-peak 60 mm) in the AP direction only. The authors explained that the good postural performance identified in these individuals with DPN was due to the adoption of anticipatory postural strategies (Nardone et al., 2006). An additional justification might arise from three reasons: (1) compensating for missing lower limb sensitivity with larger sensory input provided by sinusoidal perturbation during quiet standing (Nardone et al., 2006); (2) vestibular (Horak and Hlavacka, 2001) or cutaneous (Meyer et al., 2004) inputs are required to control balance during the movable platform task, compared to quiet stance and their effects, therefore, contribute to residual proprioception (Bloem et al., 2002); and (3) the learning effect is known to be an influential factor in balance training, since the participants can predict perturbation after the first few cycles of platform perturbation (Schieppati et al., 2002). Thus, the individuals learn to adopt anticipatory postural strategies (Nardone et al., 2006). This is not the case in the present study, due to the different challengeable levels, as indicated in Table 16 in chapter five, which demonstrates the sequential fifteen levels of WB balance difficulty and the various tasks that led to difficulties predicting the next higher level, although the previous level might influence the learning effect upon training. The WB difficulty balance challenge was conducted via the dynamic stabilometric assessment device (Prokin 252), which can act as a WB with 50 levels of instability and maximum tilt angle of 15°, as mentioned previously in chapter five.

In conclusion, age was correlated with static balance and WB performance but its effect is more apparent during more challengeable tasks, such as double leg stance, narrow base of support, with eyes open in static balance and the same task with both eyes open and closed in WB performance at 5° and 10° of WB tilt. The explanation for these relationships depends on comprehending the physiological systems underlying these task, as narrowing BoS tasks require more ankle-hip muscle activation. These muscles are declined by aging, which might lead to a reduced ankle strategy required for balancing on wobbly surface. Additional, decline can be observed in the elderly is the sensory system deficit, resembling individuals with DPN, which contribute to this correlation finding. Finally, due to previous explanations of the effect of static balance and WB performance, clinicians are advised to consider the effects of aging, during static balance assessment and WB performance and training.

6.3.2.2 Height, weight and

6.3.2.3 Anthropometric measures

The current study failed to find any correlation between static balance performance in PWD and individuals with DPN and height, weight, BMI, anthropometric measures in either of the parameters or tasks, as shown in appendix 13. Similar to these findings Razzak and Hussein (2016) found no correlation between height, BMI and static balance in asymptomatic type II DM without DPN. This confirms the tenth hypothesis of the third study, which was that anthropometric measures will not affect static balance in PWD and individuals with DPN – though this was rejected with regard to WB performance, as will be discussed in the below section.

The study of the balance response of healthy individuals conducted in this thesis found a significant correlation between height, weight, BMI, anthropometric measures and static balance. This might be attributable to the mean for height in the healthy study (1.74 ± 0.83 m for males and 1.60± 0.59 m for females) being greater than in the diabetic study (1.70 ± 0.84 m for males and 1.56± 0.55 m for females), whereas the means in the healthy study for weight (78.3± 23.8 kg were for males and 62.5 ± 12.3 kg for females) and BMI (25.8 ± 7.6 Kg/m² for males and 24.4 ± 4.2 Kg/m² for females) were lower than in the diabetic study (weight was 82.6 ±17.8 kg for males and 75.8±14.9 kg for females and BMI was 28.50± 5.5 Kg/m² for males and 30.9± 5.5 Kg/m² for females). A significant correlation was found between height and balance, which are static and dynamic balance in the healthy study, possibly because being taller results in a higher centre of mass (COM) in healthy adults (Bryant et al., 2005), as was explained earlier in chapter five. However, the present study determined there was a very high positive correlation (r=0.959), between height and dynamic balance, namely WB performance during DLSECW 10° along the mediolateral stability index (MLSI), as depicted in Table 34 in chapter five and Appendix 14. Similarly, both height and support base explained 18% of medial displacement with eyes closed tasks among healthy young adults, who have not been regularly engaged in physical activity over the previous six months (Alonso et al., 2012). Similarly, there was a significant correlation between height and dynamic balance when measured by a FRT (Duncan et al., 1990). Height might be considered to play a role in balance, because the taller the individual, the higher the CoM distance from the base of support (Bryant et al., 2005). It is worth noting that an increased CoP pathway in the ML axis correlated with repeated falls, with the potential to cause serious injury in the elderly (Bergland and Wyller, 2004). Furthermore, controlling the pathway for CoM in the ML axis was responsible for the hip abductor and adductor muscles during perturbation (Winter, 1995). The correlation found in this study was that during DLSECW at 10°, a larger movement of the CoM might be required at higher velocities by the acquisition of a hip strategy to maintain balance (Cook and Woollacott, 2016). Potentially, the DLSEC condition may have resulted in a re-evaluation of the weighting of input parameters to the biofeedback loop (Benjuya et al., 2004). Due to all previous requirements, this might be more difficult in taller individuals; thus, the high positive correlation between height and the ML axis during DLSECW was significant at 10°, as shown in Table 34 in chapter five and Appendix 14. Additionally, the correlation between weight and WB performance along the percentages of time spent in inner and outer time, ranged from low (r=-0.365 - 0.365) to high (r=-0.891 - 0.891) correlations, depending on the complexity of the task; that means the harder and more challenging the task on the WB (greater inclination, narrow base of support and eyes closed) the greater the correlation, as depicted in Table 35 in chapter five. Furthermore, there was a significant correlation between anthropometric measures (shoulder, chest, hip circumferential measures and shoulder-hip ratio) and WB performance (APSI, MLSI, percentages of time spent in inner and outer zones) ranged from low (r=0.335 – 0.387) to moderate (r= 0.417 – 0.691), high (r=0.803 – 0.918) and very high (r= 0.938 – 1.000), as shown in Tables 38 and 39. These degrees of correlation increased again, according to the complexity of the task; suggesting that the harder and more challenging the task on the WB (greater inclination, narrow base of support and eyes closed), the greater the correlation. Similarly, there was a very high negative correlation between BMI and the mean scores for dynamic balance, which was assessed by BBS in individuals with DPN, although no correlations were found among healthy aged and sex matched individuals (Fahmy, 2014). This correlation, as investigated in the present study, might arise from the fact that increasing the difficulty of the task required both additional torque to be exerted and greater muscle strength to maintain balance at the harder WB level. This is not the case in the obese population with DM and DPN, who are known to have experienced a decline in muscle power that appeared to be magnified at higher limb velocities in the posterior calf muscles, contributing to much weaker (lower peak torque and power) ankle dorsiflexor and plantar flexor muscles than the control group (Hilton et al., 2008). Additionally, obese individuals seemed to have a shorter amplitude of movement, dyspnoea, discomfort, early fatigue and a lower capacity for shock absorption, leading to joint degradation, which might affect gait (De Souza et al., 2005).

A further explanation might be the strong association between type II DM and increased BMI leading to slowing metabolic status, insulin resistance and increased prevalence of related complications (Aghili et al., 2013). This insulin resistance, will lead to an accumulation of intracellular fat in PWD, compared to individuals of the same age without DM (Volpato et al., 2012). Consequently, this impaired insulin function in hepatic tissue, skeletal muscle and adipose tissue will lead to increased blood glucose levels (Lee et al., 2022a). In turn, this increased blood glucose will lead to increased fat content in the liver, known as visceral fat, which is commonly observed in obese individuals with type II diabetes (Colberg et al., 2010). Therefore, obese individuals have greater amounts of subcutaneous adipose and visceral fat distributed around their abdomens, leading to a protruding abdomen, and resulting in an anterior displacement of the CoM and increased anteversion of the pelvis and lumbar lordosis (De Souza et al., 2005). Thus, increased body mass and the subsequent result for a greater horizontal CoM distance, contributes to increased ankle torque generation to maintain postural stability (Meng et al., 2016) and places the centre of gravity (CoG) closer to the boundaries of the base of support (Corbeil et al., 2001). This was represented by modelling the human body using a 15-segment mathematical humanoid to determine the relationship between obesity and postural control (Corbeil et al., 2001). This model confirmed the anterior shift of the CoM in obese individuals was caused by abdominal obesity and may restrict the range of stability at the boundaries (Corbeil et al., 2001). Consequently, greater ankle torque will be required for balance during perturbations (Corbeil et al., 2001). If insufficient torque is produced, then the obese person is more susceptible to loss of balance and falling (Corbeil et al., 2001). During dynamic balance, such as on an unstable platform, obese sedentary individuals showed greater ML displacement, leading to an increased risk of falls and a longer mean time to perform the limits of the stability test and TUG test (Nascimento et al., 2017).

Further biomechanical explanations for poor WB performance were associated with a larger waist circumference and heavier body weight, which shifted CoM anteriorly, as mentioned previously (Corbeil et al., 2001), leading to challenges affecting proprioception (Wang et al., 2008), which was accompanied with weakened muscle strength (Tomlinson et al., 2016), as well as increased fatiguability (De Souza et al., 2005; Pajoutan et al., 2016), especially in PWD and individuals with DPN (Hilton et al., 2008). Fatigability will lead to reduced ADL such, as difficulty in ascending and descending stairs and increased use of assistive walking aids, which eventually leads to increased risk of falling (Callaghan et al., 2015; Hoffman et al., 2015). Therefore, recommendations from the ADA (2021b) on obesity management by controlling diet and enhancing physical activity were provided. Additionally, the ADA (2021b) suggests considering the effect of medication on obesity when prescribing exercises. Thus, the below section will discuss the effect of physical activity on static balance and WB performance.

6.3.2.4 Physical activity

Overall, there was no correlation between the majority of tasks during both static balance and WB performance with physical activity (PA). This confirmed the eleventh hypothesis of the third study, that physical activity will not affect static balance or WB performance. This corresponded with the previous study in this thesis, conducted on healthy adults and Sakaue et al.'s (2020) study, which found no correlation between the total PA index, which included three indices concerning (1) work, (2) sport, and (3) leisure time, when measured using the same scale (which is the Baecke questionnaire) and DM. However, individuals with DPN might experience an impact on their ADL, due to neurological impairments arising from muscle weakness and sensory disturbances (Hoffman et al., 2015), as discussed previously in chapter two.

Regarding single leg stance (SLS), which is a simple and special condition of narrowing the base of support (Masdeu et al., 1997), despite its simplicity, it is difficult to maintain in elderly individuals, who are above 80 years, due to motor dysfunction (Masdeu et al., 1997).

Thus, the present study found two exceptions in terms of correlations between PA and static balance (ellipse area) during SLS moderate (r=-0.434), as shown in Table 36 and WB performance (percentage of time spent in inner and outer zones) during DLSECN 5°, very high (-0.900 - 0.900), as shown in Table 37. These correlations were due to the nature of tasks and complexity requiring greater muscle coordination and certain strategies to maintain balance. During both tasks, SLS and DLSECN with a narrow base of support, a challenge arises due to the smaller distance the CoG can move within the base of support, when compared to the wide base of support, which has a wider distance (Alonso et al., 2012), as was described in chapter two. The narrow base of support requires more ankle-hip muscle activation to control balance, which is usually manageable in young adults (Amiridis et al., 2003). However, muscle weakness and deconditioning are symptoms of DPN (Kutty and Majida, 2013) and with a narrow base of support there is greater reliance on the central nervous system (CNS) (Beaulieu et al., 2010; Alonso et al., 2012). However, increased reliance on the CNS might alter neuroplasticity, leading to prolonged re-weighting of sensory information in more severe DPN (Li et al., 2019). DPN can be developed in elderly individuals who have had DM for a long time (Young et al., 1993). Therefore, the duration of DM will be discussed in the below section.

