Hip dysplasia: Adult patients' movement patterns during walking, single limb stance and squatting and patients' experience of rehabilitation: A quantitative study

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Abstract

Background

Rehabilitation programmes for patients with Developmental Dysplasia of the Hip (DDH) differ across hospitals. When patients with hip dysplasia are diagnosed, they are usually advised to undergo hip preservation surgery. The most common hip preservation surgery that patients with DDH undergo is Periacetabular Osteotomy (PAO). The effect of exercises prescribed during rehabilitation postoperative mainly focuses on hip muscles and postoperative rehabilitation experience of patients with DDH is unknown. This was a quantitative study consisting of three parts guided by Evidence Based Practice (EBP) framework. Part 1 explored the existing clinical expertise papers, editorials, guidelines, case reports and case series to identify the main elements of clinical guidelines. Part 2 involved exploring patients with hip dysplasia movements during exercises that represent functional activities as part of their daily lives in an observational laboratory-based study. In Part 3, the patients' value was targeted by exploring the patients' rehabilitation experience

Methods

Literature search was done first to explore the existing clinical expertise papers, editorials, guidelines, case reports and case series. Hip dysplasia movements during exercises that represent functional activities as part of their daily lives were explored in an observational laboratory-based study, from an objective biomechanical point of view. Three functional exercises were measured using the Gait Real-time Analysis Interactive laboratory (GRAIL) and Vicon motion capture systems: walking, squat and single limb balance (SLB). Patients' rehabilitation experience was explored with an online questionnaire, investigating general demographic, rehabilitation theme which contains types of exercises recommended, intensity and frequency of the exercises, rehabilitation period and movement compensation theme which contains strategies to avoid pain, the patients' opinion around the rehabilitation they had, the University of California and Los Angles (UCLA) activity scale and modified Harris Hip Score (mHHS).

Results

Even though the literature was explored in Part 1, through three different areas, the surgical area, rehabilitation of DDH postoperative area and the movement patterns during activities area, there are several areas that were not yet addressed. In Part 2, a total of 30 participants, 15 patients diagnosed with DDH and 15 control, participated in the laboratory-based study. The groups were well matched in relation to age, gender, height, weight and BMI. There were significant differences in movement between groups in all exercises explored. While walking, differences were observed in trunk lateroflexion and rotation, hip Range of Motion (ROM) in all planes and peak hip moments. Squat results showed differences in pelvis rotation, trunk rotation, hip abduction/adduction ROM, peak hip external rotation and knee abduction moments. During SLB, patients had forward trunk lean and reduced peak knee abduction moment. In Part 3, questionnaire data results showed that patients used numerous types of exercises. Mean UCLA activity scale was 5.04±2.39 and 18.8% of the respondents reported that they did not have pain or were able to ignore it. Finally, more than half of the patients were unsatisfied with their rehabilitation experience.

Conclusion

This doctoral thesis has explored the available research evidence in the literature, patients with DDH activity levels and return to sports post-operative, compensatory movements during three functional activities and patients' values. It was shown by this research data that the literature around DDH lack strong evidence regarding rehabilitation, lack of clarity whether participation of patients with DDH postoperative is adequately measured, and patients may not be sufficiently achieving their goals in this domain; patients with DDH had compensatory movements during gait, less compensatory movements during squat, and even less compensatory movements during SLB, patients values in regard to overall rehabilitation experience was unsatisfactory and variety of exercises has been used at clinics and patients sought additional exercises. The clinical guidelines found in the literature could be adopted at the clinics, however, with caution, patients with DDH post PAO show compensatory movements across walking, squat and less compensatory movements during SLB which might be better targeted during rehabilitation. Finally it seems that patient with DDH have poor satisfaction regarding rehabilitation received post-operative.

Table of Contents

List of Tables

List of Figures

Appendices

List of Abbreviations

DDH: Developmental Dysplasia of the Hip

CHD: Congenital Hip Dislocation

OA: Osteoarthritis

PAO: Peri-Acetabular Osteotomy

EBP: Evidence Based Practice

PROMs: Patient Reported Outcomes Measures

The UCLA scale: the University of California and Los Angles activity scale

HHS: Harris Hip Score

mHHS: modified Harris Hip Score

WOMAC: Western Ontario and McMaster Universities Osteoarthritis Index

OHS: Oxford Hip Score

PI: Participant Information sheet

VAS: Visual Analogue Scale

GRAIL: Gait Real-Time Analysis Interactive Laboratory

PIG: Plug-In-Gate

ROM: Range Of Motion

SLB: Single Limb Balance

VAS: Visual Analogue Scale

WB: Weight-Bearing exercise

NWB: Non Weight-Bearing exercise

MRC: Medical Research Council (MRC)

Chapter One: Introduction

1.1 Background

Developmental Dysplasia of the Hip (DDH) is the most common cause of secondary hip osteoarthritis (Bicanic 2014; Yasunaga et al. 2016). The hip starts to develop osteoarthritis (OA) due to malalignment of the hip joint in respect to the pelvis which leads to inappropriate distribution of load transfer through the hip (Janssen et al. 2009). Therefore, this could be considered a mechanical condition (Pun 2016). The term DDH has begun to be used recently whilst Congenital Hip Dislocation (CHD) was used widely in the last century (Kotlarsky et al. 2015). The reason that researchers agreed to change the previous name, to developmental hip dysplasia, is that the condition is believed to be dynamic and could potentially happen during adolescence (Klisic 1989).

The prevalence of this condition is higher in females (Paton and Choudry 2016), mostly affects the left hip and comes in a unilateral form (Lee et al. 2013). It can take years, unfortunately, to properly diagnose patients with DDH and patients are usually advised to undergo surgery to address the condition (Ganz et al. 1988; Adler et al. 2016; Kamath 2016; Lerch et al. 2017). Due to the incorrect loading mechanism, patients start to feel pain (Adler et al. 2016). Several studies have demonstrated that, by correcting the hip joint position, the progression of hip OA can be stopped or delayed and patients report significant decreases in the feeling of pain in the hip area (Yasunaga et al. 2003; Ito et al. 2011; Lerch et al. 2017). In 1981, Ganz developed Peri Acetabular Osteotomy (PAO), which then became the standard surgery for DDH (Ganz et al. 1988). During this surgery, the hip joint mechanics are adjusted to decrease pain and to facilitate better activity for daily living. The outcomes of this procedure have been monitored for 20 (Steppacher et al. 2008) and 30 years (Lerch et al. 2017) and have proven to be effective in different outcomes such as the survivor rate of the hip joint, a halt to or delay in hip joint OA and decreased pain compared to preoperative status.

In a study done by Lerch et al. (2017), a follow-up of 30 years of PAO outcomes was investigated. The authors in this study found that only 29% of the hips examined managed to be successfully preserved with no progression of OA evident. The remaining 71% of the hips developed pain and/or underwent hip arthroplasty. Surgical procedures might influence postoperative rehabilitation because of muscle retraction for instance, and the retraction of the

Rectus Femoris, for example, was found to affects patients' ambulation (Maruyama et al. 2013; Peters et al. 2014).

There are a reasonable number of cohort, case series and case studies that have investigated the condition from a surgical point of view in terms of which factors might affect the surgery outcomes (Hasegawa et al. 2007; Hara et al. 2017a), radiographic parameters pre- and post-operatively (Janssen et al. 2009; Hunt et al. 2012; Sucato et al. 2015), activity level post-operatively (Bogunovic et al. 2014; Heyworth et al. 2016; Kalore et al. 2016) and the prevalence of DDH among the adult population across different countries (Rosendahl and Dezateux 2009; Tian et al. 2017). Unfortunately, the literature severely lacks randomised control studies (RCTs). Moreover, rehabilitation of DDH post-surgery has received no or little attention to date in the literature.

Different researchers in the literature (Simmons and Smith 2013; Alshewaier et al. 2017) have strongly argued that rehabilitation of orthopaedic cases should start before surgery and shown that rehabilitation after surgery maximises the surgery outcomes.

Rehabilitation of patients with DDH, unfortunately, has not received much attention and is discussed in only a few papers (Sinitski et al. 2015; Adler et al. 2016; Kamath 2016) and hospital published protocol (Segaren et al. 2015). However, the exercises and treatment protocols recommended do not provide appropriate justification for the need to undertake certain exercises, whether they are done in a correct and safe manner, when is the proper time to do these exercises post- or pre-operatively to get better outcomes nor do they back up the evidence with research done on patients with DDH. The references that the aforementioned protocols based their rehabilitation phases on, does not contain reasonable number of studies around the rehabilitation of patients with DDH that could provide the necessary scientific evidence. Instead, the previously mentioned protocols adopt evidence from hip conditions similar to hip dysplasia post-PAO, such as Total Hip Arthroplasty (THA) rehabilitation for patients with DDH in Adler et al. (2016). The protocol proposed (Segaren et al. 2015; Adler et al. 2016) in the first phase was similar to other hip condition rehabilitation, such as that for hip arthroplasty (Pozzi et al. 2017; Bandholm et al. 2018). The aforementioned protocols are discussed in-depth in the next chapter, the Literature Chapter.

Patients with hip problems might have difficulties with important weight-bearing activities such as walking, which is crucial to perform normal daily activities. Weight-bearing exercises such as walking, double limb squat and single limb balance are functional exercises and part of DDH rehabilitation post-operative (Segaren et al. 2015; Adler et al. 2016) and represent important functional activities. In regard to walking, changes in normal muscle patterns during walking were strongly related in the literature with a pathological condition such as OA or post-surgeries (Skalshøi et al. 2015). In regard to double limb squat, squats can be a part of different daily life activities such as sitting and getting up from a chair. However, they require a sufficient range of motion to control the whole body (Stevens et al. 2018). In regard to single limb balance, 40% of the gait cycle happens during the single limb stance phase (Verhagen et al. 2005; Åberg et al. 2011; Sung 2015).

Knowledge about the dynamics of gait in patients with dysplasia of the hip is important for an understanding of the consequences of the mechanical changes in the hip joint. Different studies have been conducted to analyse a patient with hip dysplasia gait (Romanò et al. 1996; Kotlarsky et al. 2015; Chao et al. 2017; Nie et al. 2017). A patient with hip dysplasia is recognised to have a slower rate speed, short steps, longer periods of stance phase on the unaffected side and reduced rotation of the hip joint (Romanò et al. 1996; Pedersen et al. 2004; Pedersen et al. 2006; Jacobsen et al. 2013; Skalshøi et al. 2015). Apart from gait studies, no other evidence has been found in the literature that investigated or explained if there are movement compensation strategies that hip dysplastic patients adopt while doing other exercises. The effect of movement compensation on rehabilitation protocol or certain exercises on a patient’s gait or patients’ quality of life are scarce (van Bergayk and Garbuz 2002; Ettinger et al. 2015b; Segaren et al. 2015; Adler et al. 2016). This is probably due to the lack of research around DDH or lack of rehabilitation programmes in this area.

Furthermore, Adler et al. (2016) asserted that there is little known, based on the available literature around DDH, about the rehabilitation of adult patients with DDH pre-operatively as well as post-operatively. There are a small number of research articles that discuss the activity levels of patients with DDH and return to sport post-operatively (Jacobsen et al. 2013; Kalore et al. 2016; Hara et al. 2017b); however, the patient’s rehabilitation in these studies was not discussed and was not considered as a contributing factor. Young patients aged 30 years or less at surgery were investigated in Novais et al. (2013) and Matheney et al. (2016); however, young patients’ goals, needs and ambitions were not investigated in these studies. Lack of a strong evidence of what exercises should be recommended at different stages of rehabilitation of patients with DDH might affect the delivery of optimal high quality health services. In addition, borrowing and applying adjacent hip condition protocols for patients with DDH without a proper rationale and evidence, might lead to unexpected or unfavourable outcomes post-PAO. For example, the treatment aim for younger patients in terms of participation might result in underestimation of the level of activity to aim for, such as involvement in sports, walking for long distance, dancing and other activities.

Moreover, since the diagnosis of DDH takes a long time, sometimes years, investigating what these patients went through during rehabilitation, their expectations and their overall experience might indicate that there are likely to be some major issues. Measuring patient experience in the NHS has become mandatory to evaluate healthcare services delivery and identify the strengths and weaknesses in service delivery (Doyle et al. 2013). Different studies have tested the hypothesis of the possible impact of different factors such as patient experience and clinician-patient communication and their likelihood of impacting on clinical effectiveness (Street et al. 2009; Doyle et al. 2013).

Moreover, patient experience has been shown to be directly linked with clinical effectiveness and safety in Doyle et al.'s (2013) review. A positive association was consistent and found in Doyle et al.'s (2013) review in all the studies included regardless of the studies' designs, sittings, medical conditions and outcome measures between patient experience and clinical effectiveness. Clinician-patient communication is also evidenced to impact on clinical effectiveness (Street et al. 2009). Thus, there is a need for an appropriate rehabilitation protocol that is based on a high level of evidence in order to deliver the best healthcare services for patients with DDH and enhance patients' rehabilitation experiences.

1.2 Evidence Based Practice (EBP)

Since there is a lack of evidence for postoperative DDH rehabilitation, there is a need to start building research to be developed the required evidence within the Evidence Based Practice (EBP) framework. The definition of EBP is the conscientious, explicit, and judicious use of current best evidence in making decisions about the care of individual patients according to Negrini (2010). Later on Negrini (2010), as seen in Figure 1, explained the EBP as the integration of best research evidence, clinical expertise and patients' values.

Figure 1: Evidence Based Practice (EBP) Model. A figure shows the three domains creating evidence based practice. Adapted from Negrini (2010)

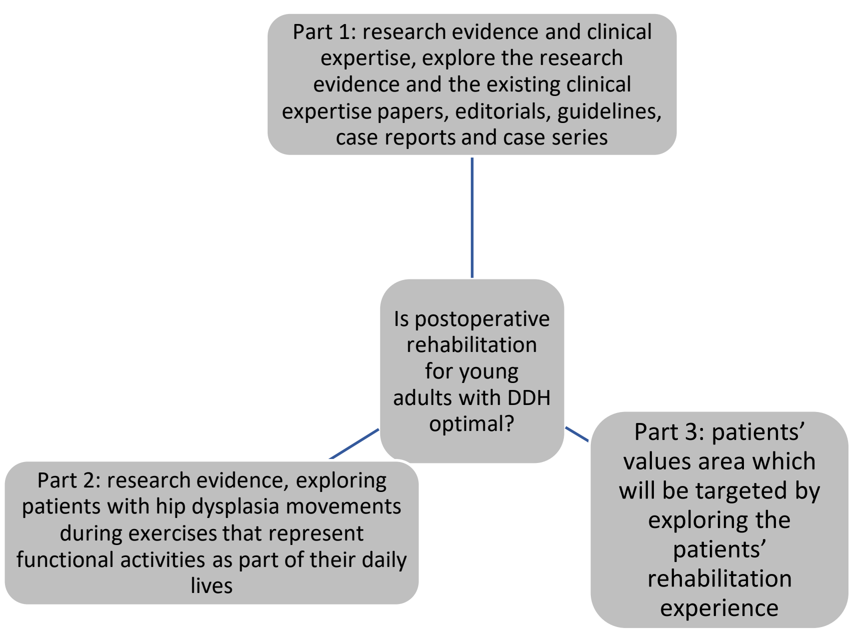
The best available research evidence is mainly the clinically relevant research, which contains the efficacy and safety of therapeutic and rehabilitative methods, for instance the fundamental sort of research that explores the different problems patients might have with their movements (Sackett et al. 1996; Negrini 2010). The evidence is meant to inform and complement the clinical expertise which is the judgement and experience clinicians acquire through clinical practice (Sackett et al.1996; Negrini 2010). The patients' values explained as patients' choices among several possibilities (Sackett et al. 1996; Negrini 2010). Importantly, this model seems appropriate as a basis to explore underdeveloped areas such as the rehabilitation of hip dysplasia post-operatively. Therefore, in this research, the EBP model is adopted to develop/shape the aims of this thesis, through dividing the areas of interest to be explored aligning with the model's domains. In addition, this model would help guide the integration of these research findings, through integration of best research evidence, clinical expertise and patients' values in the Discussion chapter. Therefore, this thesis research question is: Is postoperative rehabilitation for young adults with DDH optimal?

1.3 Aim and rationale

Based on the lack of sufficient evidence and the lack of basic outline of how the rehabilitation of patients with hip dysplasia postoperative should be, urgent investigation of this condition's rehabilitation is needed. In this thesis, the aims are aligned with the EBP model domains as seen in Figure 2 below. First, this thesis aims to explore the research evidence and the existing clinical expertise papers, editorials, guidelines, case reports and case series to identify the main elements of clinical guidelines in Part 1. This is presented in Chapter Two together with the background information with respect to DDH and rehabilitation.

Second, the methodology and methods of this study are illustrated in Chapter Three; the study's Part 2 and Part 3 are explained separately and the rationale for this study's parts is explored as well. The detailed method of investigating the biomechanics of DDH patients during laboratory-based study and the process of developing the questionnaire that explores a patient's rehabilitation journey and experience are presented in detail in the same chapter. Using the EBP model to guide this research could uncover important information of different aspects of the rehabilitation of DDH by investigating different domains, help clinicians to assess patients with DDH movement patterns and possibly advise whether the adopted exercises in this research would help patients with hip dysplasia during their rehabilitation or not. The below figure combines all study parts of this study and the research question.

Figure 2: All study parts explored to answer this thesis research question.



The second aim of this thesis is exploring patients with hip dysplasia movements during exercises that represent functional activities as part of their daily lives in an observational laboratory-based study, from an objective biomechanical point of view, in order to provide research evidence. The results of this aim are reported in Chapter Four. One way to do research in a systematic and objective way is using gait laboratory technology which provides the researcher with objective and reliable biomechanical data (Hellmann et al. 2015; Vicon 2019). Biomechanical data are of great importance to help researchers to compare the effectiveness of different exercises with an objective tool (Hellmann et al. 2015). When patients' bone healing is evident post-operative, they are given permission to fully weight bear permitting progression of rehabilitation exercise choices (Adler et al. 2016). For example, weight-bearing activities include walking, running, squats and other exercises (Adler et al. 2016).

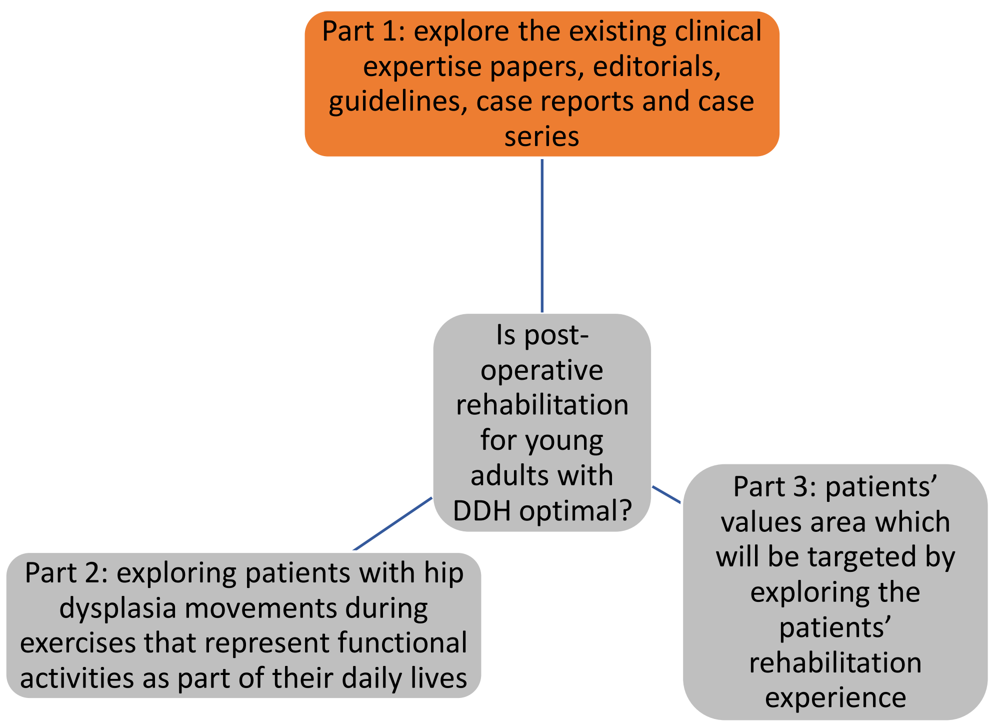
The exploration of patients with hip dysplasia movements during walking, double limb squat and single limb balance in this research were done by a 3D motion capture system which is considered an objective measurement to monitor movements with accurate equipment (Miller et al. 2016). All the exercises carried out in the gait laboratory in this project involved the Gluteus Medius muscle as a major contributor to the movements during these exercises, as it is suspected to be weak and a main source of the problem. Different research evidence has linked the weakness of the Gluteus Medius and DDH (Murphy and Millis 1999; Kuroda et al. 2013; Novais et al. 2014a). Subsequently, the third aim of this thesis will be the patients' values domain, which will be targeted in Chapter Five by exploring the patients' rehabilitation experience by investigating types of exercises recommended, intensity and frequency of the exercises, rehabilitation period, strategies to avoid pain and finally the patients' opinion around the rehabilitation they had using online questionnaire.

It is expected that patients' answers about their rehabilitation experience will reflect and capture the current level of what happens in physiotherapists' clinics, the progression of rehabilitation, their opinion about rehabilitation services and their current and previous physical status throughout the rehabilitation process. Therefore, the overall aim of this thesis is to encompass elements of research to understand the recovery process of patients with hip dysplasia post-operative. For this purpose, this thesis explored and synthesised the existing and new evidence in the context of EBP model. In addition, it expected to shed light on how these patients manage rehabilitation at home to enrich the project and literature with valuable information.

Chapter Two: Literature Review

The exploration of the current available research evidence and clinical guidelines around DDH condition is the focus of this chapter. The literature searched and explored in-depth with guidance of the three domains of EBP model in this chapter in order to help in answering whether the current clinical guidance patients with DDH receive is optimal. This chapter first addresses the basic information about developmental dysplasia of the hip, followed by a systematic search for available evidence around DDH. First area of literature search was surgical options available for patients with DDH, second area was gait and movement patterns due to dysplastic hip joint postoperative, and finally DDH rehabilitation postoperative as the last area of literature search. At the end of this chapter, an overall summary of the literature, followed by exercises of interest to this research study, gap of knowledge and purpose of the study were presented. Below is Figure 3 which highlight the focus of this chapter.

Figure 3: All parts of this study. Part 1, which is the focus of this chapter, highlighted with the orange colour.



2.1 Developmental Dysplasia of the Hip (DDH)

Developmental dysplasia of the hip is a complex condition; the aetiology and epidemiology of this condition is either controversial or unclear (Chan et al. 1997; Lehmann et al. 2000). DDH is abnormal development of the acetabulum leading to shallow socket and insufficient coverage of the femoral head (Lehmann et al. 2000; Paton and Choudry 2016). There are pathological changes affecting the surface area that the femoral head can cover in relation to the acetabulum. According to Hadley et al. (1990) and Murphy et al. (1990) the femoral head does not cover the socket properly. Diagnosis of hip dysplasia among the adult population requires radiographic measurements by calculating the Centre-Edge (CE) angle of Wiberg (Troelsen et al. 2010; Loder and Skopelja 2011).

As mentioned previously, since there is a lack of head of femur coverage over the socket, the CE angle has been used to identify the lateral coverage and it is the common method for DDH diagnosis (Croft et al. 1991; Loder and Skopelja 2011; Ricciardi et al. 2017). There are different CE angles that have been used in the literature and the range of CE starts from less than 20 to 22.5, 25 and up to 30 degrees (Loder and Skopelja 2011). There is a strong relationship between family history, breech presentation, foot deformities and other conditions with DDH (Rosendahl and Dezateux 2009; Pollet et al. 2017). Interestingly, according to Paton and Choudry (2016), if DDH is not treated properly during childhood it appears again in adulthood and could lead to further complications such as abnormal gait, abductor muscles weakness, an increase in the probability of developing severe Osteoarthritis (OA), pain and decreased range of motion. Gluteus Medius weakness is expected in patients with DDH (Murphy and Millis 1999; Kuroda et al. 2013; Novais et al. 2014). One of the signs of the weakness of Gluteus Medius is Trendelenburg gait, which is seen in some patients with DDH (Romanò et al. 1996; Inan et al. 2005).

There are recommended therapies/treatments from both research evidence and clinical publications regarding hip pain in different hip conditions and its related complications such as pain relief modalities, functional training and a wide variety of hip muscle exercises (Enseki et al. 2006; Wahoff and Ryan 2011; Adler et al. 2016; Pozzi et al. 2017). Patients with hip pathology might also be advised to lose weight if the patient is overweight in order to decrease the stress on the affected hip joint (Haverkamp et al. 2011; Elkins et al. 2013; Matheney et al. 2016). This might be explained as proper body alignment and increasing the strength and flexibility of muscles around the hip joint would lead eventually to decreasing the stress around the affected hip joint. Unfortunately, that does not necessarily apply to all adult patients with DDH, or at least extensive research is needed to validate if these therapies could be beneficial, and the results could be then generalised to the DDH population.

Hunt et al. (2012) conducted a study to compare conservative treatment, such as physiotherapy, patients education and activity modification and intervention treatment, where patients undergo surgery, for patients with prearthritic, intra-articular hip pain. The study sample size did include hip dysplasia patients; however, the hip dysplasia patients were only 8 subjects out of 58 patients. There was no significant difference between the conservative group and the treatment group in terms of hip pain improvement. Moreover, both groups showed hip pain improvement the following year. However, there was decreased activity intensity during the following years for the conservative group. Even though that the sample size of the DDH patients included in the previous study was low, it raises information regarding the possible effect of physiotherapy to manage hip dysplasia as conservative treatment and maybe could explore the effect of the physiotherapy as preoperative need.

Paton and Choudry (2016) and Klisic (1989) have argued that the term developmental hip dysplasia is vague, does not necessarily reflect the condition and might even lead to false diagnosis. The authors have argued about whether the term really helps doctors to diagnose based on this term and criticised the ambiguity of the condition’s definition, examination tools and clinicians’ skills as reasons for conflicting results in the literature. Even though numerous research studies have been conducted in the past two decades around developmental hip dysplasia (DDH), regardless of the term changes, the aetiology and prevalence of DDH within the adult population is still unknown (Chan et al. 1997; Lehmann et al. 2000; Tian et al. 2017). Conflicting findings, for instance, could be seen in the prevalence of DDH among adults studies (Klisic 1989; Paton and Choudry 2016; Tian et al. 2017). The prevalence in China is 1.52 % (Tian et al. 2017) and in two different studies on Caucasians, the prevalence was approximately 2-4% (Croft et al. 1991; Jansson et al. 2004). The majority of research has mainly targeted the child population where the prevalence is known and thought to be relatively high (Rosendahl et al. 1996; Rosendahl and Dezateux 2009). More research into DDH prevalence among the adult population is needed in order to determine the onset of DDH and whether it started at an early age or developed later during adulthood. Although the prevalence of having unilateral or bilateral hip dysplasia is reported in the literature, only a small number of studies discussed it in the literature (Lehmann et al. 2000; Jacobsen et al. 2006). The availability of few studies in the literature might explain the ambiguity and conflicted results around DDH. Manifestation of unilateral hip dysplasia usually includes a short steps gait, Trendelenburg gait and sign, limited hip joint movement and eventually lead to the progression of hip joint osteoarthritis (Pedersen et al. 2004; Jacobsen et al. 2006; Skalshøi et al. 2015).

On the other hand, patients with bilateral hip dysplasia might develop bilateral osteoarthritis and this might increase the need for total hip arthroplasty (Paton and Choudry 2016). These patients tend to have bilateral Trendelenburg gait with increased lumber lordosis (Paton and Choudry 2016). The relationship between pathophysiology and patient condition is crucial in order to, but not limited to, achieving better understanding of how the body works with or without pathological changes which helps the therapist to identify unusual movement patterns and differentiate between different movements patterns (Adler et al. 2016). A therapist's observation of a patient's movement is the traditional way to assess their patients, and gait laboratory or gait analysis is considered as one of the most objective and accurate ways to measure a patient's movement (Storm et al. 2016).

Nonetheless, when patients with hip dysplasia are diagnosed they are usually advised to undergo hip preservation surgery unless severe osteoarthritis exists (Ganz et al. 1988; Steppacher et al. 2008; Kalore et al. 2016). Due to the fact that hip dysplasia is a mechanical condition (Maeyama et al. 2008), surgery is indeed needed to resolve the joint mechanics. In addition, surgery has been shown to preserve the hip joint for up to 30 years (Lerch et al. 2017). In the recent literature, different surgical intervention approaches were used to correct and preserve DDH patients' hip joints such as periacetabular osteotomy (PAO), Rotational acetabular osteotomy (RAO), The Birmingham Interlocking Pelvic Osteotomy (BIPO) (Steppacher et al. 2008; Sucato et al. 2015).

The success of these surgeries is measured from a surgical perspective by using either CT scan, MRI, questionnaires such as Harris Hip Score and other patient reported outcome measures (van Bergayk and Garbuz 2002; Novais et al. 2013; Matheney et al. 2016).

The ultimate goal for all hip preservation surgeries for people with dysplasia is to re-align the hip joint biomechanics in order to prevent severe hip arthritis due to an incorrect loading mechanism so that patient pain improves (Jacobsen et al. 2013; Kamath 2016). Peri-acetabular osteotomy is the most common and widely used approach to treating hip dysplasia (Nishimura and Takahira 2015). In this procedure, the surgeon re-orientates the acetabulum to a better position and it involves cuts to the acetabulum (Steppacher et al. 2008; Jacobsen et al. 2013; Kamath 2016). The reason for this is to adjust the forces travelling through the hip joint to be distributed equally during weight-bearing and daily life activities post-PAO (Ganz et al. 1988). Based on Steppacher et al. (2008), the ideal patients for PAO is a young adult, less than 30, with no or minimal OA and no severe pain.

Patients' activity levels were measured by different authors pre and post-operative (Ettinger et al. 2015a; Heyworth et al. 2016; Hara et al. 2017b). In Ettinger et al. (2015a) the authors investigated 77 young patients with congenital dysplasia of the hip increased their participation in sports, with regard to both the sports activity and level of intensity, after open hip preservation surgery. Mean age of the patients was 26 and the authors used the University of California and Los Angeles (UCLA) activity scale to measure the patients' activity levels post-operative. The UCLA activity scale, as a scale, covers level of activity from “'wholly inactive'” which is equivalent to score of 1 to “'regularly participates in impact sports” which is equivalent to number 10. Mean UCLA activity scale increased in patients with congenital dysplasia of the hip from 4.8 preoperative to 7.7 post-operative. The authors found that young patients with congenital dysplasia of the hip increased their participation in sports, with regard to both the sports activity and level of intensity, post-operative. Patients also avoided further degenerative changes in hip joint osteoarthritis within the period of follow-up.

In Heyworth et al. (2016) investigated the PAO results and the rates of athletes to return to play. The UCLA activity scale was also used to measure the activity levels post-operative. Forty-one patients were included with a mean age of 26. The authors found that PAO is generally an effective treatment for acetabular dysplasia in adolescents and young adults hoping to return to athletics. In addition, the authors also suggested that found that three-quarter of the patents were able to return to athletics. The mean UCLA activity scale was not changed preoperative where patients scored 8 compared to postoperative where patients scored 8. Most treated athletes demonstrated improved function and high activity levels and returned to sports at a level comparable with their prior performance. In Hara et al. (2017b) the authors investigated 161 patients with DDH participation pre and post-operative. The UCLA activity scale was used to measure participation in sports similar to Heyworth et al. (2016) and Ettinger et al. (2015a).

Mean UCLA activity scale increased from 4.7 to 5.5 post-operative. The authors found that after PAO, both participation in sports and the UCLA activity score significantly increased. Moreover, 55.3% of patients participated in sports post-operatively, which did not significantly or negatively affect progression of the OA stage over a mean follow-up of 100 months. Even though the literature includes hip dysplasia surgery case control trials (Chan et al. 1997; Hara et al. 2017a; Hara et al. 2017b) and case series studies investigating sport and activity levels (Bogunovic et al. 2014; Ettinger et al. 2015a; Heyworth et al. 2016), little is known about the rehabilitation of hip dysplasia patients in the aforementioned studies.

The role of rehabilitation after different types of surgeries on the lower limbs, more specifically on the hip joint has been shown in the literature to be beneficial for cases such as hip replacement (Wahoff and Ryan 2011; Enseki et al. 2006) or hip arthoscopy in Sahu et al. (2018). In the case of rehabilitation of DDH, there are few papers that suggested that there are sufficient benefits of rehabilitation postoperative for patients with DDH (Ito et al. 2014; Adler et al. 2016; Kalore et al. 2016; Mortensen et al. 2018) and few guidelines were found in the literature suggested by hospitals such as Segaren et al. (2015).

In the literature, strengthening rehabilitation programmes of the Gluteus Medius were the focus of a DDH patients' programme recommended in two clinical publications (Segaren et al. 2015; Adler et al. 2016). For clarification, Single Leg Balance (SLB) activities require hip abductor muscle activation of the weight-bearing side in order to control pelvic positioning in the frontal plane during the exercise (Takacs and Hunt 2012; Prior et al. 2014). When patients with DDH who have just had osteotomy are considered, a gradual rehabilitation programme is typically used by physiotherapists and a gradual loading of the Gluteus Medius muscle since it is suspected to be weak (Homan et al. 2013; Ebert et al. 2016).

The impact and the relationship between the muscles' injury and compensatory movements in patients was explored by different authors (Hurwitz et al. 1997; Harris et al. 2017). Performing functional movements with correct or within normal ranges biomechanics may improve hip muscle recruitment and force production of the extensors and abductors during functional and sports specific movements (Chang et al. 2005; Hall and Brody 2005; Boudreau et al. 2009). Functional exercises such as standing, walking, stair climbing, sitting on a chair and running could be improved by doing certain weight-bearing exercises at clinics that represent these functional movements which are, indeed, important for patients to do daily activities that might be affected if a certain muscle group is injured (Bird et al. 2001; Chandrasekaran et al. 2015). For patients with DDH, unfortunately, the lack of research is expected to strongly influence physiotherapists' practice and the use of a wide variety of exercises is also expected. It is also anticipated, due to lack of best available research evidence, physiotherapists might force to borrow from other conditions literature similar to DDH which might increase the chance of delivering inappropriate treatment after PAO.

The need for such literature is crucial for therapists to deliver high-quality healthcare services with confidence. Since there are few research studies found in the literature, as mentioned earlier, a systematic search was explored comprehensively to find what exists in the literature linked to rehabilitation of DDH and to have a good understanding of what is the current best available research evidence, clinical expertise and patients' values, the first, second and third domains of EBP. Although this search is relatively systematic, this was not a systematic review. This search is indeed needed to confirm that the literature is providing supporting evidence for rehabilitation of DDH post-operative.

The areas of interest were surgery approaches, patients' gait, biomechanics postoperative and rehabilitation and physiotherapy. As mentioned earlier in this chapter and the Introduction Chapter, an extensive systematic search of the literature is needed to explore the supporting evidence for rehabilitation of DDH post-operative. This led the researcher, based on the information provided in the "2.1 Developmental Dysplasia of the Hip (DDH)", to search the surgical area for the movement pattern during activities expected to be affected postoperative and the rehabilitation patients receive post-operative. The aforementioned areas were chosen since most of the research articles found in the Introduction and Literature Review chapter were exploring these areas.

2.2 Systematic search

2.2.1 Databases

A systematic literature search was performed using the following databases:
CINAHL/ PEDro/ Medline/ AMED/ ASSIA/EMBASE.

2.2.2 Inclusion criteria

- All studies with no specific date
- Studies published in the English language
- Participants diagnosed with DDH
- Any study including adulthood DDH
- All DDH hip preservation studies
- Unilateral hip dysplasia
- Rehabilitation post-surgery

2.2.3 Exclusion criteria

- Studies that included children with DDH
- Studies that focused on Total Hip Arthroplasty for the dysplastic hip
- Bilateral hip dysplasia

The first area explored the surgical options to treat DDH. The search of the first area was done using the following medical subject headings (MeSH) [hip dysplasia OR congenital hip dislocation OR developmental dysplasia of the hip OR DDH AND hip dislocation OR subluxation OR Adults Hip AND Surgery/osteotomy OR PAO/periacetabular OR Surgical treatment OR Operation OR Surgical procedure OR Hip preservation surgery AND Adult OR Adolescence OR Old OR Women and men]. An example of the first area search terms can be seen in Table 1.

The second area explored patients with DDH gait and movement patterns across different activities. The search of the second area was done using the following medical subject headings (MeSH) [hip dysplasia OR congenital hip dislocation OR developmental dysplasia of the hip OR DDH OR hip dislocation OR subluxation OR Adults Hip AND Biomechanics OR kinematics OR kinetics OR Gait OR Mobility OR Gait analysis OR Dynamic OR movement OR pattern OR Ambulation/locomotion AND Adult OR Adolescence OR Old OR Women and men].

The third area explored the rehabilitation and treatment options given to patients with DDH post-operative.

The search of the third area was done using the following medical subject headings (MeSH) [hip dysplasia OR congenital hip dislocation OR developmental dysplasia of the hip OR DDH

OR hip dislocation OR subluxation OR Adults Hip AND Physiotherapy OR Physical therapy OR Rehabilitation OR Treatment/Therapy OR Abductor muscle strengthening exercise OR Exercise OR activity OR activity levels OR sport AND Adult OR Adolescence OR Old OR Women and men].

2.2.4 Search terms

Table 1: An example of the keywords used in the systematic search of the first area across all databases.

First area keywords		
Surgery/osteotomy	Hip	Adult
PAO/periacetabular	Hip dysplasia	Adolescence
Surgical treatment	Developmental hip dysplasia	Old
Operation	Congenital hip dislocation	Women and men
Surgical procedure	Dislocated hip ***or*** subluxation	
Hip preservation surgery	Adult hips	

2.2.5 Search results

The first area search found as many as 815 articles in the CINAHL database alone and 857 articles in all databases searched, see Appendix 1 First Area for the results of all databases. Different surgical approaches were identified, such as PAO (Ganz et al. 1988), RAO (Yasunaga et al. 2016), minimal PAO (Khan et al. 2017), and triple pelvic osteotomy (Kumar et al. 2002). Not all the articles found in this search discussed the surgery approach alone; some authors explored the factors affecting the surgery outcomes (Yasunaga et al. 2016; Hara et al. 2017b). The articles retrieved from this search area were discussed further under the heading "2.3 First area of literature search: Surgical intervention".

After a thorough reading of different surgical approach articles, it was found the previously mentioned articles have not explained the rehabilitation protocol in detail (Adler et al. 2016). The majority of the articles identified from using the previous keywords were aimed mostly, but were not limited to, the different surgical approaches, factors affecting surgeries, surgery outcomes and follow-up outcomes post-operatively through different years. Movement patterns of patients with DDH during different exercises have been investigated only during patients walking and running (Jacobsen et al. 2014; Nie et al. 2017). Since activities of daily living and participation in sports require more movements to be included, further exploration of this area is needed to explore how these patients progress post-operatively.

The second area results were very limited, see Appendix 1 Second Area for the results of all databases. For example, in the CINAHL search results, there were 122 articles and several articles were found that studied the gait of patients with DDH (Jacobsen et al. 2013; Karaismailoglu et al. 2019; Loverro et al. 2019). A total of 680 articles was found in all databases searched. There were several articles that discussed hip dysplasia patients' gait (Novais et al. 2013; Matheney et al. 2016) and other articles discussed patients with hip dysplasia gait with mixed hip conditions such as hip arthroplasty (Nie et al. 2017; Karaismailoglu et al. 2019).

The third area results were very limited with very low numbers of articles identified after conducting the search across different databases with a total of 276 articles found across all databases searched. The difference between this area and the second area is that in the second area the articles found were more relative to the search keywords. For example, only 31 articles were identified in CINAHL and none of these were aimed at the rehabilitation of patients with DDH or at least discussed exercises or the impact of rehabilitation on patients with DDH. For complete search results and search records for each database for different areas, see Appendix 1 Third Area.

Interestingly, this search revealed a single physiotherapy paper done by Mortensen et al. (2018) investigating the effect of exercises on patients with DDH post-operatively. The majority of physiotherapy research in the literature was done on patients with hip arthroplasty, whether these articles investigated patients with DDH solely or other hip conditions that included DDH cases (Stockton and Mengersen 2009; Gawel et al. 2013). After reading the abstracts of the articles appearing in the search results of the third area, there were multiple articles discussing patients with DDH activity levels and their ability to be able to participate in high impact sports (van Bergayk and Garbuz 2002; Ettinger et al. 2015b; Matheney et al. 2016; Hara et al. 2018). It needs to be noted that none of the previous studies investigated the patients' rehabilitation as an outcome measure, however, this seemed an important topic to explore further in third area search.

2.3 First area of literature search: Surgical intervention

The first area of the systematic search was around surgical intervention options. Hip dysplasia is considered by many authors as the primary factor in developing secondary hip osteoarthritis (Weinstein 1987; Murphy et al. 1990). According to Aronson (1986) and others (Kuroda et al. 2013), up to 50% of OA cases are caused by DDH. Unfortunately, the articles that investigated secondary OA did not always discuss the underlying causes of each case or how it developed in the first place. Therefore, no definite conclusion could be derived from these articles that could strongly link hip dysplasia and secondary OA and further research is recommended. Despite the real cause of patients' arthritic hips, patients with DDH are usually advised to do either THA or hip preservation surgery based on different factors such as the patient's age, preoperative hip joint status and preoperative surgery's outcomes (Kalore et al. 2016).

If OA is detected in early adulthood, total hip arthroplasty would not be a recommended option due to huge conflict around the proper age of candidates and how long the joint will survive (Kalore et al. 2016). Hip preservation surgeries, such as osteotomy, might be the best solution for a young patient aged 30 or less with DDH, (Kalore et al. 2016). On the other hand, a patient who is more than 50 with a significant arthritic joint, is strongly advised to have total hip arthroplasty (Kalore et al. 2016). Fortunately, both surgeries show a high rate of success, with long survival rates and a return to normal activity.

In Steppacher et al.'s (2008) study, the authors followed the outcomes of PAO in 58 patients and 68 hips, for 19 years. The authors found that PAO did indeed preserve the hip joint in all radiographic parameters except osteoarthritis progression. Further studies need to be conducted in order to explore the factors that might decrease the time for the need of a second operation. In the following sections, the indication of each approach is illustrated carefully, since the focus of this research will be on patients post-operative.

2.3.1 Types of available hip preservation surgeries

2.3.1.1 Periacetabular osteotomy (PAO) or pelvic osteotomy

This surgery is considered the most common procedure for patients with hip dysplasia and was developed by Ganz et al. in Switzerland (Ganz et al. 1988; Leunig et al. 2001). It is performed first when the fascia of the rectus femoris is opened and rectus femoris tendon transacted then 'by creating three periacetabular osteotomies and a controlled fracture in order to completely mobilize the acetabulum from the remaining pelvis' (Kraeutler et al. 2016). This allows acetabular reorientation to provide greater coverage of the femoral head. Briefly, this surgery involves cutting the acetabulum through three different osteotomies and repositioning it in order to decrease insufficient coverage to avoid pain and improve function. By improving the coverage area, all the biomechanical alteration will be countered as suggested by Ganz et al. (1988) and Leunig et al. (2001).

2.3.1.2 Rotational acetabular osteotomy (RAO), Chiari osteotomy and shelf procedure

These are three different periacetabular osteotomies, which are often used for adolescents and adult patients with DDH (Fu et al. 2014; Imai et al. 2014; Adler et al. 2016). All of them re-adjust the positional relationship of the acetabulum and femoral head to increase the acetabular coverage of the femoral head, restore normal anatomical structures, and then improve the biomechanical properties of the hip (Fu et al. 2014).

In RAO, the position of the femoral head is readjusted to increase acetabular coverage of the femoral head and reduce acetabular shear force, which leads to restoration of normal hip joint anatomy and biomechanical properties (Fu et al. 2014). A less invasive RAO was introduced by Maruyama et al. (2013) where the Gluteus Medius muscle is retracted to expose the ilium without detachment from the iliac crest. Similarly, the Rectus Femoris muscle tendon is retracted, not excised. The predicted 10-year survival rate of a hip joint ranges from 71% for advanced stage OA hips up to 79 % following RAO (Maruyama et al. 2013). Moreover, according to the authors, this operation results in reducing the progression of osteoarthritis and Trendelenburg gait is avoided.

2.3.1.3 The Birmingham Interlocking Pelvic Osteotomy (BIPO) for Acetabular Dysplasia

This procedure includes ischial osteotomy, a superior pubic ramus bony cut and three interconnected iliac osteotomies (Kumar et al. 2002). According to Mei-Dan et al. (2017), the three interconnected iliac osteotomies form an 'interlocking construct with good bony apposition and improved fragment stability, increasing the patient's and therapist's confidence with immediate unrestricted weight bearing' (Kumar et al. 2002, p. 726). Due to the fact that BIPO allows a DDH patient to weight bear immediately after surgery, this might enhance the patients' rehabilitation (Mei-Dan et al. 2017). Unfortunately, there is not enough information regarding the rehabilitation post this surgery similar to the aforementioned surgeries.

Determining how patients with DDH walk and the common compensations strategy adopted by these patients postoperative during different exercises is relevant for management and evaluation of various treatments, such as physiotherapy. Little is known about the movement compensation patients with DDH are using (Romanò et al. 1996; Kotlarsky et al. 2015; Chao et al. 2017; Nie et al. 2017). A patient with hip dysplasia is recognised to have a slower walking speed, short steps, longer periods of stance phase on the unaffected side and reduced rotation of the hip joint (Romanò et al. 1996; Pedersen et al. 2004; Pedersen et al. 2006; Jacobsen et al. 2013; Skalshøi et al. 2015; Sucato et al. 2015).

In the next heading, the movement of patients with DDH adopt preoperative and more specifically postoperative is explored in greater depth after a brief introduction about movement analysis. In addition, further analysis of the previously mentioned articles (Pedersen et al. 2006; Skalshøi et al. 2015; Sucato et al. 2015) that focus on patients with DDH gait postoperative is carried out under the heading “2.4.2 Movement compensation during DDH patients' gait”.

2.4 Second area of literature search: Patients with DDH movement patterns

The second area of the systematic search was on patients’ movement patterns. Gait analysis provides an objective and accurate data when patients’ movement patterns are measured (Storm et al. 2016). By having data from an objective analysis measurement, the findings of the analysis would provide therapists with more detailed data from a patient’s musculoskeletal system and hence the therapeutic goals and plan can be set more specifically (Romanò et al. 1996). Human observation could analyse patients’ movements and gather some information around the movement; however, not the detailed information of movements, for instance, hip joint moments. Different researchers have used movement analysis within the research field as an objective measurement to assess the musculoskeletal system to predict and prevent injuries (Romanò et al. 1996; Escamilla et al. 2001; Nishimura and Takahira 2015).

The need for an accurate analysis system might reveal the need for specific rehabilitation exercises and may even increase researchers and clinicians understanding of the pain these patients may experience during movement. For instance, if the findings revealed lack of a certain joint range of motion during certain movement, such as walking or insufficient delivery of the required joint movements, then the therapist should focus on these muscles in order to prevent future injuries. If a muscle cannot function properly, then a patient tends to compensate for the movement patterns. In the next section, further exploration of movement patterns and compensation found in patients with DDH found in the literature is discussed.

2.4.1 Movement compensation

Knowledge about the dynamics of gait in patients with dysplasia of the hip is important for an understanding of the consequences of the mechanical changes in the hip joint. As mentioned earlier, different studies have been conducted to analyse a patient with hip dysplasia gait (Pedersen et al. 2006; Sucato et al. 2010; 2015; Jacobsen et al. 2014).

In the Pedersen et al. (2006) study the authors explored patients with DDH gait post-PAO. The authors explored hip, knee and ankle ROM, hip, knee and ankle moments of nine patients. The authors found that peak values for the knee joint angles were significantly different; maximum extension angle at heel strike was significantly different post-operatively and maximum knee flexion first half of the stance phase and maximal extension of the knee were also significantly different. In addition, peak hip extensor moment decreased post-operatively; shift from hip flexor dominance started after 51% of the stance phase pre-operatively compared to 48% of the stance phase post-operatively.

In another study, Sucato et al.'s (2010) explored patients with DDH gait post-PAO and investigated the walking speed, pull off power and the kinetics and kinematics of lower extremities in 21 patients. The authors reported no significant difference in walking speed pre-operatively, one year post-operatively and two years post-operatively (1.18 m/s to 1.23 m/s to 1.24 m/s), respectively. In regard to lower extremities, a significant increased anterior pelvic tilt leading to increase hip flexion. The hip flexion pull-off power and abductor moment impulse were not changed post-operatively. Jacobsen et al. (2014) explored patients with DDH gait post-PAO. The spatiotemporal, hip, knee and ankle ROM and hip, knee and ankle moments kinetics were explored in 23 patients. The authors reported hip, knee and ankle ROM and hip, knee and ankle moments of nine patients. The peak hip flexion movement increased post-operatively by 26% at six months and 12 months compared to baseline. Hip extension angle increased by 8% in 12 months. In addition, no significant difference was found in the primary outcome measures of their study, which were peak hip flexion moment at second half of stance phase and peak hip extension angle during stance. The authors also reported lower knee extensor moment in the second half of stance phase, however, not statically different.

Opposing findings could be found in the literature that assert the need for more research in this area, especially on patient gait post-operative. For example, the peak hip extension angle during the stance phase was reported with opposite findings in Pedersen et al. (2004) and Jacobsen et al. (2014). In addition, only Endo et al. (2003) have studied patients with DDH gait post-RAO. In Endo et al.'s (2003) study, spatiotemporal, hip angles and moments and ground reaction force were investigated in 22 patients with DDH post-RAO. The authors compared also between the results of unilateral cases and bilateral cases. The authors found that gait velocity, stride length and cadence were significantly lower in the patients group preoperatively and increased significantly postoperatively. Hip extension angle increased around three degrees postoperatively. Trunk maximum tilt and obliquity angles were significantly increased postoperatively; preoperative tilt 2.5 degrees to 3.5 degrees post-operatively and obliquity from 2.2 degrees preoperatively to 3.4 degrees postoperatively. No Trendelenburg sign in all patients was included in the study.