6.3.2.5 Duration of diabetes mellitus (DM)

As mentioned above, both the duration of living with DM and age are considered to be predisposing factors for acquiring neuropathy (Young et al., 1993). A duration of 5 years of DM is sufficient to cause elevated plantar foot pressure, if there are no biomechanical factors involved (Falzon et al., 2017). A long duration of DM might lead to chronic hyperglycaemia, resulting from a decreased lipid, protein and carbohydrate metabolism, which leads to progressing diabetic complications (Lee et al., 2022b) (see chapter two).

There was a significant positive low (r=0.374 – 0.460) correlation between the duration of diabetes and static balance during DLSEON and SLS during the present study, as shown in Table 40 in chapter five. The longer the individual had DM, the poorer the static balance performance at the perimeter during DLSEON and SLS. This result is similar to that reported in the study of Giacomini et al. (1996) that found a significant low positive correlation between the duration of DM and static balance parameters. Regarding WB performance, there was also a significant positive low (r=0.398 – 0.425) correlation between the duration of diabetes and WB performance during DLSEOW 10°; which are the APSI, the percentage of time spent in the outer zone, although the inner time was negatively correlated (r=-0.425), as depicted in Tables 41 and 42 in chapter five of the current study, that was conducted in this thesis. This led to the rejection of the twelfth hypothesis of the third study, that duration of DM will not affect static balance or WB performance. This agrees with the previous study, which found a positive moderate correlation between duration of DM and dynamic balance; as measured by quantifying the sway on foam with eyes open, after controlling for age (Lord et al., 1993).

These results might be explained by the fact that, duration of DM and an elevated haemoglobin A1c might be considered a predisposing factor for acquiring neuropathy (Young et al., 1993). Therefore, the previous literature investigated the correlation between incidence of neuropathy and duration of DM and demonstrated a significant correlation between those two factors, which remained even after adjustments were made for other risk factors and diabetic complications (Tesfaye et al., 2005).

Consequently, acquiring DPN due to a long duration of DM can result in significant skeletal muscle deficits, such as neurogenic muscle atrophy, loss of muscle strength, power and endurance, depending on the severity of the disease (Andreassen et al., 2006). Additionally, recent cognitive impairment research has reported an association between Alzheimer's disease and DM, which has shown an influence in the neurons and glial cells of CNS caused by DM, which consequently could lead to dysfunction and cell death (Muramatsu, 2020) (discussed in chapter two).

Thus, all the factors that are required to maintain balance in the somatosensory and musculoskeletal systems might decline with an increasing duration of DM, resulting in a compromised balance.

6.3.2.6 Severity of diabetic peripheral neuropathy (DPN)

It is essential to consider the severity of diabetic neuropathy, since it might be an independent predictor of a risk of falling in DPN populations with type II DM (Timar et al., 2016) (see chapter two). DPN changes in postural coordination might offer an additional contribution to balance impairment in DPN (Bonnet and Ray, 2011). One complication of severe neuropathy is the loss of foot sole sensation (FSS), which might be one of the earliest clinical signs of the disease (Zhang and Li, 2013). Cutaneous tactile receptors in the soles play an essential role in providing constant feedback about surface characteristics, when it becomes slippery, unstable or irregular during standing and gait (Li et al., 2019). This feedback is transmitted by small cutaneous tactile sensory afferent fibres (SAF), which play a significant role in maintaining balance, because they inform the CNS on how the body's CoM and the CoP are moving relative to the base of support (BoS) (Nardone et al., 2007; Li et al., 2019). Additionally, neuropathic individuals might experience limitations when re-weighting sensory information based on the sensory context, which might lead to vulnerability to falling in specific sensory contexts (Horak, 2006), as discussed in chapter two. Examples of such contexts are walking blindfolded, or with experimentally reduced somatosensation, which requires acute somatosensory reweighting (Li et al., 2019). However, prolonged reweighting might be a consequence of neuroplastic changes to the CNS, caused by chronic impairments in DPN (Li et al., 2019).

Therefore, the present study results, show a significantly low positive (r=0.446, 0.338, 0.379) correlation between severity of DPN and static balance during DLSEON (perimeter and ellipse area), as well as during SLS (ellipse area) as shown in Table 40. This indicates that the presence of DPN, such as a decline in both sensory and motor systems, might relate to poor static balance, because maintaining balance during quiet standing might require sufficient sensory information from intact somatosensory and visual systems, especially with a narrow base of support (Horak, 2006). This led to rejection of the thirteenth hypothesis of the third study, that the severity of neuropathy will not affect static balance. The narrow base of support task was tested by Boucher et al. (1995) to find a correlation between the severity of neuropathy and static balance parameters in three eye conditions; eyes open, closed and in recovery; postural instability was linearly increased with the severity of the DPN. Similarly, decreasing the BoS, such as the semi stance position, might impact static balance parameters among individuals with DPN with confirmed neuropathy ≥ 8, as assessed by the MNSI (Fortaleza et al., 2013). The difficulty with a narrow base of support arises from the smaller distance that CoG can move within the BoS, unlike the wide base of support (Alonso et al., 2012). This narrow base of support requires additional ankle-hip muscles activation to control balance, which is sufficient in young adults (Amiridis et al., 2003). However, muscle weakness and deconditioning are both symptoms of DPN (Kutty and Majida, 2013). Weakness in ankle muscles, especially plantar flexors and dorsiflexors correlated with neuropathic scores (Andreassen et al., 2006). Therefore, the above signs and symptoms might affect individuals with neuropathy and the progressive nature of the disease, potentially contributing to the poor static balance relationship, as balance requires coordination from both the motor and sensory systems and will be affected progressively with the prognosis of the DPN.

These results agree with previous studies, which found that static balance has been previously correlated with the severity of neuropathy (Boucher et al., 1995; Giacomini et al., 1996; Uccioli et al., 1997; Fortaleza et al., 2005; Palma et al., 2013). These studies assessed the severity of neuropathy with various evaluative instruments, such as nerve conduction velocity (Giacomini et al., 1996; Uccioli et al., 1997), clinical tests, such as Valk (Boucher et al., 1995), Diabetic Neuropathy Examination (DNE) (Palma et al., 2013) and MNSI (Fortaleza et al., 2013). Despite the variety of tests and different age ranges (from 35 years old (Giacomini et al., 1996; Uccioli et al., 1997) to 70 years old (Fortaleza et al., 2013), static balance was correlated with the severity of the neuropathy. Furthermore, not only DPN severity was correlated with static balance but also DPN onset time (Aly et al., 2007). Additionally, people with diabetes but without DPN and control groups, were able to maintain an upright posture by assessing static balance (measuring envelop area and length per time) more effectively than the DPN group (Yamamoto et al., 2001).

Regarding SLS, Richardson et al. (1996) established that individuals with DPN were unable to maintain SLS for more than three seconds and showed greater ground reaction forces and CoP excursion, contributing to high rates of falling among individuals with moderate DPN. Similarly, Richardson and Hurvitz (1995) found that individuals with DPN and a history of falling were unable to maintain balance for longer than 3 seconds during the SLS test, which was a shorter time span relative to their control group.

A further study found a significant negative correlation between the severity of neuropathy scores, when assessed by the MNSI (which is similar to the chosen diabetic study scale in the present study, the Toronto Clinical Neuropathy Score) and SLS time (Timar et al., 2016). This shorter time maintaining SLS may be due to the utilisation of the hip strategy, rather than the ankle strategy, to maintain balance in individuals with loss of somatosensory input (Horak et al., 1990). The hip strategy might result in rotational acceleration in the upper and lower segment, which led to an increased ground reaction force as a way to maintain balance (Richardson et al., 1996). A further explanation is that lateral bending around the femoral head will be generated by body weight, because of shifting the centre of gravity away from the supporting leg during single leg stance tasks (Pauwels, 2012). This will result in rotation of the whole body in the opposite direction, due to the conservation of angular momentum, using the “counter rotation” mechanism of segments to enhance the limit of stability, especially when the ankle strategy alone becomes insufficient to control balance (Hof, 2007; Silva et al., 2018), as was described earlier in this chapter and in chapter two. This mechanism was called the hip strategy (Horak and Nashner, 1986).

The hip bending moment is balanced by the coordination of two joints: the hip abductor muscles at the level of hip joint (Kapandji, 2011) and the ankle invertors and evertors at the ankle joint level, which might be considered a component of axial rotation (Liu et al., 2012). Moreover, an additional result of the reduced BoS during SLS is the demand to augment the CNS compared to the double leg stance (Beaulieu et al., 2010). However, in more severe DPN, the CNS might affect neuroplasticity, leading to prolonged re-weighting of sensory information (Li et al., 2019), which might explain the SLS performance result in this present study. This result in the present study found a significant positive low (r=0.379) correlation between static balance during SLS and the severity of the neuropathy, although SLS was assessed by the stabilometric assessment device, unlike other studies that count the time spent during SLS, as shown Table 40 in chapter five. On the other hand, regarding dynamic balance, there was a significant negative correlation between the severity of DPN and the BBS in the two studies (Ghanavati et al., 2012; Timar et al., 2016). Despite both studies using different clinical tests to assess the severity of DPN, where one study utilised MNSI (Timar et al., 2016), the other study utilised DNES scores (Ghanavati et al., 2012). Both authors investigated each item of BBS in depth, and found that single leg stance, tandem standing and forward reaching (P-value < 0.001) were the most challenging tasks, followed by standing unsupported with feet together, sit to stand, stand to sit, transfers, standing unsupported with closed eyes and placing alternative feet on a step or stool while standing unsupported (P-value < 0.05) (Ghanavati et al., 2012). Similarly, the present study revealed a significant low (r=0.382) positive correlation between the severity of DPN and WB performance parameters, during DLSEOW 10 °, which are the percentages of time spent in outer zone, although the percentage of time spent in inner zone was negatively (r=-0.382) correlated, as shown in Table 42, in chapter five. Thus, suggesting that the more severe an individual's DPN, the poorer their WB performance in percentages of time spent in the inner and outer zones during DLSEOW 10°. This might be explained due to the nature of this task when conducted using a WB, as this method necessitates a quick response from the muscles to return CoM with the BoS. However, in individuals with DPN there are signs and symptoms, such as ankle muscle weakness, impairment of the small afferent fibres and reduced ankle torque, all of which are required to maintain balance during perturbation (Nardone and Schieppati, 2004; Andreassen et al., 2006; Salsabili et al., 2011; Li et al., 2019) (see chapter two). Furthermore, there is a reduction in, or loss of, ankle joint proprioception (Li et al., 2019). However, most cases of DPN are progressive and so individuals adapt to proprioceptive impairment by neuroplasticity (Li et al., 2019). This was affirmed here, as the individuals with DPN adapted to the impaired proprioception by adopting a compensatory strategy called deactivation, which refers to stiffening the muscles during the static balance condition to maintain balance. However, this was not the case during unexpected perturbation, where these muscles were released from stiffness, as indicated by the early latency of proximal muscles, such as the gluteus medius and paraspinal muscles (Bloem et al., 2002).

Therefore, due to all previous signs and symptoms of DPN, the correlation between dynamic balance and the severity of DPN has clearly appeared among individuals with DPN. This again led to the rejection of the thirteenth hypothesis of the third study, that severity of neuropathy will not affect WB performance.

It is not only severe DPN that results in postural instability; mild DPN in older women might also create postural instability, more so than in age matched diabetic women without DPN, as decreased ankle torque can develop quickly, failing to return the CoM over the BoS before balance is lost in response to lateral lean force (Gutierrez et al., 2001).