Regarding kinetics, the authors found decreased hip flexion and extension moments pre-operatively and increased significantly post-operatively. In addition, there was no significant difference between unilateral cases and bilateral cases as regard gait parameters pre-operatively and post-operatively. Trendelenburg gait is a common indicator in patients of DDH due to the fact that hip abductors are weak (Nishimura and Takahira 2015; Paton and Choudry 2016). When patients with Trendelenburg gait walk, the tilted pelvis – inferiorly – is obvious and the Gluteus Medius does not exert enough power in order to maintain normal pelvis position (Inan et al. 2005). Other authors have pointed out that the main issue is the Gluteus Medius muscle, where this muscle fails to maintain the pelvis level and therefore results in pelvic drop (Chang et al. 2005).

There were studies that explored patients with DDH gait pre-operatively, such as Romano et al. (1996) who proposed that the cause of pelvic drop when patients walk was that it decreases the energy demand in order to move the body forward; by doing this, less energy is needed but movement compensation is required. This could mean that a patient tries to balance body weight by controlling the centre of gravity. The pelvic drop can be related to clinical observation of a Trendelenburg gait. In addition to that Romanò et al. (1996) found that the decrease in external adduction moment within the more severe dysplastic hips was also a neuromuscular protective mechanism to reduce the pain. However, they suggested that there were cases where the adductor moments were increased but this might be caused by a poor proprioceptive mechanism. Furthermore, Romanò et al. (1996) investigated the moments of forces around the hip in the sagittal plane and found there was a reduction which they explained as a protective mechanism as well as being directed from the neuromuscular system in order to reduce the stress on the hip joint. Ground reaction force during the weight–acceptance phase was reduced pre surgery, which could be due to muscles weaknesses or cautious loading response (Romanò et al. 1996).

Skalshøi et al. (2015) demonstrated that the position of the pelvis strongly relates to hip joint degenerative status and was linked primarily to weakness of the hip abductors. Reduced push-off was noticed also in Skalshøi et al.'s (2015) study, probably because of a pain avoidance mechanism and to reduce the load on the affected limb. Apart from gait studies, no other evidence has been found in the literature that investigated or explained if there are movement compensation strategies that hip dysplastic patients adopt while doing other exercises. Studies on the effect of movement compensation on rehabilitation protocol or certain exercises on a patient’s gait or patients’ quality of life are scarce (van Bergayk and Garbuz 2002; Ettinger et al. 2015b; Segaren et al. 2015; Adler et al. 2016). Using gait laboratory-based movement analysis might reveal the need for specific rehabilitation exercises and may even increase researchers and clinicians’ understanding of the pain these patients may experience during movement. Using a 3D motion analysis system to explore movement compensation and whether the patients compensate or not seems a reasonable place to start to look for movement compensations or abnormalities that can be targeted in rehabilitation.

This area also adds to the research evidence domain within the EBP framework. This area enrich the information within research evidence domain rather than clinical expertise domain. The patient’s movement compensation during functional exercises post-operatively, other than walking, is not known and has not been investigated yet and needs to be addressed carefully in order to help in building the evidence regarding these patients’ rehabilitation protocols.

In the next section, the hip muscles and the effects of the surgical intervention on hip muscles, if investigated in the literature, were explored first before moving forward to the rehabilitation search area.

2.4.2 Hip muscles and Electromyography (EMG)

Electromyography (EMG) provides researchers with a measurement of muscle activation for each muscle tested and it is assumed that a higher EMG signal means greater potential strengthening effects (Ayotte et al. 2007; Ebert et al. 2016). Abductor muscles are believed to play a crucial role in rehabilitating DDH patients, to correct the gait and even to relieve the pain (Adler et al. 2016; Kamath 2016). It is believed by many authors/surgeons that the abductor strengthening exercises are the first step to rehabilitating hip dysplastic patients (Kuroda et al. 2013; Kamath 2016). Therefore, strengthening rehabilitation programmes for the Gluteus Medius were recommended for patients with a DDH rehabilitation programme (Adler et al. 2016). According to Kuroda et al. (2013), abductor muscle exercises lead to hip joint stability; however, the underlying mechanism is not clear in the authors study. The motion of the pelvic hip complex within the frontal plane is controlled mainly by the Gluteus Medius muscle (Chang et al. 2005; Reiman et al. 2012). According to Clark and Haynor (1987), the Gluteus Medius is almost two thirds (60%) of the cross-sectional area of hip abductors. The Gluteus Medius consists of three portions: the first portion is the anterior portion where it helps with hip abduction, hip flexion and medial rotation.

The second portion is the middle portion that mainly contributes to hip abduction only and the third portion is the posterior portion that contributes to abduction, lateral rotation and extension (Bowman et al. 2010; Byrne et al. 2010). Gluteus Medius provides support for the hip and prevents pelvic drop on the unsupported side during the unilateral stance phase and, during the closed kinetic chain, it controls the internal rotation of the hip. Furthermore, the impact of Gluteus Medius weakness and its relation to hip and knee pathology is well-identified in the literature (Cichanowski et al. 2007; Robinson and Nee 2007; Reiman et al. 2009; Hinman et al. 2010; Strauss et al. 2010). When considering patients with DDH who have just had an osteotomy, a gradual rehabilitation programme should be proposed by physiotherapists and the gradual loading of the Gluteus Medius muscle which is supported by Kuroda et al. (2013) and Kamath (2016) studies.

A number of systematic reviews have been done on the Gluteus Medius muscle during therapeutic exercises for rehabilitation on different range of conditions, mainly on knee and hip joints, in order to investigate muscle activation (French et al. 2010; Reiman et al. 2012; Ebert et al. 2016; Marshall et al. 2016). These reviews divided the Gluteus Medius exercises into four categories based on EMG activity (low EMG activity, moderate EMG activity, high and very high EMG activity). According to Reiman et al. (2012), in order to gain strength, the exercises require great EMG activity; therefore, in order to gain strength clinicians could benefit from such information and expect that patients would gain muscles strength if EMG activity is more than 40% MVIC.

Reiman et al. (2012) reported that, if a rehabilitation programme aims at the maximal load of a certain muscle, the EMG signal or the muscle activation should be >40% to gain significant strength. Since the criteria for choosing a specific exercise depend on the patient's individual factors, a careful progression for the rehabilitation exercise programme is recommended, to procced from less to more challenging exercises. Andersen et al. (2006) reported that exercises showed signals with <25% Maximum Voluntary Isometric Contraction (MVIC) are considered as endurance exercises. Patients' postoperative progress with the exercises from easy to more difficult, and exercises with <25% MVIC possibly are suitable for prescription at the start of any rehabilitation programme such as for DDH patients immediately post-operatively. In addition, by benefiting from such information, the muscles strength postoperative could be guided by the strength gain based on EMG activity, as found in the previous studies.

The primary objective of the laboratory study was to look for movement changes in other movements besides gait. Standing, walking, stair climbing and running are important daily activities that might be affected if the Gluteus Medius muscle is injured (Bird et al. 2001; Chandrasekaran et al. 2015). Therefore, in this project, all the exercises that will be carried out require Gluteus Medius involvement, as it is suspected to be weak, the source of the problem and the focus of the rehabilitation programme, as mentioned earlier (Murphy and Millis 1999; Kuroda et al. 2013; Novais et al. 2014a; Kamath 2016). A rational for choosing the exercises that require Gluteus Medius involvement are explored under the heading "2.6 Exercises of interest to laboratory-based study" later in this chapter. In the next section, the patients with DDH rehabilitation, not limited to Gluteus Medius, found in the literature through the systematic search of the third area, were explored first.

2.5 Third area of literature search: DDH rehabilitation post-PAO

The third area of the systematic search was on rehabilitation/physiotherapy treatment post-PAO. So far, the previous two areas of the systematic search showed only little attention towards rehabilitation post-operative. Even when patients are referred to physiotherapy, it is likely that they are misdiagnosed and treated as having another medical condition rather than DDH (Paton and Choudry 2016). Surgical procedures might influence postoperative rehabilitation because of muscle retraction, such as the retraction of the Rectus Femoris that affects patients' ambulation (Maruyama et al. 2013; Peters et al. 2014).

It is true that PAO surgery is likely to be very different from surgery of other hip or lower limbs conditions; therefore, condition-specific research is needed. PAO is usually followed by a rehabilitation programme for the following months in order to restore full Activity of Daily Living (ADL) (Adler et al. 2016). From the limited number of research articles, (Adler et al. 2016; Kamath 2016; UW Health Sports Medicine 2018), the rehabilitation of patients with DDH was outlined with not many references to articles that investigated DDH rehabilitation. Also, there are other published protocols found in literature discussing DDH rehabilitation, such as hospital protocols (Segaren et al. 2015).

The traditional physical therapy goals for patients with DDH and generally for other hip conditions include the following (Hall and Brody 2005; Simmons and Smith 2013; Segaren et al. 2015; Adler et al. 2016; Kamath 2016; Alshewaier et al. 2017):

- Reduce pain
- Strengthen the affected muscles such as hip abductors and external rotators muscles
- Improve and maintain soft tissue flexibility
- Improve and maintain ROM
- Enhance gait patterning

2.5.1 Protocols and guidelines post-PAO

As opposed to clinical guidelines that are based on evidence which has been reviewed using systematic review approaches, Segaren et al. (2015) protocol and Adler et al. (2016) protocol were explored further and compared with each other. The previously mentioned protocols underlie the clinical expertise domain in the EBP model. Clinical expertise provides us with the judgement and experience clinicians acquire through clinical practice. Therefore, from the available published protocols, two protocols from Adler et al. (2016) and the Royal National Orthopaedic Hospital NHS by Segaren et al. (2015) are compared in terms of the average period for each phase, goals, exercises, precautions, datasets/criteria for progression to combine or contrast protocol phases, goals and restrictions. The reason to do the comparison is to see if the two protocols share similar goals, follow the same procedures in regard of how many phases and whether these protocols prescribe similar exercises.

It is important to be noted that, from the systematic search done at the beginning of this chapter, no evidence was found in the literature that either proves or disproves these protocols and why certain exercises should be focused on. From Table 2, number 1 represents Adler et al. (2016) protocol and number 2 represents Segaren et al. (2015) protocol. It seems that the two protocols were similar in regard to exercises and when to proceed. Segaren et al. (2015) did not include any progression criteria except bone healing to proceed to strengthening exercises.

Table 2: A comparison between different protocols found in the literature. Number 1 represents Adler et al. (2016) protocol and number 2 represents Segaren et al. (2015) protocol.

Average period (weeks)	**Goals**	**Exercises**	**Precautions***	**Criteria of progression**
1 to 6	• Optimise tissue healing (2) • Independent walking with aids (2,1) • Regain hip ROM to preoperative level (2) • Reduce pain to 0/10 (1)	• Hip ROM exercises (2,1) ankle ROM (1) • Isometric muscle strengthening exercises (2,1) • Circulatory exercises (2) • Mobilise with walking aids (2) • Stairs if possible (2) • Hydrotherapy after wound heal (2) or at six weeks (1) • Self-management (2)	• No sit up restriction (2) • Mobilise with crutches, 10 kg partial weight-bearing (2) no more than 20% of body weight (1) • Discourage tip toe walking (2) • Avoid sitting more than an hour when hips flexed to 90 or more (1). • Patients' education: rehabilitation guidelines and home exercise programme (1)	• Normal gait (2) • Minimal to no pain (2) • No criteria for progression (1)
6 to 12	• Improve function and balance of the lower limbs (2) • Hip flexors, abductors and quadriceps muscles (2) • Walk without walking aids (2,1)	• Strengthening with resistance of hip muscles and quadriceps muscle (2) • Gait re-education (2) • Balance/proprioception exercises (2) • Core stability exercises (2) • Active ROM (1) • Upper limps resistance training (1)	• Use of assistive device until gait is normal (1) • Avoid post activity swelling and muscle weakness (1) • Impingement of iliopsoas (1)	• Normal gait (1) • Adequate ROM to carry on ADL (1) • Ascend and descend 8" step (1) • Good pelvic control during SLB for 15 seconds (1)

	• Good core control and pelvic stability (1) • Ascend and descend 8” step (1)	• Closed chain exercises (squat, step up and down, lunges and leg press) (1)		
12 to 16-18	• Return to full ADL (2,1) • Improve lower limbs’ strength to 5/5 (1) • Improve core strength (1)	• Similar to the second phase with progression (2,1) • Balance/proprioception exercises and sport related balance/proprioception (1) • Stretching (1)	• Avoid over stretching (1) • Avoid pelvic and lumber compensatory movement (1)	• Level 3 on Sahrmann core test (1) • 5/5 lower limb strength (1) • Adequate ROM and pelvic control during SLB (1) <u>Return to sport or high impact activities expectation</u>: - Around six months (2) - More than three months and after showing hip and lower limb proper control (1)
More than 16-18	• Being able to walk long distances (1) • Independence (1)	• Similar to the third phase with progression (1) • Plyometrics and running (1)	• Maintain adequate strength (1)	

From the previous table, it appears that patients with DDH go through three or four phases during rehabilitation post-operative. **Phase one** starts immediately after any surgery with teaching the patient how to use the crutches, Range Of Motion (ROM) exercise and isometric muscle strengthening exercises (Kalore et al. 2016; Hara et al. 2017b). This phase is considered an acute stage and the bone healing process is taking place (Adler et al. 2016). **Phase two** starts after the muscles reattach and the bone heals and that takes place usually after around six to eight weeks (Kamath 2016). Therapists start this phase after significant muscle strengthening is expected and bone healing at the site of surgery is evident in a radiograph (Adler et al. 2016). During this phase, gait re-education, progression of strengthening exercises and proprioception exercises are given.

Phase three starts when a patient has full pain-free ROM and extends for several months afterwards, and it has been given different terms, such as return to sport, functional training, chronic and other terms (Adler et al. 2016). In this phase, therapists usually start progressive resistance exercises, proprioception and gait re-education exercises (Adler et al. 2016). It needs to be noted that, although the mentioned protocols share the overall concept of rehabilitation stages, they do not agree on the number of postoperative phases. **Phase four** could be considered as the final phase and the preparation of the patient to go back to high level of activities and return to sports. During this phase, being independent and able to do high level of activities and impact sports are the main goals. Running and plyometrics are recommended at this phase with progression.

Regarding the three domains of EBP, research evidence seems the domain most affected. Even though the previous protocols are providing us with valuable information, the science behind the protocols and relevance to patients with DDH could be questioned. Rehabilitation post-PAO, as mentioned already, varied and did not follow evidence-based approach. This means that EBP research evidence domain is missing. Lack of evidence-based guidelines might increase the risk of making mistakes and lead to a patient's poor quality of life. The exact timeline of the rehabilitation is questionable in the previous protocols. In addition, the intensity and duration of these exercises were unclear from the protocols.

Return to sport and high level of activities are suggested to start from phase three, which is an important area that needs to be explored in order to avoid complications due to early return to high level of activities. In addition, this area could be of interest to young patients with DDH who wish to get back to sports and high level of activities. Although there are several questions that arise from the aforementioned literature, only one question is the main focus of this research, which is; Is postoperative rehabilitation for young adults with DDH optimal?

This is also an ideal time for patients to get used to crutches or a walker and for the therapist to let them know what exactly they might be facing in the weeks after the surgery. As mentioned before, according to the available protocols discussed above, physiotherapists start the rehabilitation programme after a patient's surgery, primarily to avoid muscle weakness and avoid potential gait disturbance. Optimal rehabilitation is expected to include high level of activities and sports. Unfortunately, based on the findings of the systematic search of the third area little research has been done on this area for patients with DDH.

2.5.2 Activity levels and return to sport

The patients who underwent PAO were able to return to high levels of activities and impact sports post-PAO as reported by multiple authors found in the systematic search of the third area (van Bergayk and Garbuz 2002; Ito et al. 2011; Klit et al. 2014; Hara et al. 2018). The majority of the articles found around this area involve cohort (Klit et al. 2014), case control (Hara et al. 2018) and case series trials (Ettinger et al. 2015a; Heyworth et al. 2016). There is variability in study settings and methods between the studies found in the previous systematic search, such as exploring the activity levels of patients with DDH postoperative (Novais et al. 2013), inclusion of different age groups or comparison between them (Ito et al. 2011); another study has assessed the ability of athletes diagnosed with DDH in terms of their return to a high level of activities (Heyworth et al. 2016), whereas other study compared PAO and THR outcomes (Hara et al. 2018).

In Heyworth et al.'s (2016) study, 41 patients were included, and the sports practised in these patients were running, skiing, swimming soccer, basketball, cycling and other different sports. Running was the most popular type of sport followed by skiing. Heyworth et al. (2016) found that three-quarter of the patients were able to return to athletics. In addition, Heyworth et al. (2016) suggested that there is little research focused specifically on athletic function for patients undergoing PAO. Even though the previous study does report promising findings, the small sample size and not recruiting a proved athletic professional patient might affect the results slightly and suggests further research.

There was a wide variety of measurements used by different authors to assess the ability to return to a high level of activities and sport among patients with DDH post-PAO. As regard activity levels, the UCLA activity scale has been the most commonly used Patient Reported Outcome Measures (PROMs) in the previously mentioned studies and other studies to measure activity levels and back to sport postoperative (Harris-Hayes et al. 2012; Ettinger et al. 2015a; Hara et al. 2018). The UCLA is a scale from 1 to 10 that measures the intensity of activity level for the last six months, where 1 is the minimum activity and 10 is the maximum (Zahiri et al. 1998). So, it only measures the success of the surgery from the patients' perspective. In all the studies which measured the UCLA activity scale of the patients post PAO (Novais et al. 2013; Heyworth 2016; Kalore et al. 2016; Hara 2017; Khan 2017; Hamai 2018; Hara et al. 2018) there was an increase in the UCLA activity scale scores; the authors reported this as a positive finding and concluded that, based on this score, the PAO is a successful surgery even for patients who consider returning to high impact activities and sport.

It needs to be noted that scoring 9 or 10 means that patients are able to participate in impact sports. Two studies' mean age group at surgery was less than 30 years (Novais et al. 2013; Heyworth et al. 2016) with a mean follow-up duration of 6.2 years. Five studies' mean age of the patients at surgery was more than 30 years and up to 51.4 years (Kalore et al. 2016; Hara et al. 2017b; 2018; Khan et al. 2017; Hamai et al. 2018) with a mean follow-up duration of 16.9 years. No link has been made between the UCLA activity scale and patient rehabilitation in the previous studies. It needs to be noted that the activities before the six months of administration of UCLA activity scale were not addressed. Little information could be extracted if such a tool is used inappropriately to enrich the literature with valuable information regarding patients' different activity levels.

Other Patient Reported Outcome Measures (PROMs) used in aforementioned studies were Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) the modified Harris Hip Score (mHHS), Harris Hip Score (HHS) and Oxford Hip Score (OHS). These PROMs were used mainly to measure the pain, function, absence of deformity and range of motion pre-operatively post-operatively through different time points: six months post-operatively, one year and two years post-operatively. In addition, there is not enough insight existing in the rehabilitation process and how it might influence pain level and function. WOMAC was the first choice to investigate pain, stiffness and function post-PAO in four studies (van Bergayk and Garbuz 2002; Ito et al. 2011; Novais et al. 2013; Heyworth et al. 2016). The mean age at surgery in these studies ranged from 26 to 32 years. All the aforementioned studies reported significant improvement post-PAO in all PROMs explored. Follow-up duration was two years in van Bergayk and Garbuz (2002) and 11 years in Ito et al.'s (2011) study.

Unfortunately, most of the research that has been done on return to sport and return to high level of activity post-operatively for patients with DDH were poorly designed studies with weakness of either the methodology, data, inappropriate design and, therefore, are considered to have a low level of evidence, according to Kuroda et al. (2013). As mentioned earlier, the relevance of such a topic to patients with DDH is that the population tends to be young (Kalore et al. 2016) and, therefore, activity levels and participation in sports, for example, are more popular during young age. The outline for rehabilitation protocols was mentioned in six studies (Ito et al. 2011; Hamai et al. 2014; Kalore et al. 2016; Hara et al. 2017b; 2018; Jacobsen et al. 2018). The outline for rehabilitation protocol was brief in all studies and none of them discussed in detail the intensity, frequency or the duration of the rehabilitation or how the patients progressed from one stage to the other. No study investigated the rehabilitation protocol directly as a factor or its influence on PAO post-operatively on ability to return to a high level of activities and sport among the DDH patients. However, change from preoperative to postoperative was due to a combination of factors, including surgery, rehabilitation and the natural healing process. Within a rehabilitation context, comparing different exercises and investigating the benefits of them with appropriate tools lead to the development of a clear and consistent rehabilitation protocol.

Thus, several issues could be raised from third area search, such as, the effect of age on increase or decrease of level of activity in patients with DDH post-operatively, and the possibility of all patients with DDH returning to a high level of activities when rehabilitation finishes. It could be concluded that there is underrepresentation of the rehabilitation process in the studies found in the literature. It seems that a missing factor that might affect the rehabilitation goals or the type of surgery chosen is the age of a patient at surgery since some surgeries are advised to be done to specific age group or for hip joint status (Gray et al. 2015; Kamath 2016). Athlete patients might not choose PAO surgery if the outcomes of the rehabilitation are unknown and might choose hip arthroplasty where they will be guided with more solid or well-researched clinical guidelines rehabilitation. The search of the third area also revealed an interesting paper by Gambling and Long (2019) which will be discussed next.

2.5.3 Patients' values

As mentioned in the Introduction, according to EBP, patients’ values are best explained as the choices of the patients among other several possibilities (Sackett 1996; Negrini 2010). A semi-structured interviews and gathering of online stories posting from one message board has investigated the rehabilitation process of patients with DDH experiences post PAO in 97 patients (Gambling and Long 2019). The authors found two common plots. Plot 1 focused around those participants who received an early diagnosis. Plot 2 was focused on patients experienced delayed diagnosis and thus delayed treatment.

The impact of early diagnosis on participants’ daily lives, patient’s lifestyle, and treatment options was found through patients’ stories. In addition, the authors suggested that patients in plot 1 who had a quicker pathway to diagnosis and treatment tend to recover and adapt better than those in plot 2. In addition, the authors suggested that patients in plot 1 might recover and return to normal activities within the recommended parameters of time. Patients in Gambling and Long (2019) study raised concerns on the lasting impact of DDH in relation to physical and emotional aspects. Patients in plot 1 asked questions around the possibilty to do anything further that might help the survival of their native hip. On the other hand, patients in plot 2 were afraid of further operations in future.

Gambling and Long (2019) could be seen as a key paper on the rehabilitation process as a similar approach will be conducted as a part of this research project when the patients' values area will be targeted by exploring the patients' rehabilitation experience by investigating types of exercises recommended, intensity and frequency of the exercises, rehabilitation period, strategies to avoid pain and finally the patients' opinion around the rehabilitation they had. Unfortunately, due to lack of evidence-based research around rehabilitation, apart from Gambling and Long (2019), there was no other research found in the literature investigating DDH patients' experiences of rehabilitation. The patients' values domain within the EBP was not enriched with many research studies; therefore, it seems unclear what are the views of patients with DDH regarding their rehabilitation and journey post-operative.

2.6 Exercises of interest to laboratory-based study

There is wide variety of exercises for the hip to choose from when dealing with DDH patients (Robinson and Nee 2007; Fotoohabadi et al. 2010; Reiman et al. 2012; Segaren et al. 2015; Adler et al. 2016; Ebert et al. 2016). Weight-bearing exercises include a variety of exercises and performing these exercises with proper biomechanics may improve hip muscle recruitment and force production of the extensors and abductors during functional and sports-specific movements (Kamath 2016). For example, single leg standing activities require hip abductor muscle activation of the weight-bearing side in order to control pelvic positioning in the frontal plane during the exercise (Romano et al 1996).

The following pages explain the approach used for decision-making for the functional exercises included in this study based on the available literature around rehabilitation of hip joint conditions in general since there is a lack of research regarding the rehabilitation of DDH. Walking, double limb squat and single limb balance were the functional exercises the patients were asked to do. The previously compared protocols in section 2.5.1 recommended these exercises as a part of patients with DDH rehabilitation post PAO. The reasons that the researcher chose the exercises mentioned earlier were:

1. The proposed exercises are part of the rehabilitation programme for hip dysplasia (Segaren et al. 2015; Adler et al. 2016).
2. It can be done easily and suits the majority of the hip dysplastic adult population with no or minimal risk (Segaren et al. 2015; Adler et al. 2016).
3. It is easy to calculate at gait laboratory and does not include any non-weight-bearing (NWB) exercises.
4. It is practical and does not need sophisticated procedures or more equipment. More specific criteria are explained underneath each individual functional exercise.

2.6.1 Walking

The literature around how DDH patients walk could be found in several studies in the literature (Pedersen et al. 2004; Skalshøi et al. 2015). The first study that describes how patients' with DDH walk pre-operatively is by Romano et al. (1996). As suggested previously in the movement compensation section 2.4.1, even though there are studies which have explored how patients with DDH walk, there are conflicting results between the papers in the literature of other variables and a systematic review is needed to review the articles and level of evidence once sufficient studies of high quality have been published.

In addition, Skalshøi et al. (2015) suggested that DDH patients post-surgery tend to adapt to new positions to avoid pain-triggering positions. Changes in normal muscle patterns during walking were strongly related in the literature with a pathological condition such as OA or post-surgeries (Skalshøi et al. 2015). The main assumption is that having a pathological condition or undergoing surgery might cause muscle imbalance, which leads to abnormal gait. Knowledge about the dynamics of gait in patients with dysplasia of the hip is important for an understanding of the consequences of the mechanical changes in the hip joint (Romanò et al. 1996; Pedersen et al. 2006; Skalshøi et al. 2015). Moreover, determining which gait compensations these patients adopt is relevant for the management and evaluation of various treatments, such as physiotherapy. Exploring compensatory movements during walking is essential to enable the clinical community to understand the underlying causes of gait deviations and enhance treatment plans.

2.6.2 Single limb balance (SLB)

In addition, single-leg standing activities require hip abductor muscle activation of the weight-bearing side in order to control pelvic positioning in the frontal plane during the exercise (Chang et al. 2005). There is not enough information found in the literature about whether this is a beneficial exercise for DDH patients post-surgery or whether patients compensate during SLB. 40% of the gait cycle s during the single limb stance phase (Verhagen et al. 2005; Åberg et al. 2011; Sung 2015). Clinicians tend to ask patients to do a one-leg stance test to assess any compensation strategies patients do, in order to counter them when setting rehabilitation goals and use this exercise during the rehabilitation post-operative (Segaren et al. 2015; Adler et al. 2016).

No evidence in the literature has found, investigated or explained if there are movement compensation strategies that hip dysplastic patients tend to do during different functional exercises. SLS is considered as an essential element during functional activities, such as in walking, during the single limb stance. Exploring the kinematic and kinetic data would offer knowledge around ROM and forces across different joints to help in understanding how patients with DDH might compensate in their movement to maintain postural stability. Therefore, the knowledge expected from this exercise for clinicians aims to assist in the planning of and evaluation of rehabilitative procedures.

2.6.3 Squat

Squats from the perspective of many therapists replicate different daily life activities such as sitting, getting up from a chair, phases such as running, hopping and ascending stairs (Barton et al. 2014). However, they require a sufficient range of motion to control the whole body (Stevens et al. 2018). Lower extremities joints are interrelated; therefore, abnormal/excessive stress, inefficient neuromuscular patterns or muscular weakness at one joint may have an effect on the entire lower extremities kinetic chain (Lubahn et al. 2011).

The biomechanics of squat exercises haven't been investigated in DDH patients and compared to a control group. From the surrounding literature, the benefits of understanding squat by studying kinematic and kinetics variables could show altered loading during exercises which could affect all lower limb joints (Roos et al. 2014). Roos et al. (2014) showed that there were differences between squat mechanics of participant patients with ACL injury post-operatively compared to a control group. The study found patients tend to adopt different squatting strategies in order to avoid knee loading using different behaviour avoidance mechanisms.

The patients in the study showed reduced performance and adopted compensatory movements as avoidance mechanisms to avoid loading the knee joint. The researcher assumes the same might happen with DDH patients in order to avoid pain-aggravating positions on the hip joint more specifically. Therefore, the squat exercise needs good joint biomechanics to be done without harming lower limb joints. These combined effects influencing the LE kinetic chain, hip and ankle kinetics and kinematics during weight-bearing activities may have a direct impact on knee biomechanics and, thus, relate to knee injury risk (Lubahn et al. 2011). Performing these exercises with proper biomechanics may improve hip muscle recruitment and force production of the extensors and abductors during functional and sports specific movements (Lubahn et al. 2011).

Moreover, understanding and investigating compensatory movements and predisposing factors in DDH patients hopefully facilitate the choice of rehabilitation exercises by avoiding aggravating positions being done by patients due to movement positions.

To illustrate further the importance of the previously mentioned exercises, walking, SLB and squat, if DDH patients are found to be compensating during a certain exercise, this movement compensation might have adverse effects on other joints. Instead, therapists should re-educate patients on how to do the exercises in the proper way. Consistency of evidence is needed to develop a rehabilitation programme that is based on scientific fact, instead of targeting certain muscles randomly without a high level of evidence, which might lead to inconsistency of results. Therefore, understanding and investigating compensatory movements and predisposing factors in DDH patients would facilitate the choosing of rehabilitation exercises. As far as the researcher knows, there are no papers in the literature that have investigated squat and SLB exercises of patients with DDH and compared to control group.

2.7 Overall summary of the literature (gap of knowledge)

Even though the literature was explored through three different areas, yet there are several areas that are not addressed. By using EBP as guidance of this research, the best available research evidence was searched. Even though relevant literature was searched, the following issues might be of interest for therapists or in future studies to understand the effect of PAO on rehabilitation programme in patients with DDH post-operative. Issues that might be considered as an indication of the gaps in our knowledge are such as:

1- From the first area of systematic search: the recommendation of postoperative rehabilitation based on the available literature.
2- From the second area of systematic search: possibility of patients with DDH able to be able to return to high level of activities safely.
3- From the third area of systematic search: Which exercises should be recommended and what should be avoided?

All the previous issues might influence the therapist's decision about whether to recommend rehabilitation before surgery or not and possibly affect the rehabilitation outcomes. It is possible that the available guidelines were linked and borrowed by authors from either secondary OA or THA, which led them eventually to apply these rehabilitation protocols to DDH patients. The ambiguity around the rehabilitation process leads to different recommendations for exercises, different categories of phases of rehabilitation, when to start and when to stop (Adler et al. 2016; Kamath 2016). It is anticipated that the lack of evidence regarding a proper rehabilitation protocol or studies around the rehabilitation of patients with DDH post-PAO, might strongly influence the physiotherapists' practice and the use of a wide variety of exercise is anticipated. This might lead to therapists having to borrow from similar literature, which could arise the chance of delivering inappropriate treatment after PAO. However, further investigation of condition-specific research is needed. The need for such literature is crucial for therapists and for the use of the best possible exercises with confidence.

Hip dysplasia patients suffer from a wide range of issues that limit their daily life activities, such as having decreased overall function in terms of ROM, pain, gait difficulties and compensation and muscle weaknesses (Romanò et al. 1996; Adler et al. 2016). In general, rehabilitation programmes include gait re-education, muscle strengthening exercises, range of motion exercises and proprioception training (Segaren et al. 2015; Adler et al. 2016). Based on the few protocols found within research evidence and clinical expertise domains within EBP, rehabilitation programmes in general concentrate specifically on strengthening hip muscle abductors and hip flexors. As a matter of fact, in clinical settings, rehabilitation programmes for DDH patients might be influenced by different factors such as age, weight, pain, expectations, goals, and hip joint status before surgery (Kalore et al. 2016).

To illustrate further, the following elements of rehabilitation are not known about from the previously mentioned research and guidelines: type of exercises, intensity, frequency of the exercises, duration of the rehabilitation post-operatively and when to progress to the next phase (from non-weight-bearing to weight-bearing exercises). In addition, the possibility of measuring benefits and the adverse effect of certain exercises is hard to establish due to the lack of a longitudinal study. Therefore, the effects of the different functional exercises within the rehabilitation process on the dysplastic hip joint are still unknown. The main issue related to physiotherapy practice is that researchers have not conducted research aimed at investigating DDH rehabilitation post-operative and it appears a novel area of research, as proven in the systematic search above.

In addition, it seems rather urgent to investigate the effect of exercises done at clinics on DDH patients regardless of the findings of this project in order to build a solid foundation or at least attract more attention to research for this underdeveloped area. The importance of such research that investigates DDH rehabilitation programmes is to minimise the gap in the knowledge, and start a novel work around hip dysplasia to inform clinicians about the importance of evidence that supports their choice since patients with DDH patients receive rehabilitation post-operative. Hopefully, in the long term, this study would provide essential information to support the development and powering of a future clinical trial of a DDH rehabilitation programme for patients with DDH in physiotherapy clinical practice.

Unfortunately, the overall rehabilitation process post-PAO might be affected due to lack of knowledge provided to therapists and lack of evidence investigating exercises prescribed for patients with DDH. After a comprehensive search guided by the EBP model, so far, the researcher is not aware of any research paper that has investigated how the kinetic and kinematic data of the pelvis, hip, knee, ankle and foot, during different functional exercises alters the hip joint biomechanics for patient with DDH post-PAO in a laboratory-based study. Understanding whether the chosen functional exercises are done in normal or altered way may assist clinicians in developing more targeted treatment approaches towards the findings of this research (Bagwell et al. 2016). Finally, the importance of such research might help clinicians to benefit from the available literature in addition to providing details around the movements these patients do during different functional exercises.

2.8 Purpose of the study

As stated in the Introduction Chapter, the overall aim of this thesis is to encompass elements of research to understand the recovery process of patients with hip dysplasia post-PAO. This chapter explored the first aim around the existing clinical expertise papers, editorials, guidelines, case reports and case series to identify the main elements of clinical guidelines in addition to background information with respect to DDH and rehabilitation post-operative. The purpose of this study's Part 2 is, therefore, to investigate, concurrently, the kinetic and kinematic effects of functional exercises on patients' hip joints for adults with dysplastic hip, by means of a combination of kinematic and kinetic hip joint analyses of the lower extremities and trunk and comparing them with healthy hip joints in a laboratory-based study. It was found based on previous research (Romanò et al. 1996; Pedersen et al. 2004; Adler et al. 2016; Kamath 2016) that patients with DDH showed compensatory movements during gait or adopted strategies aimed at alleviating pain.

Therefore, I hypothesised that patients with hip dysplasia would compensate during all the three functional exercises by adopting new positions to avoid aggravating positions or due to pre-operatively adopted compensatory movements during these exercises. In order to do so, this project investigated three functional exercises to see whether they are worth recommending or not and whether there are unusual movement patterns. Consistency of evidence regarding exercises is needed to develop a rehabilitation programme based on scientific facts, instead of targeting certain muscles randomly without a high level of evidence, which might lead to inconsistency of results and unfavourable rehabilitation delivered for this population.

The purpose of Part 3 involves patients' values domain that were explored by a questionnaire, to understand the current level of rehabilitation practice by investigating the common exercises prescribed in rehabilitation clinics and home, investigating the duration, frequency and intensity of the rehabilitation programme for patients on a DDH rehabilitation programme post-operatively. Additionally, patients with DDH are hypothesised they might receive a variety of exercises due to lack of evidence. From the previous summarised background, some elements around patients with DDH rehabilitation were either unknown, such as rehabilitation protocol phases and exercises of each phase, missing, such as movement patterns of patients with DDH post-operatively, unclear, such as sports and activity levels post-operatively, or need further exploration and clarification.

Next, the methodology and methods of this research are illustrated. The study's Part 2 and Part 3 are explained separately and the rationale for these study parts is explored. The detailed method of investigating the biomechanics of DDH patients during laboratory-based study and the process of developing the questionnaire that explores a patient's rehabilitation journey and experience are presented in detail in the same chapter.

Chapter Three: Methodology

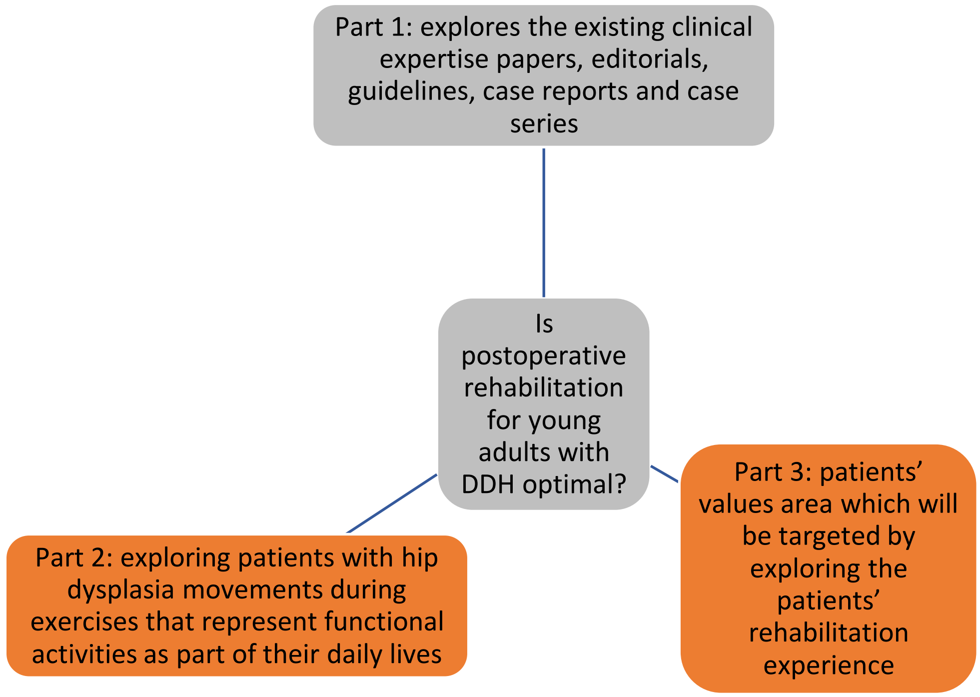
3.1 Part 2 and Part 3: Observational laboratory-based study with control group

In regard to Part 2 and Part 3, both parts were explored by collecting new data; therefore, a methodology chapter is needed. In this chapter, Part 2 of the study was explored in detail first followed by Part 3. The overall aim of this thesis is to encompass elements of research to understand the recovery process of patients with hip dysplasia post-operative. For this purpose, this thesis explored and synthesised the existing and add new evidence in the context of EBP model. Based on what was found in the literature and concluded in the Literature Review Chapter, lack of research in the literature search around the rehabilitation of DDH patients makes it hard to attain an overall understanding of the condition and more specifically, understand the role and impact of rehabilitation on their daily lives post-operatively. In order to gain better insights into patients with DDH rehabilitation, Part 2 and Part 3 are conducted next to take a step forward in adding new evidence within the research evidence and patients' values domains of EBP, see Figure 4.

3.2 Aim and rationale for Part 2

Part 2 aimed to explore patients with hip dysplasia movements during exercises and was done by comparing three-dimensional trunk and lower limb biomechanics during three exercises, between patients with DDH and a control group, from an objective biomechanical point of view. An objective methodological design seemed an appropriate study design to adopt that could provide answers for all the objectives of this research without researcher interference. By using a quantitative method, the biomechanical data, more specifically kinematics and kinetics variables, of the trunk, pelvis, hip, knee and ankle in three planes of movement were investigated during three different exercises.

Figure 4: All parts of this study. Part 2 and Part 3, which are the focus of this chapter, are highlighted with the orange colour.



The movement compensation patterns during these exercises were investigated using a motion capture system due to the fact that this method is considered valid, reliable and objective (Weeks et al. 2012; Vicon 2019). Motion capture system validity and reliability were discussed further under the heading "4.5.8 Laboratory-based outcomes measurements". In addition to provide best research evidence that possibly would explain how patients with hip dysplasia move and whether there are compensatory movements that might be possibly targeted during the rehabilitation post-operative. By investigating the way patients do exercises at the laboratory, clinicians might be able to target specific exercises, avoid others during rehabilitation post-operative. Hopefully, this will decrease the time spent in rehabilitation and avoid long-term pain due to compensatory movement.

3.3 Aim and rationale Part 3

Subsequently, the third aim of this thesis was the patients' values area which was targeted by exploring the patients' rehabilitation experience by searching, types of exercises recommended, intensity and frequency of the exercises, rehabilitation period, strategies to avoid pain and finally the patient's opinion around the rehabilitation they had post-operative. The current level of rehabilitation services delivered for DDH patients was explored in order to enrich the project and literature with reliable and valuable information. By conducted an online questionnaire as a method in this research project, it was hoped that this approach would reflect on and provide an overview of patients' experiences of rehabilitation recovery, more specifically exercises undertaken during rehabilitation at clinics or at home, compensatory movement to avoid aggravating pain, expectations of high impact activity and sports in the future postoperative and overall opinion about rehabilitation services delivered.

There are several types of methods that the researcher of this study could have used to collect the data from DDH participants, such as but not limited to observation, interviews and focus groups. In order to answer the aim of identifying the most common exercises prescribed in clinical practice, adopting observational studies or interviews would not be the first choice and could be considered as time-consuming due to the fact that such an aim could be achieved in an easier way, such as by an online questionnaire. In addition to that, such methods would not include a large number of participants in a short time, e.g., as allowed for by a PhD project, and this would stop the researcher from generalising the findings of this research to the wider population.

Therefore, it was appropriate to conclude that a questionnaire might be a proper method to use as it could provide answers for this study's aim, to explore the current level of rehabilitation services delivered for DDH patients, and it seemed to be a suitable approach to start exploring undiscovered and unknown areas. It allowed for opportunity to explore the current level of rehabilitation for DDH patients in order to enrich the project and the literature with novel and valuable information. If a questionnaire is compared with other types of methods, it is considered a fast and efficient means to obtain valuable information from a high number of respondents (Jones et al. 2008). One of the advantages of questionnaires is that it is possible to quantify the findings (Jones et al. 2008; Handscomb et al. 2016). Other advantages are low cost of data collection, requires minimal training and easy to process (Jones et al. 2008).

In addition, disadvantages to use online questionnaire are converting questionnaire to online questionnaire requires more effort and some expertise and low response rates and an associated bias (Jones et al. 2008). However, the aforementioned disadvantages, would be offset by the advantages mentioned earlier, most importantly, to quantify the findings and require minimal training and easy to process. By understanding the patients' perspective of the rehabilitation postoperative process, clinicians might be able to target specific exercises, avoid others and include the patients in the goal-setting process. Hopefully, this will decrease the time spent in rehabilitation post-operative. In addition, in this study, there was a use of multiple methods in order to inform the study with multiple answers to this thesis question, is postoperative rehabilitation for young adults with DDH optimal? In addition, a key component of selecting multiple methods to answer the research question and objectives was the possibility of explaining the quantified biomechanical results with the results of the patients' values during the discussion of all study parts results.

3.4 Objectives of Part 2 and Part 3

Part 2 objectives:

- To undertake a 3D movement analysis study to provide a detailed biomechanical description of the main variables characterising the different functional exercises for postoperative patients with hip dysplasia.
- To determine whether walking, squatting or single leg balance are being done with compensatory movements that might affect other joints for postoperative patients with hip dysplasia.

Part 2 hypothesis: patients with DDH compensate their movement during three functional activities compared to the control group.

Part 3 objectives:

- To explore the exercises prescribed post-operatively for patients with hip dysplasia as reported by patients themselves after completing their own postoperative rehabilitation.
- To understand the current level of rehabilitation practice for postoperative patients with hip dysplasia by investigating the patients' opinion around rehabilitation received, common exercises prescribed in rehabilitation clinics and at home and exercises duration, frequency and intensity.

3.5 Methods: observational laboratory-based study with control group

3.5.1 Ethics

Ethical approval was obtained from the HCARE Research Ethics Committee on 16/11/18, Cardiff University, see Appendix 2.

3.5.2 Ethical considerations

Any act that could be considered immoral would affect the trustworthiness of the research project. Therefore, all ethical problems were dealt with mindfully to ensure the rationality and dependability of this research. All participants in this research received a written form describing their rights and the goals of this study (see Appendix 3). The participants were asked to do three exercises as mentioned earlier in the Literature Review chapter. walking, squat and standing in one leg. The participants were also informed that their participation was voluntary, that they could withdraw at any time without giving a reason and that they had the right to not answer any of the given questions. The researcher believes that a trust-based relationship was vital for this research since it would strongly inform this project and provide both valuable and in-depth information.

3.5.3 Inclusion and exclusion criteria of DDH group

The main inclusion criterion was young adult patients diagnosed with hip dysplasia. All postoperative patients who had just had PAO for their affected hip were included in this study. All patients still relying on walking aids were excluded, patients 6-8 weeks post PAO mainly rely on walking aids. The reason for this exclusion was that such patients would not be able to do the proposed exercises on the laboratory treadmill based on Motek guidelines (Motek Forcelink, Amsterdam, the Netherlands). Hip arthroplasty was an exclusion criterion as well, since it involves the removal of the hip joints and different biomechanics are expected. The inclusion criteria were broad; hence, the potential number of participants willing to participate in this study was expected to be large. Furthermore, complex comorbidities such as secondary complications resulting from the surgery, such as fracture and arthroscopy were an exclusion criterion from the study.

3.5.4 Inclusion and exclusion criteria of the healthy group

The inclusion criteria were set to make sure that all the included healthy subjects did not suffer from any weaknesses in the lower limb or back area that might directly influence the pelvic area and hip, eventually influencing the reliability of the data. All the participants were adults, above the age of eighteen, and were able to do the functional tasks pain free. Lower limb assessment was the first step in order to make sure that all the healthy controls did not experience any pain during the functional tasks, which might alter the data collected. Therefore, during the assessment normal ROM, Duchenne and Trendelenburg gait observation and several tests such as the Thomas test was done first to ensure that participants fulfil the inclusion criteria.

Movement compensation due to pain is a key factor that needs to be avoided. Therefore, any participant who reported hip or back pain during the last six months was excluded from the study. The inclusion criteria for control group were adult with 18 years or more and able to do the required functional tasks. The exclusion criteria for control group were back or hip pain in the last six months, history of major medical surgery, pelvic abnormalities and positive Trendelenburg sign. Finally, when participants met the criteria for inclusion, they were informed of the study objectives and asked to fill in an informed consent form to start the data collection.

3.5.5 Recruitment journey

There are thousands or maybe millions of research studies happening every year. For each research study there is a unique recruitment journey. The recruitment took place at Cardiff University Hospital during the period of December 2019 until the researcher was forced to stop in March 2020 due to Covid-19. The path of this research study journey was not smooth most of the time and there were many challenges and obstacles that either resolved or changed the shape of the recruitment path and timeline. Challenges and obstacles are discussed in Sections 6.7, Limitation of the study.

There were many approaches that the author of this research had in mind at the beginning to reach as many patients as possible. This research was advertised through charities, social media and word of mouth. DDH patients were recruited through DDH and STEPS worldwide charities. The DDH charity is ‘the UK’s only DDH dedicated charitable trust (DDH-UK.ORG). The STEPS charity was founded in 1980 and is recognised as one of the leading DDH charities in the field. One of their aims is ‘that those affected by childhood leg conditions are fully informed and supported, from diagnosis to treatment‘ (STEPS DDH website). Both charities helped the researcher to advertise and recruit participants involved in this study and reminders were sent to the members every month. The reminders posts were on their social media accounts. The patients were provided with a contact email and a phone number so that phone/email screening was conducted in order to make sure that patients met the inclusion criteria. The patients were given the choice to be asked the screening questions through a phone call or email and provide the main researcher with answers. The phone/email screening was done by the main researcher. The patients then were sent an email containing a Participant Information sheet (PI), Appendix 3, to have a look at, and fill them out if this had not been done before.

All participants who achieved the inclusion criteria were emailed a consent form to be read and signed, see Appendix 4. In addition to that, three students studying at Cardiff University who have a DDH diagnosis were met and asked to help with recruiting. All the three students underwent hip arthroplasty and were not invited to be part of this study group. However, they distributed the flyers, as seen in Appendix 5, and information on this study through word-of-mouth with their friends or through social media. A voucher of £20 was given to all participants of this study.
In contrast, control group participants were recruited from Cardiff University and the wider community by distributing flyers and sending emails through the postgraduate office, Cardiff University notice board and emails through Postgraduate admissions.

Posters and word-of-mouth were used also to advertise and recruit the healthy subjects who met the inclusion criteria. One of the main issues the researcher faced was that all the patients who participated in this study were from outside Cardiff. The distance between the participants' homes to Cardiff varied between patients. The minimum journey to the Research Centre for Clinical Kinesiology (RCCK) laboratory was one hour and the longest was six hours. Some patients asked their partner or mother/father to drive them all the way to Cardiff or took a 5.00 am train to arrive on time. This led to exhaustion and sometimes patients felt pain due to sitting in the car for a long time, for example one patient came to the laboratory on train with total journey time of three hours. As this was predicted before conducting the research, this was one of the reasons that Visual Analogue Scale (VAS) was added, to measure the effect of the feeling of pain prior to the study.

The previous issue was either resolved, led to rescheduled appointments or sometimes cancellation of the appointments. One of the main obstacles that affected the recruitment process severely was the Covid-19 pandemic. Covid-19 affected every aspect of our lives. The negotiation with the patients regarding taking the journey to Cardiff was impossible since the whole country went into lockdown for more than three months and everyone started social distancing. Covid-19 made the recruitment almost like 'mission impossible'. Four patients cancelled their appointments in April 2020 and two who were interested in participating in the summer also withdrew due to Covid-19. This forced the study researcher and supervisors to have a meeting and discuss if there was a possibility of carrying on with recruitment. The supervisors of this research agreed to stop recruiting due to the prolonged period of lockdown and universities remained closed.

3.5.6 Sample size

The estimated sample size was calculated using the G*Power software. According to Cohen (1988), a meaningful effect size for biomechanical variables does not exist. According to the author's classification, a large effect size of 0.8 was aimed for in this study in order to identify significant results. The large effect size was adopted due to the fact it indicates the research findings have practical significance, opposite of using small effect size which means limited practical applications of the findings. The settings used were: α set with 0.05 and power (1-beta) was 0.80. Based on the previous calculation, the total number of participants for each group was calculated to be 21.

3.5.7 Laboratory-based study procedure/measurement protocol

Before the study started, a brief welcome and brief description of the study was given to all participants/patients. Participant/patient information sheet and consent form were given. If the participant/patient agreed to participate, then they asked to wear appropriate clothes. During the start of the study, hip was inspected for possible scars on affected leg and age, height and weight were taken. Gender and age of each participant/patient were written down on the data collection sheet. Body mass index (BMI) score was calculated after the measurements of participant/patient height and weight. Body weight was calculated using digital floor weighing scales (Seca 888, Seca Ltd., Medical Scales, Birmingham, UK) and height was calculated using mechanical telescopic measuring (Marsden HM-250P Leicester Portable Height Measure).

Both shoes and socks were taken off for height and weight measurements. After that, knee and ankle width were measured and a tape measure was used to calculate the lower limb length (from the anterior superior iliac spine [ASIS] to medial malleolus) bilaterally. After measuring and writing down all the prior information, the participant/patient was asked to do two exercises, squat and SLB, while collecting the data on Vicon overground. After that, the participant/patient was asked to rest until the turning on the Gait Real-time Analysis Interactive laboratory (GRAIL) treadmill. When the GRAIL system was ready to use, the participant/patient was asked to walk for two minutes on the treadmill. A detailed movement analysis procedure is discussed in-depth later in this chapter. Then, the muscle test with Biodex was done. Pain measurements and fatigue analogue scale were taken before and after doing the three exercises and after Isometric muscle test. Finally, the participant/patient was thanked, making sure everything is done and they signed to get the voucher.

3.5.8 Laboratory-based outcomes measurements:

3.5.8.1 Vicon motion capture system

In the literature, three-dimensional motion capture systems are shown to have accuracy and reliability (Miller et al. 2016). Vicon system has shown excellent test-retest reliability and validity and is considered as gold standard (Meldrum et al. 2014). In Tsushima et al. (2003) study, the authors explored the test-retest reliability and inter-rater reliability of kinematic measures using Vicon system. Kinematic data of lower limbs of six healthy participants was explored during walking. The mean age of the included participants in Tsushima et al. (2003) study was 35.2 ± 6.2. Data of lower limbs joint angles was collected in two different trial sessions through two expert physiotherapists.

In order to explore the reliability between the kinematic variables across raters and sessions, coefficients of multiple correlations (CMC) were performed. The authors found that test-retest and inter-rater reliability were high for motion across different planes. For instance, inter-rater reliability were high for motion in the sagittal plane (R_a = 0.971 to 0.994) and the frontal plane (R_a = 0.759 to 0.977). The authors concluded that there is evidence for the reliability of motion analysis for use in analysing walking. The Vicon motion capture system (Vicon B.V., Oxford, UK), with two force platforms, was used to assess two of the proposed exercises, single limb stance and double limb squat.

It needs to be noted that weight, height and knee and ankle width were measured before the start of collecting the data. The knee width was taken with Vicon provided measurement, aligning the measurement with medial and lateral collateral ligaments. The same measurement was used for ankles by aligning the Vicon measurement with medial and lateral epicondyles.

3.5.8.2 GRAIL system

Participants conducted the walking exercise in a Gait Real-time Analysis Interactive Laboratory (GRAIL) motion analysis system (from GRAIL, Motek Medical B.V., Amsterdam, The

Netherlands). This includes a dual-belt treadmill, a motion-capture system (Vicon B.V., Oxford, UK) and two embedded force plates beneath the treadmill (Lansink et al. 2017; MotekforceLink 2018). The main reason to choose treadmill instead of normal walking, is that the MOTEK treadmill gives more gait cycles in short time for analysis compared to Vicon overground system (van den Bogert et al. 2013; Lansink et al. 2017). This resulted in calculating spatiotemporal and lower limbs' joint kinematics and kinetics (van den Bogert et al. 2013; Lansink et al. 2017).

In Liu et al. (2016) study, the authors compared Vicon overground system to GRAIL system during 6-minute walk test in patients with chronic obstructive pulmonary disease and control group. The authors assessed the reproducibility and validity of the 6-minute walk test. Patients found to walk further in the second overground test (24.8 m, 95% CI 15.2-34.4 m, $p<0.001$) and in the second GRAIL test (26.8 m, 95% CI 13.9-39.6 m). The authors reported that the GRAIL 6-minute walk test was reproducible (intra-class coefficients = 0.65-0.80). Validity of the GRAIL 6-minute walk test was assessed and intra-class coefficient values ranged from 0.74-0.77. However, this was the first time anyone has implemented this system on DDH patients. All systems were integrated using the software D-flow. The GRAIL system has been used by many authors recently as a gait laboratory for rehabilitation (van den Bogert et al. 2013; Lansink et al. 2017; Prinsen et al. 2017).

According to Prinsen et al. (2017), this system provides:

- Real-time analysis
- Easy access to the averages of different trials due to multiple data recordings
- The ability to identify "pathologic responses to perturbations"
- The identification of sway and belt changes
- The identification of movement strategies that patients tend to do
- Easy access to implementing a rehabilitation process and research
- An off-line analysis tool for the gait

3.5.8.3 Plug-in-Gait model

3.5.8.3.1 Plug-in-Gait modelling

According to Newington-Helen Hayes, gait is a biomechanical model that can calculate the body joints' kinematics and kinetics. The XYZ markers' position and anthropometric measurements are needed for each subject in order to run the model. The output of this model is achieved by applying the moments of inertia and masses to body segments after defining the rigid body segments and the angles between them. For further information regarding these outputs, see the next section. The real marker trajectories generate virtual marker trajectories when Plug-in Gait modelling is used. These virtual markers represent kinematic and kinetic quantities (angles, moments, etc.) and representations of the modelled segments (Nexus 2008).

3.5.8.3.2 Plug-in-Gait output

First, the model checks if the markers and anthropometric data exist. Then, during the static trial, the model calculates the fixed static values in order to define the body segments. Afterwards, the model defines the rigid body frame-by-frame. Finally, the Plug-in-Gait model outputs are calculated. The kinematic outputs are joint angles and Plug-in-Gait bones. The kinetic outputs are forces, moments and powers for the targeted area.

3.5.8.3.3 Custom Plug-in-Gait template

The trunk is one of the outcome measures that cannot be measured with the lower Plug-in-Gait template. A full body Plug-in-Gait requires more markers in order to run properly. Therefore, a custom Plug-in-Gait template was created specifically for the purpose of this study. The two additional markers were added to the template in order to identify the Anterior Superior Iliac Spine (ASIS) markers accurately during the data processing. Adjustments were made to the Plug-in-Gait template in order to achieve the aim of this study and measure the lower limb plus the trunk lean.

Two additional markers were added, left and right lateral sides of the iliac crest, Right Anterior Superior Iliac Spine (RASIS) and Left Anterior Superior Iliac Spine (LASIS) to help in the gap filling process and to get accurate pelvis positions, especially during squats following Roos et al.'s (2014) study. The adjustments were made on the Plug-in-Gait lower body template that uses both Posterior Superior Iliac Spine (PSIS) to identify the pelvis. During the squat, the additional markers were used to identify both RASIS and LASIS. The reason for adding these two markers is that both markers can be blocked from the cameras depending on the participants' way of squatting. In addition, the two additional markers (ILIC) and (RELIC), were used when gap filling by using a rigid body gap filling process. The template consisted of 23 markers.

3.5.8.3.4 Marker setup

Following standard procedure, twenty-three markers were placed over the anatomical landmarks as illustrated by the Plug-in-Gait product guide – foundation notes (Nexus 2008); 14 mm spherical retro-reflective markers were used during data collection. The markers used during the data collection were the markers for the torso (5 markers) and the lower limb (18 markers). Torso markers were: 7th Cervical Vertebrae (C7), 10th Thoracic Vertebrae (T10), Clavicle (CLAV), Sternum (STRN), and Right Back (RBAK).

The lower limb markers were: (LASIS), (RASIS), LPSI Left Posterior Superior Iliac Spine (LPSIS), RPSI Right Posterior Superior Iliac Spine (RPSIS), Left Knee (LKNE), Right Knee (RKNE), Left Thigh (LTHI), Right Thigh (RTHI), Left Ankle (LANK), Right Ankle (RANK), Left Tibial wand marker (LTIB), Right Tibial wand marker (RTIB), Left Toe (LTOE), Right Toe (RTOE), Left Heel (LHEE) and Right Heel (RHEE).

Next, the biomechanical parameters chosen to be compared in this study's Part 2 with control group are discussed in the next heading. Walking, double limb squat and single limb balance were the functional exercises the patients and control group were asked to do. The exercises chosen require different hip ROM degrees, from small hip flexion during walking to high hip flexion during squat. The rationale for choosing these exercises and the clinical relevance of each exercise were mentioned earlier in Chapter Two.

3.5.8.3.5 Movement analysis procedure

In the trial, the participant/patient was asked to walk in the GRAIL treadmill for two minutes to get familiar with walking in the treadmill. After the end of the first two minutes the walking data was collected from the beginning of the third minute until the end of the fourth minute. This mean 2 additional minutes after the first 2 minutes which was used for familiarisation. Ten clean walking trials were collected from the start of third minute until the end of the fourth minute and the average of these clean trials was used during analysis. On the other hand, the Vicon system was used to collect squat and SLB data. In the trial, the participant/patient was asked to stand on the force platforms to perform both squat and SLB. During squat, the participant/patient asked to stand comfortably then squat to the lowest point possible and return to the original standing position. This count as one repetition of squat. The patients asked to squat 10 times and the average of these 10 squats was used during analysis.

During SLB, the participant/patient asked to position their leg on force platform and raise the other for 10 seconds. The foot position was based on their preference. This task was repeated 3 times and the average of these three trials was used in the analysis. All data collection instructions were provided to the participant/patient according to a standardised protocol to minimise possible researcher bias. The participant/patient was given one minute rest period between each test. The reason for this is to avoid fatigue as confounding variable. Finally, the reflective markers were removed from participant/patient skin. The whole trial session was designed to last approximately an hour and a half.

3.5.8.4 Biomechanical parameters being assessed during walking

The kinematic data of interest were pelvis all planes, thorax all planes, hip all planes and knee sagittal plane. Regarding kinematic data, the pelvic tilt, drop, and rotation degrees were chosen in addition to thorax lean, lateral flexion and rotation degrees. Moreover, the hip degrees in all planes and knee degrees in sagittal plane only. The kinetic data of interest were net joint moments of force, during walking, of the hip and knee, and hip power generation and ground reaction force all planes. Regarding kinetic data, the net joint moments of force applied on the hip and knee were chosen. Hip power generation and ground reaction forces were chosen as well.

The relevance of choosing the earlier mentioned kinematic and kinetic parameters is that asymmetry might be expected between limbs post-operatively (Jungmann et al. 2015; Matsumoto et al. 2017). Some kinematic variables of the lower limb were reported in the literature for patients with DDH (Romanò et al. 1996; Pedersen et al. 2004; 2006; Skalshøi et al. 2015). However, the studies found in the literature were done with different designs, at different timelines and different inclusion and exclusion criteria. This research recruited adult patients who underwent PAO and walked independently. Therefore, new variables were reported in this study that have not been reported previously in the literature.

3.5.8.5 Biomechanical parameters being assessed in this study during SLB

The kinematic data of interest were pelvic tilt, drop and rotation degrees were calculated in addition to thorax lean, lateral flexion and rotation degrees. Hip degrees in all planes and ankle sagittal plane degrees only were calculated. The kinetic data of interest were net joint moments of force during single limb balance of hip, knee and ankle were calculated, in addition to hip power generation. There is not enough information found in the literature about whether this is a beneficial exercise for DDH patients' post-surgery or whether patients compensate during single limb balance. Kinematics and kinetics indices are important to show the quantitative evaluation of altered hip joint and pelvis movement in DDH participants during SLB.

The reason for this is because it might explain lower limb movement compensation by using motor control and integration patterns. In addition, compensation strategies during this exercise, based on kinematic and kinetic data, would hopefully lead to understanding the lower limb movement patterns for DDH patients. Indirect information about muscular control is expected by combining the kinematics and kinetics data.

3.5.8.6 Biomechanical parameters being assessed in this study during squat

The kinematic variables included were pelvis tilt, drop and rotation degrees, in addition to thorax lean, lateral flexion and rotation degrees. Hip degrees in all planes and knee sagittal plane degrees only were calculated. On the other hand, the kinetic variables were net joint moments of force of hip and knee, in addition to hip power generation. Squats require a sufficient range of motion to control the whole body (Stevens et al. 2018). The biomechanics of squat exercises haven't been investigated in DDH patients and compared to a control group. The benefits of understanding squat by studying kinematic and kinetics variables could show altered loading during exercises, which could affect all lower limb joints (Roos et al. 2014).

Squats from the perspective of many therapists replicate different daily life activities such as sitting, getting up from a chair, and phases such as running, hopping and ascending stairs (Barton et al. 2014). Moreover, understanding and investigating compensatory movements and predisposing factors in DDH patients will hopefully facilitate the choice of rehabilitation exercises by avoiding aggravating positions being done by patients due to movement positions. From the literature of other hip condition, abnormal ROM of the hip and pelvis was considered a predisposing factor for pain when patients with femoroacetabular impingement were investigated (Bagwell et al. 2016). The previously mentioned reference was borrowed from surrounding literature due to lack of relevant literature for this specific patient group. Therefore, understanding and investigating compensatory movements and predisposing factors in DDH patients would facilitate the choosing of rehabilitation exercises. As far as the researcher knows, there are no papers in the literature that have investigated functional exercises.

3.5.9 Related ethical issues using a movement analysis laboratory

Two forms were created specifically to assess any hazards that might happen during this research project, and these can be found in the Appendix 6-A and Appendix 6-B. As far as the researcher knows, there were no side effects relating to the use of the treadmill except if the virtual environment is used and then dizziness might occur due to the screen. In order to avoid that, the researcher either turned off the screen and carried on the exercise or gave the patient enough time between the trials. Regarding falling while walking on the treadmill, all the participants wore a safety harness that was linked to a lifeline attached to the celling that would prevent them from falling.

3.5.10 Risk assessment form

Three forms of assessment were created to evaluate the possible hazards that participants might face. The first one was associated with the GRAIL system, see Appendix 6-A. The second form was associated with Vicon overground system, see Appendix 6-B. The third one was associated with the BIODEX system, see Appendix 6-C.

3.5.10.1 Laboratory Risk Assessment Form (GRAIL system)

Location: Research Centre for Clinical Kinesiology (RCCK)

Equipment/system: Gait Real-time Analysis Interactive laboratory (GRAIL) contains: Instrumented treadmill; D-Flow software; Vicon motion capture system; 180^{o} semi-cylinder projection system; safety harness system.

Task being assessed: Walking.

3.5.10.2 Laboratory Risk Assessment (Vicon over-ground motion capture system)

Location: Research Centre for Clinical Kinesiology (RCCK)

Equipment: Vicon motion capture system

Task being assessed: Single limb balance and double limb squat

3.5.11 Data processing

All data were collected via the custom Plug-in-Gait template created specifically for the purpose of this study and based on the Vicon guide (Vicon 2019). Data were inspected and markers were checked using Vicon Nexus (Nexus 2.8 Vicon Motion Systems, Oxford, UK). At the beginning, subject calibration was done, where participants were asked to stand still for five seconds while cameras were recording. Immediately after capturing, an auto initialise pipeline was run to check if there were missing markers, auto label and check for data quality. Then after collecting all the data, one custom pipeline (Nexus 2.8 Vicon Motion Systems, Oxford, UK) and two other custom pipelines (Cardiff University, UK) were used by the researcher to process all the remaining data before proceeding to MATLAB.

The following is the order followed for all data: The auto initialise pipeline created by Vicon Nexus was used to calibrate data. The pipeline is the first step that auto initialises labelling of the data and removes any unlabelled or ghost markers before capturing further data. Then, all gaps which exist are manually filled with a rigid body gap filling method if gaps exist in the pelvis or trunk, otherwise a spline filling method is used for other joint marker gaps. Finally, a custom pipeline which consists of delete unlabelled markers, filter trajectories butterworth, filter analogue data butterworth, process static plug-in-gait and process dynamic plug-in-gait was used to filter and smoothen the data before transferring the data to MATLAB.

It needs to be noted that the following procedures were done whenever an error happened, or a further data check was needed:

- Manual labelling was used if the pipeline did not run appropriately.
- The quality window was opened up to check if there is/are ghost marker/s that were not removed by the pipeline.

3.5.12 Data quality

Three successfully completed trials with 100%, shown in Nexus software, were needed in order to carry on to data analysis. If data quality is less than 100%, the whole data set was excluded. One control datum was excluded due to an incomplete Isometric muscle test. Two patients' data were excluded as well due to poor quality and missing data from the GRAIL system.

3.5.13 Data processing using Matlab®

MATLAB 2020a (The MathWorks, USA) was used after processing the data and quality checks were done. A custom analysis code was developed by the main researcher with the help of Prof. R. van Deursen (School of Healthcare Sciences, Cardiff University, UK). The Vicon Matlab code (version R2020a, The MathWorks Inc., Natwick, MA, USA) was the basis of the custom developed Matlab code for this study. First, the code retrieves the following demographic information from the Vicon Nexus file: Subject Name, Weight, Height, Subject Number and other variables that can be seen in a sample of the code in Appendix 7-A.

Then, the code retrieves all the study outcome measure values sought in this study and creates figures, see Appendix 7-B. The figures were checked to look for abnormalities such as abnormal graph shape, after resampling the data to 100 points, incorrect graph start and end and filter effect. At the end, the code exported all the outcome measures values into different Excel sheets. Two different sheets for each task for the right side and left side values were exported for each participant and grouped into a specific folder. Specific commands were written in the code in order to arrange all the values underneath a specific label and in columns rather than rows, so that it was easy to transfer to SPSS.

3.6 Clinical outcome measures

3.6.1 ROM

Range Of Motion (ROM) is one of the parameters used by physiotherapists to diagnose certain diseases and during assessment (Nussbaumer et al. 2010). A manual goniometer was used in this study in order to measure the ROM of the hip, knee and ankle in all directions. Common manifestations which patients with DDH have are lack of hip flexion noted after PAO surgery, noted lack of hip extension during walking, and limited abduction at the source of the hip weakness, as reported by many authors (Romanò et al. 1996; Chao et al. 2017; Nie et al. 2017). Validity and reliability of manual goniometers to measure the passive hip range of motion was investigated by Nussbaumer et al. (2010). The authors included femoroacetabular impingement patients and control. Passive hip flexion, abduction, adduction, and internal and external rotation ROM was evaluated by goniometer and an electromagnetic tracking system (ETS) in two trial sessions. 15 patients and controls participated with age and gender matched. The findings of the study showed good concurrent validity observed in hip abduction and internal rotation, with ICCs of 0.94 and 0.88, respectively. Goniometer showed greater hip ROM values than the ETS (range: 2.0–18.9 degrees, $p<0.001$). The ICCs was higher than 0.90 during test-retest reliability, except for hip adduction (0.82–0.84). The authors concluded that there was no significant difference in reliability between the goniometer and the ETS.

Moreover, the authors suggested that conventional manual goniometers can be used confidently for longitudinal assessments in the clinic. A simple long-arm goniometer (Idass Goniometer, Launceston, UK) with a 360-degree scale marked in one-degree increments was used in this project to test ROM of lower extremities in patients with DDH and control groups. The protocol for measuring lower extremity ROM is illustrated in the following table based on Fox and Day (2009) protocol (Table 3).

Table 3: Goniometer Protocol for hip and knee

Goniometer protocol						
	Extremity position	Goniometer axis	Goniometer: stationary arm	Goniometer: movable arm	End position	Comment
Hip flexion	The subject is in the supine position on the plinth. Their hip is in neutral, and the knee is in extension.	Placed over the greater trochanter of the femur.	Parallel to the mid-axillary line of the trunk.	Parallel to the longitudinal axis of the femur, pointing towards the lateral epicondyle of the femur.	The hip is flexed to the limit of motion.	Compensation can be made by flexion of the lumbar spine.
Hip extension	The subject lies prone in anatomical position on a firm, flat surface. The subject should maintain contact of both iliac crests with the surface during measurement.	Placed over the greater trochanter of the femur.	Parallel to the mid-axillary line of the trunk.	Parallel to the longitudinal axis of the femur, pointing towards the lateral epicondyle of the femur.	The hip is extended to the limit of motion.	Compensation can be made by extension of the lumbar spine.
Hip abduction	The subject is in the supine position on the plinth.	Placed over the anterior superior iliac spine (ASIS) of the innominate bone, on the side of the hip being measured.	Placed along a line between the two ASISs.	Parallel to the longitudinal axis of the femur.	Hip abducted to limit of motion.	The pelvis can be stabilised by fixing opposite leg slightly abducted and flexed over edge of plinth.
Hip adduction	The subject is in the supine position on the plinth. Their hip is in neutral, and their knee is in extension.	Placed over the ASIS.	Placed along a line between the two ASISs.	Parallel to the longitudinal axis of the femur.	The hip is adducted to the limit of motion.	The opposite leg is abducted over the side of the plinth and the foot is resting on a stool.
Hip rotation	The subject is in the sitting position on a raised plinth. Their hip is in 90° _of flexion and neutral rotation, with the knee flexed to 90°. The opposite hip is abducted, and the foot is supported on a stool.	Placed over the mid-point of the patella.	Perpendicular to the floor.	Parallel to the longitudinal axis of the tibia.		External or internal rotation to the limit of motion just before the pelvis starts to lift from the plinth.
Knee flexion	The subject is in the supine position on the plinth.	Placed over the lateral epicondyle of the femur.	Parallel to the longitudinal axis of the femur.	Parallel to the longitudinal axis of the fibula.		The hip and knee are flexed to the limit of motion.
Knee extension	The subject is supine with extended hips and knees.	Placed over the lateral epicondyle of the femur.	Parallel to the femur and trochanter major.	Parallel to tibia and the lateral malleolus.	The knee is extended to the limit of motion.	Extension deficit is reported with a minus.

3.6.1.1 Hip and Knee ROM

Participant hip flexion, adduction and abduction were measured while the participant was in a supine position, hip internal and external rotation were measured while the participant was on the edge of the bed and only hip extension was measured from a prone position. The method used for taking ROM measurements was described in detail in Fox and Day (2009). Three measurements were taken for each variable and the mean of the three measurements was written down and included in the results. Regarding knee joint, knee flexion and extension were measured when the participants were in a supine position. The method of ROM was described in detail in Fox and Day (2009). Three measurements were taken for each variable and the mean of the three measurements was written down and included in the results.

3.6.2 Equipment used for muscles strength (Biodex)

The Biodex system 4 (Biodex Medical Systems, Shirley, New York, USA) was used to measure the muscles' ability to contract and produce force. It is considered an objective way to measure the muscles' strength (Feiring et al. 1990). The variables of interests in this study were the isometric strength tests for hip flexors, extensors, adductors, abductors, knee flexors and extensors. Participants were asked to do one set of five repetitions for each muscle group tested. Ankle was not part of the data included due to time limitation. Participants started by testing their right knee, left knee, left hip flexion and extension, left hip abduction and adduction, right hip flexion and extension and finally ended up testing their right hip abductors and adductors.

The same procedure was followed on all participants who participated in this study. Since the Isometric muscle protocol was based on a test protocol, not an exercise protocol, the primary outcomes of interest were peak torque values and the coefficient variances where both data were included in analysis. Coefficient variance checks the consistency of repetitions during a set. Low scores, closer to zero, mean more consistent and valid data (Dvir 2004).

3.6.2.1 Muscle test mode

Isometric: during this mode, the dynamometer was at zero velocity and there were no changes in joint angle or in the muscle length. Rationale for choosing Isometric mode was that the participant was strapped, and the limb being tested was stabilised and no movement compensations were expected during the test.

3.6.2.2 Isometric muscle preparation

When the Biodex machine was switched on, the dynamometer needed to be calibrated in order to run the Biodex software, which routinely took place at the beginning of the test. Protocols for knee and hip muscle were set in advance. The overall procedure during muscle testing was kept the same for all the participants. Participants were strapped with four straps (two across the trunk, one on the waist and one over the tested thigh) during the knee tests and during the hip tests participants were standing and no need for straps.

All hip tests were done from a standing position during isometric hip protocol. The participants were allowed to balance themselves by holding the top of the dynamometer box but not relying on it to do the exercise. The fulcrum was in alignment with the hip joint while standing on all tests. No straps were used during this test. In-between repetitions, rest time was ten seconds. The chair was at 90 degrees and the participants were sitting and strapped with four straps, two across the trunk, one on the waist and one over the tested thigh during isometric knee protocol. The fulcrum of the tested knee was aligned with the lateral epicondyle of the knee. In-between repetitions, rest time was ten seconds and the anatomical position was 90 degrees of flexion. During the knee tests, there was one requirement by the Biodex software in order to do the knee tests, which was measuring the limb weight. This was done by asking each participant to extend their knee while sitting on the chair, and then Biodex was put on hold when participants fully extend their knees.

Regarding familiarisation of the test and in order to eliminate any learning effect, the participants were asked to do two trials to become familiar with the test. The participants were asked to put in only minimal effort and up to moderate effort of their muscle effort. Based on the Biodex system 4 manual's (Biodex Medical Systems) recommendation, the participants were asked to do three moderate trials and one maximal trial as a warm up. This was done to avoid any muscle injury and to make sure that all the muscles that were being tested would work in an efficient way. In addition to the two-familiarisation trials, this helped as well to decrease the chance of learning curve.

All participants were encouraged by verbal encouragement and the same tone and words were adopted and applied to all the participants. The principal investigator was the one who was encouraging the participants. The phrase of "kick as much as you can" was used during extension and adduction and the phrase "pull back as much as you can" was used during flexion and abduction. All the participants were asked to watch the computer screen to see the graph shown by the software. Verbal coaching was given during warm up if patients did not know how to do the exercises properly. Two minutes rest time was given if the participant felt fatigued. Outcomes of interest were the average of five peak torque of hip flexion, hip extension, hip abduction, hip adduction, knee flexion and knee flexion.

3.6.3 Pain measurement

Visual Analogue Scale (VAS) is one of the most common ways to measure pain (Ferreira et al. 2004). The VAS is a 10-cm line with the descriptors 'no pain' and 'worst possible pain' at each extreme. Participant/patient was asked to mark a line at the point which best represents their pain as suggested by (Hawker et al. 2011). In Baamer et al. (2022) the authors investigated unidimensional and functional pain assessment tools in adult postoperative patients in a systematic review. Unidimensional pain assessment tools include the numerical pain rating scale, VAS and verbal rating scale. 31 studies were reviewed. Eight studies reported the convergent validity of the VAS with moderate-to-high correlations between several self-report scales that also measured pain intensity. In addition, the authors reported that VAS showed high scale and test–retest reliability with an intraclass correlation coefficient of 0.79 (95% confidence interval [CI], 0.49–0.91). In addition, several studies included in the review reported nearly similar cut-off points for VAS, indicating that VAS ratings of 0–5 mm were very likely to be rated as no pain by patients, 6–44 mm were considered mild pain, 45–69 mm were considered moderate pain, and VAS ratings ≥70 mm were suggestive of severe pain. The authors concluded that there was good reliability of pain assessment for all unidimensional tools.

A high score indicates high intensity of pain. The VAS was given to the participants before the start of the study, after doing the three exercises and after Isometric muscle test. The participants were asked to mark their pain level immediately after the exercises. The VAS was used to identify if participants felt pain prior the exercises, during the exercises and after Isometric muscle test.

3.7 Data storage

An anonymised subject number was given to each subject who participated in the study. Any document that links the subject number with the subject identity has been stored in a locker within the university premises and only accessed by the researcher. Patient electronic data were stored on a protected and clean hard drive. No anonymised video data or pictures of the participants were collected.

3.8 Confidentiality

All personal details were kept confidential and removed later on so that no one could identify the participant. All data collected during this research, after signing the consent form, were kept confidential according to Cardiff University guidelines. To adhere with the Data Protection Act, subjects' information and data collection were saved anonymously, and confidentiality maintained by recording identification numbers. Information was preserved on an electronic record system in a password-protected computer within the RCCK that has a digital password door. Raw data were stored on a secure server in Cardiff University. All data will be deleted 10 years after the study. It needs to be noted that there is a changing room and a toilet in the laboratory.

3.9 Data analysis of the laboratory-based study, Part 2

In the Excel sheets, the data were checked so that they were in the correct units before importing the data. With regard to other outcome measures that could not be retrieved from Nexus, some demographic information such as type of DDH, VAS, Isometric muscle and ROM were entered manually in separate Excel sheets. All Excel sheets were imported to SPSS version 25 (SPSS Inc, Chicago, USA) to do the analysis. The statistical analysis was done using SPSS. A Shapiro Wilk test ran at the beginning to see if the data were normally distributed. If not, then a Mann Whitney U test was used. The quantitative phase compared between the DDH patients' affected hip and the healthy participants' hip; therefore, the independent t-test was the choice of tests to compare between the two groups. Kinematic and kinetic data for each exercise the DDH patients did were compared to a healthy subject's data. It needs to be noted that a comparison was done first between the control group participants' right side and left side key variables to confirm the symmetry assumption, in order to compare and report only one side if symmetry found.

Moreover, the data were collected from the affected hip and non-affected hip of patients with DDH and compared with the healthy subjects. The comparisons done for statistical significance were set at $p < 0.05$, for repeated tests using SPSS version 25 (SPSS Inc, Chicago, USA).

Due to large number of comparisons that were done in the analysis process a 3-tiered approach was adopted after meeting and discussing this approach with the supervisors. If $p<0.05$, this means the finding is significant but not a robust finding given the many comparisons used in this study and was referred to as “normal level of confidence”. If $p<0.01$, this indicates a serious contender for indicating a real difference and was referred to as “high level of confidence”. Finally, if $p<0.001$, this suggests that this result should be seen as quite definitely significantly different and was referred to as “very high level of confidence”. The use of *, **, and *** in the tables in the Results chapter is to make the distinctions between the three levels of confidence where * refers to “normal level of confidence”, ** refers to “high level of confidence” and *** refers to “very high level of confidence”. For example, if hip extension ROM p value was 0.012 and the peak knee extension and pelvis rotation ROM were 0.04 and 0.03, respectively, this means that results of hip extension significant at the ** level could be reported with “high level of confidence” and the rest reported with normal level of confidence.

In addition, graphs of average scores of patients’ different joints were followed each exercise results. However, the interpretation of the graphs was based on the average scores throughout gait cycle, squat ascending descending phases and 10 seconds standing during SLB. The reason to add this method was to detect unusual patterns that might not necessarily appear as a significant finding and could be clinically relevant.

3.10 Comparisons used in SPSS to report the results

For each datum collected, a comparison using SPSS between the two groups was made. Starting with demographic data that contains, for example, age, height and type of surgery, followed by ROM, leg length, Isometric muscle, walking across different joints, squat across different joints and SLB across different joints. Three types of comparisons were made for each exercise. First type was patients’ operated side compared to unaffected side of the control group. Second type was patients’ non-operated side compared to unaffected side of the control group. Third type was patients’ non-operated side compared to patients’ operated side. In the first two types of comparisons Mann-Whitney U Test/Independent t-test was used. In the third type of comparison Paired-Samples t-test was used.

3.11 Bilateral cases

Patients with bilateral cases were included in this research in the hope that they might reveal interesting or significant findings that differed to the unilateral group. Even though the inclusion criteria did not exclude different types of DDH, such as bilateral DDH, a comparison between subgroups of bilateral and unilateral patients could not be carried out because of small sample size. Prior to the beginning of the analysis, a randomisation process was conducted in order to choose only one leg of the patients with bilateral DDH to avoid selection bias. The process of randomisation is explained in the next heading.

3.11.1 Randomisation of bilateral cases

Since the randomisation adopted in this research was only to choose which leg for bilateral cases should be included in the analyses, a simple and straightforward process of randomisation was sought. The randomisation process adopted in Baldi et al.'s (2017) RCT was followed. The randomisation process was done using Research Randomizer, a program published on a publicly accessible official website (Urbaniak & Plous, Research Randomizer Version 4.0; www.randomizer.org).

The process of randomisation was short and straightforward, as follows: each patient with bilateral operated legs was assigned two unique numbers for each leg (from 1 to 10). For example, the first patient with bilateral operated legs got the number 4 for their right leg and the number 5 their left leg. Odd numbers represent right legs and even numbers represent left legs. At the end of this process only one leg from each patient with Bilateral DDH was chosen. The Research Randomizer was used in order to get the randomised numbers included in the analysis.

3.12 Part 3: Patients' values (DDH questionnaire designed by researcher, Appendix 8)

After reading different questionnaires administered to patients with hip problems and careful investigation of the literature, it seemed that all the questionnaires used in the literature in hip dysplasia research (van Bergayk and Garbuz 2002; Hara et al. 2017b; 2018; Ricciardi et al. 2017) were aiming to link/look at activity level or the pain and disability of the condition rather than looking at it from a wider perspective. As seen in Chapter Two, most of the studies investigated sport and activities levels using PROMs did not enrich the literature with valuable information regarding the patients with DDH activity progression, rehabilitation, the common status of patients with DDH post-operatively and how patients felt regarding their rehabilitation experience.

None of the studies reviewed in the literature created a questionnaire to investigate the rehabilitation protocols or exercises for patients with DDH post-operative. Unfortunately, no specific PROMs satisfied the aim of exploring the rehabilitation experience of patients with DDH in this research. It is true that UCLA activity scale is the most used PROM in the literature; however, as explained earlier, the UCLA activity scale alone does not provide researchers with sufficiently rich information regarding rehabilitation or even what sort of activity and sport the patients were doing. Therefore, it seems appropriate to create a new questionnaire that fulfils the aim, understanding the recovery process and exercises commonly prescribed post-PAO, to suit DDH patients' needs and possibly reveal new areas that have not been investigated before. In addition to the created questionnaire both the UCLA activity scale and mHHS scale were used and more information regarding these two scales will follow the procedure of creating the DDH questionnaire.

Murray's (1999) guide on "Fundamental issues in questionnaire design" was followed when DDH questionnaire was created. Murray (1999) indicated that prior to the construction of a questionnaire, one must ask some fundamental questions, such as, what is the purpose of the research? and the development of questionnaire has a major influence on quality of information received and the response rate. The purpose of the research was revisited prior developing the questionnaire. While doing this step, Part 1 enriched the researcher with information missing in the literature such as patients' rehabilitation period postoperative, compensatory movements postoperative and frequently prescribed exercises postoperative by healthcare staff. There are six steps in Murray's (1999) guide to take into consideration when developing a questionnaire; question wording, question type, scales, analysis, question order and presentation.
Therefore, a questionnaire was designed in order to identify the patients' recommended exercises at clinics and home and the duration of the rehabilitation movement strategies they did when they felt pain, guided by Murray's (1999) guide.

When the questions were developed, a careful wording of the questions was sought. According to the guide, the words should be simple, and unambiguous. Abbreviations, unusual words and acronyms should be avoided if possible. Therefore, the words were simple, and abbreviations were tried to be avoided as possible and if needed an explanation was provided. For example, the weight-bearing exercises were explained more for respondents and an example given of what they are. No abbreviations were added to the questionnaire. Moreover, the question type was either open-ended questions or closed-ended questions. With open-ended questions more information is expected where the respondents formulate their own response. This type was adopted to reveal the type of exercise done at clinics due to the lack of such information in the literature. However, according to the guide, too many open-ended questions could be off-putting. Therefore, only three open-ended questions were added in this study questionnaire.

Open-ended questions were used to get more answers and knowledge that might add new information and aspects that do not exist in the literature (Schleinich et al. 2008). The other option was added when the question was around exercises. Closed-ended questions could take many forms, such as dichotomous questions, checklists, and fixed choice questions. All the previously mentioned questions were adopted in this study's questionnaire; see Appendix 8 for all questions included in the questionnaire. For example, in regard to scales, question around patients' opinion regarding the patients rehabilitation questionnaire were added in the questionnaire and the answers took the form of negative to positive.

In addition, the guide suggested that the analysis of the questionnaire should be considered while developing the questionnaire. This step was taken into consideration when two types of questions were adopted, and the analysis was then expected to be done by SPSS and content analysis. Open-ended questions were analysed by content analysis and closed-ended questions were analysed using SPSS, with more information added under the heading "3.2.4". After that, the questions order was done. It was suggested by the previous guide to group questions with similar themes and basic questions such as demographic to be asked first, followed by the important questions. Therefore, in this study questionnaire, demographic data were asked first, followed by the questions regarding rehabilitation experience theme followed by questions around movement compensation theme.

The rehabilitation experience theme covers what the recommended exercises are postoperatively to do in a clinic or at home, for how long they have been doing the exercises and how this condition might affect their daily life activities. This will possibly uncover the limitations that these patients might face if they neglect certain exercises or even if the therapists neglect them and hopefully reveal the patients' opinions regarding the rehabilitation services they received. To illustrate this point further, the intensity and duration of certain exercises, which is considered a key factor in physiotherapy practice and rehabilitation, could be discussed during this phase. The movement compensation theme contained questions that tried to identify any movement compensation these patients adopted or were doing. Patients with hip problems usually avoid standing or sitting for long times and alter their gait trying to avoid aggravating the pain on the hip joint by compensating for the movement (Novais et al. 2014a; Kalore et al. 2016). Therefore, patients were asked questions regarding the effect of hip pain on their prolonged standing or sitting and questions regarding any compensatory movement strategy that they were doing to overcome pain.

Regarding the final step, presentation of the questionnaire, it was suggested by the guide to add a cover letter and thank the respondent at the end of filling the questionnaire. In this study questionnaire, a cover letter contains a brief explanation of the study and the aims of the study and ends with page thanking respondents for their participation and containing more information about the researcher, such as email address. It was also written in the cover page that the participation is voluntary and assurances with regard to confidentiality and anonymity were stated. Finally, all questions were numbered, as suggested by the guide.

The questions adopted in this questionnaire were designed after extensive reading of the literature on PROMs, and more specifically after reviewing the literature around PROMs used for patients with DDH postoperatively. All questions were derived from the literature from different sources such as the UCLA activity scale, the Copenhagen Hip And Groin Outcome Score (HAGOS) and International Hip Outcome Tool (IHOT). For example, the UCLA activity scale asks patients to check one box that best describes current activity levels which is related to question number 21. Moreover, questions derived from HAGOS were (question 27) Do you have difficulties taking full strides when you walk? Questions derived from IHOT were; (question 27) How difficult is it for you to walk for long distances? and (question 24) How much trouble do you have with stepping over obstacles?

As mentioned earlier in this section, two PROMs that have been used extensively in the literature were adopted, the UCLA activity scale, Appendix 9 and mHHS, Appendix 10. The two questionnaires were included as different pages in order to ascertain the activity and pain level among the population participating in this research, more specifically the group who participated in the two parts of this research, and whether there is a link to movement compensation or other constructs of the rehabilitation process. The first questionnaire was the UCLA activity scale, a valid questionnaire that has been used to assess patients' level of activity (Zahiri et al. 1998). DDH participants' level of activity was measured using UCLA activity scale which is a valid and popular outcome measure used which targets this population (Naal et al. 2009). In Naal et al. (2009) study the authors compared the metric properties of the UCLA activity scale, the Tegner score, and the Activity Rating Scale for assessment of activity levels. The study included 105 patients undergoing total hip arthroplasty with mean age of 63.4 years and 100 patients undergoing total knee arthroplasty with mean age of 66.5 years. The authors found that the UCLA activity scale was the only scale that discriminated between insufficiently and sufficiently active patients in both total hip arthroplasty and total knee arthroplasty groups. Reliability of the UCLA activity scale in patients undergoing total hip arthroplasty was weighted kappa (kw) = 0.80 (0.70–0.90) and the UCLA activity scale was the highest completion rate and no floor effect. It is a scale that categorises the level of activities from 1 to 10. From 1 to 4 is considered mild to regular participation on activities, 4 to 7 is considered moderate to regular participation in activities and from 7 to 10 is considered very active.

The second questionnaire was the modified Harris Hip Score and this is also a valid questionnaire for active patients, as it captures patients' functional outcomes and pain level (Hinman et al. 2014). Pain and functional outcomes having been assessed using a modified Harris Hip Score (mHHS) by many authors in the literature (Novais et al. 2014a; Ettinger et al. 2015a; Ricciardi et al. 2017) due to its high responsiveness to the pain and functional outcomes. mHHS was used in conjunction with UCLA activity scale to support the findings by assessing the level of activity from the patient perspective. In addition mHHS was found to correlate with other PROMs found in the literature. In Potter et al. (2005) the authors investigated the correlation of Short Form-36 Scale with mHHS in 40 patients with mean age of 34.6 years who underwent hip arthroscopy. Pearson correlation coefficients were 0.73 in bodily pain subscale, 0.71 in physical function subscale, and 0.85 in physical component subscale.

The two additional questionnaires, UCLA activity scale and mHHS, were added after the designed questionnaire and it was compulsory to fill these in. The three questionnaires were added to onlinesurveys.ac.uk in order to achieve the aim and objectives of Part 2 in this study. The aim of combining the results of the previous questionnaires was to gain an overview of what is really happening in the rehabilitation process for patients with DDH and ease the integration process.

3.12.1 Questionnaire validity and reliability

The definition of validity is the extent to which an idea is accurately evaluated in a study (Heale and Twycross 2015). In addition, validity could also be defined as measuring what is intended to be measured (Taherdoost 2016). According to Taherdoost (2016) validity test should be done after designing any questionnaire. Content, construct and criterion are the main three types of validity (Taherdoost 2016). Taherdoost (2016) defined each type as following:

First, content validity check whether the created instrument addresses adequately the elements it should with reference to the variable components. Face validity is a subcategory of content validity where experts in the field provide their feedback and suggestions whether the instrument measures the concept. Second, the ability to draw inferences regarding the concept being evaluated id the definition of construct validity. Third, Heale and Twycross (2015) define criterion validity as a way that looking for the degree that the research instrument tool is relevant to other instruments that evaluate the same variables

Because this PhD study was time-constrained, and consisted of three parts that guided by EBP, face validity was the best available option. Face validity evaluation, relying on experts' opinions was approached in order to check clarity and understandability of each question.

Face validity was applied to the questionnaire to ascertain that it was testing what it was supposed to test (Hardesty and Bearden 2004). It is considered a subjective but necessary method of validation (Hardesty and Bearden 2004). There are a number of researchers throughout the literature who have used face validity to remove ambiguous, arguable, unrelated items and evaluate the overall quality of the questionnaire (Cialdini et al. 1995; Puri 1996). Evaluation of face validity was achieved via three senior physiotherapists.

The feedback received from the senior physiotherapists contained spelling errors, grammar mistakes and clarifying certain terms. Even though the Murray (1999) guide was followed, the term weight-bearing and non-weight-bearing exercises were suggested to be clarified further in one to two sentences by one senior physiotherapist. This was suggested that it might help respondents to understand the aforementioned terms better. All spelling and grammar mistakes that appointed to from the three physiotherapists were adjusted and proofread. It was also suggested to separate the consent form from the cover page and add it in a different page which was done prior to the administration of the questionnaire. When participants met the criteria for inclusion, they were informed of the study objectives and asked to fill in an informed consent form to start the data collection.

3.12.2 Questionnaire piloting

Questionnaire piloting was conducted since piloting helps to reframe the questionnaire if it is not clear or vague, and if more items need to be included, in order to test its feasibility before the application of the questionnaire to the targeted population. Connelly (2008) suggested that the proper amount for a sample size for piloting should be 10% of the larger study. On the other hand, Julious (2005) and van Belle (2008) suggested that 12 participants for a pilot study is enough. For PhD researchers Oppenheim (1992) suggested several questions to be asked following the filling of piloted questionnaire:

1. How long did it take you to complete?
2. Were the instructions clear?
3. Were any of the questions unclear or ambiguous? If so, will you say which and why?
4. Did you object to answering any of the questions?
5. In your opinion, has any major topic been omitted?
6. Was the layout of the questionnaire clear/attractive?
7. Any comments?

Hence, in order to pilot the created questionnaire, 12 patients with DDH were contacted at the beginning to fill in the questionnaire. The questionnaire was sent by email and their feedback was also received by email. After receiving the questionnaires, the questions that looked ambiguous or hard to understand were either rephrased or removed. For example, one patient commented in question number 17, and specifically said that she added exercises from sources that are not listed in the answers given. Therefore, the option other was added in that question and other questions to not limit patients of adding more answers. Also when patients were asked if they think that any major topic been omitted from the questionnaire, three comments were made. The first one was around adding about hydrotherapy and strength exercises.

There are questions that asked around the type of exercises patients were doing post-operative, however, no specific exercise was asked around since the aim of questionnaire was to look for all possible questions patients were doing post-operative and limiting the options to one exercise. The second comment regarding omitting major topic was adding around physiotherapy pre-surgery. since this study explore patients with DDH post PAO this comment was not considered. And finally the third comment was, patient agreed that this questionnaire was good as long as it asked about their opinion around rehabilitation they had received post-operative. All patients reported that instructions, layout and were clear. All relevant suggestions were applied.

Table 4: Questionnaire piloting results

Results of questionnaire piloting study				
Questions	Patients 1	Patients 2	Patients 3	Patients 4
1) How long did it take you to complete?	10-12 minutes	Roughly around 10 minutes	15 minutes or so	10 minutes
2) Were the instructions clear?	Yes	Yes	Yes	Yes
3) Were any of the questions unclear or ambiguous? If so, will you say which and why?	No	All questions were clear	All were clear, however, while answering question number 17, I added a source from outside what was given as options	No
4) Did you object to answering any of the questions?	No, seems all relevant to my condition	No	Not really	No
5) In your opinion, has any major topic been omitted?	Hydrotherapy and strength exercises?	Physiotherapy before doing the surgery maybe?	No as long as you asked about my opinion around the rehabilitation I received	No
6) Was the layout of the questionnaire clear/attractive?	Very clear	Yes	Yes	Yes, however I wonder if this looks the same in an online questionnaire.

7) Any comments?	No	No	Perhaps adding about the goals, I as a patient with dysplasia looking for.	No

See above table, Table 4 for the answers of the first 4 patient, and the rest of the results can be seen in Appendix 11. In addition, it needs to be noted that no ethical considerations were reported due to the fact that no personal or private information was required when filling in the questionnaire.

3.12.3 Setting, recruitment and data collection

The questionnaire was distributed as an online questionnaire at the onlinesurvey.ac.uk. The online questionnaire was available to participants from February 2019 until 31st of December, 2020. In order to approach as many participants with DDH as possible, two charities were contacted, Steps worldwide and DDH UK, to help in recruiting patients with DDH and an invitation letter was sent covering all the project details, as shown in Appendix 12-A and Appendix 12-B. Therefore, the sample size for this questionnaire was larger than the first part since any patients diagnosed with DDH and who had undergone hip surgery were approached. The questionnaire was advertised on Facebook groups such as the DDH UK and Periacetabular osteotomy group, where there are high number of active members to ensure that a high number of DDH patients saw the questionnaire. In addition, all the patients who participated in Part 2 were asked to fill in the questionnaire on arrival at RCCK if they had not filled the online questionnaire. A reminder was sent one week prior to the deadline date to remind participants to participate in this study and complete the unfinished questionnaire.

3.12.4 Data analysis Part 3

All the data were stored on the website and could be analysed individually or as a group. The data were password protected and only accessible to the researcher. The questionnaire results were divided into two phases during analysis. The first phase was the general analysis of all the participants' results. The first phase was descriptive, based on frequency data analysis using the SPSS. For the second phase, in addition to the SPSS tests used for the closed-ended questions, content analysis was done to open-ended Questions 10, 11 and 13 (Coe and Scacco 2017). The reason for conducting content analysis specifically for those three questions was to try to identify the most commonly prescribed exercises to patients postoperatively after getting clearance to fully weight bear, to identify the exercises prescribed to be done at home and to explore whether a type of exercise (such as non-weight-bearing exercises) are preferred by certain physiotherapists for patients with DDH.