Therefore, it is necessary to assess the severity of DPN when assessing static balance and WB performance. One of the items evaluated when assessing any severity of DPN is neuropathic pain, as will be discussed in the below section.

6.3.2.7 Neuropathic pain

The results of the present study revealed the more severe an individual’s neuropathic pain, the poorer their static balance (perimeter and ellipse area) during DLSEON (low positive correlation r=0.382 – 0.415) and WB performance (percentages of time spent in inner and outer zone) during DLSEON 5° (low positive and negative correlations r=0.491 - -0.491), as shown in Tables 40 and 42, in chapter five. Three studies affirmed this result (Boucher et al., 1995; Daousi et al., 2004; Fortaleza et al., 2013). This led to the rejection of the fourteenth hypothesis of the third study, that neuropathic pain will not affect static balance or WB performance. However, pain in the present study was assessed subjectively by the VAS.

Despite those previous studies, assessing pain with various methods, such as VAS and pain disability index, Valk score and MNSI (Boucher et al., 1995; Daousi et al., 2004; Fortaleza et al., 2013), neuropathic pain was assessed within MNSI, which grades a score ≥ 8 as abnormal and confirmation of DPN (Feldman et al., 1994). Previous authors have found a significant correlation between neuropathic pain and static and dynamic balance in terms of the extent to which chronic pain can interfere with various ADL (Boucher et al., 1995; Daousi et al., 2004; Fortaleza et al., 2013). This indicates that the more severe the peripheral neuropathic pain is in DM, the more severe the disruption experienced by diabetic individuals when engaging in activities, compared to individuals without chronic painful peripheral neuropathy (Daousi et al., 2004). Individuals with DPN and chronic pain reported spending less time exercising than individuals without chronic pain (Butchart et al., 2009), as was discussed earlier in this chapter. Additionally, the correlation between neuropathic pain and static balance indicated that with increased severity of DPN, including neuropathic pain, the postural instability increased linearly (Boucher et al., 1995; Fortaleza et al., 2013). These correlations might be explained by the nature of the pain phenomenon, which is multi-dimensional and comprises cognitive, emotional and physical components (Lee, 1985), as was discussed earlier in this chapter. Considering the physical component, in addition to other signs and symptoms that individuals with DPN complain of (and which are included in the MNSI and Valk scale), effects, such as muscle weakness and loss of proprioception contribute to the correlation between neuropathic pain and balance. Regarding the emotional component, lack of balance confidence due to pain, might lead to an avoidance of activity. Therefore, balance confidence will be explored in the below section.

6.3.2.8 Balance confidence

Balance confidence plays an essential role in PWD, specifically individuals with DPN, especially among the elderly. Lack of confidence to maintain balance might result in activity avoidance during feared or more challenging activities (Hewston and Deshpande, 2018), as was discussed earlier chapter five. Balance confidence can be assessed using the ABC-questionnaire (ABC-16), although there was limited evidence available among diabetic and individuals with DPN (Hewston and Deshpande, 2017). The results on this scale have been reported to be 11% lower in elderly PWD who were fallers than in non-fallers (Hewston and Deshpande, 2017). Thus, it can be used to differentiate between fallers and non-fallers in similar individuals (Lajoie and Gallagher, 2004). However, Schepens et al. (2010) contradicted this finding, reporting that the recent version of this scale (ABC-6), which was derived to save time when identifying 6 items (items 5, 6, 13–16) (Hewston and Deshpande, 2018) that could effectively differentiate between fallers and non-fallers, although the ABC-16 version fails to do so. Thus, the two versions cannot be used interchangeably, and the ABC-6 version is recommended primarily for use in environments that are cold, urban or well-resourced (Tiernan and Goldberg, 2023).

Thus, the present study used the ABC-16 version. The results of the present study showed significant correlations between static balance, WB performance and balance confidence. That means, the lower an individual's confidence when balancing, the poorer their static balance and WB performance during DLSEON and DLSEON 5° respectively, as depicted in Tables 40, 41 and 42, in chapter five. The degree of correlation was low negative (r=-0.471) between balance confidence and the static balance parameter (perimeter) during DLSEON, as depicted in Table 40, in chapter five. Additionally, the degree of correlation was low negative (r=-0.421, -0.471) between balance confidence and the WB performance parameters (APSI, percentage of time spent in the inner and outer zones), except in the inner zone, there was low positive (r=0.471) statistically significant correlation during DLSEON 5°, as shown in Tables 41 and 42, in chapter five. This led to the rejection of the fifteenth of the third study, that balance confidence will not affect static balance or WB performance.

These previous findings agree with two studies which used same ABC-16 version (Cho et al., 2004; Schepens et al., 2010). Balance measurements included the SLS and TUG test. These correlations were significant, where higher balance confidence translated to better balance performance (Cho et al., 2004; Schepens et al., 2010).

This is attributed to the fact that these tasks (narrowing base of support and SLS) require intact somatosensory and visual systems to provide sufficient sensory information (Horak, 2006). However, these systems are not intact in diabetic individuals and those with DPN and so might result in greater postural sway, especially in the elderly rather than young adults (Nagy et al., 2007).

DLSECW 10° was an additional task that correlated with balance confidence in the present study. The degree of correlation was high negative (r=-0.957), which was observed between the WB performance parameter (MLSI) and balance confidence during DLSECW 10°, as shown in Table 41 in chapter five. That means the less confident an individual is, regarding their balance, the poorer their WB performance along the MLSI during DLSECW 10°. This MLSI parameter was found to be unstable in individuals with DPN, which might lead to difficulties performing tasks that require a shift to the ML direction (Ghanavati et al., 2012). The visual system plays an important role in balance control among elderly individuals (Hytönen et al., 1993). Absent or degraded visual or vestibular cues were identified in individuals with DPN relative to age-matched diabetics without neuropathy and healthy control subjects without DM, during quiet standing (Simoneau et al., 1994). Due to the similarities in signs and symptoms between the elderly and individuals with DPN, such as a reduction or loss of proprioception, muscle weakness and joint mobility restrictions (Kutty and Majida, 2013), it is worth reviewing the literature concerning the elderly population to support the diabetic study, as in the below section.

Healthy elderly individuals rely not only on richer sensory information (cutaneous and proprioceptive) during increased sway to replace other sensory inputs (vision) but also maintain their balance by adopting a strategy underpinning a mechanism of muscular co-contraction, as indicated in a low soleus/tibialis anterior EMG ratio (Benjuya et al., 2004). This strategy is adopted by the elderly as a solution to body sway reduction, to deal with threatening conditions, such as closed eyes and narrow base of support (Benjuya et al., 2004). This is based on an agreement with Teasdale et al. (1991), that found the elderly were able to compensate for a lack of visual systems, or a compliant surface, with their remaining sensory organs and thus, a disruption of a single sensory input made it impossible to differentiate consistently between the elderly and young adults.

Additionally, with respect to the application of the ABC scale in the present diabetic study, the baseline mean value was 75.41%, within the range of >50 and <80, is associated with a moderate level of functioning, characteristic of the elderly population and individuals with chronic health conditions, while scores above 80 in the ABC scale are indicative of high functioning in a physically active elderly population (Myers et al., 1998), as was pointed out in chapter two. The present result, below 75.41%, is indicative of a moderate level of physical functioning in older adults with DPN, as shown in Table 25 in chapter five. Additionally, a score < 67% indicates fall risk (Lajoie and Gallagher, 2004) and in the present study there were 13 out of 36 participants who were scored <67% indicating high fall risk, however, after the exercise intervention there was only one participant who was scored <67%. This indicated that this intervention decreased the risk of falling indirectly by increasing the balance confidence scores. However, more direct methods of fall risk assessment are required for future study, such as a structured questionnaire, especially for the elderly over 65 years of age with type II DM, who reported an annual fall incidence rate of 39% (Tilling et al., 2006), as mentioned previously in chapter two. The two strong predictors of falls in PWD, individuals with DPN, particularly with type II DM and the elderly are decreased proprioception and weakness in the lower limbs (Timar et al., 2016; Chatzistergos et al., 2020; Maki and McIlroy, 1996; Masdeu et al., 1997). Thus, muscle strength is an important factor that can be considered when assessing static balance and WB performance, which will be explained in the below section.

6.3.2.9 Ankle muscle strength

Overall, there were significant low (r=-0.396) to moderate (r=-0.504, -0.425, -0.472, -0.457) negative correlations between most ankle muscles on both limbs and static balance (perimeter) during DLSEON, as shown in Table 43 in chapter five. Additionally, there were statistically low negative (r=-0.352) significant correlations between plantar flexors and static balance (ellipse area) during DLSECW on the Lt side only and DLSEON on the Rt side only (r=-0.355), as shown in Table 43 in chapter five. That indicates, the weaker the ankle muscles at baseline, the poorer static balance during DLSECW and DLSEON. Regarding WB performance overall, there were low and moderate (r=-0.415, -0.414, -0.397, -0.405) to high negative (r=-0.903 - -0.880, -0.964) correlations between ankle muscles and WB performance (APSI) during DLSEON 5° and (inner and outer times) during DLSEON 10°, DLSECN 5° and DLSEOW 10°, as shown in Tables 44 and 45 in chapter five. This indicates that the weaker the ankle muscles are at baseline, the poorer WB performance during DLSEON 5°, DLSEON 10°, DLSECN 5° and DLSEOW 10°. This led to the rejection of the sixteenth hypothesis of the third study, that muscle strength will not affect static balance or WB performance.

These findings might be explained by the decline in peripheral nerve function, with both sensory and motor nerve involvement in diabetic and DPN cases, potentially leading to muscle atrophy (Andersen et al., 1997; Bus et al., 2002; Greenman et al., 2005), decline in strength (Andersen et al., 2004; Andreassen et al., 2006), and reduced ability to generate force (Andersen et al., 2004), which are all required for WB performance, as was pointed out in chapter two. Both muscle atrophy and loss of strength have been found to be greater distally in the leg compared to proximally (Andersen et al., 1997; Andersen et al., 2004). Such atrophy might be a consequence of degeneration and demyelination of axons, as indicated by the nerve conduction and amplitude reduction shown in electrophysiology studies (Boulton et al., 2005), as explained earlier in chapter two.

While DM changes in muscle power appear to be detected before those in muscle as discussed previously in chapter two, this loss of muscle force occurs after a loss of muscle mass and quality (Le Corre et al., 2023). Loss of muscle mass, quality, force and strength increase as diabetes worsens and becomes significantly worse when DPN starts (Le Corre et al., 2023). This was evidenced in the ankle dorsiflexors and plantar flexors, as muscle weakness was associated with neuropathy scores (Andreassen et al., 2006); notably, ankle and toe flexors resulted in impairment throughout the course of the disease (Monteiro et al., 2018) (see chapter two).

Returning to the balance impairment, a significant contributory factor might be an altered intrinsic foot muscle action (Bus et al., 2002). Postural change refers to an involuntary movement that is controlled by the extrapyramidal system, responsible for the indirect pathway to the spinal cord via the nucleus of the brainstem (Muramatsu, 2020). In turn, balance is regulated by the interaction between the peripheral and the central nervous systems (Mancini et al., 2020) and both systems appear to be affected in PWD (Muramatsu, 2020), contributing to motor deficits, such as inadequate muscle response leading to balance impairment and increased risk of falling among type II DM individuals (Hewston and Deshpande, 2016) (see chapter two).