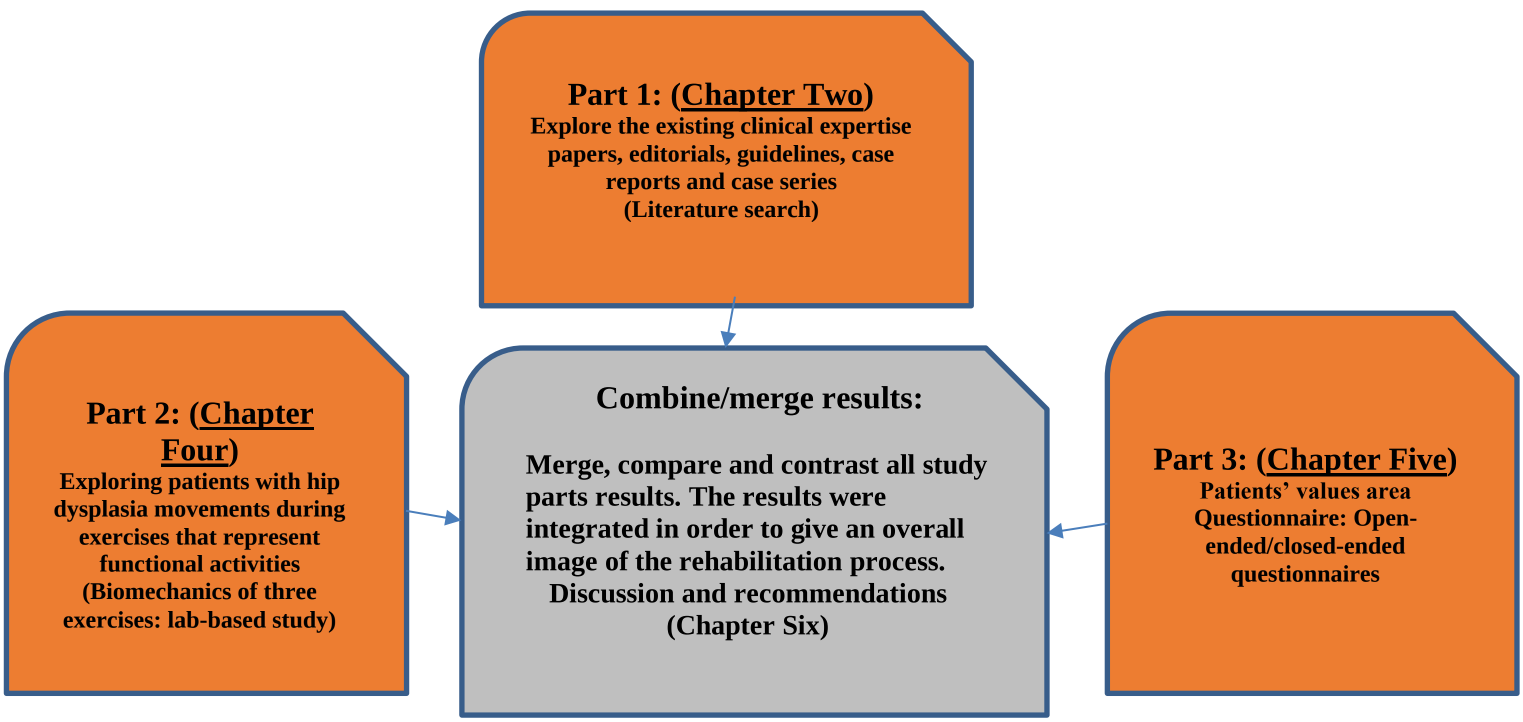
Content analysis was done using NVivo Version 12 (QSR International Melbourne, UK), qualitative computer software which can be used in quantitative content analysis (Coe and Scacco 2017). First, the texts of open-ended questions were exported from the onlinesurvey.ac.uk to Excel sheets, then the sheets were imported to NVivo. A codebook was then created from the codes retrieved from the texts containing definitions for each code and variable, number of references and subcodes if they existed. A sample of the codebook can be seen in Appendix 13. Similar codes were then grouped together and represented counts/codes. Finally counts/codes were analysed with regard to the frequency of items that had been coded and then are interpreted and discussed in the Discussion Chapter. Since the frequency and type of exercises recommended at clinics, an objective of the study Part 3, could be identified with frequency analysis, no further analysis followed.

3.13 Integration of all study parts results

Findings of Part 1, systematic search of the literature, findings of Part 2, patients' data from patients who participated in the laboratory-based study and the findings of Part 3, patients who filled in the online questionnaire, were integrated after the discussion of Part 2 and Part 3 in the Discussion chapter in relation to EBP. By doing this, a deep understanding of all study parts findings would lead eventually to meaningful understanding of the rehabilitation patients with DDH receiving post-PAO, see Figure 6. There are multiple ways of integrating data found in the literature (Lee and Smith 2012; Guetterman et al. 2015). The most frequent integration method as suggested by Guetterman et al. (2015) to adopting type of joint display is the themes-by-statistics type. In this method, it typically involves reporting categorical data such as patient satisfaction scores, to organise the presentation of themes or quotes.

The display assists readers in understanding how quantitative and qualitative data interfaced and in considering inferences. However, in this study, no qualitative data were collected and seems hard to adopt. In addition, all the integration methods were suggested for mixed methods study and this study was a quantitative study. See Guetterman et al. (2015) for all the integration methods suggested. In Lee and Smith's (2012) article, the authors suggested a way of integration quantitative and qualitative data sets. The authors explored five criteria to integrate multiple data; however, the integration method assumes the collection of different data sets with shared aims. Therefore, it seems hard to use any method that Lee and Smith (2012) and Guetterman et al.'s (2015) articles suggested due to the fact it would raise too many concerns regarding the criteria application for each study part explored in this study. Since there were different datasets collected with different aims, this means none of the integration methods discussed earlier can be adopted. In addition, the methods of integration investigated the same area, which does not apply on the different areas explored in this study. The EBP was used as a guide to explore different aims; therefore, the EBP three domains will be revisited during the integration process. After describing the methods of the study, Part 2 and Part 3, the following two chapters report the results of these parts.

Figure 5: Integration of all study parts (Part 1, Part 2 and Part 3)



Chapter Four: Laboratory-based study results (Part 2)

In this chapter, the first part is the results of the laboratory-based study. The purpose of this laboratory-based study was to explore if movement is affected post PAO for patients with DDH. This laboratory-based study involves a high number of comparisons and, therefore, a decision rule was applied to facilitate interpretation of significant differences. In addition, preliminary results of the movements and kinematic and kinetic parameters for the different joints during walking, squat and SLB were reported first followed by the clinical outcome measures such as VAS and Isometric muscle results.

From the large number of parameters that could be extracted and reported from the movement analysis, the aspects of movement which seem most affected in the patient group were focused on and compared between the two groups. A comparison of healthy group right and left side was done first to confirm that the symmetry assumption can be used in the healthy group so that a single limb can be selected for the remainder of the analysis. The order of the reporting the results is always control right side compared to patients' affected side then control right side compared to patients' non-affected side and then patients affected side compared to patients' non-affected side.

As mentioned in the Methodology chapter, a 3-tiered approach was adopted after meeting and discussing this approach with the supervisors. The $p<0.05$ means the finding is significant and referred to as "normal level of confidence". The $p<0.01$ means a serious contender for indicating a real difference and is referred to as "high level of confidence". Finally, the $p<0.001$ means the result should be seen as quite definitely significantly different and is referred to as "very high level of confidence". The use of *, **, and *** below each table is to make the distinctions between the three levels of confidence where * refers to "normal level of confidence", ** refers to "high level of confidence" and *** refers to "high level of confidence". At the end, a summary table that gives all the *** together, all the ** together and the * together was presented. Graphs of average scores of patients' different joints followed each exercise results.

The interpretation of the graphs is based on the average scores throughout gait cycle, squat ascending descending phases and 10 seconds standing. The reason to add this method was to detect unusual patterns that might not necessarily appear as significant finding and could be clinically relevant. The order of laboratory-based study results is participants' demographic data, gait kinematic and kinetic results, squat kinematic and kinetic results, SLB kinematic and kinetic results, VAS, passive ROM scores and Isometric muscle scores. Finally, a summary of all results was provided at the end of the chapter.

4.1 Demographic data:

A total of 33 patients attended to the laboratory-based study and three patients' data were removed due to corrupted c3d files of the 3D motions capture data. Therefore, a total of 30 participants, 15 patients diagnosed with DDH and 15 control, were included in the final data analysis. The recruitment was stopped due to Covid-19 pandemic and 15 participants recruited in each group. It was impossible to recruit more participants to reach the calculated sample size, since the hospitals were limited to coronavirus cases. Demographic data, gait, squat and SLB, VAS scores, ROM scores and Isometric muscle results were compared between 15 control participants and 15 patients with DDH. First, Table 5 below shows participants' demographic data results:

Table 5: Demographic data

Variable	Control Group (15 participants) Mean (SD)	Patients Group (15 participants) Mean (SD)	SPSS test	Significance Level
Age (Years)	33.4±9.8 Maximum age: 54 Minimum age: 22	34.7±10.2 Maximum age: 56 Minimum age: 18	Independent t-test	P= 0.719
Gender	Male: 3 Female: 12	Male: 0 Female:15	Fisher's exact test	P= 0.224
Height (cm)	1.64±0.09	1.60±0.05	Independent t-test	P= 0.129
Mass (kg)	67.1±13.9	66.7±13.5	Independent t-test	P= 0.929
BMI (kg/m2)	24.80±4.73	25.96±4.87	Independent t-test	P= 0.515
Type of DDH		Bilateral DDH: 8 patients. N.B. only 5 have had surgery on both legs. Unilateral DDH: 7 patients (4 left DDH and 3 right DDH)		

Operated Leg		Right leg operated: 3 (all unilateral patients) Left leg operated: 7 patients (4 unilateral patients + 3 bilateral patients) Both legs operated: 5 patients		

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

The groups were well-matched in relation to age, gender, height, weight or BMI. The mean age of both groups was close at around 33.4±9.8 years for control group and 34.7±10.2 for patient group with the maximum age in the patient group being 56 years and 54 years in the control group. Although there were three males in the control group and no males included in the patient group, there was no significant gender difference between the groups after conducting Fisher's Exact Test; see Table 6 for full results of this test. All patients who participated in this study were females. It is important to highlight the fact that this condition affects females more than males.

Table 6: Fisher's Exact Test results

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	3.333[a]	1	.068		
Continuity Correction[b]	1.481	1	.224		
Likelihood Ratio	4.493	1	.034		
Fisher's Exact Test				.224	.112
N of Valid Cases	30				

a. 2 cells (50.0%) have expected count less than 5. The minimum expected count is 1.50.

b. Computed only for a 2x2 table

All patients participated in the laboratory-based study underwent PAO. There were eight patients diagnosed with bilateral DDH. Out of the eight patients with bilateral DDH, three patients were scheduled for a second PAO in the future and five patients had already had

PAO surgery for both legs. The remaining seven patients were diagnosed with unilateral DDH (three patients had left unilateral DDH and four had right DDH).

4.2 Control group right and left side comparison

As stated previously in the data analysis in the Methodology chapter, in this section, a comparison was done between the control group participants' right side and left side key variables to confirm the symmetry assumption. As seen in Table 7 below, there was no significant difference in any of the variables compared. For example, control right hip ROM in all planes scores were close to control left scores. Control right hip flexion ROM was 107±11 compared to control left hip flexion ROM which was 110±8.

Peak torque of knee extension comparison resulted the lowest p value that was p = 0.051 with almost eight degrees difference and highest p value was the hip abduction/adduction ROM, p = 0.83. There might be a difference in other variables that were not included in this table; however, symmetry of all variables was not one of the main study objectives. Therefore, the assumption of control group right and left side symmetry was accepted. Only the control group's right sides were compared and reported.

Table 7: Control group participants right and left side comparison of different variables.

Variable	Control right leg (n=15)	Control left leg (n=15)	Average difference	SPSS test	Significance Level
Hip flexion ROM (Degrees)	**107.46**±11.43	**110.60**±8.90	**3.14**	Paired-Samples T Test	**0.17**
Hip extension ROM (Degrees)	**14.13**±6.40	**12.40**±4.92	**1.73**	Paired-Samples T Test	**0.08**
Hip abduction ROM (Degrees)	**34.06**±5.86	**33.53**±8.48	**0.53**	Paired-Samples T Test	**0.80**
Hip adduction ROM (Degrees)	**28.00**±6.16	**29.13**±6.39	**1.13**	Paired-Samples T Test	**0.41**

Hip flexion Biodex (Peak torque) (N.m)	**175.49**±65.26	**172.60**±56.13	**2.89**	Paired-Samples T Test	**0.74**
Hip extension Biodex (Peak torque) (N.m)	**75.25**±33.06	**71.12**±22.93	**4.13**	Paired-Samples T Test	**0.50**
Knee extension Biodex (Peak torque) (N.m)	**62.26**±16.35	**70.13**±24.03	**7.87**	Paired-Samples T Test	**0.051**
Gait: Hip Flex/Ext ROM (Degrees)	**40.90**±6.66	**42.19**±4.24	**1.29**	Paired-Samples T Test	**0.36**
Gait: Hip Abd/Add ROM(Degrees)	**13.65**±4.32	**13.92**±4.55	**0.27**	Paired-Samples T Test	**0.67**
Gait: Knee Flex/Ext ROM (Degrees)	**61.61**±8.87	**62.40**±6.35	**0.79**	Paired-Samples T Test	**0.68**
Gait: Peak Hip Extension Moment (N.m)	**-0.85**±0.61	**-0.71**±0.32	**0.14**	Paired-Samples T Test	**0.26**
Gait: Peak Hip Adduction Moment (N.m)	**0.22**±0.16	**0.26**±0.18	**0.04**	Paired-Samples T Test	**0.37**
Gait: Peak GRF (Newton)	**10.45**±0.85	**10.38**±0.87	**0.07**	Paired-Samples T Test	**0.16**

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

4.3 Gait results

4.3.1 Control right side compared to patient's operated side

When control right side and patients' operated side were compared between the two groups, there was a significant difference across multiple joints, as seen in Table 8. There was a significant difference in hip joint across all the three planes. Hip internal/external rotation was 11.30±3.72 and 9.43±7.79, $p=0.030$, around two degrees lower in patients' group, which is considered as normal level of confidence. There was also a statistically significant difference in patients' trunk lateroflexion; however, the difference in degrees was very small at 0.75 degrees lower compared to control group, $p=0.011$, which is considered as normal level of confidence.

There was a significant difference between the two groups in hip flexion/extension ROM degree (40.40±5.97 and 36.21±5.67, $p=0.007$, around four degrees lower in the patients group), which is considered as high level of confidence. This might be associated with ROM difference between the control right leg and patients' operated leg, when there was a 14% reduced significant difference in hip flexion ROM. In addition to that, the knee joint flexion/extension ROM degree was significantly lower in the patients group (61.77±8.69 and 51.29±11.96, $p=0.002$), which is considered as high level of confidence. Patients scored lower knee flexion ROM degrees at around 10 degrees.

Hip abduction/adduction ROM degree between the two groups was 14.27±4.01 and 9.27±4.05, $p=0.001$, around five degrees significantly lower in patients' group which is considered as high level of confidence. There was also a significant difference in thorax rotation ROM between the two groups, decreased trunk rotation in the patients group (10.95±3.02 control group and 6.12±3.11 patients' group, $p<0.001$), with an average difference in degrees of around four degrees. In addition, higher peak hip extension moment in control group (-0.55±0.19 and -0.28±0.17, $p<0.001$), higher peak hip abduction moment in control group -0.53±0.21 and -0.26±0.20, $p=0.001$), higher peak hip internal rotation moment in control group (-0.36±0.13 and -0.13±0.10, $p<0.001$) and higher peak hip flexion moment in control group (0.86±0.20 and 0.62±0.20, $p=0.001$) were also significantly different between the two groups.

This might also be associated with Isometric muscle data measured when there was a 24% reduced significant difference in peak hip flexion torque and 20% reduced significant difference in hip extension torque for the patients' groups. All the previous results with $p<0.001$ were considered as very high level of confidence and the results of $p=0.001$ were considered as high level of confidence.

Table 8: Control right side compared to patient operated side (right side and operated side)

Joint	Variable	Control Group (15 hips) Mean (SD)	Patients' Group (15 hips) Mean (SD) †	Average Difference (Degrees)	SPSS Test	Significance Level
Pelvis	Pelvis Flex/Ext ROM	3.11±0.70	3.58±1.67	-0.47 (14%)	Independent t-test	P=0.521
	Pelvis Abd/Add ROM	7.35±3.72	5.56±2.10	1.79 (24%)	Mann-Whitney U Test	P=0.268
	Pelvis Int/Ext ROM	6.70±2.36	6.91±3.56	-0.21 (3%)	Independent t-test	P=0.848
Thorax	Thorax Flex/Ext ROM	2.86±0.69	2.70±1.12	0.16 (6%)	Independent t-test	P=0.681
	Thorax Abd/Add ROM	4.05±1.75	3.30±4.24	0.75 (19%)	Mann-Whitney U Test	P=0.011*
	Thorax Int/Ext ROM	10.95±3.02	6.12±3.11	4.83 (45%)	Independent t-test	P<0.001***
Hip	Hip Flex/Ext ROM	40.40±5.97	36.21±5.67	4.19 (11%)	Independent t-test	P=0.007**
	Hip Abd/Add ROM	14.27±4.01	9.27±4.05	5 (18%)	Independent t-test	P=0.001***
	Hip Int/Ext ROM	11.30±3.72	9.43±7.79	1.87 (17%)	Mann-Whitney U Test	P=0.030*
Knee	Knee Flex/Ext ROM	61.77±8.69	51.29±11.96	10.48 (17%)	Mann-Whitney U Test	P=0.002**
Hip	Peak Hip Flexion Moment	0.86±0.20	0.62±0.20	0.24 (28%)	Independent t-test	P=0.001***
	Peak Hip Extension Moment	-0.55±0.19	-0.28±0.17	-0.27 (50%)	Mann-Whitney U Test	P<0.001***

	Peak Hip Abduction Moment	-0.53±0.21	-0.26±0.20	-0.27 (51%)	Mann-Whitney U Test	P=0.001***
	Peak Hip Adduction Moment	0.26±0.24	0.37±0.33	-0.11 (30%)	Independent t-test	P=0.564
	Peak Hip Internal Rotation Moment	-0.36±0.13	-0.13±0.10	-0.23 (64%)	Independent t-test	P<0.001***
	Peak Hip external Rotation Moment	0.09±0.06	0.12±0.12	-0.03 (25%)	Independent t-test	P=0.780
Knee	Peak Knee Flexion Moment	-0.40±0.19	-0.33±0.23	-0.07 (18%)	Independent t-test	P=0.344
	Peak Knee Extension Moment	0.46±0.2	0.38±0.28	0.08 (18%)	Mann-Whitney U Test	P=0.341
Hip	Peak Hip Power Generation	0.99±0.32	0.78±0.36	0.21 (22%)	Mann-Whitney U Test	P=0.078
Ground Reaction Force	GRF_Y (Anteroposterior)	-0.55±0.19	-0.28±0.17	-0.27 (50%)	Independent t-test	P=0.111
	GRF_Z (Vertical)	10.42±0.85	10.09±0.59	0.33 (3%)	Mann-Whitney U Test	P=0.314

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

†Negative values mean higher patient scores

4.3.1.1 Gait: Control right side and patients' operated side graphs comparison

In Figure 7, ROM average scores of patients' pelvis are represented in a red line compared to control group average scores represented in a green line (from heel strike to heel strike). The grey area is Standard Deviation (SD) of the control group scores. N.B. Interpretation of the graphs is based on the average scores throughout gait cycle.

Pelvic tilt (7A): although both groups' pelvic tilt means followed the same path, patients tended to have increased anterior pelvic tilt with a difference of 2-3 degrees; however, there was no significant difference between the two groups. Pelvis is at an anterior tilt throughout the whole gait cycle.

Pelvic obliquity (7B): decreased pelvic lift at heel strike, initial stance phase and end of swing phase and increased pelvic drop degree during midstance three degrees compared to the control group.

Pelvic rotation (7C): decreased pelvic retraction at heel strike, early and mid-swing phase. This means the pelvis had decreased range on both sides around 0 degrees. There was no difference across the different planes between the two groups.

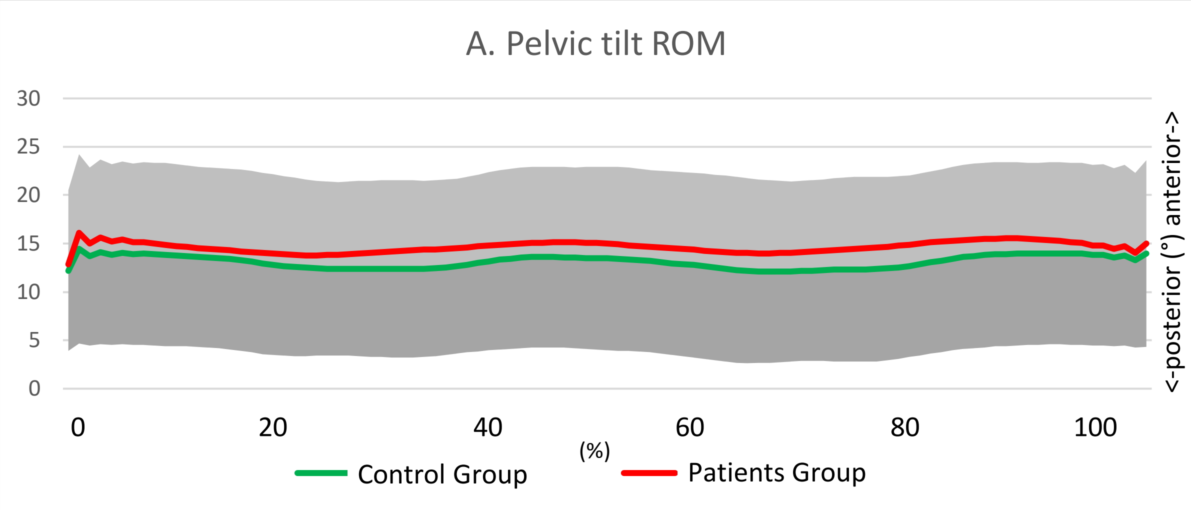
In Figure 8, ROM average scores of patients' thorax are represented in a red line compared to control group average scores represented in a green line (from heel strike to heel strike). The grey area is Standard Deviation (SD) of the control group scores.

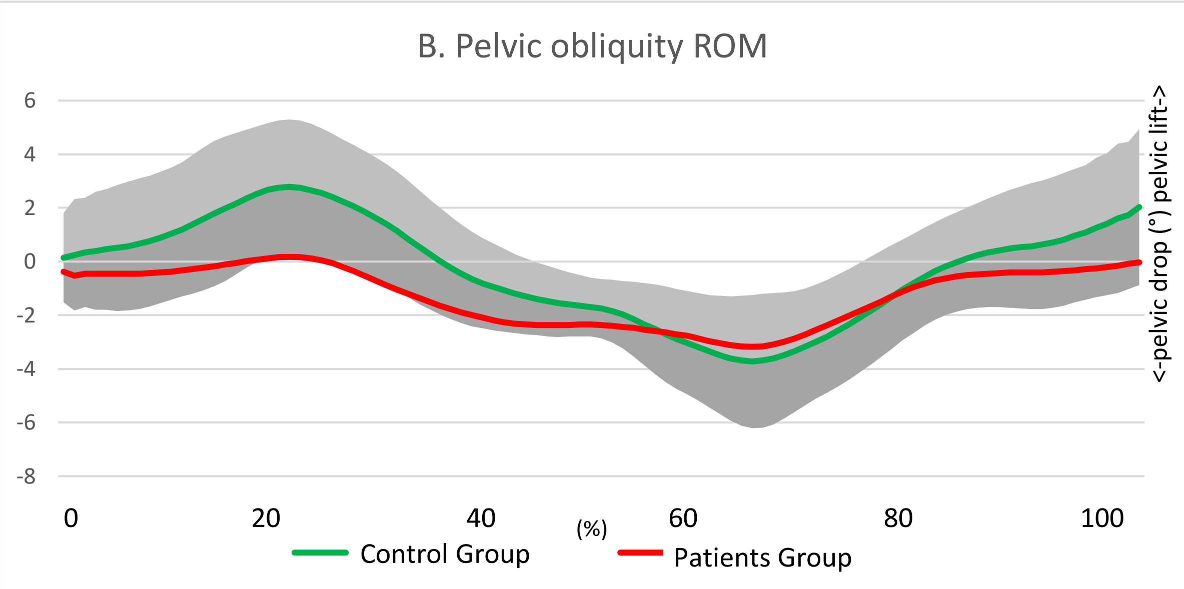
Trunk tilt (8A): patients were at a slight forward lean throughout the gait cycle, around two to three degrees more than the control group; however, this did not amount to a significant difference.

Trunk lateroflexion (8B): patients did have a slight increase in trunk lean until heel off, around 2 degrees difference where it reached central, before dropping to the ipsilateral side again. Patients did not laterally flex their trunk to the contralateral side during the swing phase, opposite to the control group. Therefore, there was a significant but slight pattern difference between the two groups at heel off.

Trunk rotation (8C): patients rotated their trunk backward slightly less than the control group at heel strike with three degrees difference. There was a noticeably reduced patients' forward trunk rotation by around three degrees during the late stance phase compared to the control group. Restricted ROM on both sides. There was a significant difference between the two groups.

Figure 6: Pelvis ROM (left pelvis data in Vicon Nexus):





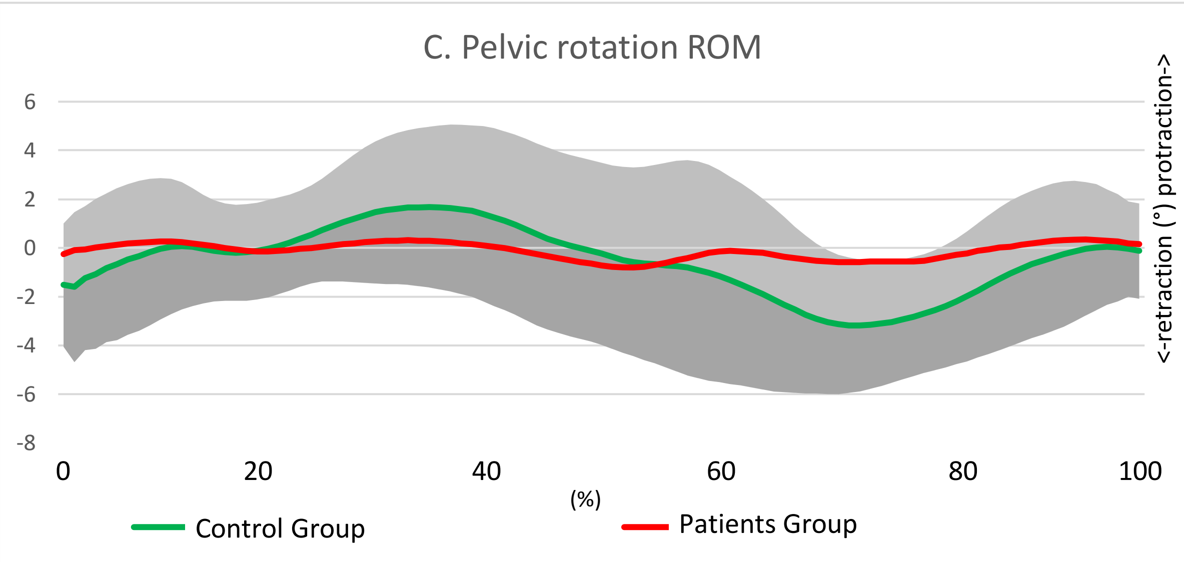
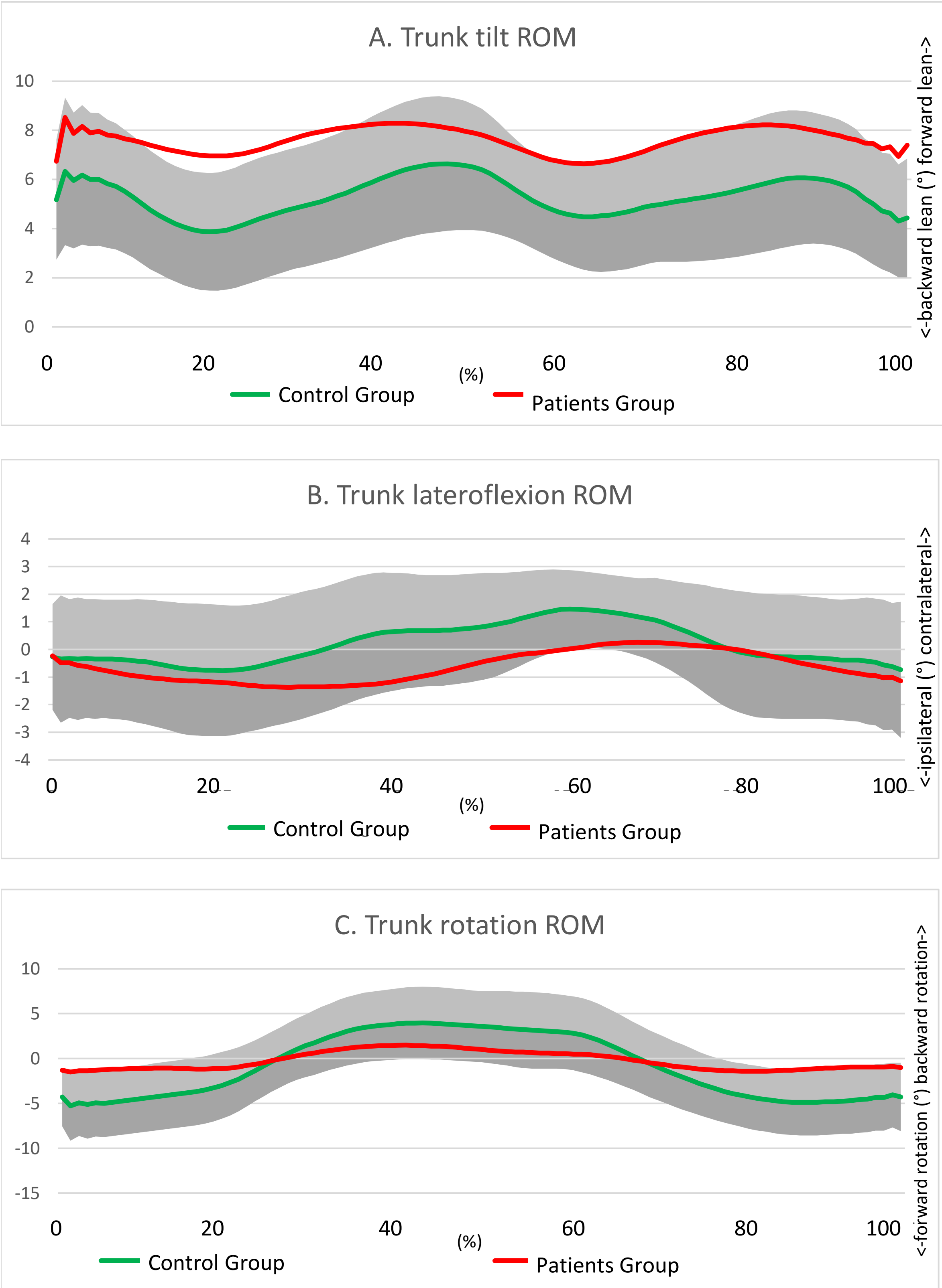


Figure 7: Thorax ROM (right thorax data in Vicon Nexus):



In Figure 9, ROM average scores of patients' hip are represented in a red line compared to control group average scores represented in a green line (from heel strike to heel strike). The grey area is Standard Deviation (SD) of the control group scores.

Hip Flexion/Extension (9A): patients maintained hip flexion at the end of the terminal stance and did not extend their hip; patients maintained around 10-13 degrees of hip flexion compared to the control at 0 to -1 hip extension at the end of the terminal stance. Patients had less hip flexion degree and extended their hip less than the control group. There was a significant difference between the two groups.

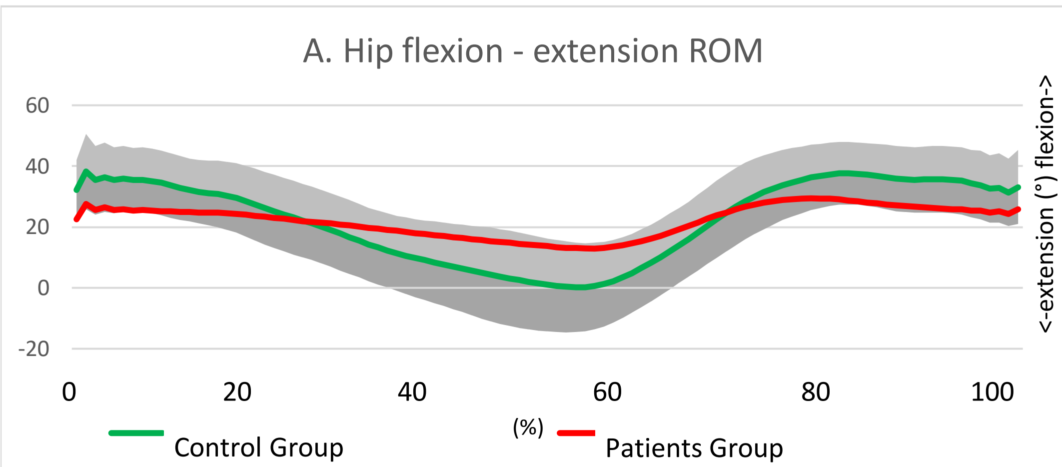
Hip Abduction/Adduction (9B): overall patients had decreased hip abduction ROM. Patients had significantly decreased hip abduction at toe off with around 5 degrees difference and the initial swing phase.

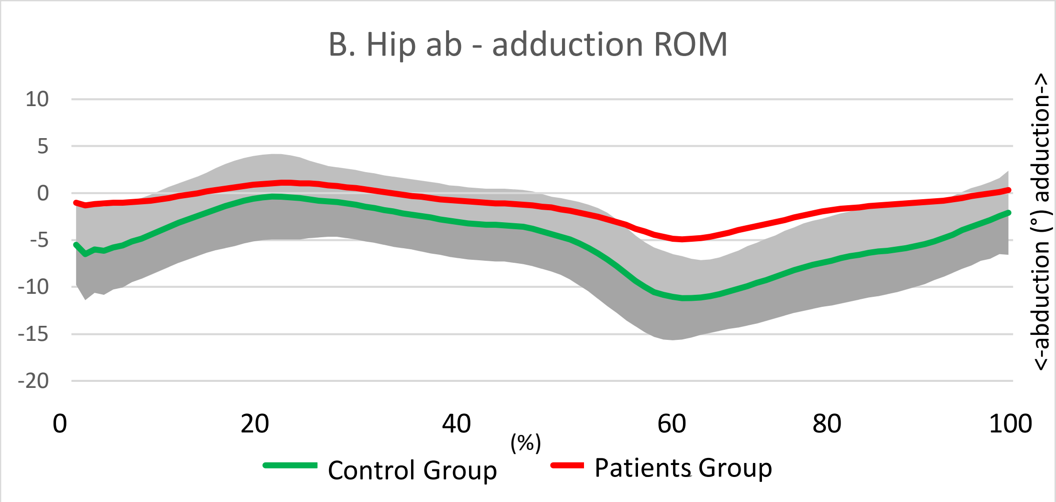
Hip Internal/External rotation (9C): patients tended to slight internally rotate their hip, close to have neutral hip rotation throughout the whole gait cycle, compared to the control group who had an internally rotated hip which decreased to the lowest hip internal rotation at heel strike and the end of the swing phase. There was a significant difference between the two groups with around seven degrees difference at swing phase.

In Figure 10, average peak scores of patients hip abduction/adduction moment are represented in a red line compared to control group scores represented in a green line (from heel strike to heel strike). The grey area is Standard Deviation (SD) of the control group scores.

Hip Abduction/Adduction moment (10A): there was a significant reduction in patients' hip abduction moment at midstance and terminal stance with around 0.4 Nm/kg difference.

Figure 8: Hip ROM:





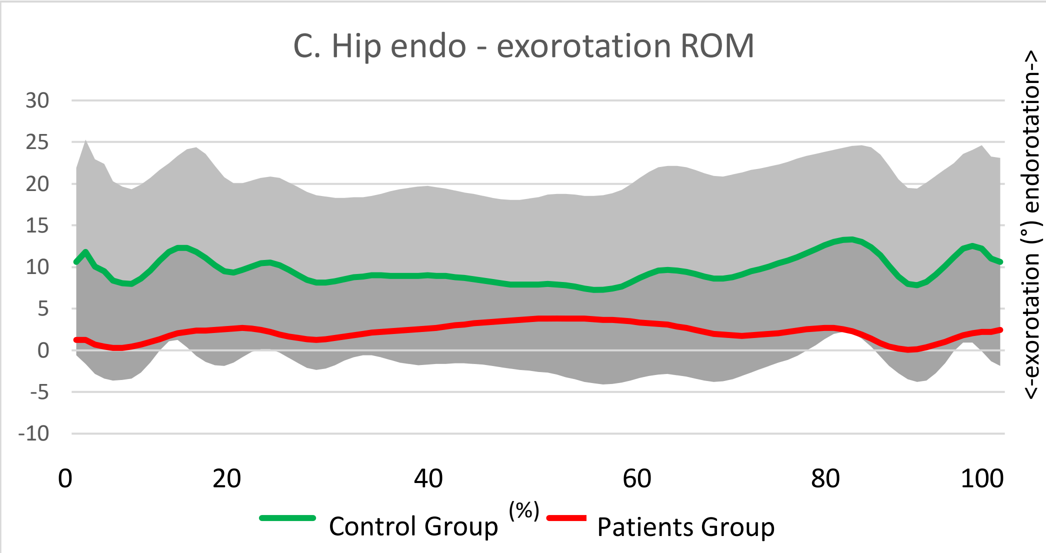
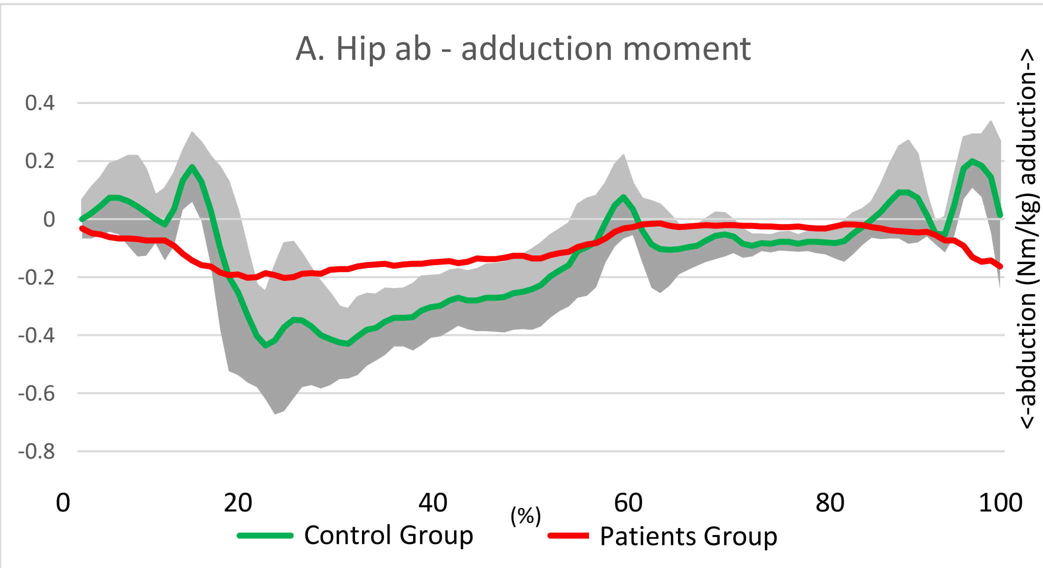


Figure 9: Hip joint moment:



In Figure 11, patients average peak hip power generation and absorption and ROM scores of patients knee are represented in a red line compared to control group scores represented in a green line (from heel strike to heel strike). The grey area is Standard Deviation (SD) of the control group scores.

Hip Flexion/Extension power (11A): reduced hip joint absorption during the terminal stance phase and reduced peak hip power generation at heel off with around 0.5 W/kg power difference.

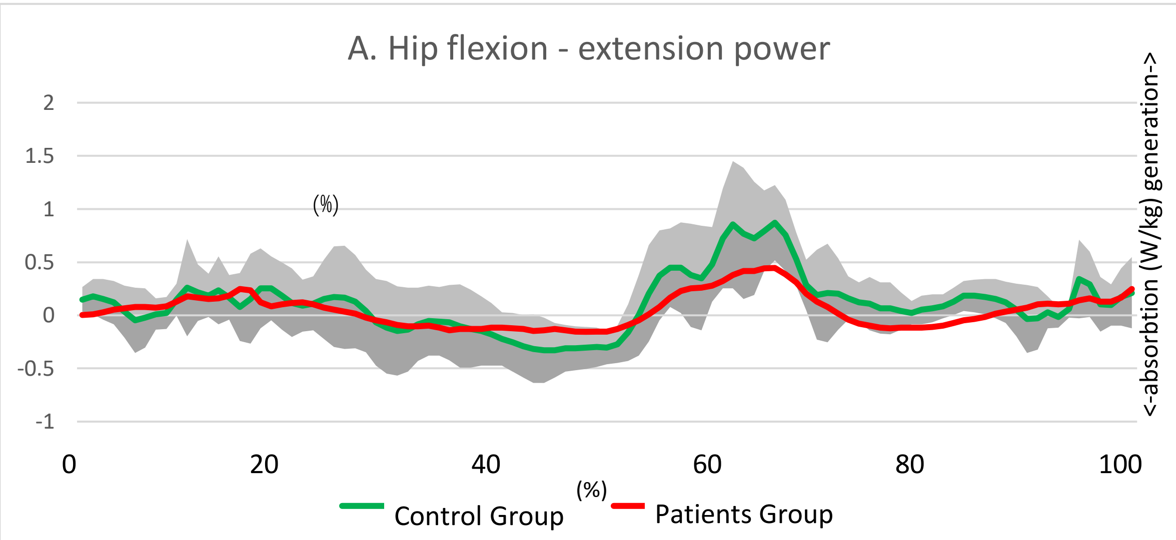
Knee Flexion/Extension ROM (11B): slight increase in patients' knee flexion at the terminal stance (around five degrees difference) and significantly reduced peak knee flexion in patients (around 20 degrees difference) during the initial swing phase and mid-swing phase.

In Figure 12, forces scores of patients represented in a red line compared to control group scores are represented in a green line (from heel strike to heel strike). The grey area is Standard Deviation (SD) of the control group scores.

Anterior/Posterior GRF (12A): noticeable decrease in braking peak and delayed reduced propulsive peak during toe off. No significant difference between the groups.

Vertical GRF (12B): reduced peak vertical force in both loading response peak and terminal stance peak humps during the stance phase; however, not significantly different. No significant difference regarding right vertical GRF between the two groups.

Figure 10: Hip joint power and knee ROM:



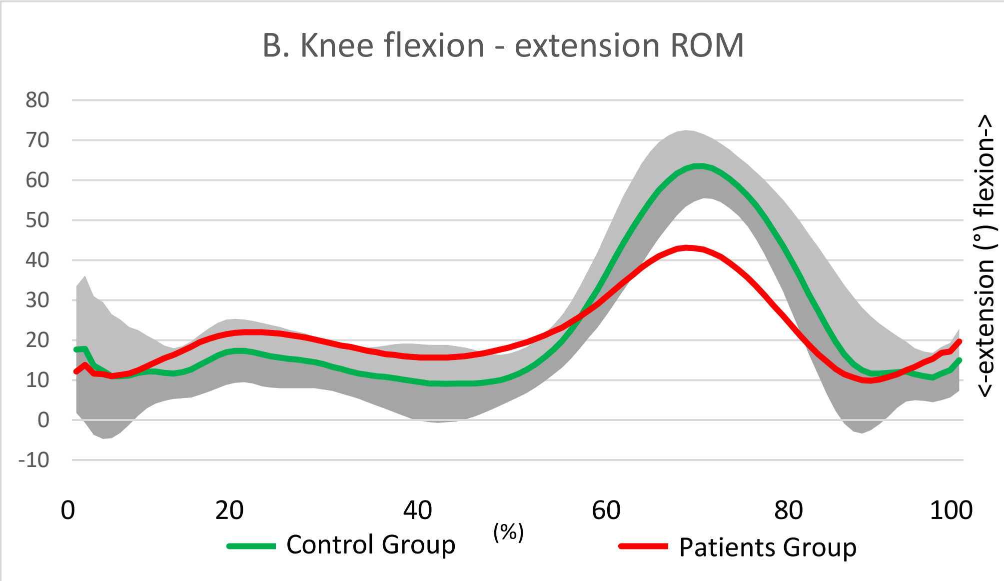
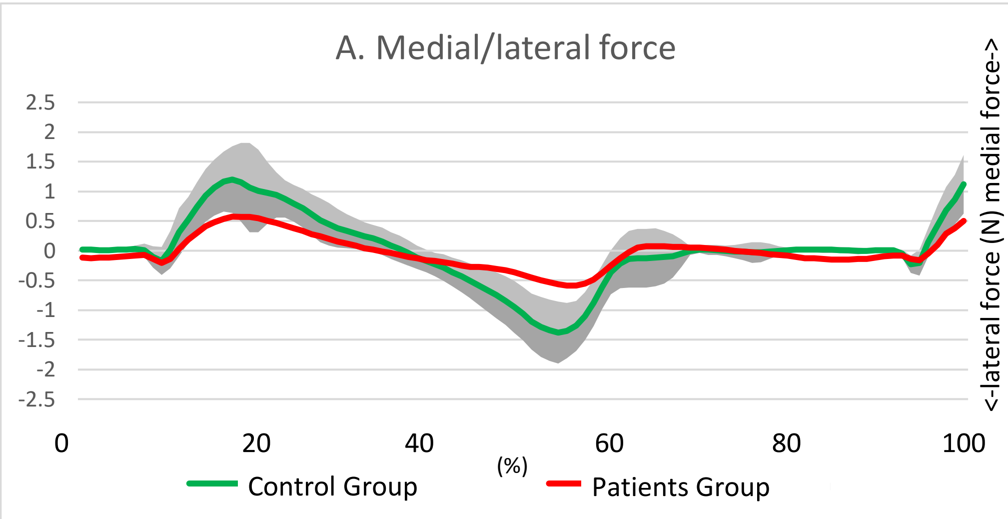
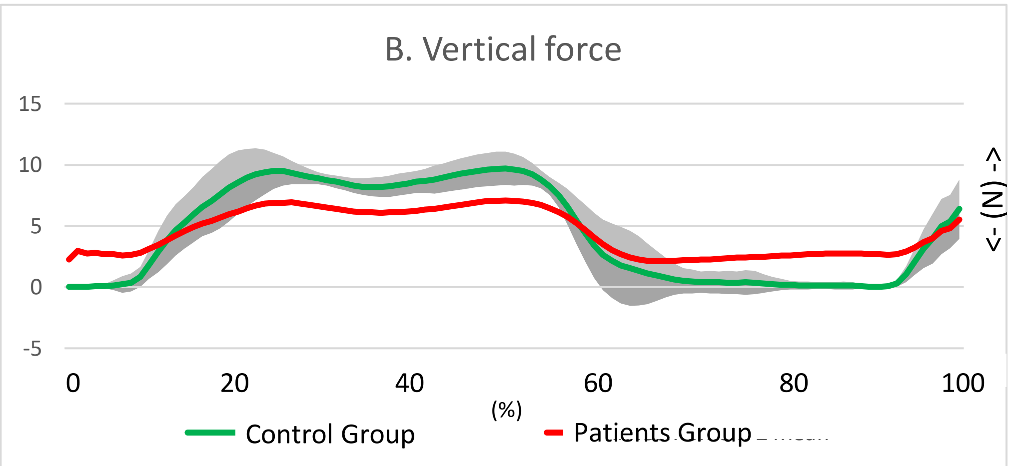


Figure 11: Ground reaction force:





4.3.2 Control right side compared to patient non-operated side

On the other hand, when patients' non-operated side and the control group were compared between the two groups there were significant differences in the thorax and hip joints, as seen below in Table 9. Similar to the operated side, patients scored lower for trunk ROM (control trunk lateroflexion 3.44±2.08 compared to 2.15±0.92, p=0.011. In addition, hip abduction/adduction ROM (15.35±4.28 and 10.82±3.57, p=0.013 around 4.5 degrees lower) was significantly different between the two groups (14.11±5.79 and 9.67±4.55, p=0.021). ROM comparison prior to the laboratory-based study showed 13% reduced hip adduction ROM and similar hip abduction ROM.

None of the previous ROM were significantly different. Peak hip abduction moment (-0.50±0.11 and -0.35±0.17, p=0.039), was also significantly different lower in the patients group. With regard to Isometric muscle data between the non-operated side and control group, peak hip abduction torque was 18% less; however, not significantly different between the groups. The previous three results are considered as normal level of confidence. Moreover, control trunk rotation of 10.93±3.22 compared to patients' trunk rotation of 7.43±3.04, at around 3.5 degrees, p<0.001, which is considered as very high level of confidence. Finally, notably reduced scores were noted for the following variables: peak hip flexion moment, peak hip adduction moment and peak knee flexion.

Table 9: Control right side compared to patient non-operated side (right side and non-operated side)

Joint	Variable	Control Group (10 hips) Mean (SD)	Patients' Group (10 hips) Mean (SD)	Average Difference (Degrees)	SPSS Test	Significance Level
Pelvis	Pelvis Flex/Ext ROM	3.08±0.74	4.02±1.30	-0.94 (24 %)	Independent t-test	P=0.521
	Pelvis Abd/Add ROM	8.84±4.01	6.02±2.43	2.82 (32 %)	Mann-Whitney U Test	P=0.268
	Pelvis Int/Ext ROM	6.84±2.70	6.90±2.06	-0.06 (1%)	Independent t-test	P=0.848
Thorax	Thorax Flex/Ext ROM	3.19±0.81	3.04±0.56	0.15 (5%)	Independent t-test	P=0.681
	Thorax Abd/Add ROM	3.44±2.08	2.15±0.92	1.29 (38 %)	Mann-Whitney U Test	P=0.011*
	Thorax Int/Ext ROM	10.93±3.22	7.43±3.04	3.5 (33 %)	Independent t-test	P<0.001***
Hip	Hip Flex/Ext ROM	39.39±6.75	41.33±3.82	-1.94 (5%)	Mann-Whitney U Test	P=0.481
	Hip Abd/Add ROM	15.35±4.28	10.82±3.57	4.53 (30%)	Independent t-test	P=0.020*
	Hip Int/Ext ROM	11.20±2.28	12.73±7.32	-1.53 (22%)	Mann-Whitney U Test	P=0.971
Knee	Knee Flex/Ext ROM	58.81±9.16	57.60±4.41	1.21 (2%)	Mann-Whitney U Test	P=0.711
Hip	Peak Hip Flexion Moment	0.79±0.26	0.57±0.17	0.22 (28%)	Independent t-test	P=0.063
	Peak Hip Extension Moment	-0.61±0.25	-0.65±0.37	0.04 (6%)	Mann-Whitney U Test	P=0.782

	Peak Hip Abduction Moment	-0.50±0.11	-0.35±0.17	-0.15 (30%)	Independent t-test	P=0.039*
	Peak Hip Adduction Moment	0.22±0.17	0.43±0.28	-0.21 (49%)	Independent t-test	P=0.059
	Peak Hip Internal Rotation Moment	-0.42±0.06	-0.33±0.17	-0.09 (22%)	Independent t-test	P= 0.353
	Peak Hip external Rotation Moment	0.09±0.06	0.12±0.06	-0.03 (25%)	Independent t-test	P=0.371
Knee	Peak Knee Flexion Moment	-0.30±0.13	-0.20±0.07	-0.1 (33%)	Independent t-test	P=0.055
	Peak Knee Extension Moment	0.62±0.13	0.61±0.14	0.01 (2%)	Independent t-test	P=0.893
Hip	Peak Hip Power Generation	1.11±0.35	1.05±0.39	0.06 (5%)	Mann-Whitney U Test	P=0.700
Ground Reaction Force						
	GRF_Y (Anteroposterior)	1.38±0.41	1.31±0.33	0.07 (5%)	Independent t-test	P=0.703
	GRF_Z (Vertical)	10.25±0.53	10.45±0.34	-0.2 (2%)	Mann-Whitney U Test	P=0.579

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

†Negative values mean higher patient scores

4.3.2.1 Gait: control right side and patients' unaffected side graphs comparison

In Figure 13, ROM scores of patients' hip are represented in a red line compared to control group scores represented in a green line (from heel strike to heel strike). The grey area is Standard Deviation (SD) of the control group scores.