Another possible explanation for weakened distal muscles are the greater accumulations of intramuscular fat and a reduced muscle volume (Almurdhi et al., 2016). An accumulation of intramuscular fat in the muscle is associated with an increased muscle stiffness, which eventually affects the contractility of the muscle, resulting in reduced muscle quality and a reduced ability to generate force (Rahemi et al., 2015). Therefore, peripheral neuropathy might not be the only cause of muscle weakness, although muscle disorders, such as increased intramuscular fat deposits due to obesity, might contribute to such a weakness, especially in calf muscles that interfere with physical function among obese PWD and individuals with DPN (Hilton et al., 2008). Thus, ankle muscle strength plays an important role during static balance assessment and WB performance, which have to be assessed pre and post balance training.

6.3.2.10 Conclusion, clinical implications and future studies

The above section explains the relationship between static balance and WB performance and baseline characteristics, which are age, height, weight, anthropometrics measures, duration of DM, severity of DPN, neuropathic pain, balance confidence and ankle muscle strength. It also explores the mechanisms behind these correlations. Therefore, the final aim of this study, which was to understand the relationship between baseline characteristics or confounding factors, static balance and WB performance in PWD and individuals with DPN was successfully achieved. First, the relationship between these baseline characteristics fails to affect static balance assessment among PWD and DPN during most simple tasks. There were some exceptions to this, which are during more complex tasks, that required cortical coordination between sensory and motor nerves, which are deteriorated in PWD and individuals with DPN, especially in the elderly. For example, during assessing static balance with complex tasks, such as DLSEON, DLECW and SLS, clinicians might take into consideration the baseline characterises, such as age, duration of DPN, severity of DPN, balance confidence and muscle strength. Therefore, there is a requirement to consider all previous baseline characterises when assessing static balance during prescribing and providing balance training programme intervention, such as the suggested progressive WB training programme in this thesis. Furthermore, it is recommended to combine clinical static balance assessment with quantifiable objective static balance tests, to obtain better outcomes. For example, use of a stabilometric assessment device and sensors to quantify the trunk movement in future studies. An additional recommendation for future studies, is to utilise EMG to examine the lower limb muscle activity to prove the assumption that muscle activity improves, which is crucial to trigger the reactive balance response required for balancing on a WB. Second, the WB performance was affected by most baseline characteristics, especially when the WB task becomes more challenging. Being older, taller, obese, having DM for a prolonged period, having weakness in the ankle muscles, being less confident and less active makes WB balance performances more difficult, especially when narrowing the base of support, closing eyes and increasing the tilt angle. Finally, the knowledge about the effect of the aforementioned baseline characteristics and confounding factors on static balance and WB performance is important in gaining confidence in clinical decisions making and when assessing and prescribing a WB intervention training programme in PWD and individuals with DPN.

Chapter 7: Conclusion of the thesis

This chapter provides the conclusions derived from the three studies conducted in assessing and training balance through WB, among healthy, elderly, PWD and DPN individuals. These conclusions will explain based on fulfilling the planned aims and objectives of this thesis. It will also highlight the limitations and future scope of the WB assessment and training to enhance balance rehabilitation in healthy, elderly, PWD and DPN individuals.

7.1 Achieving the planned aims and objectives of this thesis.

7.1.1 First aim was to investigate the efficacy of WB training among elderly population.

First, this aim was set based on the gap found in the elderly literature that discussed in chapter three. Therefore, this gap was filled through SR of all previous studies that incorporate WB training to improve balance in elderly population. Methodological qualities of those included studies were checked based on Downs and Black (1998) checklist, which was discussed in further details in chapter three. Results of this SR yielded conflicting findings to support WB training in enhancing balance among same population, however, a modest effect sizes were achieved with multimodal balance assessment tests, such as BBS, with further detail were explained in chapter three also. Finally, this SR findings were compared with previous literature to figure out whether it is supporting or not those SR results, which were discussed in depth in chapter three also. So, first aim was successfully achieved through conducting this SR to answer the first research question which was, does WB training enhance balance in elderly population? The answer was yes.

7.1.2 Second aim was to determine the effect of certain factors that might affect WB performance, as well as static balance assessment, such as biological sex, anthropometric characteristics, footwear, total physical activity and dual tasking on both static balance and WB performance.

First, in order to set standardised or normative values for WB performance and static balance assessment, an observational study was conducted among healthy adults to fulfil this second aim. Procedure and protocols of this experimental study were established and explained in detail in chapter four. The results of this experimental study were demonstrated also in chapter four. Overall females outperformed males in most of tasks with some large effects during both static balance and WB performance. Additionally, DT and footwear produced minimal effect in both static balance and WB performance. Anthropometrics effects with regards to weight was strongly correlated with WB performance. There were moderate correlations between shoulder, waist and hip circumferences with WB performance. All previous findings were discussed in detail in chapter four. Finally, discussing those findings and comparing it with previous literature was explored in chapter four. This study was achieving its aim which was to understand deeply the effect of all previous factors in order to achieve the optimal approach of static balance assessment and intervention, as well as WB assessment and training which are essential in any physiotherapy and clinical practice.

7.1.3 Third aim is to design a novel 6-week of progressive WB training in PWD and DPN individuals and determine the effect of this novel training and provide an explanation for this effect.

First, in order to design this training program, a deep understanding of Prokin machine (252) that assemble WB performance was gained, this can be found in detail in chapter five. Then, deep digging in the WB literature to understand how previous researcher performed their training. Further digging in diabetic and DPN literature was conducted in chapter five in order to understand why balance affected among those population and how previous researcher train them and this can be found in chapter five also. After gaining all literature required for designing this novel training program, a design was planned and explored its efficacy through, an experimental study which was conducted among PWD and DPN individuals to fulfil this third aim. This experimental study was demonstrated in further depth in chapter five. Throughout this training, certain parameters were assessed pre and post training and on bi-weekly basis, such as static balance, WB performance, ankle muscle strength, severity of neuropathy, neuropathic pain, balance confidence, and physical activity level. All those parameters were explained and justified in chapter five and how to be conducted were demonstrated in the chapter five also. Results of this novel training program were shown in chapter five also. Finally, generally, there were improvements in most of parameters and the mechanisms beyond this improvement were discussed in chapter five also.

7.2 Limitations and future scope

There were number of limitations in each study as the following.

7.2.1 First study, which was the SR study had several limitations, as the following.

First, it is important to bear in mind the possible selection bias due to involving studies written in English only in this review. Second, with the relatively small number of included studies, that provided small sample sizes, caution must be applied, as the findings might not be generalised, and the impact of synthesis might be reduced. Third, due to Covid circumstance, this year was changing the plan from conducting the study in UK to be shifted in Saudi Arabia, but this period was the product of this SR, due to lock down period at that time. Final limitation is that, only healthy older adults were included in this study, limiting the generalisability to other populations. Further studies might include larger sample sizes. Recommendation to integrate DT during WB training in the elderly population with specifying goal of fall prevention. Final recommendation is to investigate whether specific types of cognitive task during WB training can enhance balance and thereby reduce falls in the elderly.

7.2.2 The second study, which was the observational study conducted among healthy adults.

The population of this study might be taken into consideration when interpreting the findings of this study with caution taken when applying these findings to other population. Due to the nature of this study that required repetitive tasks, a learning effect of fatigue might be achieved, which might impact the findings, but this is likely to be minimised because of randomisation of the task allocation. It is still unknown why certain tasks were influenced by DT, whereas other not. Future research can concentrate on figuring out the possible mechanisms underlying DT cost during WB performance. Additional future research might compare different footwear and different DT. Final recommendation is recruiting different populations who are vulnerable to falling or have balance impairments, in the same previous study to figure out whether they will have the same response or effect of healthy adults or not.

7.2.3 The third study, which was the experimental study conducted among PWD and DPN individuals.

This experimental study had several limitations. First, WB is unstable surface that might raise the possibility of falling. Thus, this problem was solved by adding harness to every participant to provide sense of safety. Second, muscle strength was measured with a hand-held dynamometer, which gives a more precise measurement than manual muscle testing. However, the reliability and accuracy of the measurement may be limited by the investigator's ability to hold the dynamometer stationary and by the fact that participants may overpower the testers. Thus, investigators tried to minimise this problem by ensuring that the same person always carried out the tests (Allet et al., 2010). Third, trunk sensor was not used, although core muscles might assist in balance. Thus, future study might take into consideration to measure trunk movement by placing trunk sensors. Additionally, no long term follows up was provided that might guide on how to get standard of WB training, how to keep improvement and prevent decline. Therefore, future studies may extend period of follow up and monitor when decline will appear or when there is ceiling effect, since this study did not show any ceiling effect. Furthermore, high dropout was a problem in this study. So, encouraging the commitment of completing the whole training programs will advise to be taken place. Moreover, due to the Saudi rules, this study was required to be registered as clinical trials in the Saudi Food and Drugs Authority (SFDA). So, this delay the conducting of this study, but adding a credit to be registered in this authority as found in appendix 5. Additionally, there were some outliers detected from the Prokin, but it was solved by applying interquartile rule. However, it is recommended in the future, to use other device such as instrumented WB, that can be provided to patient individually, to enhance their commitment by doing all prescribed WB exercises at home, as well as utilising EMG to examine the lower limb muscle activity to prove the assumption of muscle activity improvement, that is fundamental to trigger the reactive balance response, required for balancing on WB. In addition, effect of this training program in quality of life might be taken into consideration in the future study. Utilisation of technology was recommended by the ADA to monitor blood glucose and improve quality of life (Johnson et al., 2019) and proved beneficial, especially during the Covid lock down period (Elsayed et al., 2023). Examples of this technology is the use of wearable sensor (AlShorman et al., 2021). However, there are some of limitations or weakness, such as the high cost of continuous monitoring, sensor calibration, energy efficiency and patient acceptance (AlShorman et al., 2021). Therefore, professional medial engineers are required to overcome some of these complications. Additional source for promote physical activity among PWD individuals is the online courses, which are so many available online and proved to be successful for providing lifestyle counselling to help with weight loss and physical activity motivation (Chao et al., 2019). Additional resources for improving activities in PWD, might involve the use of an educational booklet (Monteiro et al., 2020).

Finally, it is recommended to use other dynamic clinical balance tests, to determine the effect of this training program in other dimensions, such as functional ability and gait, as well as to recruit other neurological individuals, such as stoke or multiple sclerosis, or other neurological conditions, who are vulnerable to falling or have balance impairment and figure out the effect of this training programs on those individuals, but ensure safety measures by the addition of harness and a therapist or assistant must standing beside the participant in case he/she loses his/her balance.

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Appendix

Appendix 1: Functional assessment tests adopted from (Mancini and Horak 2010; Iverson and Koehle 2013).

Balance functional test	Content	Advantages	Disadvantages
Berg Balance Test (BBS) (Berg et al., 1995)	• 14-item functional activities ranging from sitting to standing to performing postural transitions, rated from 0 to 4 points with a maximum score of 56. • Increased risk of falling is associated with a score of less than 45 (Mancini and Horak, 2010).	• It takes just 15 minutes (Mancini and Horak, 2010). • High reliability in terms of inter-rater reliability (98% agreement) (Mancini and Horak, 2010). • Good specificity in terms of 96% of correct non-fallers classification (Mancini and Horak, 2010).	• Unable to determine type of balance disorder (Mancini and Horak, 2010). • Low sensitivity in terms of falls – only 53% were identified (Mancini and Horak, 2010). • There is no assessment of dynamic balance during both gait or sensory conditions (Mancini and Horak, 2010). • Ceiling effect (Mancini and Horak, 2010).
Tinetti Balance and Gait Assessment (Tinetti, 1986) also called Performance Oriented Mobility Assessment (POMA)	• Consists of two tests: balance with 14 items, and gait, with 10 items. • It can predict falls in the elderly at least once in the next year (Mancini and Horak, 2010) . • Maximum score is 40. • Increased risk of falling is associated with a score of less than 36 (Mancini and Horak, 2010).	• It consumes 20 minutes (Mancini and Horak, 2010). • High reliability in terms of inter-rater reliability (85% agreement) (Mancini and Horak, 2010). • Good sensitivity, 93% fall identification (Mancini and Horak, 2010).	• Unable to determine type of balance disorder (Mancini and Horak, 2010). • Low specificity in terms of non-falls, only 11% were identified (Mancini and Horak, 2010). • Ceiling effect (Mancini and Horak, 2010) .

Balance functional test	Content	Advantages	Disadvantages
Timed Up and Go test (TUG) (Mathias et al., 1986)	• Consists of sitting on a chair, rising up, walking 3 metres, turning around, walking back and sitting down. • All the activities are measured by a stopwatch. • Increased risk of falling is associated with a time more than 13.5 minutes.	• It takes just 3 minutes, it is simple and widely used (Mancini and Horak, 2010). • High reliability in terms of inter-rater reliability (ICC=0.99) and test-retest (ICC=0.99) (Mancini and Horak, 2010). • Can predict falls (Mancini and Horak, 2010) .	• Unable to determine type of balance disorder (Mancini and Horak, 2010). • Limited to only one functional activity, hence it not comprehensive (Mancini and Horak, 2010). • Ceiling effect (Mancini and Horak, 2010).
One-leg-stance (Fregly and Graybiel, 1968). Or Single leg stance (SLS).	• Consists of standing unassisted on one leg with eyes open and arms at hips (Fregly and Graybiel, 1968). • Time is measured from raising foot by flexing knee to time when foot touches the ground or the arm leaves hips (Fregly and Graybiel, 1968). • Increased risk of falling is associated with inability to perform one-leg stance for at least 5 seconds (Fregly and Graybiel, 1968).	• It takes just 1 minute(Mancini and Horak, 2010). • High reliability in terms of inter-rater reliability (ICC=0.75 in disability-free elderly) and (ICC=0.85 in disabled elderly) (Mancini and Horak, 2010). • Inter-subject reliability (ICC=0.73) (Mancini and Horak, 2010).	• Unable to determine type of balance disorder (Mancini and Horak, 2010). • Unrelated continuously to fall (Mancini and Horak, 2010). • Limited to one task of static balance assessment (Mancini and Horak, 2010).
Functional reach test (FRT) (Duncan et al., 1990)	• Consists of measuring the maximum distance a subject can reach beyond the arm's length in a condition of maintaining base of	• It takes just 1 minute (Mancini and Horak, 2010). • High reliability in terms of inter-rater reliability (ICC=0.98) and	• Unable to determine type of balance disorder (Mancini and Horak, 2010).

Balance functional test	Content	Advantages	Disadvantages
	support (BOS) while standing (Duncan et al., 1990). ● Increased risk of falling is associated with a reach ≤6 inches (Fregly and Graybiel, 1968).	test-retest reliability (ICC=0.92) (Mancini and Horak, 2010). ● High validity in terms of susceptible fall subjects (Mancini and Horak, 2010).	● Limited to one task only (Mancini and Horak, 2010). ● Not dependent on centre of mass (COM) or centre of pressure (COP) limits of stability (Mancini and Horak, 2010).
Balance Evaluation Systems Test (BESTest) (Horak et al., 2009)	● Consists of 36 items, subdivided into six systems as follows: ● biomechanical constraints, stability limits, anticipatory postural adjustment, postural responses, sensory orientation, and stability in gait (Horak et al., 2009) ● Each item is scored on 4-point scale according to performance, from 0 (worst performance) to 3 (best performance).	● Ability to determine type of balance disorder based on systems (Mancini and Horak, 2010) ● Ability to focus treatment based on type of balance disorder (Mancini and Horak, 2010). ● High reliability in terms of inter-rater reliability (ICC=0.91) (Mancini and Horak, 2010).	● Time-consuming, taking 30 minutes. However, there is a new, short version, which takes just 10 minutes, called mini BESTest (Mancini and Horak, 2010). ● It requires equipment (Mancini and Horak, 2010).
Balance Error Scoring System (BESS) (Iverson and Koehle, 2013)	● Consists of three stances: 1)-Narrow double-leg stance, 2)-Single-leg stance, and 3)-Tandem stance All the above stances are performed on various surfaces: firm surface/floor or medium density foam.	● A rapid, cost-effective screening test of postural stability, especially static standing. ● It can be utilised in reporting deficits, following up on progression of injury, or tracking impairments in neurological condition (Iverson and Koehle,	● Results interpretation is based on subjective clinical judgement (Iverson and Koehle, 2013).

Balance functional test	Content	Advantages	Disadvantages
	• Each stance is maintained for 20 seconds with eye closure. • An error is scored if any of the following actions takes place: opening eyes, lifting hands off hips, stepping, stumbling or falling out of position, lifting forefoot or heel, abducting the hip by more than 30 degrees, or failing to return to the original test position within five seconds (Bell et al., 2011; Iverson and Koehle, 2013)	2013).It has good reliability and validity (Bell et al., 2011).	
Physiological Profile Approach (PPA) (Lord and Clark, 1996)	• Consists of six tests to measure the following: vision, peripheral sensation, strength, vestibular function test, reaction time and postural sway. • Scores are rated according to risk of falling as the following: Mild risk of falling, scores between 0-1. Moderate risk of falling, scores between 1-2. • High risk of falling, scores above 2.	• Ability to determine type of balance disorder depends on underlying physiological system (Mancini and Horak, 2010). • Good reliability in terms of test-retest reliability (ICC=0.51-0.97) and inter-rater reliability for proprioception 0.70 and for tactile sensitivity 0.81 (Mancini and Horak, 2010).	• Time consuming, taking 30 minutes. • It requires equipment (Mancini and Horak, 2010). • There is no functional task measurement, and it is not dependent on CoM or CoP limits of stability (Mancini and Horak, 2010).

Appendix 2: Ethical approval for observational study conducted in healthy participants to explore the impact of biological sex, anthropometrics, footwear, dual task (DT) and physical activity level on static balance assessment and WB performance.

Kingdom of Saudi Arabia
Ministry of Education
Princess Nourah bint Abdulrahman University
(048)
Graduate Studies and Scientific Research Vice- Rectorate

المملكة العربية السعودية
وزارة التعليم
جامعة الأميرة نورة بنت عبدالرحمن
(٠٤٨)
وكالة الجامعة للدراسات العليا والبحث العلمي

IRB Registration Number with KACST, KSA: H-01-R-059

October 25, 2020
IRB Log Number: 20-0392
Project Title: Measuring balance in young healthy adults by tracking center of pressure
Category of Approval: EXEMPT

Dear Mrs. Madawi ALJawaee and Dr. Afrah ALMuwais,

Thank you for submitting your proposal to the PNU Institutional Review Board. Your proposal was evaluated considering the national regulations that govern the protection of human subjects. The IRB has determined that your proposed project poses no more than minimal risk to the participants. Therefore, your proposal has been deemed ***EXEMPT*** from IRB review. Please note that this approval is from the research ethics perspective only. You will still need to get permission from the head of the department in PNU or an external institution to commence data collection.

Please note that the research must be conducted according to the proposal submitted to the PNU IRB. If changes to the approved protocol occur, a revised protocol must be reviewed and approved by the IRB before implementation. For ***any*** proposed changes in your research protocol, please submit a Request for Modification form to the PNU IRB. Please be aware that changes to the research protocol may prevent the research from qualifying for exempt review and require submission of a new IRB application or other materials to the PNU IRB. In addition, if an unexpected situation or adverse event happens during your investigation, please notify the PNU IRB as soon as possible. If notified, we will ask for a complete explanation of the event and your response.

Please be advised that regulations require that you submit a progress report on your research every 6 months. Please refer to the protocol number denoted above in all communication or correspondence related to your application and this approval. You are also required to submit any manuscript resulting from this research for approval by IRB before submission to journals for publication.

The researcher/s is/are personally liable for plagiarism and any violations of intellectual property rights.

For statistical services you are advised to contact the Data Clinic at the Health Sciences Research Center (hsrc-DC@pnu.edu.sa) or the Scientific Research Center at the Deanship of Scientific Research (dsr-rsc@pnu.edu.sa) extension 30711.

We wish you well as you proceed with the study. Should you have additional questions or require clarification of the contents of this letter, please contact me.

You can apply for research funding at (DSR-RS@pnu.edu.sa).

Sincerely Yours,

جامعة الأميرة نورة بنت عبدالرحمن
مجلس المراجعة المؤسسي
Institutional Review Board (IRB)
25 OCT 2020

Prof. Omar Hasan Kasule

Prof. Omar H. Kasule Sr.
Chairman, Institutional Review Board (IRB)
Princess Nourah bin Abdulrahman University, Riyadh, KSA
Tel: +966 548867916
E-mail: irb@pnu.edu.sa; ohkasule@pnu.edu.sa

الرقم: .... التاريخ: ..../..../....١٤ هـ المشفوعات: ....

Appendix 3: Ethical approval for experimental study conducted in in people with diabetes mellitus diabetic peripheral neuropathic to determining the effect of a progressive six-week of WB training programme on balance.

Kingdom of Saudi Arabia
Ministry of Education
Princess Nourah bint Abdulrahman University
(048)
Graduate Studies and Scientific Research Vice- Rectorate

المملكة العربية السعودية
وزارة التعليم
جامعة الأميرة
نورة بنت عبدالرحمن
(٠٤٨)
وكالة الجامعة للدراسات العليا والبحث العلمي

IRB Registration Number with KACST, KSA: HAP-01-R-059

April 19, 2022

IRB Log Number: 22-0113
Project Title: 'Novel assessment and intervention to improve balance and assess peripheral neuropathy in diabetic peripheral neuropathic patients.'
Category of Approval: FULL REVIEW

Dear Madawi ALJawaee, Dr. Michael Jones, Dr. Jonathan Williams, and Dr. Peter Theobald,

Thank you for submitting your proposal to the PNU Institutional Review Board. Your proposal was evaluated considering the national regulations that govern the protection of human subjects. The IRB has determined that your proposed project poses minimal risk to the participants. Therefore, your proposal has been deemed ***FULL*** from IRB review. Please note that this approval is from the research ethics perspective only. You will still need to get permission from the head of the department in PNU or an external institution to commence data collection.

Please be informed that in conducting this study, you as the Principal Investigator are required to abide by the rules and regulations of the Government of Saudi Arabia, the PNU/IRB policies and procedures, and the ICH Good Clinical Practice guidelines. You also need to notify the IRB as soon as possible in the case of any amendments to the project, termination of the study, any serious unexpected adverse events, or any event or new information that may affect the benefit/risk ratio of the proposal. For any proposed changes in your research protocol, please submit a Request for Modification form to the PNU/IRB. Please be aware that changes to the research protocol may prevent the research from qualifying for full review and require submission of a new IRB application or other materials to the PNU/IRB.

Please be advised that regulations require that you submit a progress report on your research every 6 months. Please refer to the protocol number denoted above in all communication or correspondence related to your application and this approval. You are also required to submit any manuscript resulting from this research for approval by IRB before submission to journals for publication.

Clinical trials require approval by SFDA before commencing data collection. This approval can be before, after or parallel to IRB approval. In addition, the trial must be registered at the Saudi Clinical Trials Registry at https://sctr.sfda.gov.sa/.