Hip Flexion/Extension (13A): similar to the left side, patients maintained hip flexion at the midstance and terminal phases and diminished hip extension at the toe off phase. However, there was no significant difference between the two groups.

Hip Abduction/Adduction (13B): patients had significantly different peak hip abduction degrees at toe off (nearly five degrees difference) and overall reduced hip abduction ROM throughout the gait cycle.

Hip Internal/External rotation (13C): similar to the patients' affected side, the patients' unaffected side tended to have the internally rotated hip closed to neutral hip rotation and an increase in hip internal rotation during heal strike and the late stance phase. There was no significant difference between the groups.

Figure 12: Hip joint moment:

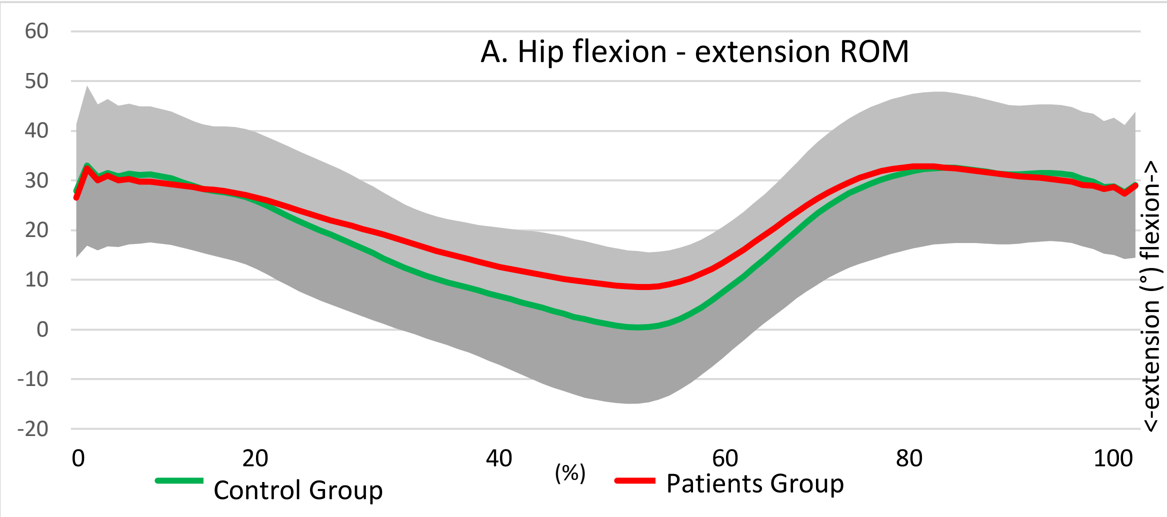
In Figure 14, average peak moment scores of patients' hip are represented in a red line compared to control group scores represented in a green line (from heel strike to heel strike). The grey area is Standard Deviation (SD) of the control group scores.

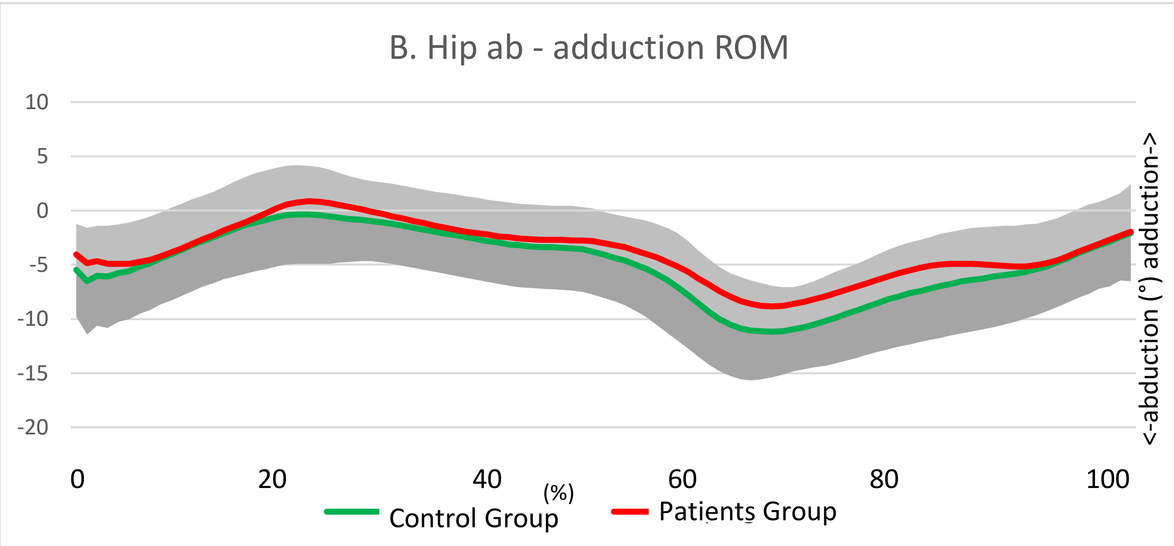
Hip Flexion/Extension moment (14A): patients tend to have a delayed and reduced peak hip flexion moment during terminal stance compared to the control group.

Hip Abduction/Adduction moment (14B): similar to the affected side, patients' unaffected side had a significantly reduced peak hip abduction moment at the midstance phase.

Hip Internal/External rotation moment (14C): patients had slightly reduced hip internal rotation throughout the whole stance phase. However, patients did have a significantly reduced peak hip internal rotation moment during the loading response phase and terminal stance phase.

Figure 13: Hip ROM:





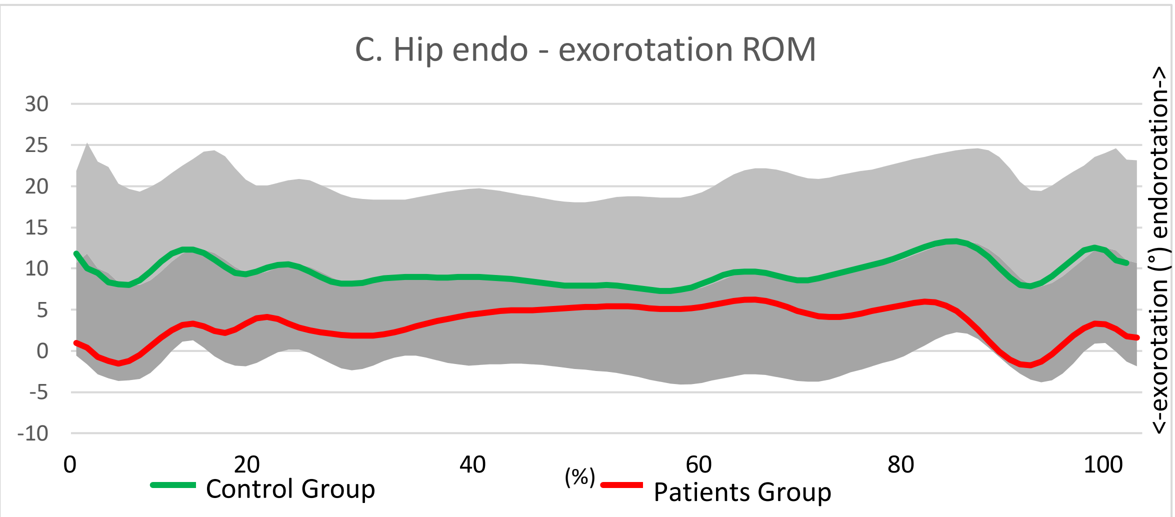
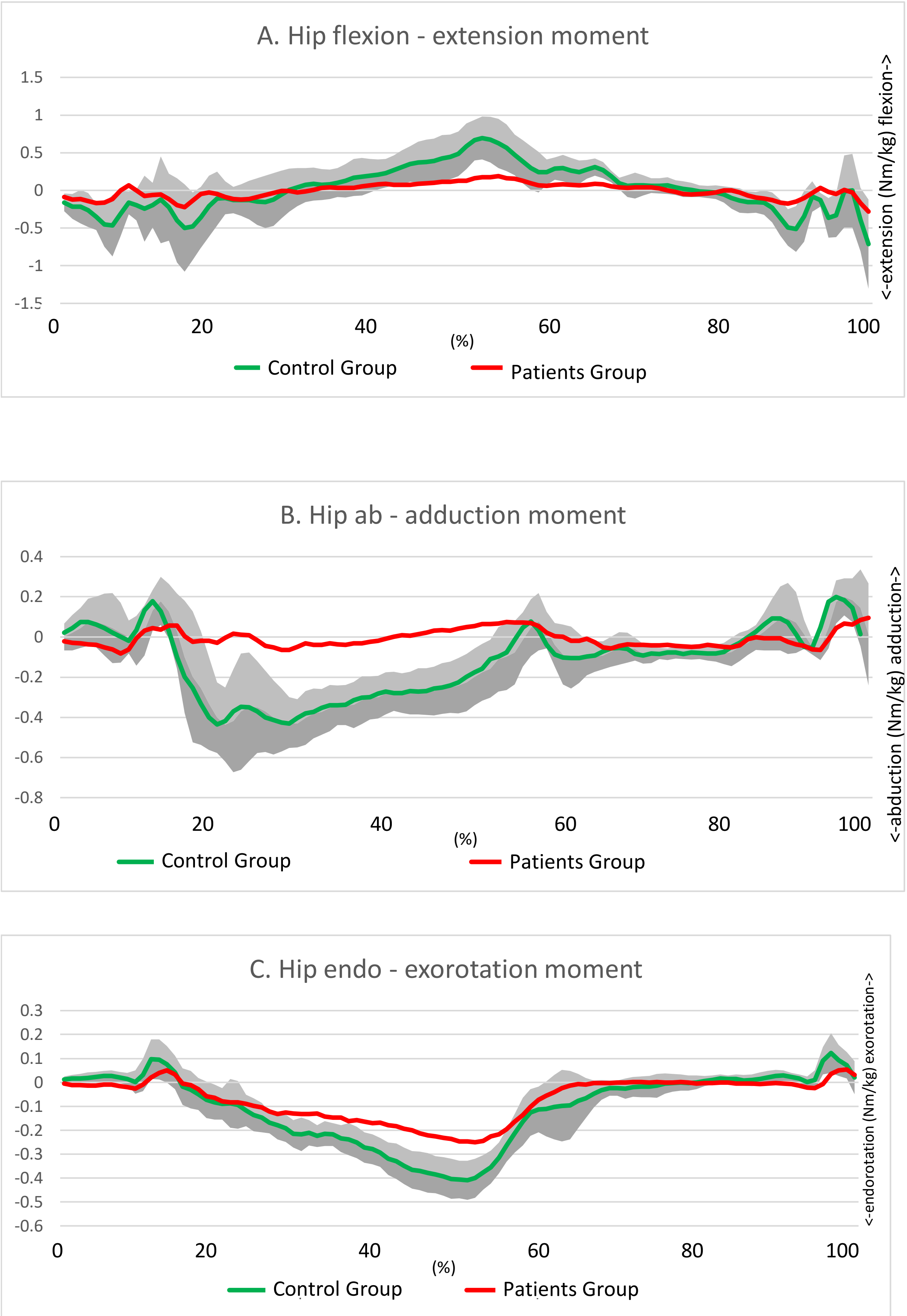


Figure 14: Hip joint moment:



In Figure 15, patients average peak hip power generation and absorption scores are represented in a red line compared to control group scores represented in a green line (from heel strike to heel strike). The grey area is Standard Deviation (SD) of the control group scores.

Hip Flexion/Extension power (15A): patients had opposite to the affected side; patients did not have significantly reduced hip joint absorption during the terminal stance nor reduced peak hip power generation at the initial swing.

In Figure 16, forces scores of patients represented in a red line compared to control group scores are represented in a green line (from heel strike to heel strike). The grey area is Standard Deviation (SD) of the control group scores.

Medial/Lateral GFR (16A): reduced peak medial force in both the loading response and end of terminal stance and reduced overall magnitude of the forces acting in the medial direction. Opposite to the left leg, there was a significant difference between the two groups.

Vertical GRF (16B): similar vertical force in both groups.

Figure 15: Hip joint power:

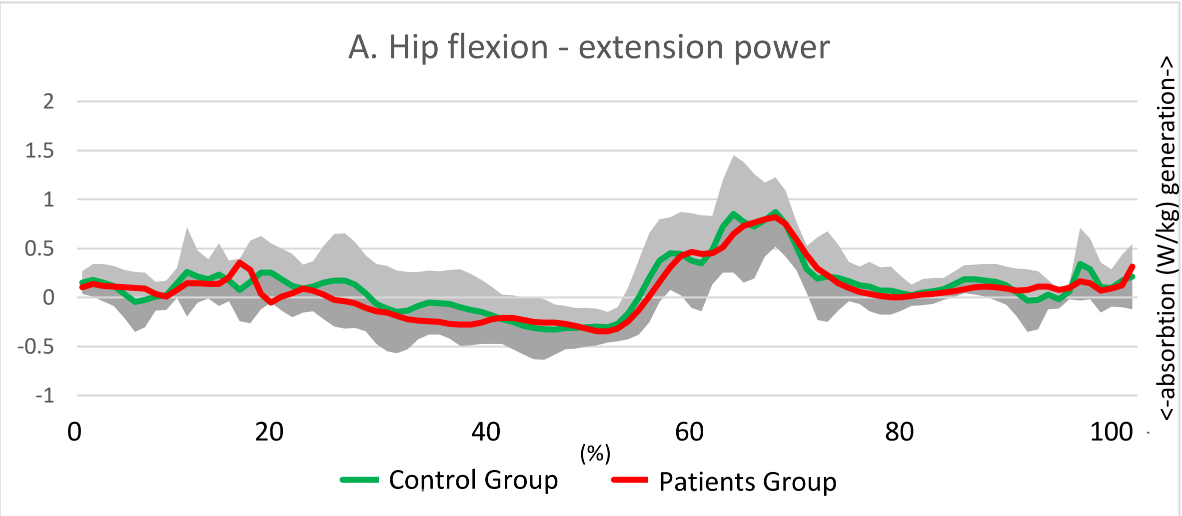
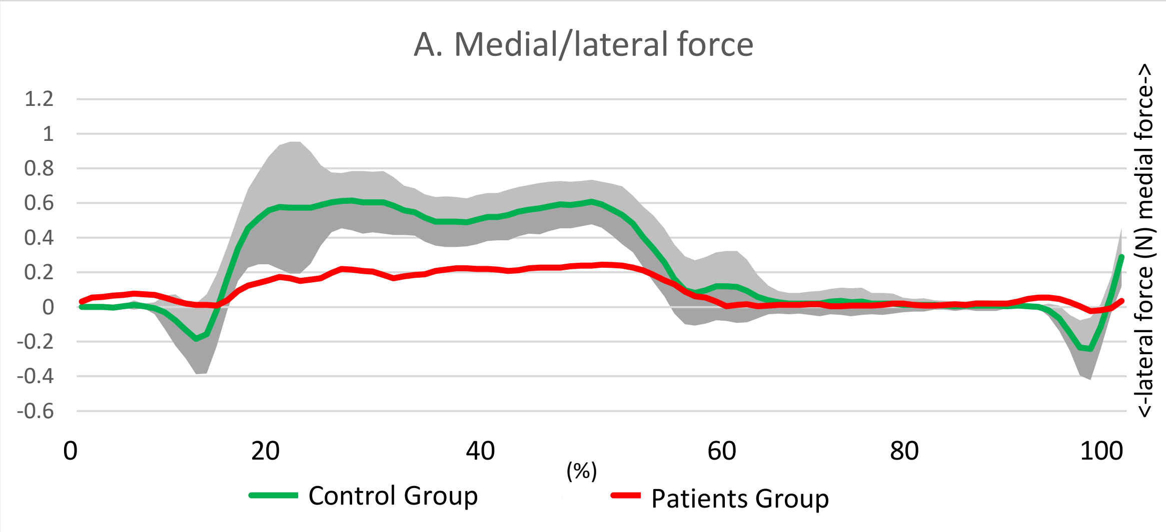
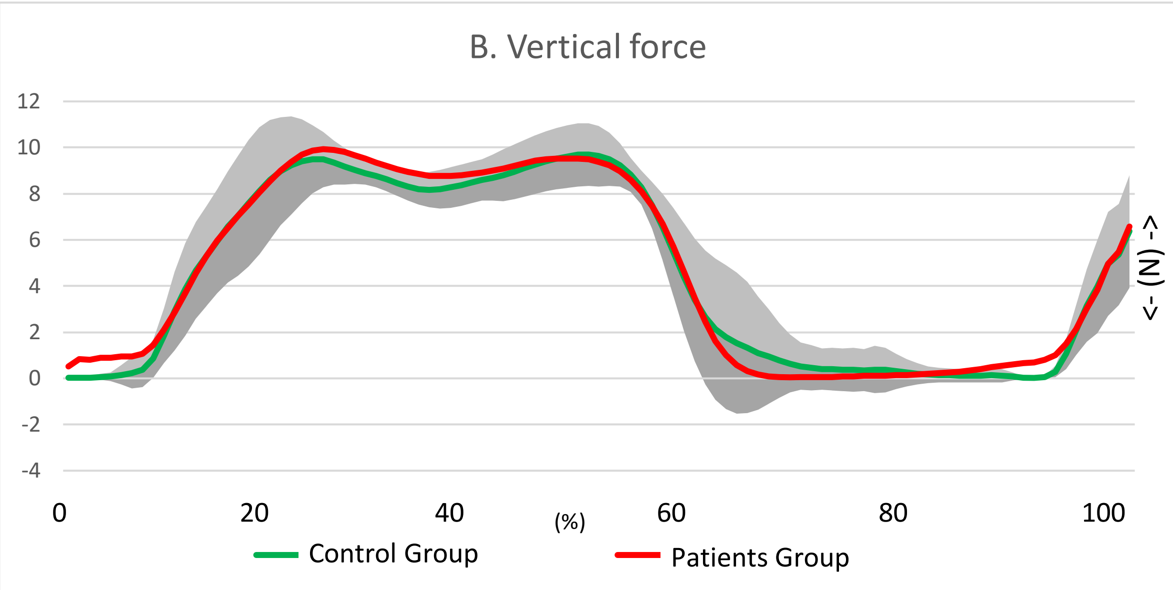


Figure 16: Ground reaction force:





4.3.3 Patients' non-operated and operated sides comparison

Patients' operated and non-operated sides were compared using Paired-Samples T Tests, as seen in below Table 10. Interestingly, there was a significant difference in one variable only. There was a significant difference in peak hip internal rotation moment of the operated side compared to non-operated side, lower in operated side (-0.33±0.17 and -0.20±0.14, p=0.031) which is considered as normal level of confidence. However, many joints scored notably lower mean scores and were notably lower in the patients' operated side, such as hip flexion/extension ROM, hip internal/external ROM, peak hip extension moment and vertical GRF. With regard to ROM prior to the laboratory-based study and Isometric muscle data, as stated previously, no significant differences were found between the patients' operated and non-operated sides.

Table 10: Patients' non-operated side compared to patients' operated side (non-operated side and operated side)

Joint	Variable	Non-operated leg (10 hips) Mean (SD)	Operated leg (20 hips) Mean (SD)	Average difference (Degrees)	SPSS Test	Significance Level
Hip	Hip Flex/Ext ROM	41.33±3.82	37.18±5.57	4.15 (10%)	Paired-Samples T Test	P=0.055
	Hip Abd/Add ROM	10.82±3.57	9.42±4.18	1.4 (13%)	Paired-Samples T Test	P=0.393
	Hip Int/Ext ROM	12.73±7.32	10.07±8.57	2.66 (19%)	Paired-Samples T Test	P=0.071
Knee	Knee Flex/Ext ROM	57.60±4.41	54.26±10.72	3.34 (6%)	Paired-Samples T Test	P=0.683
Hip	Peak Hip Flexion Moment	0.57±0.17	0.56±0.24	0.01 (2%)	Paired-Samples T Test	P=0.883

	Peak Hip Extension Moment	-0.65±0.37	-0.42±0.24	-0.23 (36%)	Paired-Samples T Test	P=0.078
	Peak Hip Abduction Moment	-0.35±0.17	-0.23±0.21	-0.12 (35%)	Paired-Samples T Test	P=0.196
	Peak Hip Adduction Moment	0.43±0.28	0.44±0.33	-0.01 (2%)	Paired-Samples T Test	P=0.965
	Peak Hip Internal Rotation Moment	-0.33±0.17	-0.20±0.14	-0.13 (40%)	Paired-Samples T Test	P=0.031*
	Peak Hip External Rotation Moment	0.12±0.06	0.11±0.07	0.01 (9%)	Paired-Samples T Test	P=0.767
Knee	Peak Knee Flexion Moment	-0.20±0.07	-0.22±0.14	0.02 (10%)	Paired-Samples T Test	P=0.702
	Peak Knee Extension Moment	0.61±0.14	0.53±0.24	0.08 (13%)	Paired-Samples T Test	P=0.361
Hip	Peak Hip Power Flex/Ext	1.05±0.39	0.92±0.40	0.13 (13%)	Paired-Samples T Test	P=0.438
Ground Reaction Force	GRF_Y (Anteroposterior)	-0.65±0.37	-0.42±0.24	-0.23 (35%)	Paired-Samples T Test	P=0.173
	GRF_Z (Vertical)	10.45±0.34	9.72±1.37	0.73 (7%)	Paired-Samples T Test	P=0.071

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

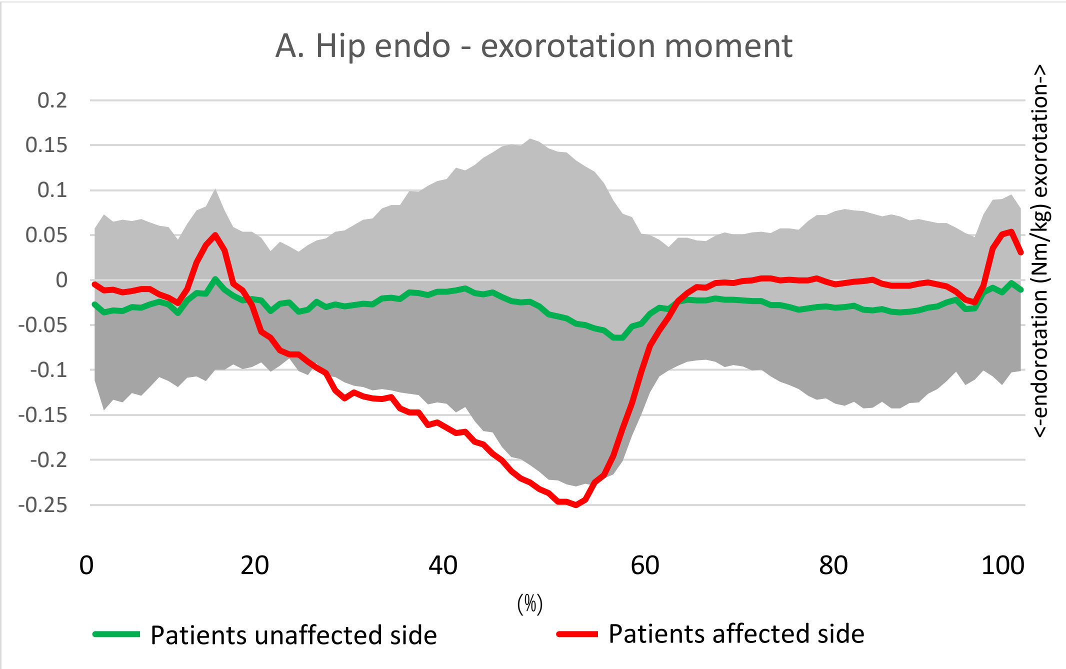
†Negative values mean higher patient scores

4.3.3.1 Gait: Patients' affected-side and unaffected-side graph comparison

Figure 17: Hip internal/external rotation moment:

In Figure 17, average peak scores of patients' hip are represented in a red line compared to control group scores represented in a green line (from heel strike to heel strike). The grey area is Standard Deviation (SD) of the control group scores.

Hip Internal/External rotation moment (17A): patients' unaffected leg had significantly increased hip internal rotation moment during the mid-stance, and terminal phase compared to the affected leg hip abduction moment.



4.4 Squat results

4.4.1 Control right side compared to patients' operated side

Control right side and patients' operated side comparison showed a significant difference between groups in multiple variables, as seen below in Table 11, at the pelvis, thorax, hip and knee joints. There is a significant difference between groups with scores of around five degrees lower for the patients' group in abduction/adduction ROM (15.46± 8.19 and 9.82±6.89, $p=0.025$). Pelvis rotation mean scores were reduced by a degree (4.00± 1.84 and 2.70±1.47, $p=0.028$). The previous two findings are considered as "normal level of confidence". Thorax rotation ROM was lower by 1.6 degrees (4.34± 4.46 and 2.73±2.40, $p=0.009$), which is considered as high level of confidence. Patients' hip external rotation moment was lower by more than half (0.07± 0.06) compared to the control external hip moment (0.18± 0.10), p<0001 which is considered as very high level of confidence.

There was a significant difference in peak knee abduction/adduction moment between the two groups (0.32± 0.21 and 0.09±0.11, p=0.001), decreased peak knee abduction/adduction in the patients group. The previous finding is considered as high level of confidence. Finally, patients' peak hip power generation was around half the control hip power generation (1.09± 0.67 and 0.66±0.41, p=0.050); although lower in the patients group, it was not significantly different between the groups.

Table 11: Control right side compared to patients' operated side (right side and operated side)

Joint	Variable	Control Group (15 hips) Mean (SD)	Patients Group (15 hips) Mean (SD)	Average Difference (Degrees)	SPSS Test	Significance Level
Pelvis	Pelvis Flex/Ext ROM	15.74± 8.21	16.02± 8.02	-0.28 (2%)	Independent t-test	P=0.919
	Pelvis Abd/Add ROM	2.61± 1.19	3.31±2.02	-0.7 (21%)	Independent t-test	P=0.521
	Pelvis Int/Ext ROM	4.00± 1.84	2.70±1.47	1.30 (33%)	Independent t-test	P=0.028*
Thorax	Thorax Flex/Ext ROM	35.19± 15.74	28.00±12.37	7.19 (21%)	Independent t-test	P=0.131
	Thorax Abd/Add ROM	2.67± 2.45	2.92±3.91	-0.25 (9%)	Mann-Whitney U Test	P=0.856
	Thorax Int/Ext ROM	4.34± 4.46	2.73±2.40	1.61 (37%)	Mann-Whitney U Test	P=0.009**

Hip	Hip Flex/Ext ROM	80.09± 26.99	72.17±20.64	7.92 (10%)	Independent t-test	P=0.332
	Hip Abd/Add ROM	15.46± 8.19	9.82±6.89	5.64 (37%)	Mann-Whitney U Test	P=0.025*
	Hip Int/Ext ROM	19.69± 14.97	13.49±13.13	6.20 (32%)	Mann-Whitney U Test	P=0.080
Knee	Knee Flex/Ext ROM	98.18± 27.09	85.32±24.31	12.86 (13%)	Independent t-test	P=0.150
Hip	Peak Hip Flexion Moment	0.88± 0.43	0.67±0.28	0.21 (24%)	Independent t-test	P=0.088
	Peak Hip Abduction Moment	0.08± 0.18	0.09± 0.11	-0.01 (11%)	Mann-Whitney U Test	P=0.458
	Peak Hip External Rotation Moment	0.18± 0.10	0.07± 0.06	0.11 (62%)	Independent t-test	P<0.001***
Knee	Peak Knee Extension Moment	0.81± 0.22	0.68± 0.22	0.13 (16%)	Independent t-test	P=0.091
	Peak Knee Abduction Moment	0.32± 0.21	0.09±0.11	0.23 (72%)	Independent t-test	P=0.001***
Hip	Peak Hip Power Generation	1.09± 0.67	0.66±0.41	0.43 (40%)	Independent t-test	P=0.050

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

†Negative values mean higher patient scores

4.4.1.1 Squat: control right-side and patients' operated sides graphs comparison

Figure 18: Thorax ROM:

In Figure 18, ROM scores of patients' thorax are represented in a red line compared to control group scores represented in a green line (squat descending phase from 0 to 50% and ascending phase from 50% to 100%). The grey area is Standard Deviation (SD) of the control group scores. N.B. the final part of the line is an artefact because PIG was set up for gait analysis. In addition, interpretation of the graphs is based on the average scores throughout the squat cycle.

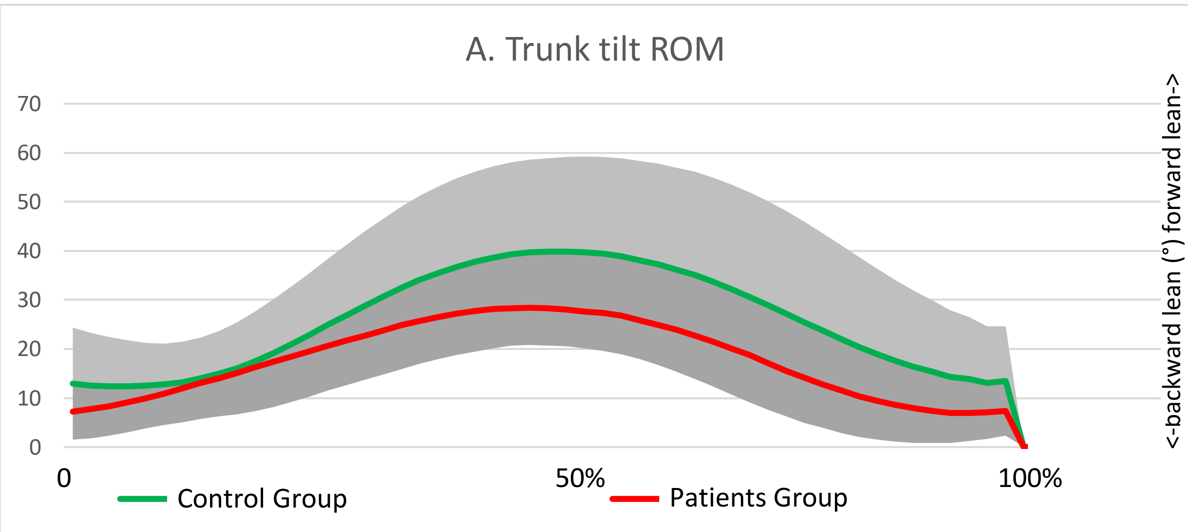
Trunk tilt (18A): patients are at a slightly decreased forward lean compared to the control group by 10-15 degrees less during squat phases.

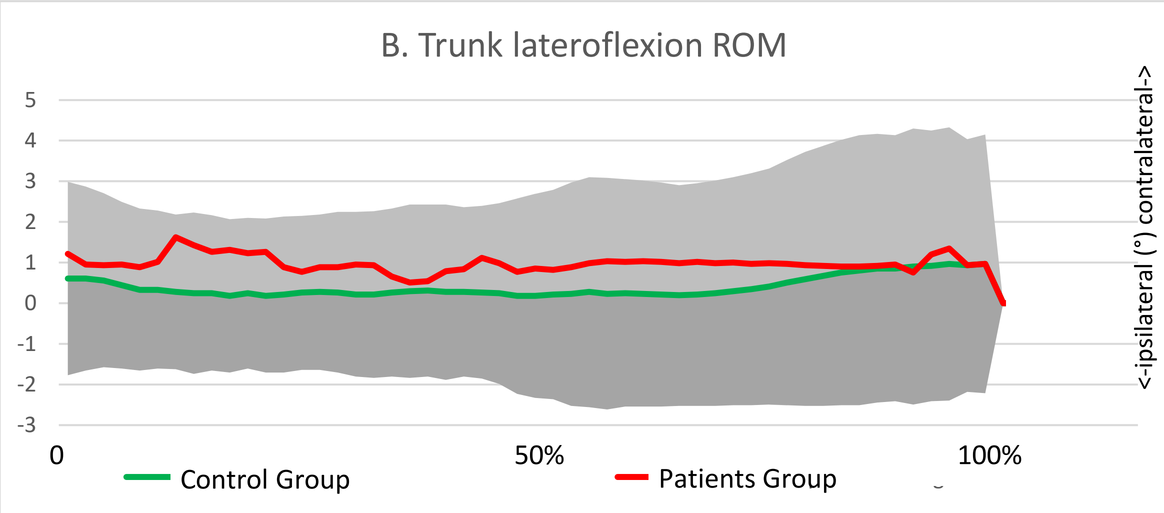
Trunk lateroflexion (18B): patients maintained slight ipsilateral trunk lateral flexion throughout both the descending and ascending phases opposite to the control group which maintained almost neutral trunk lateral flexion.

Trunk rotation (18C): patients are at significant reduced backward rotation throughout the squat phases compared to the control group.

In Figure 19, ROM scores of patients' hip are represented in a red line compared to control group scores represented in a green line (squat descending phase from 0 to 50% and ascending phase from 50% to 100%). The grey area is Standard Deviation (SD) of the control group scores. N.B. the final part of the line is an artefact because PIG was set up for gait analysis.

Hip Flexion/Extension (19A): decreased peak hip flexion ROM at the lowest point of squat depth. However, close to normal ranges.





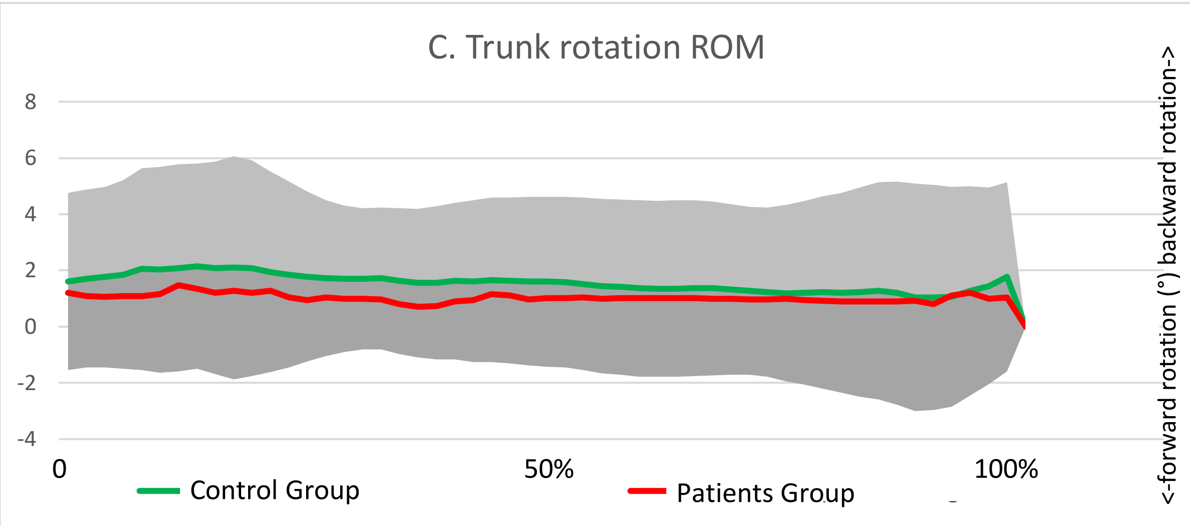
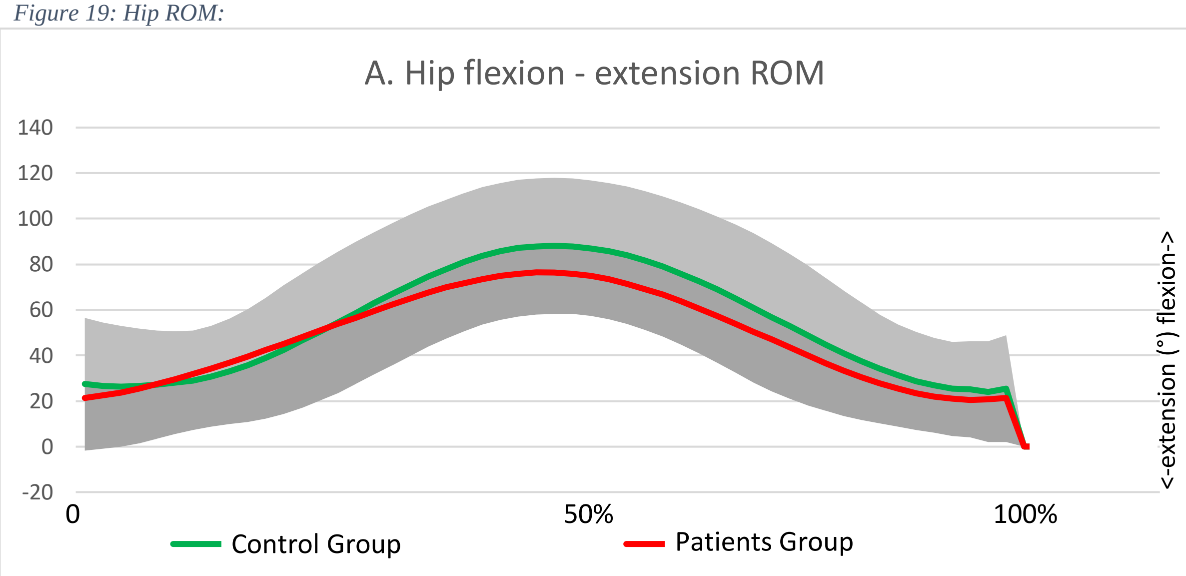


Figure 19: Hip ROM:



In Figure 20, ROM scores of patients' knee and average peak hip abduction/adduction moments are represented in a red line compared to control group scores represented in a green line (squat descending phase from 0 to 50% and ascending phase from 50% to 100%). The grey area is Standard Deviation (SD) of the control group scores. N.B. the final part of the line is an artefact because PIG was set up for gait analysis.

Knee Flexion/Extension ROM (20A): reduced patients' peak knee flexion at lowest point of squat depth by around 20 degrees.

Hip Abduction/Adduction moment (20B): significantly reduced patients' overall and peak hip abduction moment.

In Figure 21, average peak hip internal/external and knee abduction/adduction moments scores of patients are represented in a red line compared to control group scores represented in a green line (squat descending phase from 0 to 50% and ascending phase from 50% to 100%). The grey area is Standard Deviation (SD) of the control group scores. N.B. the final part of the line is an artefact because PIG was set up for gait analysis.

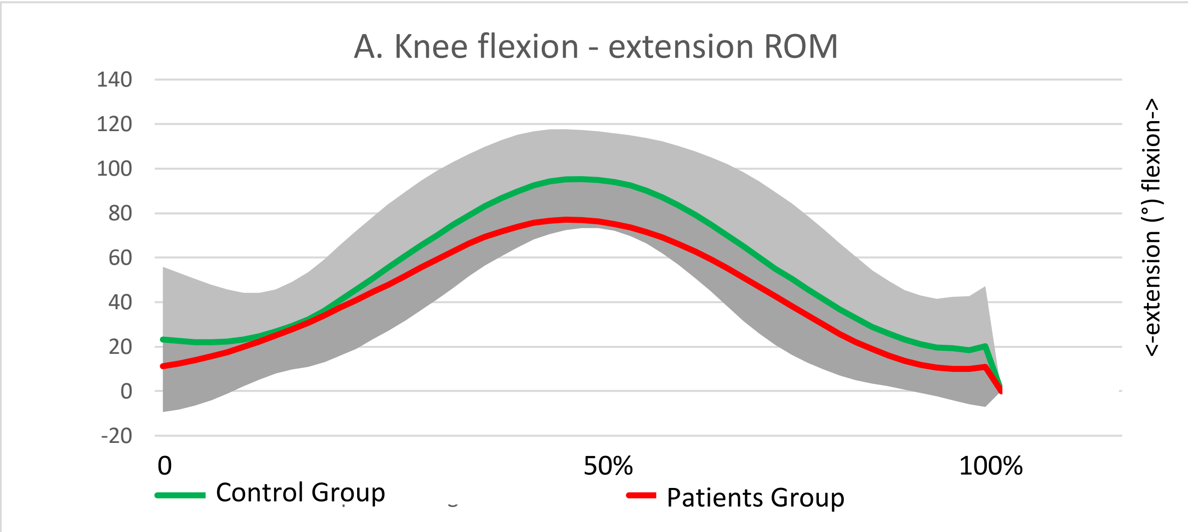
Hip Internal/External Rotation moment (21A): opposite to control group who tend to have peak hip external rotation moment at lowest point of squat depth, patients maintained neutral hip rotation moment throughout squat.

Knee Abduction/Adduction moment (21B): at lowest point of squat depth, patients had significantly lower knee abduction moment compared to control group.

In Figure 22, average peak hip power generation and absorption scores of patients hip are represented in a red line compared to control group scores represented in a green line (squat descending phase from 0 to 50% and ascending phase from 50% to 100%). The grey area is Standard Deviation (SD) of the control group scores. N.B. the final part of the line is an artefact because PIG was set up for gait analysis.

Hip Flexion/Extension power (22A): patients had decreased hip power absorption during descending phase and reduced peak hip power generation during ascending phase. However, there was no significant difference between the two groups ($p=0.050$).

Figure 20: Knee ROM and Hip joint moment:



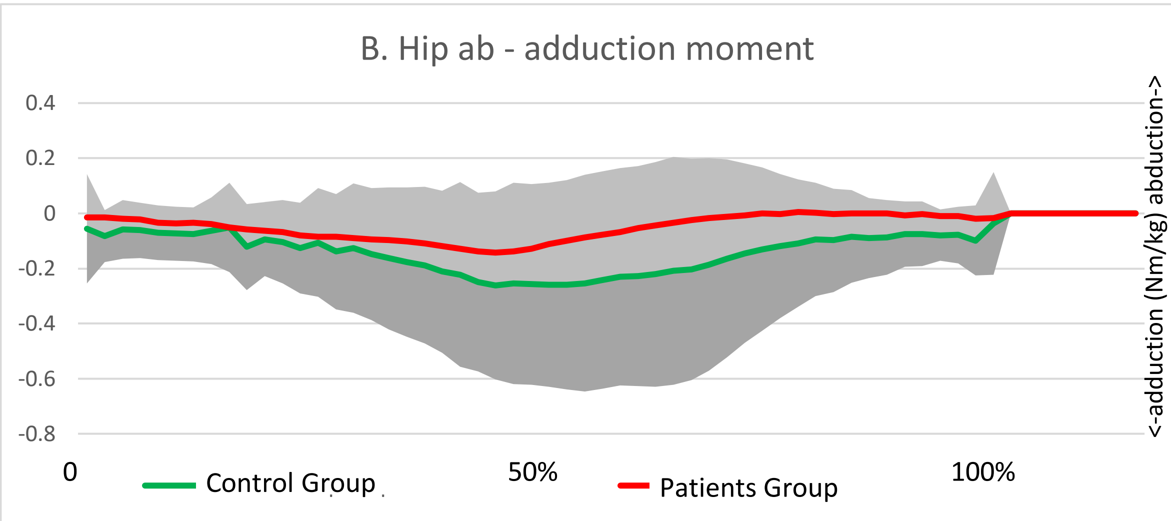
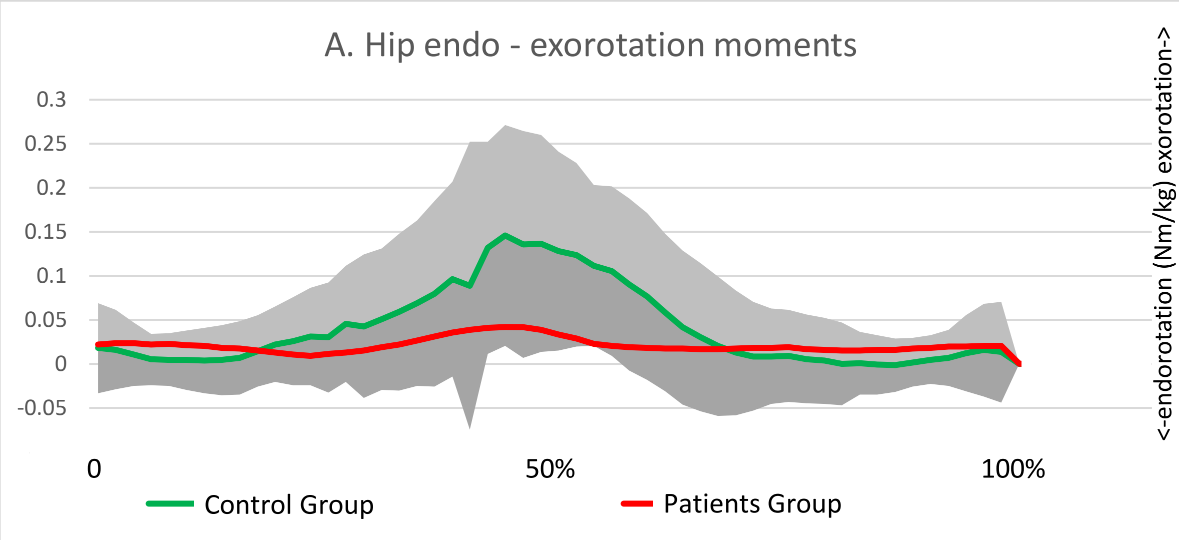


Figure 21: Hip and knee joints moments:



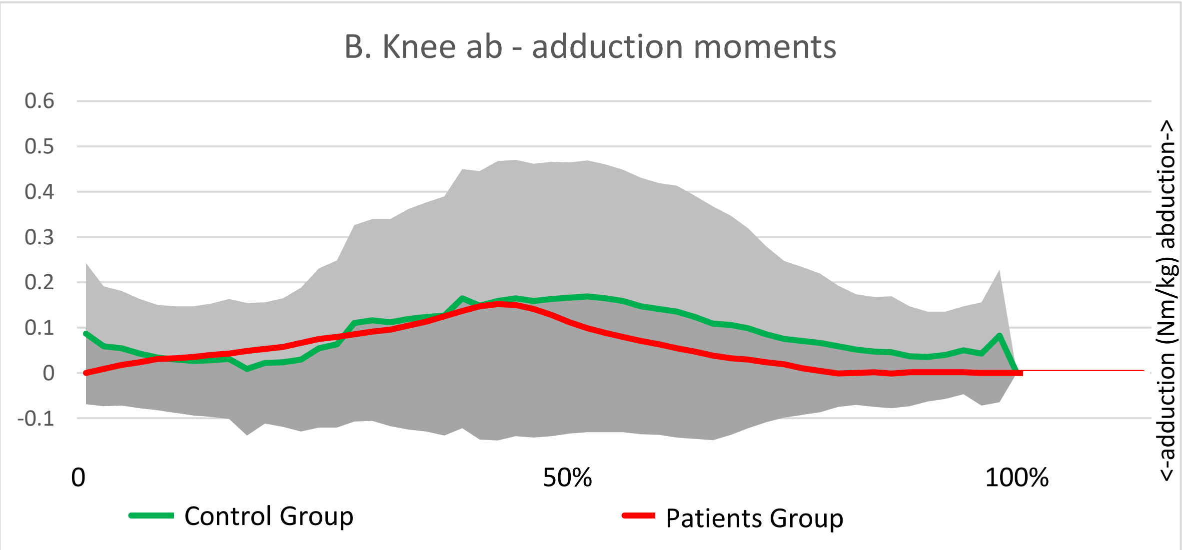
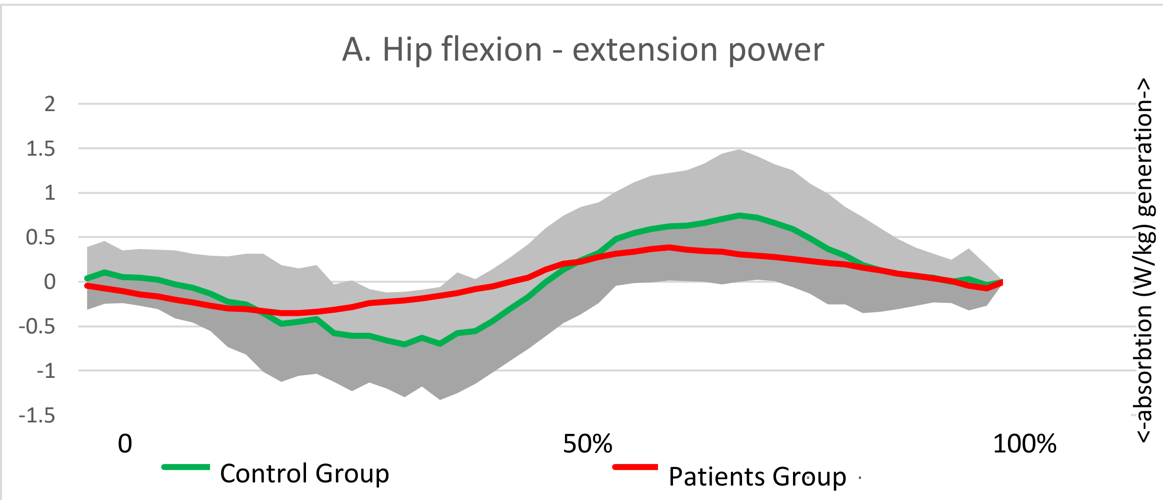


Figure 22: Hip power:



4.4.2 Control right side compared to patients' non-operated side

On the other hand, the non-operated side scores were similar to the operated side scores with regard to hip external rotation moment and knee abduction moment, although they differed in terms of knee flexion/extension ROM scores, see Table 12 below. Patients scored around 25 degrees lower in knee flexion ROM during patients' group squat (73.84±16.06), compared to control squat (98.78±18.65) p=0.005. Interestingly, patients' knee flexion ROM of the operated legs was higher by 10 degrees. In addition, hip external rotation moment significantly differed between the two groups, lower in the patients group (0.18±0.10 and 0.07±0.05, p=0.007). The previous two findings are considered as normal level of confidence based on the significance level adopted in this research. Patients scored a lower knee abduction moment mean (0.08±0.04) compared to the control mean score (0.28±0.23), by almost three times, p=0.026, which is considered as normal level of confidence based on level of confidence adopted in this research. Similar to the affected side, patients' peak hip power (0.60±0.22) was around half the control mean score (1.12±0.71), p=0.050. However, there was no significant difference.

Table 12: Control right side compared to patients' non-operated side

Joint	Variable	Control Group (10 hips) Mean (SD)	Patients Group (10 hips) Mean (SD)	Average Difference (Degrees)	SPSS Test	Significance Level
Pelvis	Pelvis Flex/Ext ROM	14.66±7.37	19.72±6.94	-5.06 (26%)	Independent t-test	P=0.132
	Pelvis Abd/Add ROM	2.68±1.05	3.12±2.02	-0.44 (14%)	Independent t-test	P=0.550
	Pelvis Int/Ext ROM	3.51±1.06	2.66±1.52	0.85 (24%)	Independent t-test	P=0.165
Thorax	Thorax Flex/Ext ROM	37.95±15.81	27.63±10.45	10.32 (27%)	Independent t-test	P=0.102
	Thorax Abd/Add ROM	3.11±2.94	3.40±5.56	-0.29 (9%)	Mann-Whitney U Test	P=0.353

	Thorax Int/Ext ROM	4.66±5.44	3.19±3.32	1.47 (32%)	Mann-Whitney U Test	P=0.075
Hip	Hip Flex/Ext ROM	77.80±20.42	75.11±19.29	2.69 (3%)	Independent t-test	P=0.766
	Hip Abd/Add ROM	13.91±5.85	9.52±4.87	4.39 (32%)	Independent t-test	P=0.086
	Hip Int/Ext ROM	19.68±16.27	14.35±11.54	5.33 (28%)	Mann-Whitney U Test	P=0.247
Knee	Knee Flex/Ext ROM	98.78±18.65	73.84±16.06	24.94 (25%)	Independent t-test	P=0.005**
Hip	Peak Hip Flexion Moment	0.89±0.47	0.59±0.21	0.3 (33%)	Independent t-test	P=0.088
	Peak Hip Abduction Moment	0.09±0.20	0.04±0.12	0.05 (56%)	Mann-Whitney U Test	P=0.684
	Peak Hip External Rotation Moment	0.18±0.10	0.07±0.05	0.11 (62%)	Mann-Whitney U Test	P=0.007**
Knee	Peak Knee Extension Moment	0.81±0.20	0.66±0.23	0.15 (19%)	Independent t-test	P=0.144
	Peak Knee Abduction Moment	0.28±0.23	0.08±0.04	0.20 (72%)	Mann-Whitney U Test	P=0.026*
Hip	Peak Hip Power generation	1.12±0.71	0.60±0.22	0.52 (47%)	Independent t-test	P=0.050

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

†Negative values mean higher patient scores

4.4.2.1 Squat: Control right side and patients' non-operated side graphs comparison

In Figure 23, ROM scores of patients' hip are represented in a red line compared to control group scores represented in a green line (squat descending phase from 0 to 50% and ascending phase from 50% to 100%). The grey area is Standard Deviation (SD) of the control group scores. N.B. the final part of the line is an artefact because PIG was set up for gait analysis.

Hip Flexion/Extension (23A): patients' unaffected side tended to have decreased peak hip flexion ROM at lowest point of squat depth. Although no significant difference between groups, the difference was around 20-25 degrees.

Hip Abduction/Adduction (23B): patients' unaffected side had reduced patients' overall hip abduction ROM. Patients had decreased peak hip abduction at lowest point of squat depth by around 10 degrees.

In Figure 24, ROM scores of patients' knee represented in a red line compared to control group scores are represented in a green line (squat descending phase from 0 to 50% and ascending phase from 50% to 100%). The grey area is Standard Deviation (SD) of the control group scores. N.B. the final part of the line is an artefact because PIG was set up for gait analysis.

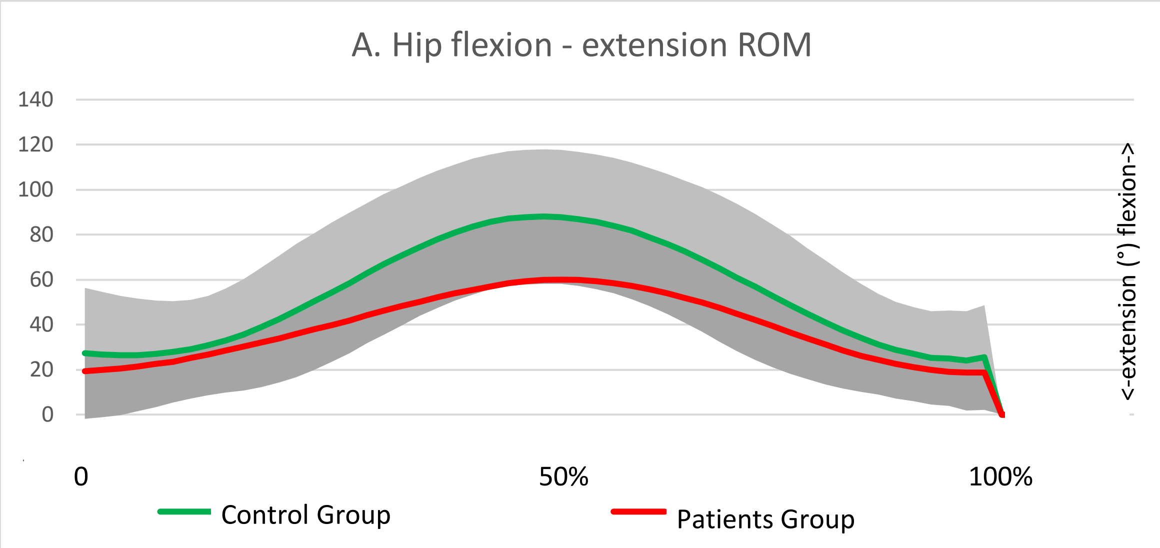
Knee Flexion/Extension ROM (24A): there was significantly reduced patients' peak knee flexion at the lowest point of squat depth. The control peak was 95 degrees compared to the patients' peak at 73 degrees.

In Figure 25, average peak hip internal/external rotation and knee flexion/extension moments scores of patients are represented in a red line compared to control group scores represented in a green line (squat descending phase from 0 to 50% and ascending phase from 50% to 100%). The grey area is Standard Deviation (SD) of the control group scores.

Hip Internal/External rotation moment (25A): opposite to the control group, who tended to have peak hip external rotation moment at the lowest point of squat depth, patients maintained slight hip internal rotation moment throughout the squat with a slight decrease at the lowest point of squat depth.

Knee Flexion/Extension moment (25B): slightly delayed and decreased knee extension moment at lowest point of squat depth.

Figure 23: Hip ROM:



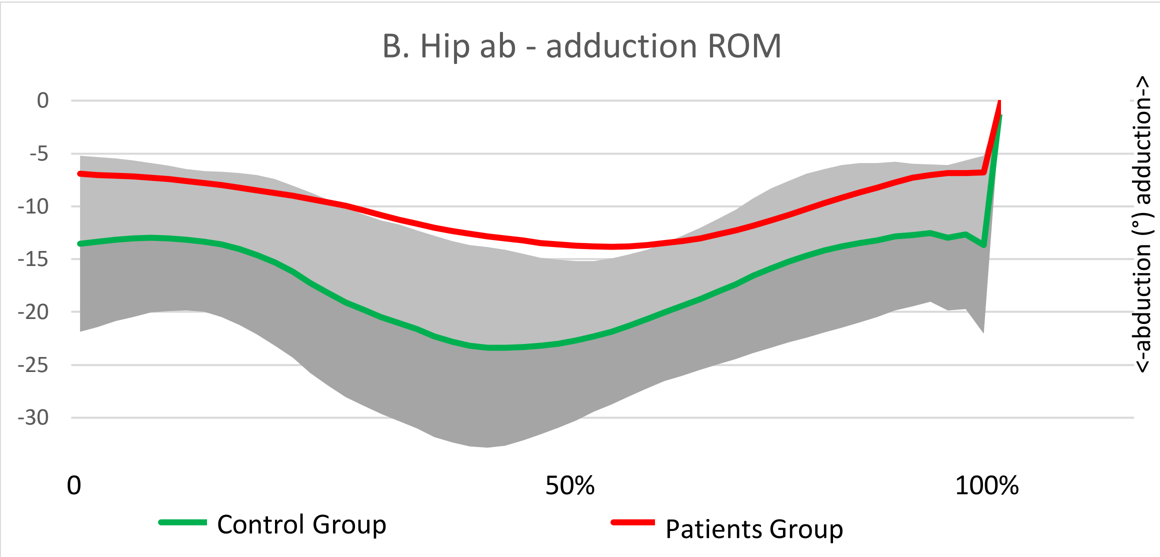


Figure 24: Knee ROM:

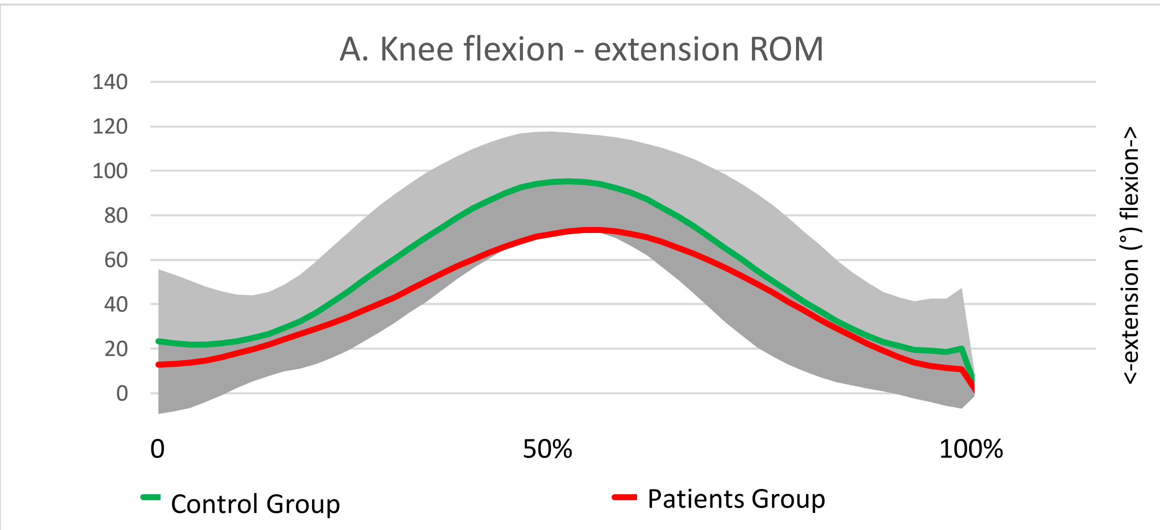
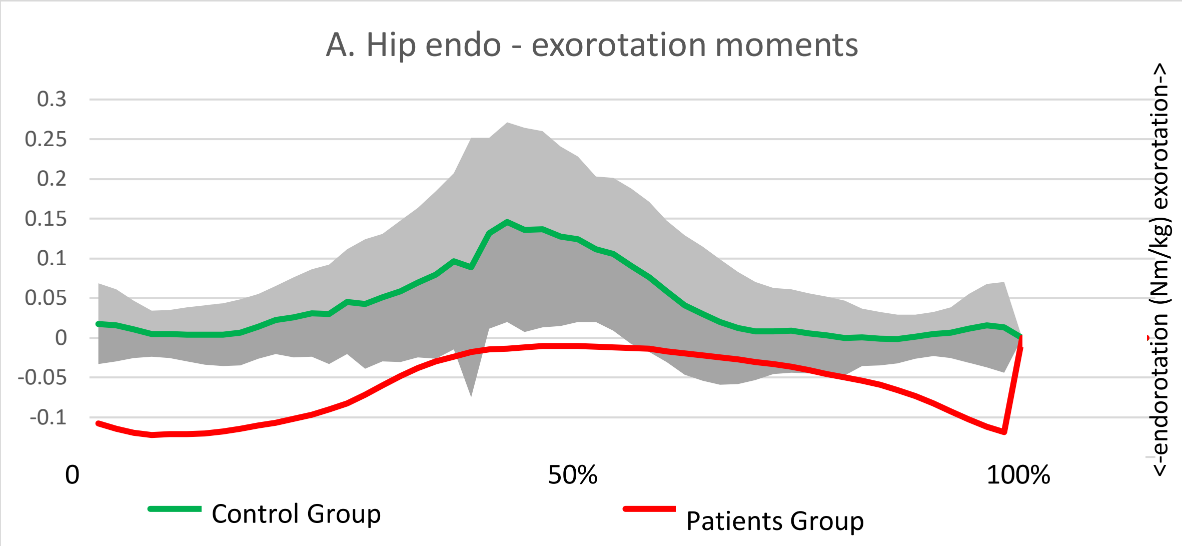
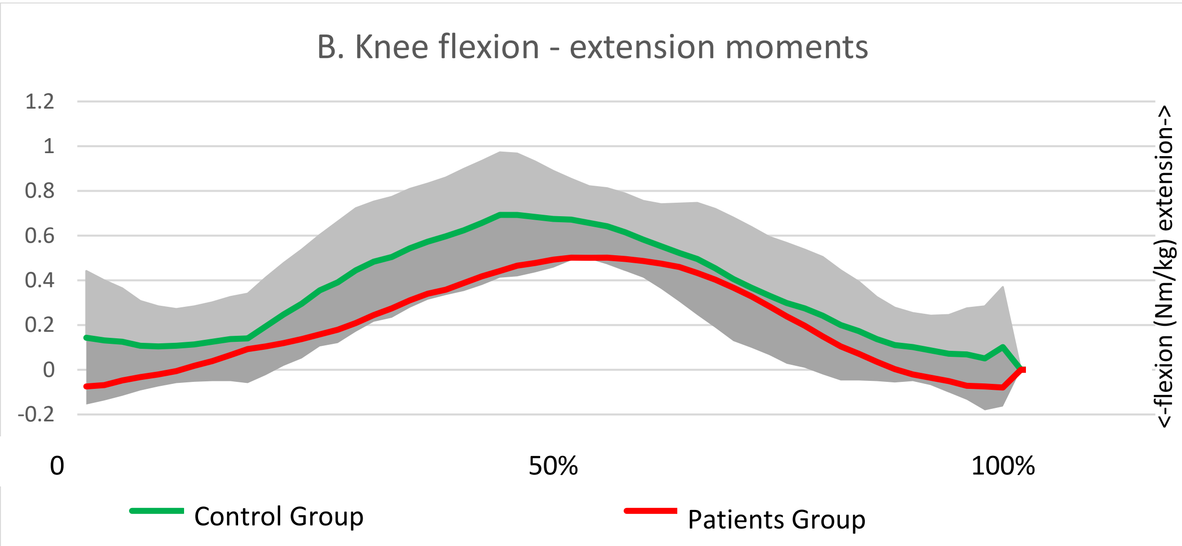


Figure 25: Hip joint and knee joint moments:





4.4.3 Patients' non-operated side compared to patients' operated side

Patients' operated and non-operated sides comparison showed no significant differences in all joints, as seen below in Table 13.

Table 13: Patients' non-operated side compared to patients' operated side (non-operated side and operated side)

Joint	Variable	Patients' non-operated leg (10 hips) Mean (SD)	Patients' operated leg (20 hips) Mean (SD)	Average difference (Degrees)	SPSS Test	Significance Level
Hip	Hip Flex/Ext ROM	75.11± 19.29	72.17±20.64	2.94 (4%)	Paired-Samples T Test	P=0.710
	Hip Abd/Add ROM	9.52±4.87	9.82±6.89	-0.3 (3%)	Paired-Samples T Test	P=0.812
	Hip Int/Ext ROM	14.35±11.54	13.49±13.13	0.86 (6%)	Paired-Samples T Test	P=0.681
Knee	Knee Flex/Ext ROM	73.84± 16.06	85.32±24.31	-11.48 (14%)	Paired-Samples T Test	P=0.189
Hip	Peak Hip Flexion Moment	0.59± 0.21	0.67±0.28	-0.08 (12%)	Paired-Samples T Test	P=0.425
	Peak Hip Abduction Moment	0.04± 0.12	0.09±0.11	-0.05 (56%)	Paired-Samples T Test	P=0.285
	Peak Hip External Rotation Moment	0.07±0.05	0.07±0.06	0	Paired-Samples T Test	P=0.746
Knee	Peak Knee Extension Moment	0.66± 0.23	0.68±0.22	-0.02 (3%)	Paired-Samples T Test	P=0.834

	Peak Knee Abduction Moment	0.08±0.04	0.12±0.08	-0.04 (33%)	Paired-Samples T Test	P=0.116
Hip	Peak Hip Power Generation	0.60±0.22	0.66±0.41	-0.06 (10%)	Paired-Samples T Test	P=0.948

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

†Negative values mean higher patient scores

4.4.3.1 Squat: Patients' non-operated side and patients' operated side graphs comparison

Samples of comparison graphs can be found in Appendix 14.

4.5 Single limb balance:

4.5.1 Right foot off results: control right side compared to patients' operated side

When the control right legs and patients' operated legs were compared, there was a significant difference in two variables, as seen below in Table 14. First, thorax flexion/extension ROM was significantly different between the two groups (control 6.37± 3.64 and patients 9.77±4.87, p= 0.030), where patients had lower ROM by three degrees. Second, the patients group scored lower peak knee moment abduction moment (0.49±0.19 and 0.32±0.18, p=0.013). Both results are considered as normal level of confidence.

Table 14: Single limb balance results

Joint	Variable	Control Group (15 hips) Mean (SD)	Patients Group (15 hips) Mean (SD)	Average Difference (Degrees)	SPSS Test	Significance Level
Pelvis	Pelvis Flex/Ext ROM	11.23±11.21	11.21±3.50	0.02 (1%)	Independent t-test	P=0.610
	Pelvis Abd/Add ROM	8.33±5.44	7.70±3.06	0.63 (8%)	Mann-Whitney U Test	P=0.934

	Pelvis Int/Ext ROM	10.86±6.24	8.98±4.60	1.88 (18%)	Mann-Whitney U Test	P=0.521
Thorax	Thorax Flex/Ext ROM	6.37±3.64	9.77±4.87	-3.4 (35%)	Independent t-test	P=0.030*
	Thorax Abd/Add ROM	9.23±6.75	8.41±6.90	0.82 (9%)	Mann-Whitney U Test	P=0.438
	Thorax Int/Ext ROM	10.84±6.55	8.02±4.27	2.82 (26%)	Independent t-test	P=0.314
Hip	Hip Flex/Ext ROM	10.95±5.38	11.95±5.02	-1 (9%)	Independent t-test	P=0.542
	Hip Abd/Add ROM	7.99±4.57	6.62±3.21	1.37 (18%)	Independent t-test	P=0.314
	Hip Int/Ext ROM	10.55±4.27	9.18±6.02	1.37 (13%)	Mann-Whitney U Test	P=0.099
Ankle	Ankle Flex/Ext ROM	7.81±2.04	8.64±2.99	-0.83 (10%)	Independent t-test	P=0.681
Hip	Peak Hip Extension Moment	0.19±0.27	0.11±0.22	0.08 (43%)	Independent t-test	P=0.388
	Peak Hip Abduction Moment	0.73±0.24	0.63±0.14	0.1(14%)	Independent t-test	P=0.149
	Peak Hip Internal Rotation Moment	0.04±0.05	0.02±0.04	0.02 (50%)	Independent t-test	P=0.282

Knee	Peak Knee Extension Moment	0.28±0.33	0.37±0.25	-0.09 (25%)	Independent t-test	P=0.359
	Peak Knee Abduction Moment	0.49±0.19	0.32±0.18	0.17 (35%)	Independent t-test	P=0.013*
Ankle	Peak Ankle Extension Moment	0.89±0.36	0.86±0.19	0.03 (4%)	Mann-Whitney U Test	P=0.766
Hip	Peak Hip Power Generation	0.08±0.08	0.04±0.02	0.04 (50%)	Independent t-test	P=0.438

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

†Negative values mean higher patient scores

4.5.1.1 SLB: control right side and patients' operated side graphs comparison

In Figure 26, ROM scores of patients' pelvis are represented in a red line compared to control group scores represented in a green line (from the first second to the tenth second). The grey area is Standard Deviation (SD) of the control group scores. N.B. Interpretation of the graphs is based on the average scores during the time of SLB.

Pelvic tilt (26A): almost identical mean paths.

Pelvic obliquity (26B): similar mean patterns

In Figure 27, ROM scores of patients' thorax are represented in a red line compared to control group scores represented in a green line (from the first second to the tenth second). The grey area is Standard Deviation (SD) of the control group scores.

Trunk lateroflexion (27A): apart from one to two degrees ipsilateral trunk difference, nearly normal and similar mean patterns.

Trunk rotation (27B): control had forward rotation, opposite to patients with no trunk rotation throughout the whole 10 seconds. There was a significant difference in trunk rotation between the groups.

Figure 26: Pelvis ROM:

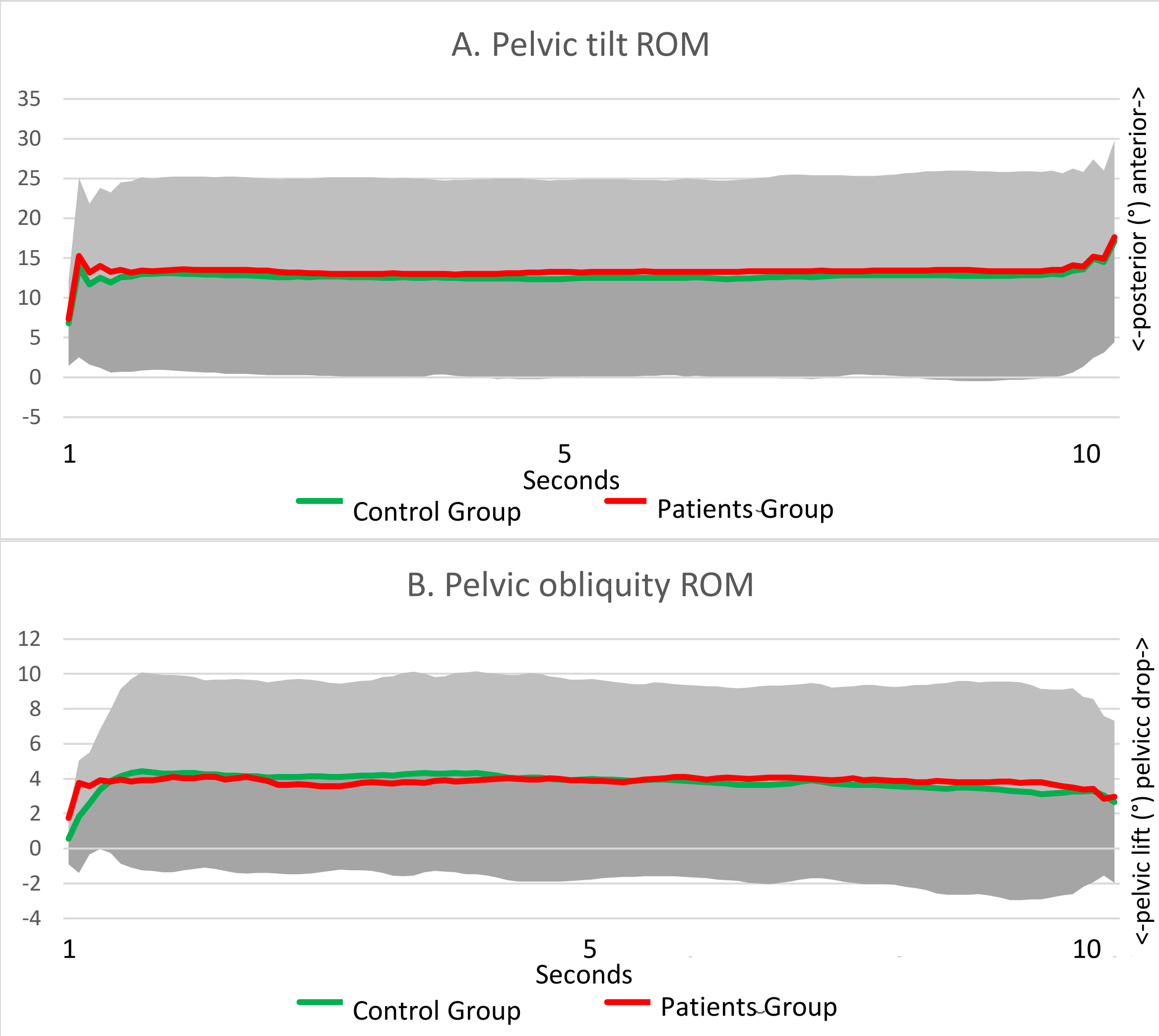
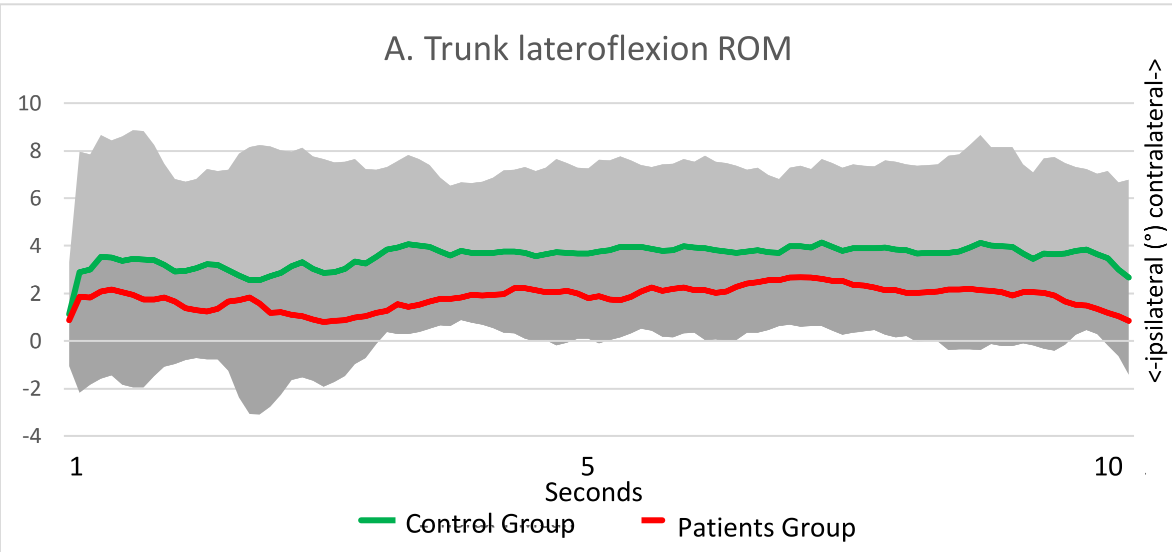
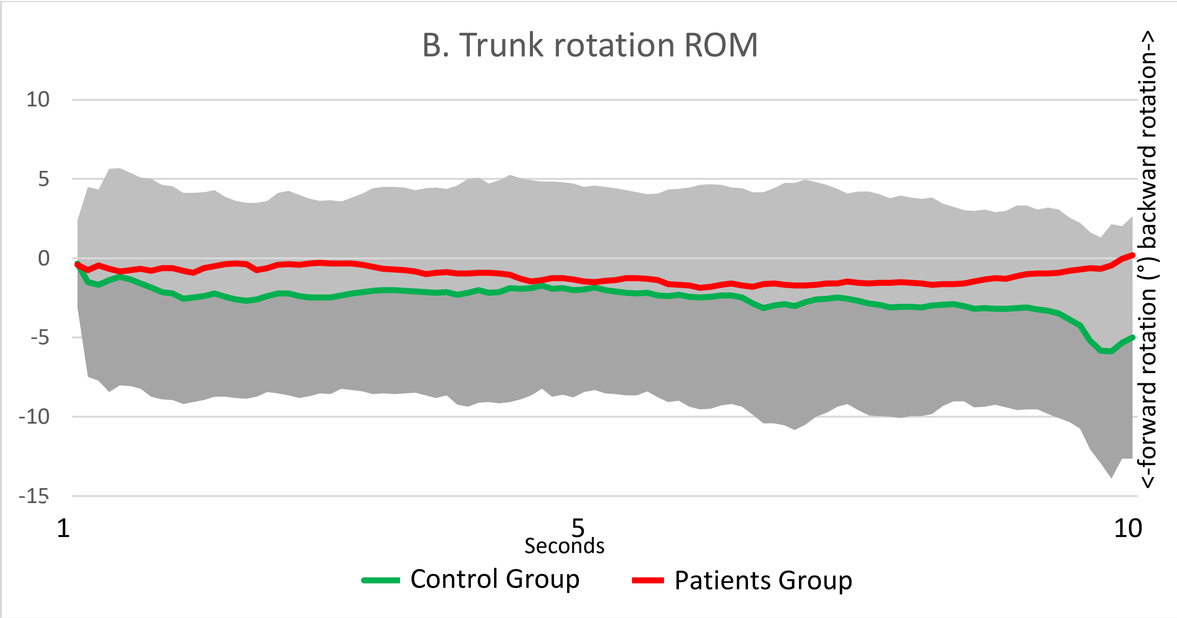


Figure 27: Thorax ROM:





In Figure 28, ROM scores of patients' hip are represented in a red line compared to control group scores represented in a green line (from the first second to the tenth second). The grey area is Standard Deviation (SD) of the control group scores.

Hip Flexion/Extension (28A): normal hip angles for both groups.

Hip Abduction/Adduction (28B): slight increase in hip abduction ROM, however, not significantly different.

In Figure 29, ROM scores of patients ankle and average peak hip abduction/adduction moments are represented in a red line compared to control group scores represented in a green line (from the first second to the tenth second). The grey area is Standard Deviation (SD) of the control group scores.

Ankle Dorsiflexion/Plantarflexion ROM (29A): patients tend to have two degrees dorsiflexion more than the control group; however, no significant difference between the two groups (within normal range).

Hip Abduction/Adduction moment (29B): almost similar hip abduction moment patterns for the two groups.

In Figure 30, average peak knee abduction/adduction moments scores of patients are represented in a red line compared to control group scores represented in a green line (from the first second to the tenth second). The grey area is Standard Deviation (SD) of the control group scores.

Knee Abduction/Adduction rotation moment (30A): significant reduced knee abduction moment in patients.

Seconds

Figure 28: Hip ROM:

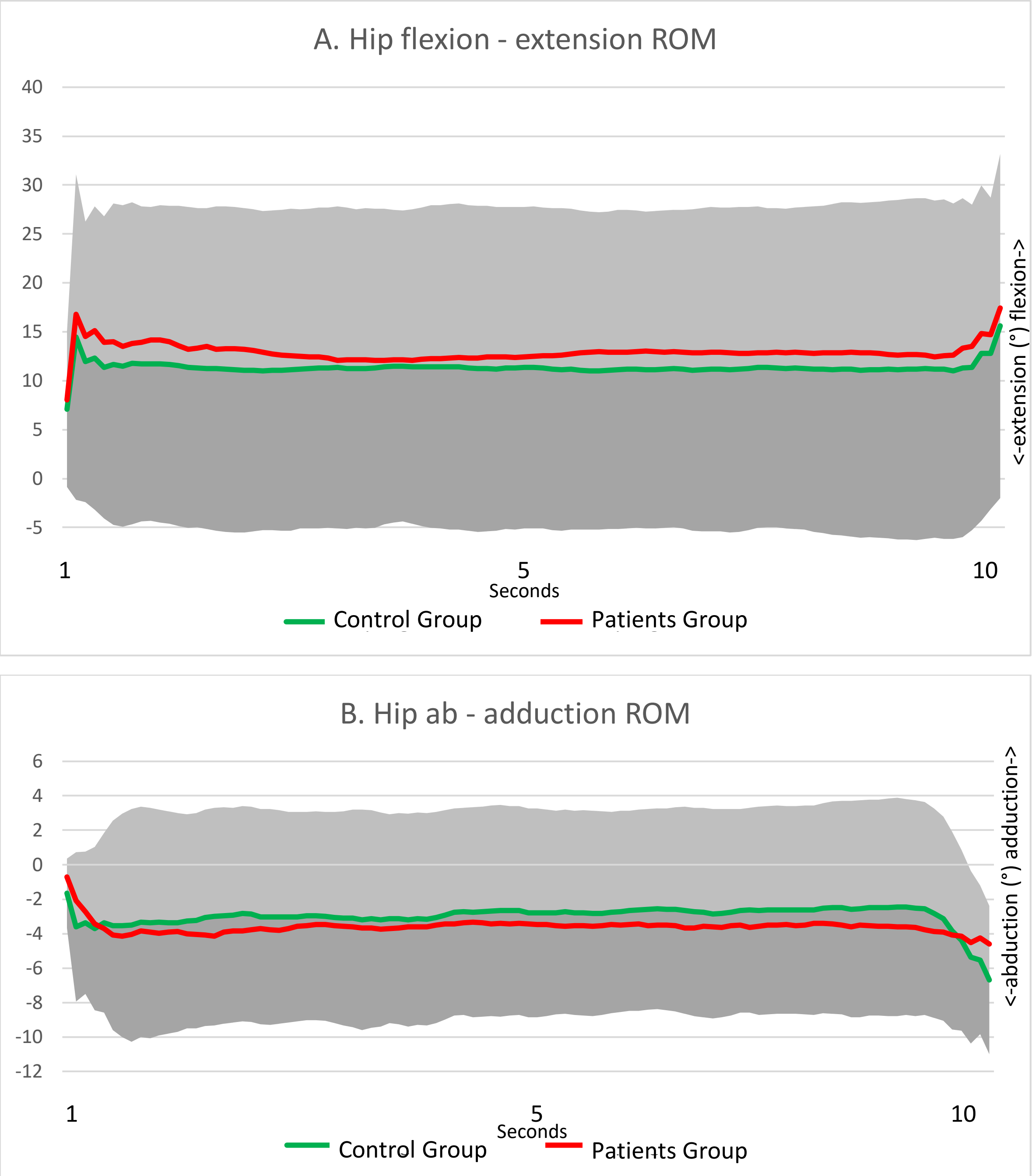
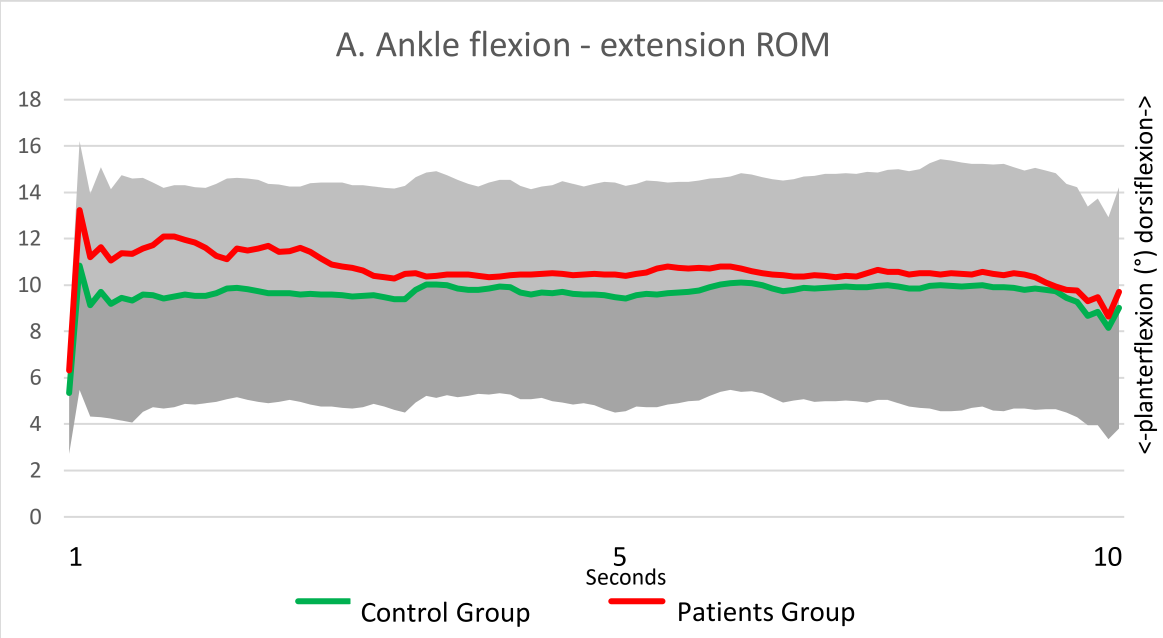


Figure 29: Ankle ROM and hip joint moments:



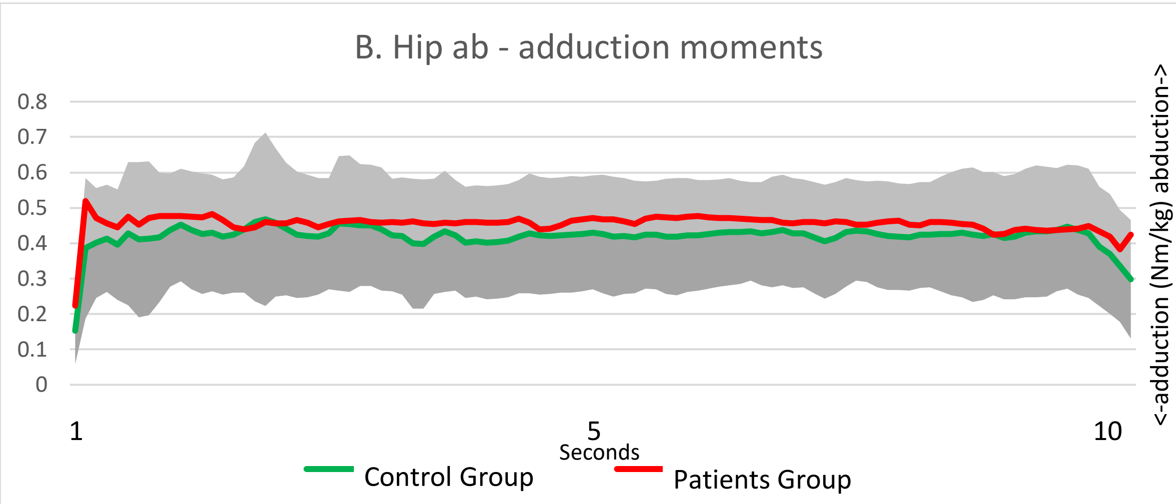
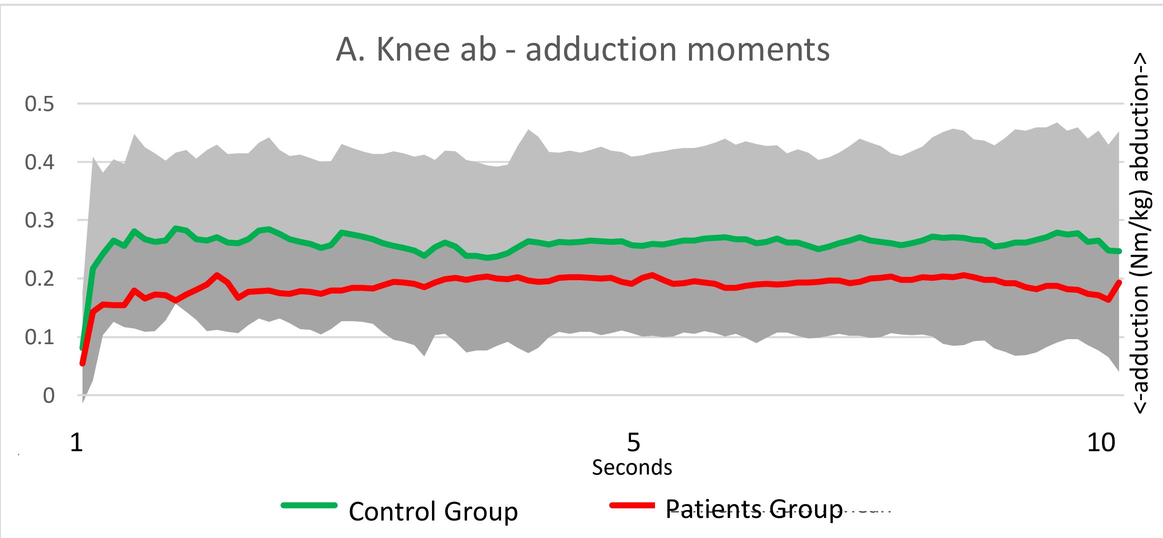


Figure 30: knee joint moments:



4.5.2 Single limb balance: control right side compared to patients' non-operated side

Opposite to the control side and patients' operated side comparison, when non-operated sides were compared to the control right side, there was a significant difference in three variables, as seen in Table 15 below. Thorax flexion/extension ROM differed between the two groups by four degrees (control mean score 5.72±2.68 lower than patients' mean score 9.92±4.27, p=0.017). Patients' non-operated side mean peak abduction moment score (0.53±0.11) was significantly decreased compared to the control peak hip abduction mean score (0.73±0.26), p=0.039. Based on significance level adopted in this research, the previous two results are considered as normal level of confidence. Finally, there was around six degrees reduction, lower scores, in patients' lateroflexion (4.64±2.37) compared to the control group (10.56±7.70), p=0.009 which is considered as high level of significance.

Table 15: Left foot off results: control right side compared to patients' non-operated side (right side and non-operated side)

Joint	Variable	Control Group (10 hips) Mean (SD)	Patients Group (10 hips) Mean (SD)	Average Difference (Degrees)	SPSS Test	Significance Level
Pelvis	Pelvis Flex/Ext ROM	10.35±5.66	10.35±4.11	0	Independent t-test	P=0.739
	Pelvis Abd/Add ROM	8.47±6.52	6.19±2.49	2.28 (27%)	Mann-Whitney U Test	P=0.436
	Pelvis Int/Ext ROM	11.68±6.96	9.12±3.12	2.56 (24%)	Mann-Whitney U Test	P=0.309
Thorax	Thorax Flex/Ext ROM	5.72±2.68	9.92±4.27	-4.19 (43%)	Independent t-test	P=0.017*
	Thorax Abd/Add ROM	10.56±7.70	4.64±2.37	5.92 (56%)	Mann-Whitney U Test	P=0.009**
	Thorax Int/Ext ROM	11.58±6.98	8.03±3.21	3.55 (31%)	Independent t-test	P=0.280

Hip	Hip Flex/Ext ROM	10.51±6.30	9.50±4.97	1.01 (10%)	Mann-Whitney U Test	P=0.529
	Hip Abd/Add ROM	7.46±5.44	6.38±2.53	1.08 (15%)	Mann-Whitney U Test	P=0.912
	Hip Int/Ext ROM	9.28±2.51	8.45±5.26	0.83 (9%)	Mann-Whitney U Test	P=0.280
Ankle	Ankle Flex/Ext ROM	7.49±2.28	7.86±2.71	-0.37 (5%)	Mann-Whitney U Test	P=0.746
Hip	Peak Hip Extension Moment	0.10±0.22	0.03±0.24	0.07 (70%)	Independent t-test	P=0.495
	Peak Hip Abduction Moment	0.73±0.26	0.53±0.11	0.2 (28%)	Independent t-test	P=0.039*
	Peak Hip Internal Rotation Moment	0.02±0.04	0.03±0.04	-0.01 (33%)	Independent t-test	P=0.746
Knee	Peak Knee Extension Moment	0.33±0.27	0.30±0.24	0.03 (10%)	Mann-Whitney U Test	P=0.819
	Peak Knee Abduction Moment	0.42±0.15	0.27±0.19	0.15 (36%)	Mann-Whitney U Test	P=0.085
Hip	Peak Hip Power Generation	0.05±0.06	0.05±0.05	0	Mann-Whitney U Test	P=0.796

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

†Negative values mean higher patient scores

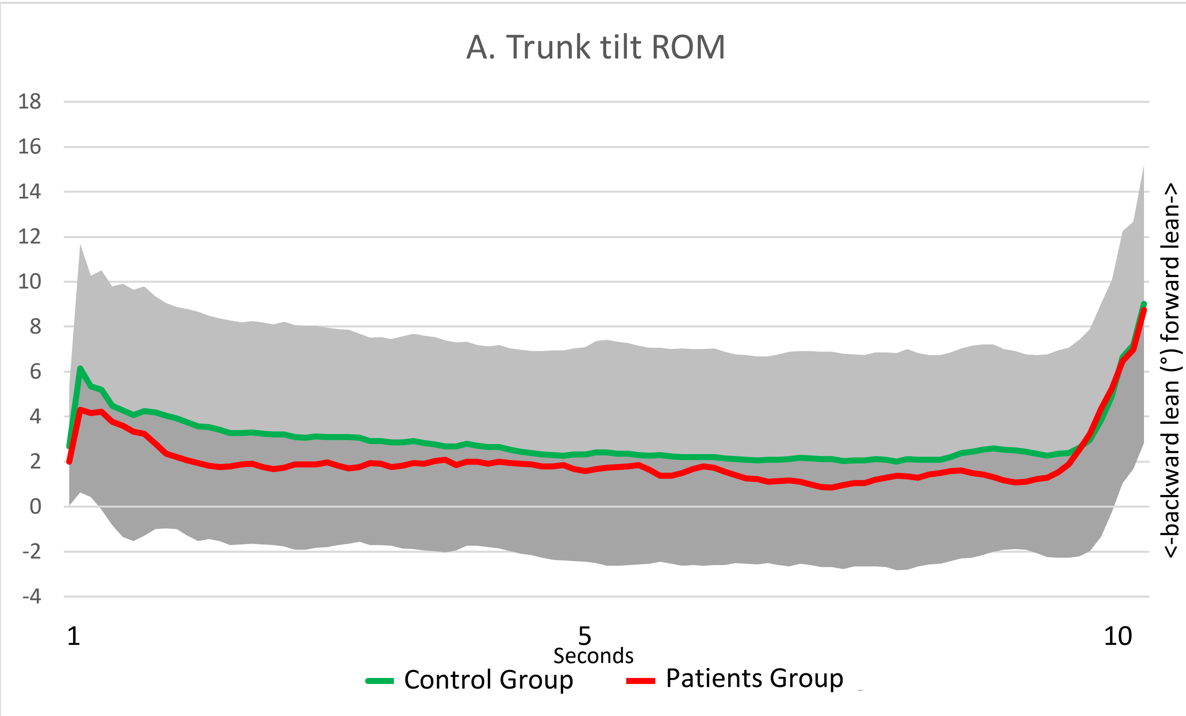
4.5.2.1 SLB: control right side and patients' non-operated side graph comparison

In Figure 31, ROM scores of patients thorax represented in a red line compared to control group scores represented in a green line (from the first second to the 10th seconds). The grey area is Standard Deviation (SD) of the control group scores.

N.B. Interpretation of the graphs based on the average scores during the time of SLB.

Trunk tilt (31A): slight reduction in patients' unaffected side forward lean during SLB when compared to the control group, however, no significant difference between the two groups.

Figure 31: Thorax ROM:



4.5.3 Single limb balance: patients' non-operated side compared to patients' operated side

There was no significant difference between the operated and non-operated sides during the SLB, as seen below in Table 16.

Table 16: Patients' SLB comparison: patients' non-operated side compared to patients' operated side (non-operated side and operated side)

Joint	Variable	Patients' non-operated leg (10 hips) Mean (SD)	Patients' operated leg (20 hips) Mean (SD)	Average difference (Degrees)	SPSS Test	Significance Level
Pelvis	Pelvis Flex/Ext ROM	10.35±4.11	11.21±3.50	-0.86 (8%)	Paired-Samples T Test	P=0.554
	Pelvis Abd/Add ROM	6.19±2.94	7.70±3.06	-1.51 (20%)	Paired-Samples T Test	P=0.131
	Pelvis Int/Ext ROM	9.12±3.12	8.98±4.60	0.14 (2%)	Paired-Samples T Test	P=0.559
Thorax	Thorax Flex/Ext ROM	9.92±4.27	9.77±4.87	0.15 (2%)	Paired-Samples T Test	P=0.935
	Thorax Abd/Add ROM	4.64±2.37	8.41±6.90	-3.77 (45%)	Paired-Samples T Test	P=0.120
	Thorax Int/Ext ROM	8.03±3.21	8.02±4.27	0.01 (1%)	Paired-Samples T Test	P=0.713
Hip	Hip Flex/Ext ROM	9.50±4.97	11.95±5.02	-2.45 (21%)	Paired-Samples T Test	P=0.217
	Hip Abd/Add ROM	6.38±2.53	6.62±3.21	-0.24 (4%)	Paired-Samples T Test	P=0.948

	Hip Int/Ext ROM	8.45±5.26	9.18±6.02	-0.73 (8%)	Paired-Samples T Test	P=0.812
Ankle	Ankle Flex/Ext ROM	7.86±2.71	8.64±2.99	-0.78 (10%)	Paired-Samples T Test	P=0.475
Hip	Peak Hip Extension Moment	0.03±0.24	0.11±0.22	-0.08 (83%)	Paired-Samples T Test	P=0.360
	Peak Hip Abduction Moment	0.53±0.11	0.63±0.14	-0.1 (16%)	Paired-Samples T Test	P=0.063
	Peak Hip Internal Rotation Moment	0.03±0.04	0.02±0.04	0.01 (33%)	Paired-Samples T Test	P=0.672
Knee	Peak Knee Extension Moment	0.30±0.24	0.37±0.25	-0.07 (19%)	Paired-Samples T Test	P=0.519
	Peak Knee Abduction Moment	0.27±0.19	0.32±0.18	-0.05 (16%)	Paired-Samples T Test	P=0.373
Ankle	Peak Ankle Extension Moment	0.77±0.18	0.86±0.19	-0.09 (10%)	Paired-Samples T Test	P=0.243
Hip	Peak Hip Power Generation	0.05±0.05	0.04±0.02	0.01 (20%)	Paired-Samples T Test	P=0.588

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

†Negative values mean higher patient scores

4.5.3.1 SLB: patients' non-operated side and patients' operated side graphs comparison:
Samples of graphs comparison can be found in Appendix 15.