The researcher is personally liable for plagiarism and any violations of intellectual property rights.

IRB is not responsible for accuracy of statements on religious and cultural affairs so researchers must consult competent authorities.

For statistical services you are advised to contact the Data Clinic at the Health Sciences Research Center (hsrc-DC@pnu.edu.sa) or the Scientific Research Center at the Deanship of Scientific Research (dsr-rsc@pnu.edu.sa) extension 30711.

الرقم: .... التاريخ: ....../....../....١٤هـ المشفوعات: ....

We wish you well as you proceed with the study. Should you have additional questions or require clarification of the contents of this letter, please contact me.

Sincerely Yours,

جامعة الأميرة نورة بنت عبدالرحمن
مجلس المراجعة المؤسسي
Institutional Review Board (IRB)
19 APR 2022

Prof. Omar H. Kasule Sr.
Chairman, Institutional Review Board (IRB)
Princess Nourah bin Abdulrahman University, Riyadh, KSA
Tel: +966 548867916
E-mail: irb@pnu.edu.sa; ohkasule@pnu.edu.sa

الرقم: .... التاريخ: ....../....../......١٤ هـ المشفوعات: ....

Appendix 4: Food and Drug Authority (SFDA) approval to register thesis's study as clinical trial in Saudi Arabia.

Executive Department of Medical Devices Evaluation
Medical Devices Sector

الإدارة التنفيذية لتقييم الأجهزة الطبية
قطاع الأجهزة والمستلزمات الطبية

خطاب عدم ممانعة

No Objection Letter

Application Number:	2207	رقم الطلب:
Issuing Date:	10/05/2022	تاريخ الإصدار:

This letter is issued in accordance with the medical devices law and executive regulation.

أصدر هذا الخطاب بموجب نظام الأجهزة والمستلزمات الطبية ولائحته التنفيذية.

This letter allows **princess Nourah Bint Abdulrahman university** to conduct the following clinical trial:

هذا الخطاب يخول **جامعة الأميرة نورة** بإجراء الدراسة السريرية التالية:

Title	**Novel assessment and intervention to improve balance and assess peripheral neuropathy in DPN patients**	عنوان الدراسة
Product	**Prokin 252**	المنتج
Manufacturer	**TecnoBody S.r.l.**	الشركة المصنعة
Location	**King Abdullah bin Abdulaziz University Hospital (KAAUH), Riyadh**	موقع الدراسة

Note:

- The clinical trial shall be conducted in accordance with the "Requirements for Clinical Trials of Medical Devices" published on SFDA website.
- The applicant shall comply with requirements and regulations of other relevant authorities.

ملاحظة:

- يجب الالتزام بإجراء الدراسة السريرية وفق ما ورد في "متطلبات الدراسات السريرية للأجهزة والمستلزمات الطبية" المنشورة على موقع الهيئة.
- يجب التقيد بمتطلبات وأنظمة الجهات المعنية الأخرى ذات العلاقة.

المدير التنفيذي لتقييم الأجهزة الطبية
Executive Director of Medical Devices Evaluation

د. عبداللطيف بن سليمان الوطبان
Abdullatif S. AlWatban, Ph.D.

Appendix 5: A safety harness worn by one of the diabetic participants after his permission.

Appendix 6: Protecting human research participants online training certificate.

CERTIFICATE

OF COMPLETION

PHRP Online Training, Inc. certifies that

Madawi ALJawaee

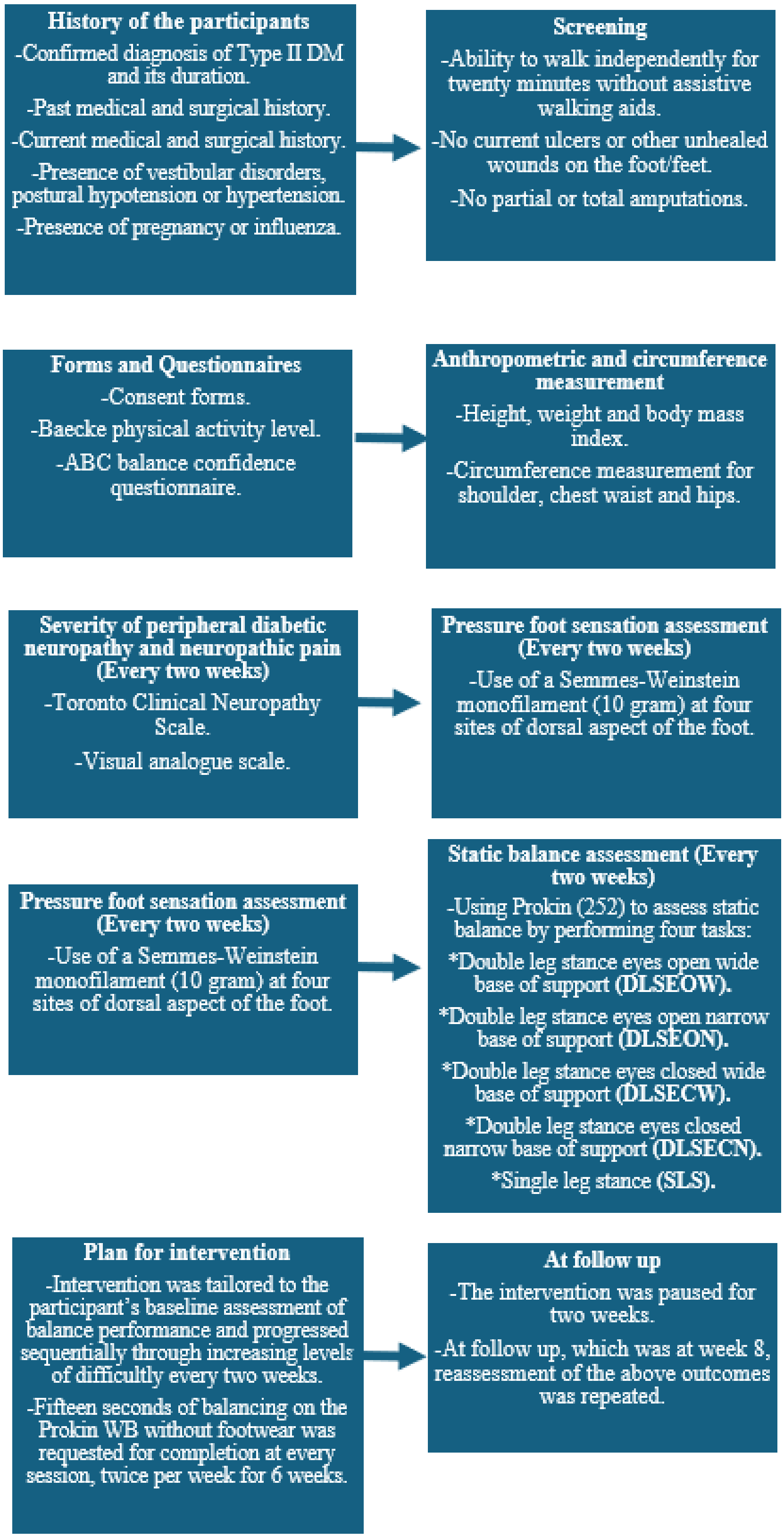
has successfully completed the web-based course "Protecting Human Research Participants Online Training."

Date Completed: **2020-10-23** Certification Number: **2858895**

PHRP
Protecting Human
Research Participants
Online Training

Appendix 7: Medical hammer, used to assess reflexes in people with diabetes and diabetic peripheral neuropathy.

Appendix 8: Flow chart showing the participants' journey through the experimental process.



Appendix 9: Spearman's rho (r) correlation between static balance assessment (Perimeter and Ellipse area) and anthropometric characteristics and physical activity level.

	Height (r)	Weight (r)	Shoulder circumference (r)	Waist circumference (r)	Hip circumference (r)	Shoulder-Waist Ratio (r)	Shoulder-Hip Ratio (r)	Physical Activity level (r)
With footwear								
DLSEOS Perimeter	**.398***	**.317***	**.338***	**.392***	.149	-**.333***	.159	.103
DLSEOS Ellipse Area	**.359***	**.394***	**.320***	**.370***	**.326***	-**.315***	-.018	.131
DLSECS Perimeter	**.436***	**.339***	**.368***	**.416***	.114	-**.374***	.207	.110
DLSECS Ellipse Area	**.373***	**.341***	.277	.299	.178	-.280	.023	.147
SLSS Perimeter	.286	.217	.294	.296	.061	-.256	.195	.038
SLSS Ellipse Area	**.412***	.278	.295	.259	.082	-.169	.240	.185
Without footwear								
DLSEOUS Perimeter	.260	**.338***	**.398***	**.380***	.217	-**.356***	.053	.075
DLSEOUS Ellipse Area	.285	**.427***	**.320***	**.368***	**.358***	-**.338***	-.037	.146
DLSECUS Perimeter	**.487***	**.414***	**.477***	**.480***	.190	-**.361***	.240	.132
DLSECUS Ellipse Area	**.385***	**.347***	**.328***	**.355***	.194	-.285	.134	.117
SLSUS Perimeter	**.344***	.189	**.309***	.297	.019	-.237	.237	.031
SLSUS Ellipse Area	.253	.222	.209	.260	.074	-.282	.108	-.024
Dual task								
DLSEODTS Perimeter	.252	.135	.152	.201	-.044	-.212	.239	.012
DLSEODTS Ellipse Area	.251	.218	.161	.184	.096	-.179	.113	-.041

	Height (r)	Weight (r)	Shoulder circumference (r)	Waist circumference (r)	Hip circumference (r)	Shoulder-Waist Ratio (r)	Shoulder-Hip Ratio (r)	Physical Activity level (r)
DLSEODTUS Perimeter	0.135	.122	.051	.118	.062	-.183	.040	.022
DLSEODTUS Ellipse Area	0.064	.132	.002	.060	.142	-.132	-.089	.075
DLSECDTS Perimeter	**.380***	**.331***	**.363***	**.404***	.124	**-.341***	.187	.073
DLSECDTS Ellipse Area	**.320***	**.350***	.287	**.357***	.177	**-.348***	.078	.088
DLSECDTUS Perimeter	.246	.117	.128	.191	-.056	-.191	.209	.122
DLSECDTUS Ellipse Area	0.195	.215	.107	.192	.083	-.213	.044	.189
SLSDTS Perimeter	**.325***	.185	.228	.243	.046	-.201	.152	-.066
SLSDTS Ellipse Area	.269	.156	.148	.136	.030	-.104	.155	.036
SLSDTUS Perimeter	**.370***	.272	**.322***	**.340***	.137	-.257	.188	-.072
SLSDTUS Ellipse Area	**.313***	**.381***	**.308***	**.377***	.241	**-.330***	.077	.011

r; spearman's rho correlation, DLSEOS; double leg stance eyes open shod, which refers to with footwear, DLSECS; double leg stance eyes closed shod, SLSS; single leg stance shod, DLSEOUS; double leg stance eyes open unshod, that refers to without footwear, DLSECUS; double leg stance eyes closed unshod, SLSUS; single leg stance unshod, DLSEODTS; double leg stance eyes open dual tasking shod, DLSEODTUS; double leg stance eyes open dual tasking unshod, DLSECDTS; double leg stance eyes closed dual tasking shod, DLSECDTUS; double leg stance eyes closed dual tasking unshod, SLSDTS; single leg stance dual tasking shod, SLSDTUS; single leg stance dual tasking unshod, * significant at $p \leq 0.004$.

Appendix 10: Spearman's rho (r) correlation between wobble board performance (stability indices) and anthropometric characteristics and physical activity level.