4.6 Summary of patients with DDH movement compensation

There were two types of information provided in this research results above; first, there was a detailed comparison of the average ROM of the joints and maximum kinetics scores based on significance level suggested in the Methodology chapter, followed by a graph interpretation of each variable from the beginning to the end of each functional task. The reason for this is that Part 2's objective was to undertake a 3D motional analysis study to provide a detailed biomechanical description of the main variables characterising the different functional exercises for postoperative patients with hip dysplasia. In addition, the second objective was to determine whether walking, squatting or single leg balance are being done in an abnormal way or being done with compensatory movements that might affect other joints for postoperative patients with hip dysplasia. Therefore, by comparing average and maximum results for both kinematics and kinetics, it might provide a clear picture of how average patients with DDH move.

It was obvious from the comparison tables and graphs above that DDH patients tend to compensate across the three different exercises post-surgery with different level of confidence as reported. A summary of patients' movement compensations based on level of significance is provided below and briefly discussed, and a detailed discussion with more information will follow in the Discussion chapter. Table 17 below gathers all the significant results and categorise them by level of evidence. However, it needs to be noted that no muscle activity measurements were done in this research and the movement description and graph interpretation focused mainly on unusual patterns in graphs.

Table 17: A combination of all significant findings across all outcome measurements used in this research throughout different exercises based on their level of confidence. The table is divided into: A. operated side and B. non-operated side.

Exercise	Variable	Significance Level
A. Patients' operated side comparison with control group		
Gait	Thorax Abd/Add ROM	Normal Level of Confidence
	Hip Int/Ext ROM	Normal Level of Confidence
	Hip Flex/Ext ROM	High Level of Confidence
	Knee Flex/Ext ROM	High Level of Confidence
	Hip Abd/Add ROM	Very High Level of Confidence
	Peak Hip Flexion Moment	Very High Level of Confidence
	Peak Hip Extension Moment	Very High Level of Confidence
	Peak Hip Abduction Moment	Very High Level of Confidence
	Peak Hip Internal Rotation Moment	Very High Level of Confidence
	Thorax Int/Ext ROM	Very High Level of Confidence
Squat	Pelvis Int/Ext ROM	Normal Level of Confidence
	Hip Abd/Add ROM	Normal Level of Confidence
	Thorax Int/Ext ROM	High Level of Confidence
	Peak Hip External Rotation Moment	Very High Level of Confidence
	Peak Knee Abduction Moment	Very High Level of Confidence
SLB	Thorax Flex/Ext ROM	Normal Level of Confidence
	Peak Knee Abduction Moment	Normal Level of Confidence
B. **Patients' non-operated side comparison with control group**		
Gait	Thorax Abd/Add ROM	Normal Level of Confidence
	Hip Abd/Add ROM	Normal Level of Confidence
	Peak Hip Abduction Moment	Normal Level of Confidence
	Thorax Int/Ext ROM	Very High Level of Confidence
Squat	Peak Knee Abduction Moment	Normal Level of Confidence
	Peak Hip External Rotation Moment	High Level of Confidence
	Knee Flex/Ext ROM	High Level of Confidence
SLB	Thorax Flex/Ext ROM	Normal Level of Confidence
	Peak Hip Abduction Moment	Normal Level of Confidence
	Thorax Abd/Add ROM	High Level of Confidence
C. **Patients' operated side comparison with patient non-operated side**		
Gait	Peak Hip Internal Rotation Moment	Normal Level of Confidence

4.6.1 Movement compensation during gait

Patients with DDH gait on average could be described in the following way based on the graphs' interpretation: with regard to patients' pelvis area, patients had anteriorly tilted pelvis throughout the gait cycle, decreased pelvic lift at loading response and mid-stance and decreased pelvic rotation ROM on both sides throughout the gait cycle. With regard to patients' trunk area, patients' trunks were at a slight forward lean throughout the gait cycle, at two to three degrees. Interestingly, there was a notable difference in the trunks' contralateral lateroflexion where patients tended to have very small/almost diminished contralateral lateroflexion and reduced backward rotation at mid-stance, pre swing and initial swing and noticeable decreased forward rotation by three degrees at terminal stance and heel strike.

Regarding patients' hip joint, patients tended to not go to hip extension at pre-swing and kept their hips at slight, higher flexion degrees at pre-swing and reduced their peak hip abduction at pre-swing, by almost half. In addition, patients tended to have reduced rotation of the hip, very close to neutral hip rotation throughout the whole gait cycle.

Patients' peak knee flexion degrees were reduced by 20 degrees compared to the control group; on the other hand, patients' average knee flexion degree was reduced by 10 degrees when the average knee flexion degree was compared between groups. Patients tended to have an early and decreased peak hip flexion moment, decreased hip extension moment, decreased peak hip abduction moment at mid-stance and terminal stance and reduced peak hip internal rotation moment. Patients also had slightly decreased hip absorption power and decreased hip power generation during pre-swing and heel off. Patients had almost similar anterior-posterior and vertical GRF compared to control group.

Regarding p value level of confidence comparison, patients' operated side comparison showed a significant difference in thorax lateroflexion and hip internal/external ROM where both are considered as normal level of confidence and greater reservation is required for these findings. A significant difference was found also in hip flexion/extension ROM and knee flexion/extension ROM which were both considered as high level of confidence and some reservation might need to be applied for these findings. In addition, a significant difference was also found in trunk rotation, hip abduction/adduction ROM, peak hip flexion moment, peak hip extension moment, peak hip abduction moment and peak hip internal rotation moment.

These variables are considered as very high level of confidence and have high possibility of being different. On the other hand, patients' non-operated side showed a significant difference in only four variables: trunk lateroflexion, hip abduction/adduction ROM and peak hip abduction moment, where all of these significant findings considered as normal level of confidence and greater reservation is required for these findings. Moreover, trunk rotation is considered as very high level of confidence and has high possibility of being different.

4.6.2 Compensation movement during squat

Based on the graph interpretation, patients had reduced pelvis rotation, reduced trunk forward lean at the lowest point of squat depth, slight right ipsilateral lateral flexion, and reduced backward trunk rotation throughout the squat at only almost two degrees. With regard to patients' hip joint, patients had normal, however, slightly reduced peak hip flexion ROM at around 10 degrees difference, and reduced hip abduction degree, at around seven to eight degrees at the lowest point of squat depth.

Patients also tended to have slight internal rotation of the hip which decreased notably at the lowest point of squat depth. Patients had decreased knee flexion degree at the lowest point of squat depth with around 20 degrees of difference. With regard to patients' hip moments, patients had reduced hip flexion, reduced abduction moments and reduced hip external rotation moment at the lowest point of squat depth. Patients also had earlier and reduced knee abduction moment as well. Patients had decreased peak hip absorption power during the ascending phase and decreased reduced peak hip power generation at the ascending phase. On the other hand, when patients' non-operated side was compared to the control group, it showed that patients had similar reduced variables.

Similar to the operated side, peak hip external rotation moment and peak knee abduction moment were reduced. Interestingly, patients' non-operated side knee mean score was around 73 degrees, which was notably reduced when compared to the control at 98 degrees with around 25 degrees of difference. With regard to p value level of confidence comparison, patients had significant reduced scores in pelvis rotation, hip abduction/adduction ROM where both are considered as normal level of confidence and more reservation is required for these findings. Trunk rotation was also significantly difference and considered as high level of confidence and some reservation might need to be applied for this finding. Peak hip external rotation moment and peak knee abduction moment were also significantly difference and considered as very high level of confidence and have high possibility of being different. For the non-operated side comparison, patients had significantly reduced peak knee abduction moment which considered as normal level of confidence and more reservation is required for these findings. In addition, patients had significantly reduced peak hip external rotation moment and knee flexion/extension ROM where both are considered as high level of confidence and some reservation might need to be applied for this finding. Finally, patients' operated and non-operated sides showed no significant difference in any of the variables compared.

4.6.3 SLB movement compensation

Based on the graph interpretation, most of the variables interpreted seem to have normal ranges. Patients' operated side had similar scores in comparison with the control group in most of the variables compared. However, patients had increased trunk forward lean by three degrees, although having similar trunk ipsilateral lateroflexion and rotation ROM compared to control group. Patients also had higher scores in ankle ROM, however, within normal ranges. With regard to patients' hip moments, patients had neutral hip flexion/extension moments, normal hip abduction moments and similar hip internal moments. Patients had normal ankle extension moments and normal hip power.

On the other hand, for patients' non-operated side, patients had increased trunk forward lean by 2.5 degrees, trunk lateroflexion was reduced by more than half, close to six degrees difference, and reduced peak hip abduction moments. Patients had reduced knee abduction moments throughout the SLB time compared to the control group. Moreover, patients' operated and non-operated sides comparison showed no differences in any of the variables compared.With regard to p value level of confidence comparison, patients had significant forward trunk lean and significant reduced peak knee abduction moment where both are reported with normal level of confidence and more reservation is required for these findings. For the non-operated side, patients had significant trunk forward lean and significant decreased peak hip abduction moment, where both are considered as normal level of confidence and greater reservation is required for these findings. Also, patients had significant reduced trunk lateroflexion, which is considered as high level of confidence and some reservation might need to be applied for this finding. There was no significant difference between the patients' operated and non-operated sides.

4.6.4 Overall summary

In conclusion, patients' operated side during walking scored the highest level of confidence across different variables. It seems that majority of the findings in squat and SLB exercises seem to lie between normal and high level of confidence. SLB significant results did not include any very high-level confidence. This informs us that patients with DDH indeed show compensatory movements results during walking, and this was reported with high level of confidence and with less confidence in that walking patient shows compensatory movements during squat and SLB. All aforementioned results are integrated with the findings from this research's Part 1, Part 2 and Part 3 in the Discussion chapter.

4.7 ROM Results

Although the patients' group scored less ROM for the operated legs as seen in Table 18, the ROM scores were close to the minimum normal limits when compared to control group results. There was a significant decrease in patients' mean hip flexion ROM at 92.75±19.65 degrees compared to the control mean hip flexion ROM at 107.46±11.34 degrees, around 15 degrees of hip flexion loss (p=0.025). There was also a significant difference between the patients' group mean hip abduction ROM scores at 26.85±12.10 compared to the control mean hip abduction ROM scores of 34.06±5.86 degrees with seven degrees difference (p=0.027) and a significant difference between the control mean hip external rotation ROM score at 36.86±5.2 degrees compared to the patients' mean ROM score at 27.75±9.23 degrees, around nine degrees difference (p=0.004).

In addition, patients' hip adduction ROM scores were noticeably limited with the patients' group mean score being 28±6.16 degrees in comparison with the control mean hip adduction ROM score of 21.15±10, around seven degrees significantly difference (p=0.026). In regard to significance level adopted in this research of the p value, significant differences found in hip flexion, hip abduction and hip adduction are considered as normal level of confidence. Hip external rotation are considered as high level of confidence.

Table 18: ROM comparison between groups (control right leg and patients' operated leg).

Joint	Control right leg (15 hips) Mean (SD)		Patients' operated leg (15 hips) Mean (SD)		Average difference (Degrees)	SPSS test	Significance Level
Hip	Hip Flexion	107.46±11.34	Hip Flexion	92.75±19.65	14.71 (14%)	Mann-Whitney U	P=0.025*
	Hip Extension	14.13±6.40	Hip Extension	14.40±7.65	-0.27 (~2%)	Test Independent t-test	P=0.911
	Hip Abduction	34.06±5.86	Hip Abduction	26.85±12.10	7.21 (22%)	Independent t-test	P=0.027*
	Hip Adduction	28.00±6.16	Hip Adduction	21.15±10.01	6.85 (25%)	Independent t-test	P=0.026*
	Hip Internal rotation	34.46±2.61	Hip Internal rotation	32.30±6.70	2.16 (6%)	Independent t-test	P=0.199
	Hip External rotation	36.86±5.28	Hip External rotation	27.75±9.23	9.11 (25%)	Mann-Whitney U Test	P=0.004**
Knee	Knee Flexion	135.73±5.79	Knee Flexion	129.90±10.04	5.83 (4%)	Mann-Whitney U Test	P=0.191
	Knee Extension	3.26±0.59	Knee Extension	3.60±1.84	-0.34 (10%)	Mann-Whitney U Test	P=0.934
Ankle	Plantarflexion	42.60±5.98	Plantarflexion	43.85±8.3	-1.25 (3%)	Independent t-test	P=0.925
	Dorsiflexion	26.60±6.92	Dorsiflexion	24.80±7.38	1.802 (7%)	Independent t-test	P=0.596

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

When patients' non-operated legs were compared to control group right legs, as seen in Table 19, there was a significant difference in only one variable. Hip external rotation was significantly different between the two groups. Patients' mean hip external rotation ROM was significantly lower with around nine degrees difference; the patients' mean score was 28.50±9.51 degrees compared to the control mean score of 37.90±6.19, (p=0.011). Opposite to the affected leg, there was no significant difference in patients' unaffected hip flexion ROM, hip abduction ROM and hip adduction ROM. In regard to significance level adopted in this research of the p value, hip external rotation significant finding is considered as normal level of confidence.

Table 19: ROM comparison between groups (control right leg and patients' non-operated leg)

Joint	Control right leg (10 hips) Mean (SD)		Patients' non-operated leg (10 hips) Mean (SD)		Average difference (Degrees)	SPSS test	Significance Level
Hip	Hip Flexion:	103.60±8.27	Hip Flexion:	100.00±12.00	3.6 (4%)	Independent t-test	P=0.445
	Hip Extension:	14.70±6.68	Hip Extension:	14.30±10.00	0.4 (3%)	Independent t-test	P=0.917
	Hip Abduction:	33.30±6.23	Hip Abduction:	33.20±11.74	0.1 (0.5%)	Independent t-test	P=0.981
	Hip Adduction:	26.60±6.25	Hip Adduction:	23.30±5.43	3.3 (13%)	Independent t-test	P=0.224
	Hip Internal rotation:	34.90±2.64	Hip Internal rotation:	36.70±7.76	-1.8 (5%)	Independent t-test	P=0.502
	Hip External rotation:	37.90±6.19	Hip External rotation:	28.50±9.51	9.4 (25%)	Mann-Whitney U Test	P=0.011*
Knee	Knee Flexion:	137.30±5.79	Knee Flexion:	133.80±4.04	3.5 (3%)	Mann-Whitney U Test	P=0.247

	Knee Extension:	3.20±0.63	Knee Extension:	3. 60±0.84	-0.4 (12%)	Mann-Whitney U Test	P=0.934
Ankle	Plantarflexion:	41.30±5.77	Plantarflexion:	44.00±11.13	-2.7 (6%)	Independent t-test	P=0.508
	Dorsiflexion:	20.26±3.71	Dorsiflexion:	25.53±6.26	-5.27 (21%)	Independent t-test	P=0.719

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

When Paired-Samples T Tests were done to test for significant differences between patients' ROM for the operated and non-operated legs, as seen in Table 20, there was no significant difference between the two sides in any of the variables compared. It needs to be noted that patients' operated legs mean scores were less across most of the variables. For example, patients' operated hips scored 10 degrees less in hip flexion than the non-operated legs scores.

Table 20: Patients' non-operated leg ROM and operated leg ROM comparison (operated side and non-operated side)

Joint	Patients' non-operated legs (10 hips) Mean (SD)	Patients' operated legs (20 hips) Mean (SD)	Average difference (Degrees)	SPSS test	Significance Level
Hip	Hip Flexion: 100.00±12.00	Hip Flexion: 92.75±19.65	7.25 (8%)	Paired-Samples T Test	P=0.422
	Hip Extension: 14.30±10.00	Hip Extension: 14.40±7.65	-0.1 (1%)	Paired-Samples T Test	P=0.976
	Hip Abduction: 33.20±11.74	Hip Abduction: 26.85±12.10	6.35 (20%)	Paired-Samples T Test	P=0.182
	Hip Adduction: 23.30±5.43	Hip Adduction: 21.15±10.01	2.15 (10%)	Paired-Samples T Test	P=0.534
	Hip Internal rotation: 36.70±7.76	Hip Internal rotation: 32.30±6.70	4.4 (12%)	Paired-Samples T Test	P=0.119
	Hip External rotation 28.50±9.51	Hip External rotation: 27.75±9.23	0.75 (3%)	Paired-Samples T Test	P=0.837
Knee	Knee Flexion: 133.80±4.04	Knee Flexion: 129.90±10.04	3.9 (3%)	Paired-Samples T Test	P=0.530
	Knee Extension: 3.60±0.84	Knee Extension: 3.60±1.84	0	Paired-Samples T Test	P=0.588
Ankle	Plantarflexion: 44.00±11.13	Plantarflexion: 43.85±7.38	0.15 (0.5%)	Paired-Samples T Test	P=0.970
	Dorsiflexion: 26.30±5.22	Dorsiflexion: 24.60±6.15	1.7 (7%)	Paired-Samples T Test	P=0.461

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

Further comparison to ROM findings of this study were made with a previous study done by Steppacher et al. (2008). Table 21, compares patients with DDH hip ROM after 10 and 20 years of follow-up (Steppacher et al. 2008) and the ROM of the hips of patients who participated in this research.

Table 21: A comparison between the average ROM of the patients included in this study with the literature.

Joint	Current study (right leg)	Current study (left leg)	Steppacher et al. (2008) (10 years follow-up)	Steppacher et al. (2008) (20 years follow-up)
Hip Flexion ROM	96.05±13.57	94.33±21.36	100 ± 11.2	93 ± 11.5
Hip Extension ROM	15.20±9.14	13.53±7.67	3 ± 4.9	3 ± 4.5
Hip Abduction	27.06±9.55	30.86±14.40	33 ± 9.3	29 ± 6.6
Hip Adduction	23.93±10.76	19.80±7.12	27 ± 6.6	25 ± 5.2
Hip Internal Rotation ROM	34.77±6.92	33.35±7.43	32 ± 15.4	18 ± 11.2
Hip External Rotation ROM	26±6.63	30.20±10.70	17 ± 12.4	14 ± 11.1

Although the current ROM scores were consistent with the literature, it was slightly higher in some of the variables, such as hip extension ROM, hip external rotation ROM; however, it was still within the range. ROM variables of patients having PAO are expected to decrease in the future. The effect of decreasing ROM on patients' activity and participation after several years post-PAO is not known. The ROM during the functional exercises done by the patients in this study will be discussed in relation to movement compensation and what effect decreased ROM could result in later on in the Discussion Chapter.

4.8 Isometric muscle results

When all hip and knee joint tests through different planes were combined for all participants, there were 45 tests in total for each leg, and the amount of each test coefficient variance was documented and was reported below. When patients' operated legs were compared to control group right legs, as seen in Table 22, there was a significant difference in three variables: knee extension, hip flexion and hip extension. Control group knee extension peak score was 175±65 N.m compared to lower patients' peak knee extension score of 116±39 N.m. Patients' operated leg peak hip flexion and extension scores were 57±24 N.m and 49±14 N.m, respectively, compared to control right leg peak hip flexion and extension scores of 75±33 N.m and 62±16N.m, respectively (p=0.006 and 0.023).

In regard to significance level adopted in this research of the p value, knee peak extension torque and hip peak extension peak torque are considered as normal level of confidence and hip flexion peak torque is considered as high level of confidence.

Table 22: Right leg muscles peak torque comparison between groups (right side and operated side)

Joint	Control group right leg (15 hips) Mean (SD)	Patients' operated leg (15 hips) Mean (SD)	Average difference (N.m)	SPSS test	Significance Level
Knee	Knee Extension: 175.49±65.26	Knee Extension: 116.65±39.10	58.84 (33%)	Mann-Whitney U Test	P=0.017*
	Knee Flexion: 70.73±27.14	Knee Flexion: 57.46±19.08	13.27 (19%)	Independent t-test	P=0.099
Hip	Hip Flexion: 75.25±33.06	Hip Flexion: 57.39±24.61	17.86 (24%)	Mann-Whitney U Test	P=0.006**
	Hip Extension: 62.26±16.35	Hip Extension: 49.93±14.11	12.33 (20%)	Independent t-test	P=0.023*
	Hip Abduction: 57.68±20.39	Hip Abduction: 46.92±14.01	10.76 (19%)	Independent t-test	P=0.073
	Hip Adduction: 58.92±25.06	Hip Adduction: 46.01±17.04	12.91 (23%)	Mann-Whitney U Test	P=0.079
Coefficient variance	Mean coefficient variance =11.88 Mean coefficient variance towards: 13.35	Mean coefficient variance = 10.27 Mean coefficient variance towards = 10.37			

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

On the other hand, when patients' non-operated and control right legs were compared, there was a significant difference in only one variable: hip joint adduction, as seen in Table 23. Hip joint adduction control group mean score was 62±22 N.m compared to a mean score of 38±14 N.m for the patients group (p=0.011). Patients' right and left leg mean coefficient variance scores were 10.27 and 9.46, respectively. In regard to significance level adopted in this research of the p value, hip adduction peak torque is considered as normal level of confidence.

Table 23: Right leg muscles peak torque comparison between groups (right side and non-operated side)

Joint	Control group right leg (10 hips) Mean (SD)	Patients group non-operated leg (10 hips) Mean (SD)	Average difference (N.m)	SPSS test	Significance Level
Knee	Knee Extension: 177.58±70.76	Knee Extension: 130.31±42.35	47.27 (27%)	Independent t-test	P=0.190
	Knee Flexion: 75.02±27.06	Knee Flexion: 63.87±16.95	11.15 (15%)	Independent t-test	P=0.090
Hip	Hip Flexion: 68.67±13.58	Hip Flexion: 65.30±27.40	3.37 (5%)	Mann-Whitney U Test	P=0.732
	Hip Extension: 61.95±14.08	Hip Extension: 55.80±22.34	6.15 (10%)	Independent t-test	P=0.471
	Hip Abduction: 58.40±19.35	Hip Abduction: 48.21±17.69	10.19 (18%)	Mann-Whitney U Test	P=0.218
	Hip Adduction: 62.94±22.48	Hip Adduction: 38.36±14.86	24.58 (39%)	Independent t-test	P=0.011*
Coefficient variance	Mean coefficient variance = 10.59 Mean coefficient variance towards = 11.71	Mean coefficient variance = 9.46 Mean coefficient variance towards = 9.53			

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

Similar to patients' operated and non-operated sides ROM, Paired-Samples T Tests were done to test for significant difference between patients' peak torque for the operated and non-operated legs. Similarly, there was no significant difference between the two sides in any of the variables compared, as seen in Table 24 below.

Table 24: Patients' group muscles test comparison (peak torque values) Isometric muscle (operated side and non-operated side)

Joint	Patients' non-operated leg (10 hips) Mean (SD)	Patients' operated leg (20 hips) Mean (SD)	Average difference (N.m)	SPSS test	Significance Level
Knee	Knee Extension: 130.31±42.35	Knee Extension: 116.65±39.10	13.66 (10%)	Paired-Samples T Test	P= 0.388
	Knee Flexion: 63.87±16.95	Knee Flexion: 57.46±19.08	6.41 (10%)	Paired-Samples T Test	P= 0.377
Hip	Hip Flexion: 65.30±27.40	Hip Flexion: 57.39±24.61	7.91 (12%)	Paired-Samples T Test	P= 0.286
	Hip Extension: 55.80±22.34	Hip Extension: 49.93±14.11	5.87 (11%)	Paired-Samples T Test	P= 0.462
	Hip Abduction: 48.21±17.69	Hip Abduction: 46.92±14.01	1.29 (3%)	Paired-Samples T Test	P= 0.846
	Hip Adduction: 38.36±14.86	Hip Adduction: 46.01±17.04	-7.65 (17%)	Paired-Samples T Test	P= 0.238

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

4.9 Visual Analogue Scale

Even though this research inclusion criteria excluded any participant suffering from pain, specifically in the back or hip area, whether they were control or a patient, there was significant difference between the two groups with regard to VAS scores pre-laboratory-based study (p=0.021), post the three exercises (p=0.004), and post-Isometric muscle (p<0.001). Mean pre-laboratory-based study VAS scores for the control group were

0.06±0.25 for control group participants. On the other hand, patients scored a mean of 2.3 ±1.7 pre-laboratory-based study.

In the patients' group, a substantial proportion of individuals experienced increased pain levels post-Isometric muscle test, as seen in Table 25. The pain levels scores after Isometric muscle tests were significantly different between the groups, where patients mean was 3.91±2.25 and control group was mean score of 0±0, p<0.001). In regard to significance level adopted in this research of the p value, pain after isometric muscle test is considered as very high level of confidence, followed by pain scores after the three exercises, which is considered as high level of confidence and finally the pre-laboratory-based study where the pain finding is considered as normal level of confidence.

Table 25: Visual Analogue Scale (VAS) scores at three different points; pre-laboratory-based study, after laboratory-based study and after Isometric muscle tests.

	Control Group (15 participants) Mean (SD)	Patients Group (15 participants) Mean (SD)	SPSS test	Significance Level
VAS score	Pre-laboratory-based study: 0.06±0.25	Pre-laboratory-based study: 2.3±1.7	Mann-Whitney U Test	P=0.021*
	After the three exercises: 0±0	After laboratory-based study: 2.63±2.11	Mann-Whitney U Test	P=0.004**
	After Isometric muscle test: 0±0	After Isometric muscle test: 3.91±2.25	Mann-Whitney U Test	P<0.001***

*Significant at p<0.05 level

**Significant at p<0.01 level

***Significant at p<0.001 level

Part 2 hypothesis was that the patients with DDH would show compensatory movements during three functional activities compared to the control group. Based on the reported findings above the hypothesis is accepted. The results of Part 3 are reported next in Chapter 5.

Chapter Five: patient values results (Part 3)

As described in Chapter Three, the questionnaire part focuses more on patients' values which explore patients with DDH rehabilitation postoperative. An online questionnaire was used as a method to measure patients' experience in this chapter. The recruitment, as explained earlier in the Methodology chapter, was approached through charities, word of mouth and the patients who participated in the laboratory-based study were also asked to fill the online questionnaire. The results of all closed-ended questions for all cohorts were reported first followed by a separate analysis for the open-ended questions results. However, a summary of all the questionnaire results is presented at the end of this chapter.

5.1 Questionnaire results for all cohorts

5.1.1 General demographic

The first question was around the consent form and all the respondents consent to participate in this survey. As can be seen in Table 26, the majority of the respondents were female, 47 out of 48 (97.9%) and the mean age of respondents was 34.8±10.2. All respondents had been through hip preservation surgery to correct their dysplastic hip joint. More than two-thirds of the respondents, (68.8%), underwent PAO. Other surgeries done reported by the respondents included THR nine respondents (18.7%), two respondents underwent hip arthroscopy (4%). Nineteen out of 48 (39.6 %) of the respondents had bilateral hip dysplasia.

Table 26: General demographic for all the cohorts. Questions from 1-6

1. Consent to participate in this survey	2. Age	3. Gender	4. Dominant leg	5. Involved leg	6. Type of surgery
Yes = 48 respondents No = 0	Mean age = 34.8±10.2	Male = 1 respondent Female = 47 respondents	Right = 41 respondents Left = 7 respondents	Right = 15 respondents Left = 14 respondents Both = 19 respondents	Hip preservation surgery = 33 respondents Hip arthroplasty = 9 respondents I don't know = 0 Other = 9 respondents (include hip arthroscopy, femoral

					osteotomy and Chiary osteotomy)

5.1.2 Rehabilitation experience theme

First it needs to be noted that three questions (questions number 10, 11 and 13) were open ended questions within rehabilitation experience theme and the analysis of these questions were reported later in this chapter under the heading “5.3 Counts/codes emerging from the open-ended answers for the overall cohort”. When respondents were asked about how many times they had attended physiotherapy sessions per week post-operatively, 27 respondents (56.3%) attended physiotherapy sessions once per week, 12 respondents (25%) attended physiotherapy sessions twice per week, and four respondents (8.3%) attended daily physiotherapy sessions.

The majority of respondents 41 respondents (85%) attended either 30-minute sessions or 30-60 minutes sessions immediately postoperatively as can be seen in Table 27. Three respondents (6%) attended 15-minute sessions, one respondent attended 10-30 minutes sessions (2%), one respondent attended 20-minute sessions (2%) and two respondents attended 60-90 minute sessions (4%). Nine respondents (18.7%) received physiotherapy for less than a month before stopping received physiotherapy. In addition, eight (16,6%) respondents received physiotherapy for more than a month and less than three months and nine (18.7%) respondents received physiotherapy more than six months. Interestingly, there were 15 respondents (31%), almost a third of the respondents, who did not receive physiotherapy.

Table 27 below shows also the results of frequency of exercises to do at home, additional exercises added by patients, additional exercises benefits, sources of the additional exercises and overall opinion regarding rehabilitation. The majority of the respondents, 36 (75%), were doing daily exercises post-PAO. The vast majority of the respondents, 40 (83.4%), agreed that they did benefit from the recommended exercises. However, two-thirds of the respondents were doing additional exercises that were not part of the rehabilitation programme. One-third of the respondents, 16 (33.3%) sought another physiotherapist for additional exercises/advice.

Table 27: Rehabilitation experience theme. Question number 7, 8, 9, 12, 14, 15, 16, 17 and 18

7. How many times have you attended physiotherapy sessions per week?	8. How long does each session last for?	9. What exercises have you been doing (did you do) immediately post-operative in the clinic or at home?	12. How long did it take physiotherapists to stop therapy sessions and recommend home exercises only?	14. How many times have you have been asked to do these exercises at home by your physiotherapist? (Frequency)	15. Do you think that the exercises recommended to you by your therapists are helping (helped) the progress of your rehabilitation process?	16. Have you been doing any additional exercises?	17. Which source of information that has led you to do these additional exercises? (more than one answer could be chosen)	18. What are the benefits that you gain when you did these additional exercises? (more than one answer could be chosen)
Once = 27 respondents Twice = 12 respondents Three times = 5 respondents Daily = 4 respondents	30 minutes = 17 respondents 30-60 minutes = 24 respondents Other = 7 respondents (include 15 minutes sessions, 10-30 minutes sessions, 20 minutes sessions and 60-90 minutes sessions)	Bed exercises for the affected leg = 22 respondents Range of Motion exercises = 14 respondents Walking training with crutches = 5 respondents Other = 7 respondents (All of the above)	Two weeks = 1 respondent Three weeks = 3 respondents One month = 7 respondents Not applicable = 13 respondents Other = 27 respondents (other includes the following answers: (More than six months 9 respondents, More than a month and less than three months 8 respondents, More than three months and less than six months 5 respondents)	Daily = 36 Five times a week = 5 respondents Three times a week = 3 respondents One time per week = 1 respondents Not applicable = 3 respondents	Strongly agree = 20 respondents Agree = 20 respondents Neither agree or disagree = 7 respondents Disagree = 1 respondent Strongly disagree = 0	Yes = 32 respondents No = 16 respondents	Expert in rehabilitation team different from your main therapist = 15 respondents Medical journal/website = 7 respondents Google = 4 respondents YouTube = 5 respondents Word of mouth (for example other patients) = 10 respondents Other = 25 respondents	Improved hip movement = 27 respondents Decreased pain = 19 respondents Increased walking time = 21 respondents Not applicable = 7 respondents Other = 13 respondents

The source of the additional exercises was word of mouth at nine respondents (18.8%), medical journals/websites at three respondents (6.3%), YouTube at two respondents (4.2%) and Google at one respondent (2.1%). When respondents were asked about the benefits of additional exercises, 25 respondents (52.1%) had improved hip movement, four respondents (8.3%) had decreased pain and three respondents (6.3%) had increased walking time. More than two-thirds, of the respondents, 33 (68.8%), think that more exercises should be added to the rehabilitation programme as shown in Table 28 below.

Table 28: Rehabilitation experience theme. Question 19, 20 and 21

19. Do you think further exercises should have been included in your rehabilitation program that may have been suggested by friends, private therapist etc.…?	20. Overall opinion regarding rehabilitation	21. Do you consider yourself able to compete to a high level of activities? such as skiing, tennis, jogging etc...
Yes = 33 respondents No = 15 respondents	Excellent = 12 respondents Normal = 11 respondents Not efficient enough = 23 respondents Not applicable = 2 respondents Other = 0	Yes = 11 respondents No = 19 respondents Maybe sometimes in future = 18 respondents

Regarding the respondents’ rehabilitation experiences post-operative, 12 respondents (25%) rated their rehabilitation experience as ‘Excellent’. Almost half of the respondents, 23 (47.9%), thought the rehabilitation programme was not sufficient enough. When patients were asked their opinion about whether they are able to do high impact activities or sports, 19 respondents (39.6%) did not think that they were not able to do high impact activities or sports, 11 respondents (23%) thought that they are able to do them and the rest, 18 (37.5%), were not sure if they would be able to get back to high impact activities. This means that only around 11 respondents (23%) were able to return to high impact activities and sports. Type of exercises done in the rehabilitation period are reported later when the open-ended questions results are presented.

5.1.3 Movement compensation theme

Prolonged sitting and prolonged standing affected the hip of 40 respondents (83.3%) and 43 respondents (89.6%), respectively, as can be seen in Table 29. Thirty-seven respondents

(77.1%) could easily step over a small box on the floor. Picking up an object was associated with a feeling of pain for 35 respondents (72.9%), and 36 respondents (75%) found walking faster than normal walking or taking longer steps than normal steps made them feel uncomfortable when asked if they are in a hurry and need to walk faster, did they find it uncomfortable taking longer steps?

When patients were asked whether they came up with new strategies to avoid pain, a different number of strategies were provided by respondents and possible interpretation was provided in Table 30.

Table 29: Movement compensation theme 22, 23, 24, 25 and 27

22. Prolonged setting affects my hip condition	23. Prolonged standing affects my hip condition	24. Can you step over a small box on the floor with ease?	25. Do you experience any hip pain when you pick up an object of the floor?	27. If you are in a hurry and need to walk faster, do you find it uncomfortable taking longer steps?
Strongly agree = 27 respondents Agree = 13 respondents Neither agree or disagree = 4 respondents Disagree = 3 respondents Strongly disagree = 1 respondent	Strongly agree = 29 respondents Agree = 14 respondents Neither agree or disagree = 3 respondents Disagree = 2 respondents Strongly disagree = 0	Yes = 37 respondents No = 11 respondents	Yes = 12 respondents Sometimes = 23 respondents No = 13 respondents	Yes = 23 respondents Sometimes = 13 respondents No = 12 respondents

Table 30: Movement compensation theme. Compensatory movements adopted by patients and possible interpretation of each. Question number 26

26. Did you come up with a new strategy to avoid pain?
Avoid bending the affected leg
Sit or stand depending mainly on non-affected leg/ position shift
Core muscles engagement
Fewer weight-bearing exercises
Avoid exercises that aggregate the pain
Trained the dog to take shoes and sock off
Limit hip flexion and externally rotate the hip

Increase wide base (Roman squat) instead of normal squat to reach the floor
Do stretches
Avoid picking up stuff from the floor
Depend on objects such as chairs to transfer position from standing to sitting
Walk at slower speed/with short steps
Reduce time of exercises when pain increases
Resting
Asking others to help with heavy objects

5.1.4 The UCLA activity scale

When patients were given the UCLA activity scale to measure their activity and sports level, 5 respondents (10.4%) of the respondents were mostly inactive and restricted in their daily activity, 19 respondents (39.6%) participated in mild activities and 13 respondents (27.1%) participated in moderate activities, as can be seen in Table 31. Only 11 respondents (22.9%) of the respondents had managed to regularly participate in in active events and participate in high impact sports. Mean UCLA activity scale score of the overall population is 5.04±2.39 with a minimum score of 2 and the highest score was 10.

Table 31: UCLA activity scale scores and patients opinion around competing in high level of activities. Question number 28

28. UCLA activity scale score	
1-Wholly inactive, dependent on others, and cannot leave residence.	Number of participants = 0
2-Mostly inactive or restricted to minimum activities of daily living.	Number of participants = 5
3-Sometimes participate in mild activities such as walking limited housework and limited shopping.	Number of participants = 13
4-Regularly participate in mild activities.	Number of participants = 6
5-Sometimes participates in moderate activities such as swimming or could do unlimited housework or shopping.	Number of participants = 4
6-Regularly participate in moderate activities.	Number of participants = 9
7-Regularly participates in active events such as bicycling.	Number of participants = 2
8-Regularly participates in active events such as golf or bowling.	Number of participants = 3
9-Sometimes participates in impact sports such as jogging, tennis, skiing, acrobatics, ballet heavy labour or backpacking	Number of participants = 3
10-Regularly participates in impact sports	Number of participants = 3

5.1.5 modified Harris Hip Score (mHHS)

In the pain domain, only nine respondents (18.8%) did not have pain or were able to ignore it, 21 respondents (43.7%) had minimal tolerable pain that did not have an effect on daily activity, 5 respondents (10.4%) had marked serious limitations and 37 respondents (77.1%) did not limp or were limping slightly postoperatively. The vast majority of the respondents, 34 (70.8%), did not need a walking aid for distance walks, while two respondents (4.2%) depended on a cane all the time. Almost half of the respondents, 23 respondents (47.9%), were able to walk for long periods without pain. Only three respondents (6.3%), were able to walk indoors only and two respondents (4.2%) were unable to use stairs.

Twenty respondents (41.7 %) had difficulty wearing socks/shoes or taking them off and when patients were asked how the condition affected their sitting, 14 respondents (29.1%) said that they were not able to sit for longer than ½ hour due to pain. Finally, the majority, 43 (89.6%), were able to enter public transportation without difficulty or pain. See Table 32 for the full results of mHHS scores.

Table 32: mHHS scores for all cohorts. Questions number 29, 30, 31, 32, 33, 34, 35, and 36

mHHS
29. Pain
None/able to ignore it = 9 respondents Slight, occasional, no compromise in activity = 8 respondents mild, no effect on ordinary activity, pain after usual activity, use aspirin/ibuprofen/Tylenol = 13 respondents Moderate tolerable makes concessions occasional narcotics = 13 respondents Marked serious limitations = 5 respondents Totally disabled = 0

Function: gait		
30. Limp	31. Support	32. Distance walked
None = 14 respondents Slight = 23 respondents Moderate = 8 respondents Severe = 3 respondents Unable to walk = 0	None = 34 respondents Cane for long walks = 7 respondents Cane all the time = 2 respondents Crutch = 3 respondents 2 canes = 0 2 crutches = 2 respondents Unable to walk = 0	Unlimited = 23 respondents 6 Blocks = 11 respondents 2-3 block = 11 respondents Indoors only = 3 respondents Bed and chair = 0

Functional activities			
33. Stairs	34. Socks/shoes	35. Sitting	36. Public transportation
Can go up/down normally = 23 respondents Can go up/down normally with banister = 21 respondents Any method = 2 respondents Unable = 2 respondents	With ease = 28 respondents With difficulty = 19 respondents Unable = 1 respondents	Any chair, 1 hour = 34 respondents High chair, 1/2 hour = 10 respondents Unable to sit, 1/2 hour, any chair = 4 respondents	Able to enter public transportation = 43 respondents Unable to use public transportation (such as bus, or airport transportation) = 5 respondents

5.2 Counts/codes emerging from the open-ended answers for the overall cohort

In-depth exploration of the respondents' answers and quotations from the three open-ended questions were analysed separately. The reason for this is that rich information was anticipated from these questions. As explained earlier in the Methodology Chapter, the first step was exporting the collected type of exercises patients had been doing during their rehabilitation into an Excel sheet. Similar texts/exercises were grouped together and a code created. The codes of similar exercises or exercises that fell into the same category/targeted the same muscle groups were grouped together and resulted in different codes/counts.

5.2.1 Question number 10: exercises done postoperatively: rehabilitation exercises at clinics

Table 33 includes all the exercises done by respondents after receiving full weight-bearing clearance. From the below table, the exercises prescribed in the clinics could be concluded as falling into the following exercises types: bed exercises for operated and no-operated leg, ROM in all directions while standing, squat or sit to stand, lunges, single leg balance, bridges, step-up and stairs, walking, swimming, stretching, strengthening exercises (isometric), balance ball, general balance exercises, clam, cycle (stationary), isometric exercises, hydrotherapy, general leg exercises and general activities and knee exercises.
The lower limb exercises were by far the most exercise reported 129 times, followed by squat which was reported 24 times, followed by balance exercises which were reported 22 times and ROM exercises and Gluteus Medius exercises which were both reported 21 times, hip strengthening exercises reported 19 times, walking reported 16 times and clam and general leg exercises which were both reported 17 times. Stationary bike and step-up and stairs exercises were common as well and both were reported 11 times. Interestingly, hydrotherapy was prescribed at least seven times. Swimming was prescribed five times.
The exercises mentioned by respondents target different parts of the body, for example hip ROM exercises mainly move the hip and lower limb part of the body and yoga are considered as a general exercise rather than specific to certain muscles group, as seen in Table 34. Therefore, the exercises were divided by the main targeting area of the body and the focus of the exercise.

Results

The exercises were categorised into general exercises and lower limb exercises. Below is the codebook of the tenth question:

Table 33: Detailed NVivo codes sheet for the tenth question. All rehabilitation exercises done by respondents post-PAO

Name	Description	References (number of this word reported)*
10. What exercises have you been doing (did you do) after you received full weight-bearing clearance (able to stand on your operated leg)? Name or describe them.		48 respondents
1. General Exercises	Any exercise that targets the whole body and different muscle groups needs to be active in order to do the exercise (no specific muscle group acts as the prime mover)	51 counts
A. Cycling	Includes stationary bike and all other variations of cycling	11
B. Hydrotherapy	All exercises done at the pool including swimming	12
C. Running	Running exercise	1
D. Step-up and Stairs	Step-up exercises, variation and stairs exercises.	11
E. Walking	Walking as an exercise	16
2. Lower limb Exercises	Any exercise that targets the hip muscles or the pelvis mainly (hip muscles are the prime mover)	168 counts
A. Balance Exercises	Any balance exercise that targets the hip muscles group.	22
B. Bed Exercises	All exercises that are done on bed including isometric exercises	6
C. Clam	All variations of clam exercises	13
D. Glutes Exercises	Gluteus Medius muscle is the prime mover for the included exercises	21
E. Hip strengthening exercises	Any strengthening exercise that targets the hip muscles mainly (hip muscles are the prime mover)	19
F. Lunges	Lunges exercise	7

Name	Description	References (number of this word reported)*
G. Pelvic exercises	Pelvic exercises	1
H. Range Of Motion (ROM) exercises	Range of motion exercises whether done on bed or while standing	21
I. Squat	All variations of squat	24
J. Stretches	Any stretching exercises	8
K. Whole leg exercises	Any exercise that requires different leg muscles to contract to do the exercises (no specific prime mover)	13
L. General balance exercises	Any exercise that targets the whole body balance (not specifically for a certain muscle group)	2
M. Knee exercises	Exercises that target knee muscles mainly	1
N. Leg strengthening exercises	Any exercise that targets the whole leg and specifically the hip muscles group in order to do the exercise.	10

* References column refer to how many times the exercises have been reported.

The exercises that patients were doing during rehabilitation were divided into two groups as follows:

Table 34: Exercises done by patients arranged into two exercise types

Exercises	
General exercises	**Lower limb exercises**
Exercises: cycle machine, step-up machine, leg press, walking, gait re-education, jogging, abdominal exercise, swimming, Pilates, yoga, hydrotherapy, cross trainer, balance board, Barre class, Alter G, balance ball, crunches, calf raises, bird dog exercises, upper back rowing, deadlift, clock steps, kicking a ball. leg stretches, gluteus stretching and piriformis, hip flexors stretch.	**Exercises:** single leg balance, step-up, single leg raising, ROM hip while standing in all direction, stairs, ROM internal and external rotation, psoas march, side walk and monster walk, dipping bird, side blank from the knee, hip extension (banded), hamstring curls, hip flexion, squad squeeze, heel slide, short arc quad, side stepping, clock steps, isometric all muscles, ankle pump, hip hitch, hip exercises + core muscles in swimming pool. Squats, single leg squat, lunges, bridges, mini squat with support, clams, hip thrust, isometric exercises, glute squeeze; pelvis tilt (mentioned once).

The exercises that made up the previous two types of groups were the focus of the rehabilitation post-operative. Therefore, the rehabilitation protocol for patients with DDH post-operative includes exercises that fall under these groups. It is true that general exercises might include unlimited numbers of exercises; however, this needs more investigation in the future to limit the exercises that fall under this domain. Unfortunately, when to prescribe specific exercises and based on what could not be retrieved from the questionnaire.

5.2.2 Question number 11: what were the most common weight-bearing and non-weight-bearing exercises recommended by rehabilitation teams in general or recommended to do at home?

As can be seen in Table 35, non-weight-bearing exercises were reported 96 times and weight-bearing exercises were reported 75 times. Swimming and cycling were the most recommended non-weight-bearing exercises to do, reported 34 and 23 times, respectively. In addition, isometric exercises were recommended nine times and ROM exercises were reported eight times. On the other hand, walking was by far the most recommended weight-bearing exercise to do for this group of patients, followed by strengthening exercises which was reported 11 times, squat was reported 10 times and general exercises were reported nine times. General exercises included Pilates which was reported five times, cross trainer was reported two times and manual therapy was reported one time and superman on a gym ball was reported one time.

Three patients were told to avoid any impact sports in the future without adding why they were told so. Interestingly, such comments should be investigated to know why or the rationale for therapist giving such advice to patients not to be involved in any high level of activities in the future or not to weightlift. If such advice is given at an early stage, then it would probably have been advised as a pain avoiding mechanism or to avoid overloading the joint; however, this does not necessarily apply to advice to not be involved in a high level of activities and sports in the future. Hydrotherapy was reported five times. However, it wasn’t obvious what patients have been doing exactly during hydrotherapy or for how long. Interestingly, one patient did not receive any guidance for what to do at home and what to avoid.

Table 35: NVivo codes sheet for the question number 11. Number of weight-bearing exercises and non-weight-bearing exercises prescribed to patients.

Name	Description	References*
11. How many non-weight bearing exercises and weight-bearing exercises are recommended by your therapist? Weight bearing exercises (supporting your own weight) such as: walking, hiking and dancing. Non-weight-bearing exercises (without supporting your own weight) such as: swimming and lifting weight.		48 respondents
1. Non-weight-bearing exercises	Any exercises done without the support of a person's body weight.	100 counts
A. Bed exercises	All Exercises done on a bed including isometric exercises	16
B. Cycling	Includes stationary bike and all other variations of cycling	23
C. Glutes Exercises	Gluteus Medius muscle is the prime mover of the included exercises	7
D. Hydrotherapy	All Exercises done at the pool including swimming	39
E. Resistance band Exercises	Resistance band Exercises	4
F. ROM Exercises	Range of Motion exercises whether done on a bed or while standing	8
G. Stretches	Any stretching exercises	3
2. Weight-bearing Exercises	Any exercise done against gravity	82 counts
A. Balance Exercises	Any balance exercise that targets the hip muscles group	6

Name	Description	References*
B. General Exercises	Any exercise that targets the whole body and different muscle groups needed to be active in order to do the exercise (no specific muscle group acts as the prime mover)	9
C. Lunges	Lunges exercises	5
D. Running	Running exercises	1
E. Squat	All variations of squat	10
F. Step-up and stairs	Step-up exercises, variations and stairs exercises.	6
G. Strengthening Exercises	Any exercise that targets the whole leg and specifically the hip muscles group in order to do the exercise	9
H. Gastro Exercises	Exercises targets Gastrocnemius	2
I. Walking	Walking as an exercise	26
J. Weightlift	Exercises that includes weight lifting (heavy or low)	3
3. What to avoid	Exercises or general advice about what patients should avoid doing.	5

* References column refer to how many times the exercises have been reported.

5.2.3 Question number 13: recommended exercises to do at home

When patients were asked whether they were told to do specific exercises at home or not, same exercises patients were doing at the clinic was reported 20 times. Weight-bearing exercises was reported 41 times, for patients to do at home. Non-weight-bearing exercises were recommended almost half the number of times as weight-bearing exercises, was reported 20 times. Four patients did not receive specific exercises or guidance about what to do when they were at home.

Similar to the results of the previous question, Gluteus Medius strengthening exercises, squats and walking were the most recommended weight-bearing exercises to do. Running was reported one time, since it was recommended to be done only one time, it seems that running is an unfavourable exercise to recommend.

See Table 36 for the list of all recommended exercises to do at home:

Table 36: NVivo codes sheet for the question number 13. Home exercises prescribed to patients to do and what to avoid.

Name	Description	References*
13. What exercises have been (were) recommended for you to do at home (if not recommended just write not applicable)?		48 respondents
1- Non-weight-bearing Exercises	Any exercises done without the support of person's body weight	23 counts
A. Bed Exercises	All exercises done on a bed including isometric exercises	10
B. Cycling	Includes stationary bike and all other variations of cycling	4
C. ROM Exercises	Range of Motion exercises whether done while standing	4
D. Swimming	Swimming	2
E. Stretching	Any stretching exercises	3
2- Weight-bearing Exercises	Any exercise done against gravity	41 counts
A. Balance Exercises	Any balance exercise that targets the hip muscles group	1
B. Clam	Clam exercise	3
C. General Exercises	Any exercise that targets the whole body when different muscle groups need to be active in order to do the exercise (no specific muscle group acts as the prime mover)	4
D. Glutes Exercises	Gluteus Medius muscle is the prime mover for the included exercises	11
E. Leg Exercises	Any exercise that requires different leg muscles to contract to do the exercises (no specific prime mover)	2
F. Lunges	Lunges exercise	2
G. Running	Running as an exercise	1
H. Squat	Includes all forms of squats	8

Results

Name	Description	References*
I. Step-up and stairs	Step-up exercises, variations and stairs exercises	2
J. Walking	Walking as an exercise	7
3- No recommendations	No specific recommendation received when rehabilitation at clinics stopped	5 counts
4- Clinic Exercises	Similar exercises to what have been done at clinics	20 counts
5. No Benefits of Exercises	No Benefits of Exercises was reported	1 count

* References column refer to how many times the exercises have been reported.