	Height r	Weight r	Shoulder circumference r	Waist circumference r	Hip circumference r	Shoulder-Waist Ratio r	Shoulder-Hip Ratio r	Physical Activity level r
Shod								
DLSEOS APSI	.367*	.678*	.529*	.560*	.579*	-.486*	-.075	.101
DLSEOS MLSI	.326*	.639*	.391*	.496*	.590*	-.501*	-.251	.109
DLSEOUS APSI	.522*	.667*	.586*	.591*	.469*	-.477*	.090	.147
DLSEOUS MLSI	.445*	.641*	.472*	.552*	.493*	-.500*	-.059	.166
DLSECS APSI	.484*	.625*	.560*	.570*	.517*	-.491*	.012	.208
DLSECS MLSI	.557*	.615*	.585*	.586*	.401*	-.446*	.108	.221
Unshod								
DLSECUS APSI	.458*	.659*	.556*	.621*	.504*	-.557*	-.006	.103
DLSECUS MLSI	.464*	.595*	.551*	.554*	.421*	-.450*	.097	.125
SLSS APSI	.287	.561*	.410*	.431*	.441*	-.354*	-.005	.207
SLSS MLSI	.281	.528*	.390*	.428*	.502*	-.381*	-.153	.127
SLSUS APSI	.311*	.652*	.465*	.514*	.532*	-.442*	-.087	.206
SLSUS MLSI	.235	.406*	.292	.377*	.340*	-.360*	-.101	-.048
Dual task								
DLSEODTS APSI	.409*	.602*	.510*	539*	.563*	-.439*	-.083	.131
DLSEODTS MLSI	.327*	.577*	.426*	.429*	.525*	-.373	-.139	.165

	Height r	Weight r	Shoulder circumference r	Waist circumference r	Hip circumference r	Shoulder-Waist Ratio r	Shoulder-Hip Ratio r	Physical Activity level r
DLSEODTUS APSI	**.415***	**.572***	**.507***	**.546***	**.480***	**-.453***	.008	.152
DLSEODTUS MLSI	**.312***	**.562***	**.460***	**.428***	**.473***	**-.306***	-.036	-.011
DLSECDTS APSI	**.369***	**.649***	**.550***	**.629***	**.570***	**-.569***	-.055	.157
DLSECDTS MLSI	**.497***	**.591***	**.609***	**.534***	**.426***	**-.358***	.124	.107
DLSECDTUS APSI	**.465***	**.665***	**.612***	**.665***	**.554***	**-.581***	.010	.072
DLSECDTUS MLSI	**.479***	**.597***	**.489***	**.535***	**.411***	**-.488***	.025	.091
SLSDTS APSI	.285	**.557**	**.454***	**.406***	**.521***	-.270	-.055	.276
SLSDTS MLSI	**.357***	**.476***	**.369***	**.350***	**.374***	-.280	-.039	.018
SLSDTUS APSI	**.342***	**.456***	**.310***	**.309***	**.358***	-.264	.000	.205
SLSDTUS MLSI	.269	**.558***	**.378***	**.477***	**.496***	**-.459***	-.179	-.037

APSI; Anteroposterior stability index, MLSI; Mediolateral stability index, r; spearman's rho correlation, DLSEOS; double leg stance eyes open shod, DLSEODTS; double leg stance eyes open dual tasking shod, DLSECS; double leg stance eyes closed shod, DLSECDTS; double leg stance eyes closed dual tasking shod, SLSS; single leg stance Shod, SLSDTS; single leg stance dual tasking shod, SLSUS; single leg stance unshod, SLSDTUS; single leg stance dual tasking unshod, DLSEOUS; double leg stance eyes open unshod, DLSEODTUS; double leg stance eyes open dual tasking unshod, DLSECUS; double leg stance eyes closed unshod, DLSECDTUS; double leg stance eyes closed dual tasking unshod, * significant at p≤0.004 level.

Appendix 11: Spearman's rho (r) correlation between wobble board performance (percentages of time in inner and outer zones) and anthropometric characteristics and physical activity level.

	Height r	Weight r	Shoulder circumference r	Waist circumference r	Hip circumference r	Shoulder-Waist Ratio r	Shoulder-Hip Ratio r	Physical Activity level r
Shod								
DLSEOS % time in inner zone	-.104	**-.499***	-.202	**-.329***	**-.549***	**.385***	**.388***	.050
DLSEOS % time in outer zone	.089	**.489***	.193	**.320***	**.545***	**-.377***	**-.395***	-.055
DLSECS % time in inner zone	**-.407***	**-.576***	**-.463***	**-.491***	**-.485***	**.422***	.073	-.173
DLSECS % time in outer zone	**.386***	**.584***	**.475***	**.476***	**.512***	**-.391***	-.083	.253
SLSS % time in inner zone	-.041	-.297	-.092	-.104	**-.340***	.122	.268	.137
SLS % time in outer zone	.047	.282	.077	.092	**.314***	-.114	-.257	-.138
Unshod								
DLSEOUS % time in inner zone	**-.309***	**-.543***	**-.355***	**-.434***	**-.458***	**.399***	.120	-.058
DLSEOUS % time in outer zone	**.304***	**.539***	**.349***	**.435***	**.452***	**-.408***	-.122	.072
DLSECUS % time in inner zone	-.242	**-.464***	**-.319***	**-.407***	**-.427***	**.425***	.125	.001

	Height r	Weight r	Shoulder circumference r	Waist circumference r	Hip circumference r	Shoulder-Waist Ratio r	Shoulder-Hip Ratio r	Physical Activity level r
DLSECUS % time in outer zone	.197	**.439***	.275	**.358***	**.437***	**-.389***	-.180	-.026
SLSUS % time in inner zone	-.070	**-.389***	-.178	-.270	**-.405***	.272	.247	.105
SLSUS % time in outer zone	.075	**.390***	.173	.273	**.406***	-.280	-.250	-.103
Dual task								
DLSEODTS % time in inner zone	-.117	**-.353***	-.160	-.165	**-.422***	.144	.274	.046
DLSEODTS % time in outer zone	.125	**.356***	.165	.165	**.417**	-.140	-.261	-.035
DLSECDTS % time in inner zone	-.210	**-.458***	**-.337***	**-.385***	**-.481***	**.350***	.210	.049
DLSECDTS % time in outer zone	.191	**.451***	**.347***	**.345***	**.489***	-.278	-.214	.027
SLSDTS % time in inner zone	-.012	-.291	-.097	-.053	**-.314***	.025	.208	.100
SLSDTS % time in outer zone	.020	.290	.108	.060	**.311***	-.027	-.196	-.125
DLSEODTUS % time in inner zone	-.101	**-.410***	-.272	-.232	**-.414***	.140	.146	.114
DLSEODTUS % time in outer zone	.104	**.410***	.271	.235	**.409***	-.142	-.137	-.116

	Height r	Weight r	Shoulder circumference r	Waist circumference r	Hip circumference r	Shoulder-Waist Ratio r	Shoulder-Hip Ratio r	Physical Activity level r
DLSECDTUS % time in inner zone	-.230	**-.546***	**-.370***	**-.414***	**-.512***	**.382***	.194	.133
DLSECDTUS % time in outer zone	.255	**.561***	**.383***	**.438***	**.517***	**-.401***	-.184	-.127
SLSDTUS % time in inner zone	.103	-.178	.081	.044	-.263	.008	**.325***	.089
SLSDTUS % time in outer zone	-.104	.156	-.094	-.064	.232	.016	**-.308***	-.082

% Inner time; percentage of time tilt in inner zone, % outer time; percentage of time tilt in outer zone, r; spearman's rho correlation, DLSEOS; double leg stance eyes open shod, DLSEODTS; double leg stance eyes open dual tasking shod, DLSECS; double leg stance eyes closed shod, DLSECDTS; double leg stance eyes closed dual tasking shod, SLSS; single leg stance Shod, SLSDTS; single leg stance dual tasking shod, SLSUS; single leg stance unshod, SLSDTUS; single leg stance dual tasking unshod, DLSEOUS; double leg stance eyes open unshod, DLSEODTUS; double leg stance eyes open dual tasking unshod, DLSECUS; double leg stance eyes closed unshod, DLSECDTUS; double leg stance eyes closed dual tasking unshod, * significant at p≤0.004 level.

Appendix 12: Mean, standard deviation (SD), mean of change, SD of change, percentage of change and effect sizes for ankle muscle strength for all assessment weeks (which were at T0, T1, T2, T3 and T4).

Muscle being tests	Side of the muscle	Week of assessment	Mean (N)	SD (N)	Mean of change (N)	SD of change (N)	Percentage of change (%)	Effect size
Dorsiflexors	Right side	T0 Baseline	193.81	18.62				
		T1	205.94	21.79	12.13	3.63	6.26	3.34 $_{\varphi}$
		T2	232.13	25.36	17.19	3.96	8.35	4.34 $_{\varphi}$
		T3	246.84	29.26	23.72	6.30	10.63	3.77 $_{\varphi}$
		T4 (Wash-out)	219.15	25.26	-26.88	8.49	-12.27	-3.16 $_{\varphi}$
	Left side	T0 Baseline	195.47	24.94				
		T1	210.19	27.61	14.72	4.25	7.53	3.46 $_{\varphi}$
		T2	229.50	31.35	19.31	4.68	9.19	4.13 $_{\varphi}$
		T3	255.41	34.26	25.91	4.65	11.29	5.57 $_{\varphi}$
		T4 (Wash-out)	229.77	29.60	-24.93	8.47	-10.85	-2.94 $_{\varphi}$
Plantar flexors	Right side	T0 Baseline	218.61	26.22				
		T1	236.54	29.87	17.94	4.65	8.20	3.86 $_{\varphi}$
		T2	259.79	34.50	23.25	5.12	9.83	4.54 $_{\varphi}$
		T3	290.18	40.38	30.39	6.49	11.70	4.68 $_{\varphi}$
		T4 (Wash-out)	260.36	41.13	-29.09	10.57	-11.17	-2.75 $_{\varphi}$

Muscle being tests	Side of the muscle	Week of assessment	Mean (N)	SD (N)	Mean of change (N)	SD of change (N)	Percentage of change (%)	Effect size
	Left side	T0 Baseline	219.82	32.90				
		T1	235.93	36.26	16.11	4.16	7.33	3.87 φ
		T2	257.63	40.62	21.69	5.07	9.20	4.28 φ
		T3	287.29	47.16	29.67	7.80	11.52	3.80 φ
		T4 (Wash-out)	252.66	44.53	-33.35	5.11	-13.20	-6.53 φ
Invertors	Right side	T0 Baseline	176.25	20.55				
		T1	188.75	23.15	12.50	3.01	7.09	4.15 φ
		T2	207.99	26.75	19.24	4.35	10.19	4.42 φ
		T3	234.35	31.06	26.36	4.83	12.67	5.46 φ
		T4 (Wash-out)	207.02	31.83	-26.81	5.66	-12.95	-4.73 φ
	Left side	T0 Baseline	181.08	25.03				
		T1	195.10	28.40	14.02	4.50	7.74	3.11 φ
		T2	216.21	33.91	21.11	6.20	10.82	3.04 φ
		T3	246.70	37.71	30.49	6.95	14.10	4.92 φ
		T4 (Wash-out)	213.34	33.77	-37.10	10.66	-17.39	-3.48φ
Evertors	Right side	T0 Baseline	176.74	20.73				
		T1	189.15	22.56	12.41	3.24	6.85	3.82 φ
		T2	208.30	27.44	19.16	5.81	10.13	3.30 φ

Muscle being tests	Side of the muscle	Week of assessment	Mean (N)	SD (N)	Mean of change (N)	SD of change (N)	Percentage of change (%)	Effect size
		T3	233.85	33.72	25.55	7.50	12.27	3.41 φ
		T4 (Wash-out)	203.31	26.28	-29.36	13.39	-14.44	-2.19 φ
	Left Side	T0 Baseline	181.26	29.38				
		T1	192.47	31.01	11.21	2.83	6.18	3.96 φ
		T2	210.70	35.26	18.23	5.65	9.47	3.23 φ
		T3	236.55	42.22	25.85	8.58	12.27	3.01 φ
		T4 (Wash-out)	206.96	35.62	-28.04	9.79	-13.55	-2.87 φ

SD; standard deviation, N; Newton, φ Effect size ≥0.8 or ≤ -0.8.

Appendix 13: Pearson's (r) correlation between static balance assessment (Perimeter and Ellipse area) and age, height, weight, anthropometric characteristics and physical activity level.

Parameter/ Task	Age (r)	Height (r)	Weight (r)	Shoulder circumference (r)	Chest circumference (r)	Waist circumference (r)	Hip circumference (r)	Shoulder-Waist Ratio (r)	Shoulder-Hip Ratio (r)	Physical Activity level (r)
Perimeter										
DLSEOW	0.051[a]	0.077[a]	-0.094[a]	-0.103[a]	-0.202[a]	-0.092[a]	-0.300[a]	-0.044[a]	0.199[a]	-0.274[a]
DLSECW	0.122	0.313	0.331	0.209	0.079	0.130	-0.055[a]	0.103[a]	0.271[a]	-0.186[a]
DLSEON	**0.478**[**]	-0.049	-0.035	-0.060	-0.155	-0.046	-0.290[a]	-0.001	0.149[a]	-0.292[a]
DLSECN	0.253	-0.048	0.070	-0.036	-0.137	0.114	-0.114[a]	-0.230	0.096[a]	0.002[a]
SLS	0.131	0.211	-0.035	0.030	-0.061	0.099	0.024[a]	-0.102	0.029[a]	-0.153[a]
Ellipse area										
DLSEOW	0.038[a]	0.071[a]	-0.085[a]	-0.144[a]	-0.182[a]	-0.134[a]	-0.131[a]	-0.089[a]	-0.113[a]	-0.271[a]
DLSECW	0.131[a]	0.108[a]	0.059[a]	0.011[a]	-0.076[a]	-0.047[a]	-0.125[a]	0.011[a]	0.066[a]	-0.318[a]
DLSEON	0.209	0.141	0.028	0.068	-0.012	-0.061	-0.180[a]	0.200	0.139[a]	-0.055[a]
DLSECN	0.084	0.140	0.169	0.171	0.014	0.164	-0.028[a]	-0.006	0.045[a]	-0.057[a]
SLS	0.241	0.247	0.113	0.129	-0.061	0.099	0.024[a]	-0.102	0.054[a]	**-0.434**[*a]

DLSEOW; double leg stance wide base of support with eyes open, DLSECW; double leg stance wide base of support with eyes closed, DLSEON; double leg stance narrow base of support with eyes open, DLSECN; double leg stance narrow base of support with eyes closed, SLS; single leg stance, [a]; Spearman's rho (r) correlation, *Correlation is significant at the 0.05 level (2-tailed), **; Correlation is significant at the 0.01 level (2-tailed).

Appendix 14: Pearson's (r) correlation between WB performance (stability indices) and age, height, weight, anthropometric characteristics and physical activity level.

	Age (r)	Height (r)	Weight (r)	Shoulder circumference (r)	Chest circumference (r)	Waist circumference (r)	Hip circumference (r)	Shoulder-Waist Ratio (r)	Shoulder-Hip Ratio (r)	Physical Activity (r)
APSI										
DLSEOW 5°	0.229	-0.190	0.239	0.071	0.209	0.044	0.214[a]	0.011	-0.121[a]	-0.229[a]
DLSEON 5°	**0.342**[*]	-0.172	0.115	0.056	0.151	0.117	0.149[a]	-0.101	-0.164[a]	-0.076[a]
DLSEOW 10°	0.159	0.221	0.234	0.140	0.114	0.100	0.117[a]	0.036	0.132[a]	-0.274[a]
DLSEON 10°	0.264	0.072	0.322	0.296	**0.417**[*]	0.309	0.077[a]	-0.044	0.185[a]	0.059[a]
DLSEOW 15°	0.146	0.076	0.453	**0.569**[*]	0.460	0.452	0.377[a]	0.293	0.308[a]	-0.070[a]
DLSEON 15°	0.181	0.158	0.471	0.332	0.312	0.179	0.588[a]	0.374	0.184[a]	-0.117[a]
DLSECW 5°	0.160	0.103	**0.896**[**]	0.511	0.549	0.509	0.479[a]	-0.004	0.371[a]	0.262[a]
DLSECN 5°	**0.881**[*]	-0.501	0.568	0.718	0.758	0.672	0.600[a]	-0.500	0.462[a]	0.700[a]
DLSECW 10°	0.839	-0.838	0.836	0.653	0.766	0.632	**1.000**[**a]	-0.568	0.000[a]	0.400[a]
MLSI										
DLSEOW 5°	0.179	-0.125	0.162	0.204	0.267	0.232	0.032[a]	-0.080	0.181[a]	0.039[a]
DLSEON 5°	0.204	-0.185	0.138	0.202	0.111	0.196	-0.106[a]	-0.050	**0.356**[*a]	0.061[a]
DLSEOW 10°	0.258	-0.173	0.156	0.213	0.283	0.157	0.223[a]	0.052	0.125[a]	0.129[a]
DLSEON 10°	0.238	-0.239	0.095	-0.025	0.165	0.052	0.115[a]	-0.120	-0.234[a]	0.005[a]
DLSEOW 15°	0.170	-0.217	**0.559**[*]	**0.541**[*]	**0.544**[*]	0.498	0.505[a]	0.138	0.229[a]	0.051[a]
DLSEON 15°	0.164	0.044	**0.748**[*]	**0.703**[*]	**0.803**[**]	0.634	0.546[a]	0.235	0.343[a]	0.167[a]

	Age (r)	Height (r)	Weight (r)	Shoulder circumference (r)	Chest circumference (r)	Waist circumference (r)	Hip circumference (r)	Shoulder-Waist Ratio (r)	Shoulder-Hip Ratio (r)	Physical Activity (r)
DLSECW 5°	-0.091	0.338	**0.904******	0.607	0.596	0.610	0.575[a]	0.013	0.275[a]	0.381[a]
DLSECN 5°	0.574	-0.529	0.129	-0.142	0.030	-0.165	0.600[a]	0.183	-0.359[a]	-0.300[a]
DLSECW 10°	0.692	**0.959***	0.630	0.450	0.641	0.426	**1.000****[a]	-0.322	0.000[a]	0.400[a]

APSI; anteroposterior stability index, MLSI; mediolateral stability index, *Correlation is significant at the 0.05 level (2-tailed), **; Correlation is significant at the 0.01 level (2-tailed), [a]: Spearman's rho correlation, DLSEOW; double leg stance wide base of support with eyes open, DLSECW; double leg stance wide base of support with eyes closed, DLSEON; double leg stance narrow base of support with eyes open, DLSECN; double leg stance narrow base of support with eyes closed.

Appendix 15: Pearson's (r) correlation between WB performance (percentages of time in inner and outer zones) and age, height, weight, anthropometric characteristics and physical activity level.

	Age (r)	Height (r)	Weight (r)	Shoulder circumference (r)	Chest circumference (r)	Waist circumference (r)	Hip circumference (r)	Shoulder-Waist Ratio (r)	Shoulder-Hip Ratio (r)	Physical Activity (r)
% time inner zone										
DLSEOW 5°	-0.123	0.106	-0.177	-0.244	**-0.387**[*]	-0.209	-0.252[a]	0.006	0.129[a]	-0.097[a]
DLSEON 5°	-0.246[a] a	-0.117[a] a	**-0.365**[*][a] **a**	**-0.335**[*][a]	-0.253[a]	**-0.431**[**][a]	-0.136[a]	0.155[a]	-0.240[a]	0.050[a]
DLSEOW 10°	**-0.375**[*]	-0.039	-0.319	-0.248	-0.278	-0.271	-0.181[a]	0.109	-0.115[a]	-0.066[a]
DLSEON 10°	-0.360	0.304	-0.248	-0.097	-0.275	-0.224	-0.183[a]	0.197	0.093[a]	0.145[a]
DLSEOW 15°	-0.030	-0.176	-0.370	-0.482	-0.447	**-0.691**[**]	**-0.611**[*][a]	0.329	-0.314[a]	-0.325[a]
DLSEON 15°	-0.374	0.069	-0.550	-0.393	-0.613	-0.505	-0.607[a]	0.208	-0.051[a]	0.068[a]
DLSECW 5°	-0.184	-0.087	**-0.891**[**]	-0.634	-0.626	-0.559	-0.476[a]	-0.160	-0.530[a]	-0.180[a]
DLSECN 5°	-0.631	0.113	-0.758	**-0.938**[*]	-0.872	**-0.918**[*]	-0.700[a]	0.810	-0.718[a]	**-0.900**[*][a]
DLSECW 10°	-0.935	0.724	-0.874	-0.630	-0.694	-0.610	**-1.000**[**][a]	0.584	0.000[a]	-0.400[a]
% time outer zone										
DLSEOW 5°	0.123	-0.106	0.177	0.244	**0.387**[*]	0.209	0.252[a]	-0.006	-0.129[a]	0.097[a]
DLSEON 5°	0.246[a]	0.117[a]	**0.365**[*][a]	**0.335**[*][a]	0.253[a]	**0.431**[**][a]	0.136[a]	-0.155[a]	0.240[a]	-0.050[a]
DLSEOW 10°	**0.375**[*]	0.039	0.319	0.248	0.278	0.271	0.181[a]	-0.109	0.115[a]	0.066[a]
DLSEON 10°	0.360	-0.304	0.248	0.097	0.275	0.224	0.183[a]	-0.197	-0.093[a]	-0.145[a]

	Age (r)	**Height (r)**	**Weight (r)**	**Shoulder circumference (r)**	**Chest circumference (r)**	**Waist circumference (r)**	**Hip circumference (r)**	**Shoulder-Waist Ratio (r)**	**Shoulder-Hip Ratio (r)**	**Physical Activity (r)**
DLSEOW 15°	0.030	0.176	0.370	0.482	0.447	**0.691****	**0.611***[a]	-0.329	0.314[a]	0.325[a]
DLSEON 15°	0.374	-0.069	0.550	0.393	0.613	0.505	0.607[a]	-0.208	0.051[a]	-0.068[a]
DLSECW 5°	0.184	0.087	**0.891****	0.634	0.626	0.559	0.476[a]	0.160	0.530[a]	0.180[a]
DLSECN 5°	0.631	-0.113	0.758	**0.938***	0.872	**0.918***	0.700[a]	-0.810	0.718[a]	**0.900***[a]
DLSECW 10°	0.935	-0.724	0.874	0.630	0.694	0.610	**1.000****[a]	-0.584	0.000[a]	0.400[a]

DLSEOW; double leg stance wide base of support with eyes open, DLSECW; double leg stance wide base of support with eyes closed, DLSEON; double leg stance narrow base of support with eyes open, DLSECN; double leg stance narrow base of support with eyes closed, [a]: Spearman's rho correlation.