5.3 Summary of the questionnaire results

The general results of all respondents were presented at the beginning of this chapter, followed by the results of the open-ended questions for all respondents. The results of this chapter reflect upon the patients' values domain within the EBP. First, the general results of the questionnaire were analysed. The vast majority of the respondents were females and almost 70% of the respondents had undergone hip preservation surgery. More than half of the respondents attended one physiotherapy session and 75% of them were doing daily exercises; luckily, more than 80% of them benefited from the exercises. Two-thirds of the respondents were doing additional exercises and two-thirds of them had either improved hip movement, decreased pain or increased walking time.

Almost half of the respondents thought the rehabilitation programme that they had was not effective enough and thought that more exercises should have been added to their rehabilitation protocol. Almost 40% of the respondents thought that they would not be able to do high impact activities in the future and almost the same percentage of respondents were not sure if they would ever be able to do a high level of activities in the future. Prolonged sitting and standing affected the hips of 83.3% and nearly 90% of the respondents; three-quarters of the respondents found that walking faster or with longer steps than normal increased the hip pain.

On the mHHS scale, only a minority of the respondents had reported no pain or being able to ignore the minimal pain. Luckily, most of the respondents did not need walking aids to walk for long distances. When functional activities were explored, around half of the respondents had difficulty wearing socks/shoes. Mean UCLA activity scale score for all respondents was 5+-2.39 and around 19% of the respondents had no pain on the mHHS scale. It is true that only 20% had reported no pain, but if these patients are combined with the 43% of the patients who had pain that did not interfere with daily activities, it gives a total of 63%, so it seems that ambitious goals for rehabilitation could be set.

Finally, when the open-ended questions were analysed, the exercises that were prescribed to the patients were divided into two exercise types. First, the general exercises included stationary cycling, walking, swimming, yoga, physio ball, balance exercises and other. Second, the hip and pelvic exercises included squats, lunges, bridges, pelvic tilt, clams and other. The respondents were advised to do swimming then walking and cycling.

Results

Overall, the patient values could be concluded by the following main points:

- More than half of the population was not satisfied with the rehabilitation services they had received.
- A huge number of exercises were given during the patient's journey.
- Patients had low scores on the UCLA activity scale and with a reduced average score of 5.
- Patients had pain, although minimal pain, post-PAO.
- There is a potential for improved scores for both the UCLA activity scale and mHHS if a proper protocol is given.
- Therapists were in favour of the following exercises: squats, clams, SLB, bridges, step-up, walking, cycle and bed exercises.

The integration of the findings of Part 1, Part 2 and Part 3 are merged within EBP and reported in the next chapter after the discussion of Part 2 and Part 3.

Chapter Six: Discussion

In this chapter, the findings of Part 2 and Part 3 are discussed first then all the study parts are integrated within EBP. At end of this chapter, the main question of this thesis, is postoperative rehabilitation for young adults with DDH optimal? is revisited and discussed in relation to the integrated results. The order of this chapter starts from Part 2 discussion, followed by Part 3 discussion. This order follows the same order started from the beginning of this thesis based on EBP framework. The order of this chapter as follows: Part 2 general findings, movement compensation during gait, movement compensation during squat, movement compensation during single leg balance and movement compensation strategies adopted by patients discussions, Part 3, patients values and most common exercises in physiotherapy clinics discussions, integration of the all study parts discussion within EBP, this study's main research question, rehabilitation as complex intervention, research implications, clinical relevance, limitations of the current study and summary of the chapter.

6.1 Part 2 discussion: General findings

According to recent research, 63.4% of patients with DDH are diagnosed with unilateral DDH (Loder and Skopelja 2011), however, the percentage of patients with unilateral DDH recruited in this study was lower than 63.4%, only 46.67% of the patients who participated in this study were diagnosed with unilateral DDH. Having mixed cases, almost 50% of each type, might be because recruitment was undertaken through charities, because of this study exclusion criteria or by chance because of the small sample size. The average patient BMI was slightly higher than for the control group; however, there was no significant difference between groups. This might be due to the fact that PAO is a major surgery and the recovery process takes around nine months to a year on average (Segaren et al. 2015; Adler et al. 2016; Kamath 2016) and, as seen in the questionnaire results, a slight increase in patients' weight is expected, since 50% of the patients were doing mild activities or were mostly inactive. Pain is a crucial factor that might need further investigation as to whether it affects the average BMI and its relation to pain, since feeling of pain was evident in the Part 2 results in Table 25.

In order to investigate pain as a contributing factor, in this research, patients' pain level was measured before and after the clinical-based study and after Isometric muscle tests. It is true that there were significant differences between groups with regard to pain levels; however, patients reported a mean 2.3±1.7 before and 2.63±2.1 after the experiment, which is categorised as mild pain according to VAS cut points scores, as suggested by Boonstra et al. (2014). In the literature, some authors (Leunig et al. 2001; Steppacher et al. 2008; Sucato et al. 2015) assert that the goal of the surgery is to eliminate pain and preserve the joint, especially for young patients, so that they are not forced to do hip arthroplasty twice and avoid it until an older age. Even though the inclusion criteria excluded any participants from both groups who had felt pain in the last six months or felt pain during the experiment, the patients reported increased pain sensations as time progressed during the laboratory-based study. This was also evident in Part 3 results with what patients reported when asked around the feeling of pain in mHHS.

Based on the findings of this research, pain levels post-PAO seem of concern even if minimal pain is felt by patients. To elaborate this further, patients reported prolonged sitting affected their hip condition, and some of the patients had to travel for hours by car or train, which might have led to increased pain sensation. This mean pain level affected patients activity of daily living, thus it might affect patients with DDH post-PAO rehabilitation. It might be considered "impossible" to rule out pain as a contributing factor postoperatively; therefore, only little interference from pain is expected in this research results. It is true that hip preservation surgeries decrease pain level (Klit et al. 2014; Kamath 2016), but there is no available evidence in the longitudinal studies proving whether patients with DDH post-PAO were able to do a high level of activities without the feeling of pain.

Different exercises that have been recommended to DDH patients are obtained from the literature (Adler et al. 2016) and other protocol from medical centre (Segaren et al. 2015), where the authors of these protocols believed that these exercises would increase hip stability by strengthening patients' hip muscles. The Isometric muscle results for both the patients' and control groups' lower limbs were reported, and it was found that patients had lower scores in all variables measured whether the comparison of the patients' group was for their operated or non-operated legs. This supports the rationale for and importance of adding strengthening exercises to post-PAO protocols and at clinics. It needs to be noted that there was no significant difference between the patients' operated and non-operated sides; therefore, the two sides' scores are comparable, which means that PAO is a minor factor for strength post-operative.

Healthcare providers should be aware of primary hip abductors, which are the Gluteus Medius, Gluteus Minimus and TFL, which are suspected to be affected in patients with DDH (Clark and Haynor 1987; Byrne et al. 2010).

When healthcare providers are aware of these muscles as primary hip abductors that generate the majority of the hip abduction torque, this allows them to examine the strength of these muscles directly if patients suffer from possible weakness. However, there are other situations where hip muscle weaknesses might restrict patients with hip conditions in terms of their movements and force them to be inactive (Ward et al. 2010). For example, if patients have an affected weak adductor magnus and hamstring muscles, they are not capable of extending their hip when the hip is flexed. This situation is explained by the fact that these two muscles generate the vast majority of the extension in that position (Ward et al. 2010). Therefore, it was recommended that careful analysis of different PAO approaches, results and effects on muscles should be undertaken and feed into rehabilitation of DDH post PAO protocols when they are created.

The average age of patients with DDH recruited in this study was 34.7 years with a minimum age of 18 years. Appropriate goals and treatment options were based on collecting data from a scale validated on an older population (Naal et al. 2009), which might influence the choices of healthcare provider to set inappropriate goals for a certain population group. For example, it might be shocking to a patient of 18 years old to be told to avoid all activities for his/her group age and instruct her/him to live an older age/elderly lifestyle. It could be frustrating to instruct an 18-year-old female not to dance, run and do high impact sports without convincing evidence. Therefore, it was expected and hoped that the treatment goals (such as being able to return to high impact sports), treatment options (such as THA or PAO), outcome measures (such as UCLA activity scale, mHHS or other scales) are delivered to suit this age group's needs and expectations. Age-specific PROMs might reveal specific goals for young patients and their expectations of what could be done in the future.

Finally, it seems difficult for patients with decreased ROM, as found in Table 18, 19 and 20, and increased pain level while doing activities, who showed lower strength compared to control group and those who felt fatigued, to perform high impact sports shortly post operative as suggested by (Adler et al. 2016) and research that explored high activity levels post PAO (van Bergayk and Garbuz 2002; Ito et al. 2011; Klit et al. 2014; Hara et al. 2018).

6.2 Part 2 discussion: Laboratory-based study, movement compensations

According to Hertling and Kessler (1994) whenever there is an unequal measurement between the two sides, a compensatory movement is expected. As can be seen in the findings of Part 3 results, based on their level of confidence, more specifically Table 17, there was an altered movement mainly in the following joints:

- Gait: hip and trunk joints, and knee joints. There were also compensatory movements at the pelvis joint.
- Squat: hip mainly, then pelvis, trunk and knee joints.
- SLB: trunk and knee joints.

This section is ordered according to the joints affected rather than the exercises. The most affected joints based on the level of confidence adopted in this research are discussed first, moving to the least affected joint. Joints' altered movements and unusual patterns found in graphs interpretation in Results Chapter, that are possibly linked to compensatory movements are discussed. Therefore, based on the level of confidence and as shown in Table 17, the most affected joints are hip where very high level of confidence results found in hip, six variables, trunk, two variables, followed by knee, one variable, pelvis with no very high level of confidence; however, significant differences and abnormal movement patterns was found in this joint.

6.2.1 Movement compensations observed at the hip

6.2.1.1 Hip joint during gait

Patients' operated hip movement comparison showed significant differences in all planes with regard to ROM. Patients maintained their hip in slight flexion, around eight degrees of hip flexion, during the terminal stance of gait. In Sucato et al.'s (2015) study, they found an increase in pelvic tilt due to an increase in hip flexion degree. The same finding was observed in this study where patients had both anterior pelvis tilt and maintained increased hip flexion.

It seems that patients try to reduce their hip extension regardless of whether the movement is dynamic or static ROM. Limiting the hip flexion movement was evident when patients' movement compensatory strategies were reported in the results for Part 3.

With regard to hip flexion moment, patients had significantly reduced hip flexion moment at the terminal stance. This was evident in Pedersen et al.'s (2006) study where they reported that patients tended to keep a reduced hip flexion moment post-operatively. This might be a strategy that patients adopt to avoid overloading the hip flexors preoperative and it seems it carries on as a compensatory movement postoperatively. This could be related to the Isometric muscle data, where patients had significantly reduced peak hip flexion torque, at 24% less. Patients had significantly reduced scores for hip extension, hip flexion and knee extension, which might also directly impact hip flexion moment. It seems that hip flexion is the main movement that triggers pain in this group of patients and it is not known if sparing hip flexors during PAO would result in better outcomes and fewer compensatory movements. Hip flexion seemed the most affected movement and presented obvious compensatory movements.

Dynamic abduction/adduction ROM was around 18% reduced. It seems that patients avoid using hip abductors properly, which was reflected in patients' pelvis levels, where there were altered movements such as increased and longer pelvic drop and almost no pelvic lift at initial contact. The pelvis was also at a slight anterior tilt and longer pelvic drop was notable which suggests weakness of both the legs' hip abductors to maintain the pelvis level. This finding is supported with Chang et al. (2005) findings where patients with weak hip muscles abductors failed to maintain pelvis level during walking.

Hip power absorption during the midstance was reduced noticeably in terms of peak hip power generation during the terminal stance and initial swing. This finding is similar to that of Romano et al. (1996) who investigated patients with DDH preoperatively and found decreased hip power absorption and generation. Although there were no significant differences in both variables, the noticeable reduction postoperatively suggests patients are still afraid to put more weight on the operated hip. It needs to be noted that reduced sample size might affect this result and other results of this study. This point will be reflected on more in the limitation of the study in Section 6.7 later on in this chapter.

6.2.1.2 Hip joint during squat

Patients' operated leg hip flexion degree was slightly less than the compared group with around 10 degrees difference at the lowest point of the squat depth. This might be because of the way patients with DDH squat and might be related to lesser forward trunk lean. From what was seen in patients' gait, it seems even during squat that patients tend to avoid going into high hip flexion degrees. This raises a warning signal around hip flexion as a movement postoperatively and might mean more attention to this movement should be given.

Patients seem to have close to normal and slightly reduced peak hip flexion moment. Limitation of hip flexion degrees might limit the pelvis from rotating more. Unfortunately, due to lack of evidence-based research around squat as an activity in patients with DDH in the literature, a comparison with the surrounding literature around DDH could not be done.

6.2.1.3 Hip joint during SLB

When patients were asked to stand on one leg, they had similar movements patterns for the pelvis, hip and ankle for all variables compared and no unusual patterns were detected; see Tables 14, 15 and 16. Patients with DDH had normal hip ROM degrees in all the three planes, had neutral hip moments and normal hip power. It seems that patients, during these exercises, did not experience or show compensatory patterns in regard to the hip joint.

6.2.2 Movement compensations observed at the thorax

6.2.2.1 Thorax joint during gait

Patients' thorax data showed multiple changes in patients with DDH post-PAO. There was only one study by Endo et al. (2003) which has investigated trunk movements in the gait of patients with DDH post RAO. The authors found a significant increase in both trunk tilt and obliquity preoperatively. In this study, there was a significant difference in both patients' lateroflexion and rotation post PAO. There was an obvious forward trunk lean throughout the gait cycle. In Endo et al. (2003), the average trunk forward tilt decreased from 3.5 degrees to 2.5 degrees, which is close to the degrees in this study: 2.7 degrees for patients with DDH post PAO.

No other studies have been found in the literature that have explored trunk angles in patients with DDH gait. Interestingly, in Pedersen et al. (2006), the authors found that patients tend to walk with an upright walking pattern postoperatively which is assumed to be a result of relieving pain. In this study, patients with DDH tend to have compensatory movements at the thorax joint even if their gait could be described as upright walking. It is true that this study did not measure trunk strength and ROM; however, it was assumed that the compensatory movements shown at the trunk might be in response to altered movements of the lower limbs. The effect of leaning forward on hip joint require further investigation in future studies.

6.2.2.2 Thorax joint during squat

Patients were at a slightly decreased trunk forward lean compared to the control group with 10 to 15 degrees less at the lowest point of squat depth. Similar to what was found for the patients' gait, a significant difference was found during patients' trunk backward rotation in the descending and ascending phases. However, the decreased two degrees in trunk backward rotation, although significantly different, might not be of clinical relevance, especially if it was taken into consideration the fact that it is hard to detect such small differences for a therapist without equipment. In contrast, less forward trunk lean at around 15 degrees with no significant difference between the two groups has a higher chance of being detected without the use of a motion capture system.

Since this squat as an exercise was not investigated post PAO in the literature, surrounding literature were approached. Different authors in the literature have compared front and back squat and suggested that forward trunk lean in front squat affects other variables and eventually leads to worse outcomes compared to back squat in other musculoskeletal condition (Diggin et al. 2011). In addition, Kulas et al. (2012) suggest that participants with a minimal and moderate forward trunk lean depend on hamstring mainly since it produced 35% more force in their data throughout both phases and participants produced less quadriceps force. Patients with DDH have weakness in the quadriceps muscles postoperatively (Maruyama et al. 2013; Novais et al. 2014b; Peters et al. 2014) which might explain the forward trunk lean during squat. This is also supported with the findings of decreased hip flexion and knee extension muscles in Isometric muscle results in Part 2 by 24% and 33%, respectively.

6.2.2.3 Thorax joint during SLB

Patients had significant differences in terms of increased forward trunk lean, in both their operated and non-operated sides compared with the control group, as seen in Table 14 and Table 15. Since this exercise has not been explored before in the literature on patients with DDH, the findings of this study were compared with surrounding literature. Patients with DDH in this study showed that they have weaker hip muscles, as stated previously in Part 2 results in both flexors, extensors and abductors. Further exploration of this area might reveal valuable information that will most likely contribute to rehabilitation protocols for patients with DDH, as it is known that patients with DDH avoid the use of abductor muscles, more specifically the Gluteus Medius.

In Prior et al.'s (2014) study, they found that the more the lateral trunk shifted the weight-bearing leg, the more demands there were on hip abductors to maintain balance. However, this was not detected as a pattern in this study's results. According to Prior et al. (2014), the increased forward trunk in the patients' group, influences the anterior hip muscles activation. In addition, knee abduction moment was also significantly decreased and possibly affected by the trunk lean. Patients showed increased forward trunk lean in walking and SLB and reduced forward lean for squats. This might mean that, where the exercises require high degrees of hip flexion, patients limit trunk movement. To explain this point further, during squat, patients had less hip flexion degrees and this led to less trunk flexion; therefore, the hip flexion might have limited the trunk movement. Compensatory movements, seen in the thorax joint, suggest the relationship between joints during movement.

6.2.3 Movement compensations observed at the knee

6.2.3.1 Knee joint during gait

Patients tend to have a slight increase in operated leg knee flexion ROM at the midstance and decreased knee flexion ROM during the initial swing, as seen in Figure 11-B. There was a significant difference between the two groups in terms of knee flexion ROM during the initial swing. In Pedersen et al. (2006), maximum knee flexion for the first half of the stance phase and maximum knee extension degree were significantly different pre and post PAO. According to the findings of this study, even though PAO does correct the knee joint movement postoperatively, patients had higher peak knee flexion at the midstance compared to the control group. Patients also showed decreased peak knee extension degree for the second half of the stance phase and decreased peak knee flexion early in the swing phase.

In contrast to the operated leg, patients had normal non-operated leg knee flexion and extension ROM throughout the gait cycle. Since there is asymmetry between the two sides, it is expected that knee joint compensatory movements are due to altered movements at the knee joint of the operated side or other joint altered movements. It is true that patients with DDH walk more slowly than the average person, which relates to decreased knee flexion degree and knee moments (Holden et al. 1997). No definitive conclusion around this point could be reached based on the findings of this research's results and due to lack of research on this area.

Knee moments were reported in a couple of studies that investigated patients with DDH preoperatively and in two other studies postoperatively (Pedersen et al. 2006; Jacobsen et al. 2013; 2014; Skalshøi et al. 2015; Sucato et al. 2015). Liu et al. (2012) reported a decrease in maximum internal knee adduction moment for the affected side and an increase in maximum knee adduction moment for the unaffected side preoperatively. This is expected to change post PAO; in this study the patients had the opposite postoperatively compared to Liu et al.'s (2012) finding. In addition, patients' peak knee abduction moments were slightly lower than the control group peak knee abduction moment throughout different points of the gait cycle; however, this was within normal limits. This could be explained by the findings for the Isometric muscles test for hip abductors; it was seen that the patients' hip abductors were weaker than those of the control group by 20%.

Gluteus Medius muscle is an important factor that might influence variables on the frontal plane which are known to be weak; however, in this research, the influence of the Gluteus Medius on the biomechanical variables has not been investigated. In another study, Inan et al. (2005) found that the change in the volume of Gluteus Medius post PAO relates to patients' age and that older people are at more risk of developing Trendelenburg gait. Therefore, more research should focus on the relationship of the activation of the Gluteus Medius and frontal plane variables during different functional exercises to possibly lead to solid grounds for recommending or approving Gluteus Medius strength programmes for patients with DDH.

6.2.3.2 Knee joint during squat

Asymmetry was shown when patients had reduced operated knee flexion degree with an average close to 15 degrees at the lowest point of squat depth compared to the significant 20-degree difference in patients' non-operated side. Patients, during squat, tended to have decreased knee flexion degrees, at an average of 85 degrees, and had a significantly lower peak hip abduction moment. It seems that patients with DDH post-PAO demonstrate a lower flexion degree and reduced peak knee abduction moment. Since the hip flexion was decreased, it is expected to affect the knee flexion degree as well. It seems that the decreased value of the knee joint was in response to the decreased hip joint angle.

Again, due to lack of research studies to compare with patients with DDH, borrowing from the surrounding literatures seems necessary. However, in this study, patients with DDH showed the opposite during the functional exercises given, with decreased knee abduction moment. Increased knee abduction moment was also associated with an increase of knee OA (Lindsey et al. 2020) and decreasing the knee abduction moment was associated with slowing the progression of OA (Miyazaki et al. 2002), decreased pain (Lindsey et al. 2020) and decreased severity (Sharma et al. 1998). This might mean that the reduced values lead to compensatory movements in other joints. In addition, lower hip abduction degrees and unusual rotation movement of the pelvis and trunk might all have influenced the reduced peak knee abduction moment.

6.2.3.3 Knee joint during SLB

There was normal operated leg peak knee extension moment and significantly reduced peak knee abduction moment for the operated leg. Increased forward trunk was the other variable with a significant difference between groups. Increased forward trunk lean might be associated with a decrease in knee abduction moment. Knee and hip muscle weakness might be the other explanation for the decrease in knee abduction moment. Shank muscles play a major role in maintaining balance during SLB (Muehlbauer et al. 2014); however, no direct contribution or effect of shank muscles on knee abduction moment in patients with DDH is expected, since there were a normal ankle ROM and moment. Since most of the variables compared in the exercises were normal or within normal limits, it is not apparent if other variables included in this study influenced the reduced peak knee abduction moment.

6.2.4 Movement compensations observed at the pelvis

6.2.4.1 Pelvis during gait

Patients' pelvis data showed that there were partial altered movements of patients' pelvis during gait. Patients had increased anterior pelvic tilt, decreased pelvic lift at the stance phase, slight increase in pelvic drop at the midstance, almost no pelvic lift at the heel strike and initial stance and decreased pelvis retraction at the heel strike and swing phase. With regard to pelvic tilt, a similar finding was shown in Sucato et al. (2015); the authors suggested that this is the reason for increased hip flexion degree in comparison to healthy participants. This supported with the finding in this study where patients have maintained a higher hip flexion degree and did not go to full hip extension, which might contribute to the pelvic compensatory movement.

Pelvic drop and pelvic rotation were reported in many preoperative studies (Romano et al., 1996).

There was a noticeable pelvic drop and diminished pelvic lift during the midstance phase; however, this was significant in Romano et al. (1996), which indicates that PAO surgery adjusts the pelvic drop to some extent. Increased pelvic tilt was noticeable when compared to the control group in contrast to Liu et al. (2012) where decreased pelvis tilt was observed pre-operatively. This means that PAO seems to correct this movement pattern post-operatively. As suggested by Romano et al. (1996), patients with DDH with severe hip OA tend to fix their pelvis in an oblique position during the entire gait cycle to help the affected hip to be in a higher position than the unaffected hip. This means that the more degenerative changes there are in the hip joint, the less pelvis movement there is to decrease energy requirements to change the body position from one place to another. Patients with DDH might be in danger of compensating by decreasing energy requirements by overcoming adapted movements pre-operatively as a pain avoiding mechanism. Patients with DDH had altered pelvis movements pre-operatively as measured, as mentioned earlier by other studies; based on the data found in this study, the patients corrected their pelvis position in all three planes post-operatively. However, it needs to be noted that, despite the movement patterns found among patients with DDH gait, there was no significant difference in the three planes of pelvis joint between the two groups.

6.2.4.2 Pelvis joint during squat and SLB

Patients seem to have a significant difference in their operated side pelvic rotation compared to the control group, which was not detected in the non-operated side. It is true that the difference in degrees was not big, only 1.30 degrees (33%); however, the clinical relevance of such small degrees of difference is not clear. This might have happened because of alterations of other joints and altered movements in, for example, the hip and trunk compensatory movements.

When comparing the pelvis of patients with DDH to the control group during SLB, patients had a slightly increased anterior pelvic tilt, by one to two degrees, as seen in Figure 26, and close to identical pelvic rotation and pelvic lift movement patterns, as seen in Figure 26. There was no significant difference in any of the previous variables between the groups.

6.2.5 Difficulty of walking, squat and SLB post PAO

In this section, the exercises are ordered based on their difficulty, from easiest to hardest. The order was based on the significant differences levels found between the groups and asymmetry between the patients' operated and non-operated sides. The exercise shows least number of compensatory movements and unusual patterns was considered the easiest.

First, SLB compared to other exercises was the easiest. It is true that patients tend to lean forward during SLB by around three degrees only; however, this could be hard to detect for therapists at clinics and irrelevant clinically with such a small difference. There was also a decreased peak knee abduction moment, which could also be hard to detect at clinics; this should be further analysed to see whether this might lead to a negative impact in the long term.

The second exercise was the squat, where patients were able to squat to 85-degree knee flexion and above 70 degrees of hip flexion post PAO. It is true that patients showed compensatory movements and scores for some of the variables showed a significant reduction compared to the control group; squats, from a general point of view, could be recommended with caution. Therapists might look carefully into pelvis rotation, trunk rotation, hip abduction/adduction ROM and knee movement during the descending phase. Patients are not expected to weight shift from the operated to the non-operated side during squat based on the results of this study. Finally, since most of the altered movements among the three exercises are seen in patients' gait, more careful observation should be done on how patients with DDH walk. Gait re-education might involve useful exercises to start with in order to pick up any noticeable compensatory movements and work towards correcting these.

6.3 Part 3: Patients' values, by exploring the patients' rehabilitation experience

6.3.1 Rehabilitation theme and movement compensation theme

First, an interesting point that needs to be noted is that, in this research, 40% of the respondents had bilateral DDH and more than half of the patients group in Part 2 had bilateral DDH. The effect of bilateral DDH was not investigated in this research and differences between unilateral and bilateral patients are expected since both hip joints are damaged in bilateral cases. Gait, trunk movement, hip and activity levels are examples of issues to consider when patients with bilateral DDH are investigated.

As stated at the end of Part 3 results summary, the main findings were; more than half of the population were not satisfied with the rehabilitation services they had received; patients had low scores on the UCLA activity scale and with a reduced average score of 5; patients who filled mHHS scale had reported pain, although minimal pain post-PAO; a huge number of exercises were given during the patient's journey and therapists were in favour of the following exercises: squats, clams, SLB, bridges, step-up, walking, cycle and bed exercises. Out of 48 respondents, 15 patients did not receive physiotherapy sessions after discharge from hospital. It was not clear from the data if the patients were offered any sort of rehabilitation programme.

The postoperative rehabilitation period ranged from as low as two weeks to more than nine months of rehabilitation. If Chan's (2007) and Host et al.'s (2014) suggestions that higher intensity rehabilitation program results in better outcomes are correct, this might explain why one patient achieved high scores for the UCLA activity scale of 9 or 10 out of 10, for example, and another one scored 1 out of 10. As stated previously, increasing the intensity of rehabilitation post-operatively and the rehabilitation period have been supported by many authors in the surrounding literature (Jogi et al. 2015; Bandholm et al. 2018).

The vast majority of the respondents received 30–60 minute physiotherapy sessions; 30-60 minutes could be considered a sufficient time in order to initiate assessments or do follow-up sessions and could produce better outcomes as Host et al. (2014) and Chan (2007) suggest. This is a positive finding in this study that patients with DDH have sufficient rehabilitation session times except for a very limited number of patients who received either less than 30-60 minutes. The real effect of the limited time for rehabilitation or when to stop the rehabilitation is beyond the scope of this research. In addition, it needs to be noted that the cost of adding, removing or adopting certain protocols, which plays a major role in any health system, was not discussed since it is beyond the scope of this project.

6.3.2 UCLA activity scale and mHHS

Nine patients reported no feeling of pain and 21 patients had minimal tolerable pain. Around half of the respondents managed to walk for long distances without pain. The previous two findings are in line with the literature, where patients scored highest in the UCLA and less number of patients reported pain during the first-year post PAO (Novais et al. 2013). It needs to be noted that in Novais et al. (2013) study, when patients' progress stopped a slight decrease in their scores were documented (Novais et al. 2013). This is predictable since patients are expected to be involved in a rehabilitation programme immediately post-operative.

In contrast to the literature (Ettinger et al. 2015b; Heyworth et al. 2016; Kalore et al. 2016), as mentioned previously in the conclusion of the systematic search of the literature in Part 1, there were only 22.9% of respondents participating in high impact sports and 27.1% participated in moderate impact activities. It is true that the patient scores increased post-operatively; however, by using such a tool, only a little information regarding activities is known. In this research, around 50% of the respondents could not engage in high impact activities/sports.

Further investigation is recommended with appropriate methods to resolve any ambiguity around this area. It is true that other factors beyond the scope of this study that are confirmed to impact on the outcomes of PAO have not been explored, such as age, degree of symptoms, OA degree, etc… (Steppacher et al. 2008; Hamai et al. 2014; Lerch et al. 2017); however, from the findings of the questionnaire and support of the literature (Chan 2007), the longer patients with DDH have supervised rehabilitation, the more high-level outcomes are achieved, such as high levels of activities and impact sports.

6.3.3 Exercises at physiotherapy clinics (open-ended questions)

There were plenty of exercises respondents were doing after receiving clearance to fully weight bear, as can be seen in Table 33. After analysing types of exercises prescribed, two types of exercise were identified which were general exercises and hip and pelvic exercises.

The recommended exercises within these two types of exercises showed a positive effect on other conditions such as THA and hip OA (Pozzi et al. 2017; Bandholm et al. 2018). Obviously, there was a wide variety of exercises prescribed to patients with DDH that target glutes and the pelvis area; however, luckily, 83.4% of the respondents agreed that the prescribed exercises had a positive impact on them. This contradicts with another finding in Part 3, where two-thirds of the respondents were doing additional exercises from different sources (such as: word of mouth, Google, medical journals, websites and YouTube).

If more than 80% of the patients felt happy with the exercises prescribed, it is not logical that more than two-thirds of them would seek additional exercises unless there was a need to. The need for additional exercises might be out of hope to find exercises that speed up progress or might be the required step, in their opinion, to allow them to engage in high impact sport. Since the majority of the respondents sought additional exercises, it was hard to separate the effect of unsupervised rehabilitation and patients' rehabilitation at clinics. It was not clear from the literature, as mentioned earlier in Chapter Two, if certain physiotherapy protocols may have a positive impact, for example, on pain reduction, improving hip movement, or increasing walking time for this group of patients. In contrast, patients who underwent THA received proper rehabilitation and the benefits of physiotherapy programmes are well-documented in the literature.

A systematic review was done by Coulter et al. (2013) on physiotherapy for patients with THA after discharge from hospital and concluded that patients had increased hip abductor strength, which is weak for those with a DDH condition (Adler et al. 2016), and improved gait speed. Another RCT study by Stockton and Mengersen (2009) found that patients who underwent THA and received initial twice-daily physiotherapy tended to have early functional benefits compared to those undergoing daily physiotherapy.

Therefore, the importance of rehabilitation and the intensity in terms of when and how long sessions last cannot be ignored and they are believed, based on the findings in the literature, to have a strong impact on surgery outcomes. Such research is indeed needed in order to deliver the best treatment to patients with DDH. Patients' searches on websites or asking other patients might be of a concern to clinicians that they might not put enough effort into these patients, which leads them to seek help outside clinics.

It was not clear from the literature whether the recommended exercises have a significant impact on patients in terms of DDH rehabilitation progress. Hydrotherapy was recommended to two patients, but not supported by the evidence; however, it was one of the recommendations by the Royal National Orthopaedic Hospital, UK (2015). Different research has been conducted to uncover the benefits of swimming and hydrotherapy exercises for hip conditions such as total hip arthroplasty (Goehring et al. 2015) and other body conditions (Sawant and Shinde 2019; Teng et al. 2019). The significance of swimming and hydrotherapy in the previous research varied from reducing swelling, decreasing pain post-operatively, increasing muscle strength to comparison of aquatic therapy versus land therapy.

It was assumed that aquatic therapy in general helps by decreasing the gravity force, thus decreasing the forces applied to the joints, which means it could be a proper place to start gait training and avoid possible movement compensations (Torres-Ronda and Alcázar 2014). This could be more beneficial in acute and post-acute stages rather than later stages in the rehabilitation of patients with DDH post-operative. However, the popularity of swimming and hydrotherapy as exercises recommended for patients with DDH post-PAO was not clear from the data gathered in the questionnaire and it is possibly best investigated by approaching therapists who recommend such exercises.

In the literature, only in Mortensen et al.'s (2018) feasibility study are specific types of exercises tested on patients with DDH. The authors included all patients with DDH preoperative to resistance training programme. It was found that patients, by the end of the study, reported decreased pain levels and increased scores in PROMs, functional performance was enhanced and they had increased strength in the hip flexion muscles. However, the rationale for conducting this specific type of exercise was not clear from the study. This research did not include patients with a Tonnis OA score of >1; therefore, it did include the patients with the least affected hip joints. If patients' gait compensatory movements were taken into consideration, for example, it is unknown whether resistance exercises would have an impact on patients' compensatory movements. Such research is indeed important; however, other types of exercises, joint and muscle functions need to be investigated to see their effect on optimising the movements of patients with DDH gait.

It seems that there is a thin line between recommending exercises with confidence and avoiding important exercises due to lack of evidence. When there is limited amount of evidence, as seen in the previous discussion, urgent steps should be taken to move this area forward. However, not all the previously mentioned practices are necessarily beneficial to DDH patients. Narrowing down some of these practices might involve testing them to understand effectiveness, which might take a long period. Patients who demonstrated compensatory movement strategies during different functional activities, such as picking up objects from the floor, are worth in-depth explorations since they are probably done on a daily basis.

Depending on the non-affected leg most of the time is an example of how depending on one side might possibly lead to more complications (Talis et al. 2008). This was evident in this study and discussed in the asymmetry section above. From what has been found in all the study parts, it seems that patients with DDH postoperative still feel pain and do have compensatory movements, which does not convince this group of patients are ready to engage in a high level of activities.

6.4 Integrating all study parts in relation to EBP

In regard to research evidence domain, it was promising that the given details of each rehabilitation phase in the guidelines (Segaren et al. 2015; Adler et al. 2016; Kamath 2016) means that these guidelines are presented in a way that shows that the processing behind making these protocols have been thought out carefully and in a rational way. Although, the available protocols found in the literature were created based on a rational method, this does not necessarily mean there is wide use and approval of these protocols to influence experience and knowledge. Findings in Part 3, where patients sought additional exercises, suggest that these guidelines fail to include exercises patients thought necessary to be added to their rehabilitation. There was a variety of compensatory movements detected during walking, squat and SLB of patients with DDH post PAO. If every hospital, surgeon or country has their own protocols that are not based on evidence this might lead to uneven rehabilitation outcomes.

In addition, the timeline for the rehabilitation in these protocols seems a little bit optimistic and it might fit only patients with specific preoperative status. In Part 3, patients participated in this study received different rehabilitation period and more interestingly nine respondents received a rehabilitation more than six months, which is higher than the rehabilitation period suggested in the available protocols in the literature. There were 15 respondents who did not receive rehabilitation, which might raise a concern on the effectiveness of the available guidelines. The integrated results of this domain suggest there is inconsistency between the findings and further investigation of this domain is required.

In regard to the clinical expertise domain, a possible reason why patients tend to do compensatory movement strategies is possibly to avoid pain, decreased ROM and possible weak hip muscles. Even with slight pain reported in VAS, patients were able to do the exercises in this research safely; however, with some movement compensations. Pain levels pre and postoperative were demonstrated by different authors (Novais et al. 2014b; Kamath 2016; Pun 2016); however, none of the authors demonstrated the effect of PAO in decreasing pain level during exercises and whether PAO minimises the feeling of pain and allows patients with DDH to be able to do a high level of activities without the feeling of pain. It hard for humans to compensate without affecting other parts of the body.

To simplify, during weight-bearing activities, the knee and ankle joints might be stressed or lead to overuse syndrome if poor hip joint mechanics and hip muscles imbalance persist (Guo et al. 2007; Takacs and Hunt 2012). Similar findings were discovered in this research, when there were compensatory movements that led to altered movements in other joints; however, the effect of these compensatory movements of a joint on other joints was not the aim of this study. The rehabilitation guidelines could possibly target the underlying causes of the pain level threshold and whether the loading on hip joint is too much or too little. Patients with DDH suggested many compensatory movements strategies, and the effect of these strategies is unknown. The finding of compensatory movements and associated strategies provides inconsistent finding with the finding of returning to sport and high level of activities post-PAO where the presence of pain and presence of compensatory movements suggest that patients did not benefit from the available guidelines and are far from returning to high level of activities.

The rehabilitation guidelines could possibly also target the underlying causes of the compensation. In addition, the majority of the patients who answered the questionnaire in Part 3, said that they had better hip movement after adding additional exercises. The ambiguity around the effect of the available protocols might lead patients to seek additional exercises to benefit from the rehabilitation post-PAO. Even though three exercises were investigated in Part 2, this suggests further research of the additional exercise patients are seeking. This means there is possible inappropriate delivery of rehabilitation protocols or maybe the rehabilitation programme lacks some useful/beneficial exercises. In addition, the fact that patients thought they did not receive adequate time for rehabilitation contradicts with the timeline of rehabilitation mentioned in the guidelines in the literature. The integrated results of this domain suggest negative perception and improvement in this domain is required.

In regard to patients' values, apart from one study by Gambling (2019), on the patients' rehabilitation experience, this area seems not well-addressed in the literature. Patients with DDH who participated in this study were not satisfied regarding the overall rehabilitation and thought they might have better rehabilitation; it seems that this area is underdeveloped and has received little attention. The individual rehabilitation journey, area of residence (Low et al. 2021), age, patient's goals, preoperative status and motivation are all possible factors that might influence the rehabilitation period and outcomes. For instance, previous studies in the literature found that lack of motivation proved to be a contributory factor of the progress/adherence to rehabilitation protocols in general (Siegert and Taylor 2009; Hammer et al. 2016).

Athlete patients willing to return to high level of activities might be motivated due the fact that they want to return to impact sports. However, as reported earlier, mean score of 5 in the UCLA suggest difficulties to return to high level of activities and impact sports. It was found that the mean score of the UCLA activity scale for patients with DDH participated in this study was 5 compared to a mean of more than 7.5 in other studies (Ettinger et al. 2015b; Heyworth et al. 2016; Kalore et al. 2016). The score was close to some studies (Hara et al. 2017b; 2018). Mean score of 5 in the UCLA activity scale suggested difficulties to return to high level of activities and impact sports. It is expected that patients who undergo PAO would need to wait at least from one year to two years to be able to return to preinjury levels due to the fact that this condition sometimes takes years to be diagnosed (Ganz et al. 1988; Adler et al. 2016; Kamath 2016; Lerch et al. 2017).

This might lead to the possibility of an overestimation of the findings reported in the literature, more specifically the return to high level of activities and sports. Age, goal setting and participation in sport and high level of activities might be of concern when sitting a rehabilitation for patients with DDH. Further research is needed to explore the rehabilitation phases of the available guidelines, which could be crucial for athletes diagnosed with DDH to return to high level of activities and sports. The integrated results of this domain suggest further investigation on inconsistency is required. Based on the integration of all study parts, it seems there is inconsistency between the findings and further investigation is required in research evidence domain, negative perception and improvement is required in clinical expertise domain and further investigation on inconsistency is required in patients' values. Finally, by knowing the patients' outcome of rehabilitation post-PAO, patients' needs, weaknesses, goals, movement patterns (such as compensating more during walking and fewer compensatory movements during SLB) and the issues that they face during rehabilitation (such as unsatisfied feeling of the rehabilitation received post-operative), it might be possible to deliver evidence-based, consistent, high quality and beneficial rehabilitation services. After exploring the evidence in Part 1 and discussing the findings of Part 2 and Part 3, the research question is re-visited next.

6.5 Is postoperative rehabilitation for young adults with DDH optimal?

This question is answered after the main findings of all study parts are rehearsed briefly. There was a lack of evidence in the literature regarding the rehabilitation of DDH postoperative and the guidelines found in the literature did not rely on evidence investigating DDH. This might raise the concern that the available guidelines found in the literature are not effective/sufficient or involve harmful practice/s and this might slow or even worsen the rehabilitation outcomes and healthcare services provided for this population. However, it would be too soon to judge or agree with available protocols found in the literature without putting them to the test and researching them.

All recent studies have investigated patients' return to a high level of activities using patient-reported outcome measures but these were found not to be appropriate to monitor patients' rehabilitation progress or sensitive enough to identify the goals of the population of young patients in their twenties. In regard to compensatory movements, in Part 2, patients showed asymmetry during the three exercises adopted in this research and walking seems the exercise that shows the most compensatory movements followed by squat. Interestingly, the majority of the patients were not satisfied, as seen in Part 3, with their rehabilitation experience, and they felt that additional exercises should be included in the protocol. In addition, the majority of patients also found new strategies to avoid pain, which should be investigated along with in-depth exploration of the real effect of these strategies on the patients' condition.

As concluded in Part 3, young patients felt somehow abandoned and their goals were not considered and were being decided for them. It is believed that patients should be involved in the project initiation to make sure that it covers their goals, which would help to the success of the rehabilitation. The integrated findings from Part 1, Part 2 and Part 3 suggest lack of clarification, depth and interpretation of the combined findings, however, little depth was found. Therefore, based on the findings of all parts of this study, and due to the fact that all study parts showed substantial shortfalls in the aspects explored, the postoperative rehabilitation for patients with DDH is considered not optimal. A possible next step after this research might be adopting an intervention that consists of exercises tested in this research and evaluate its impact further in an observational study, followed by a randomised controlled trial as an advanced stage. Exercises done with a smaller number of compensatory movements are encouraged. This raises the importance of conducting more research with appropriate study design such as observational gait laboratory research or clinical studies, which will provide researchers with more useful information. Findings from strong evidence would help patients achieve higher levels of activities and lead to optimal rehabilitation.

Moreover, it could be suggested that future steps might include the focus on the effectiveness of the available guidelines postoperative and its impact on patients with DDH, as to what is too little and what is too much to do for patients with DDH post-operative, place greater efforts in developing our understanding of compensatory movements, the unsatisfactory feeling of patients with DDH around the rehabilitation they received and the variety of exercises given to these patients during rehabilitation. To conclude, it seems, based on the findings of this study's parts, where most of the findings show lack of sufficient evidence and lack of knowledge, both of which could be considered as weakness in the postoperative rehabilitation of DDH, that we are far from optimal rehabilitation for patients with DDH postoperative.

6.6 Rehabilitation of DDH and the development of complex interventions

Rehabilitation is considered as complex intervention (Campbell et al. 2000). The Medical Research Council (MRC) is a framework that might be simply explained as a way of developing complex interventions such as rehabilitation/ physiotherapy. In addition, this framework might be of use after answering the research question of this study, is postoperative rehabilitation for young adults with DDH optimal? in order to help in guiding the development of the foundation of DDH rehabilitation research. The Medical Research Council (MRC) defines that 'Complex interventions in health care, whether therapeutic or preventative, comprise a number of separate elements which seem essential to the proper functioning of the intervention although the "active ingredient" of the intervention that is effective is difficult to specify' (Campbell et al. 2000). The MRC framework consists of four elements, development, feasibility/piloting, evaluation and implementation (Campbell et al. 2000; Craig et al. 2012).

If certain intervention is suggested to be implemented to patients with DDH or if certain practice currently implemented at clinics is questioned whether to be recommended as best practice or not, it needs to go through a development stage whereby the theories and evidence to recommend certain practice are dealt with. This should be followed by piloting this practice where actual testing of the practice takes place followed by an evaluation stage where the aim is to assess the practice effectiveness. Finally, implementing the practice clinically and monitoring its long-term effects. If such framework is adopted to guide practices as recommended in available guidelines in the literature or practices recommended to patients with DDH at clinics, as discussed in Part 1, this ensures a systematic way to develop best practice until it reaches implementation. Based on MRC (Campbell et al. 2000; Craig et al. 2008; Craig et al. 2012), at this stage theories and evidence in the literature are discussed and assessed in order to identify a potential practice to be tested.

After conducting the systematic search in Chapter Two, it seems that this stage needs the most work to develop in order to proceed to the next elements. Knowledge about compensatory movements postoperative, during gait, squat or SLB, might then allow to proceed to the next element by exploring the role of pain on the compensatory movements, the effect of and finally how much loading is acceptable in order to allow patients to return to a high level of activities and sports. However, these insights are not necessarily mutually exclusive and future research is needed. When the development phase is enriched with evidence resulting in improved theories, this might empower the development of optimal treatment for patients with DDH. Therefore, only insights from the compensatory movements are discussed next in a hope to enrich the development stage with evidence.

6.6.1 Insights around compensatory movements within complex intervention

In this research, walking, squatting and SLB were considered as exercises recommended to patients with DDH and explored by means of detailed movement analysis. A systematic search was conducted at the very beginning of this research to provide explanation and evidence. Although this area has lack of sufficient number of evidence and theories, the main explanations of compensatory movements during three exercises adopted on patients with DDH gait were partially identified. These suggested compensatory movements/altered movements post-operative, which are assumed in this research to be applied on squat and SLB as well. In addition, based on the findings of this research, the patients presented a compensatory movement in their trunk, pelvis and hip as the main affected areas followed by the knee, ankle and GRF. In the graphs analysed, SLB showed almost similar patterns on average and walking showed different patterns both in the averages and peaks of all variables tested.

The findings of this research will help the researcher continue post-doctoral work in the same area in the hope to develop best practice guided by complex intervention. This could be the first step or could be considered as a short-term goal to be attained before the development of an intervention, which is the next step in the MRC framework. In addition, interviews, focus group and workshops might be conducted as short-term goals as well in order to develop specific guidance for patients with DDH rehabilitation that has a clear rationale and is backed up with evidence. This step is recommended to involve experienced physiotherapists who dealt or are dealing with patients with DDH.

6.7 Limitations of the current study

Despite every effort to ensure a robust methodological approach, there are several limitations in this study that need to be declared and discussed. The details of the diagnosis of DDH could not be retrieved from the NHS and the roll-out of bilateral diagnosis for patients with unilateral participated in this study and considered as unilateral cases could not be ascertained. All patients who presented as unilateral DDH patients were not tested to rule out the possibility of having bilateral DDH. The role of concomitant surgeries was not taken into consideration during analysis. This is one of the downsides of recruiting from the community, where it is hard to confirm exact diagnoses and medical history of the patients.

Strict inclusion and exclusion criteria were applied limiting the number of individuals eligible for participation in the study to only those who had PAO and showed no sign of pain in the affected hip prior to the experiment. There was a small sample size of only 15 patients with DDH, and 30 in total included in this study due to the difficulty of recruitment and Covid-19. As mentioned above, four patients' appointments had to be cancelled as well as all other negotiations with other patients due to Covid-19. The fact that all patients participated from outside Cardiff and due to Covid-19 restrictions on travel from one city to another, this affected the sample size achieved. There was also some loss of data for three patients due to corrupted c3d files of the 3D motions capture data. The original files of the kinematic data were preserved; however, the kinetic data of the force platforms was not available. The reason for this was either through not calibrating the force platforms the right way or because the force platforms were turned off.

During data collection sessions, although patients with DDH postoperative presenting with compensatory movements patterns were included, insufficient numbers for comprehensive analysis were achieved, due to the fact that these compensatory movements are less commonly observed. The bespoke questionnaire created was piloted and face validity was determined; however, no content validity was undertaken, due to time restraints further validity analysis was not able to be performed. The questionnaire was not limited to patients with DDH who underwent only PAO, but also patients who underwent THA, affecting the generalisability of the findings to DDH patients who solely had PAO.

The clinical implications are presented next followed by future studies.

6.8 Clinical implications

Different research implications emerged from this research:

- Part 1 of this thesis aimed to explore the existing clinical expertise papers, editorials, identifying guidelines, case reports and case series to identify the main elements of clinical guidelines. It seems that clinical guidelines found in the literature could be adopted at the clinics; however, with caution since these guidelines were not supported with evidence-based.
- The movement compensation was proved through different functional activities. This was the aim of Part 2 to explore patients with hip dysplasia movements during exercises that represent functional activities as part of their daily lives, from an objective biomechanical point of view. It seems that patients with DDH show compensatory movements across walking, squat and less compensatory movements during SLB, which might be better targeted during rehabilitation. Walking showed more compensatory movements and there is need to be focused on the reasons behind this and a possible reason was the higher pain intensity scores by the DDH group. Depth of squat is an interesting area where patients showed less knee flexion degrees during squat.
- The aim of Part 3 of this thesis was patients' values area which were targeted by exploring the patients' rehabilitation experience by exploring types of exercises recommended, intensity and frequency of the exercises, rehabilitation period, strategies to avoid pain and finally the patient's opinion around the rehabilitation they had; it seems patients with DDH have poor satisfaction regarding rehabilitation received post-operative. Patients' opinion regarding the rehabilitation experience could be assessed during and after rehabilitation ended. Frequency and type of exercises found to be used at clinics were mostly targeted at the hip area. Patients seeking additional exercises and who

suggested that they benefited from such is an interesting point to be explored and the patients asked if they tend to add exercises. In addition, young patients are likely to aim for a high level of activities; however, it was not clear whether poor satisfaction was common for a certain age group.

- Is postoperative rehabilitation for DDH patients optimal? Unfortunately, it appears that clinical implications lean towards raising awareness.

6.9 Future studies

- The inconsistency of physiotherapists' practices, what instructions should be given, the effectiveness of preoperative rehabilitation and best home-based exercises need to be investigated further. A better support needs to be developed through evidence-based practice and clinical guidelines based on evidence. (Part 1)
- Guidelines found in the literature might be used in hospitals and clinics; therefore, the available protocols need to be investigated and monitored in a longitudinal study to examine their effect on the patient's rehabilitation journey. (Part 1)
- The use of objective tools instead of subjective PROM to track a patient's activity and participation levels might help to detect more accurate and reliable results for the patient's pathways post-operatively. However, this does not mean that the qualitative approach should be avoided, instead the combination of objective and subjective inputs might give optimal guidance. In order to track the effect of a rehabilitation programme on young patients, appropriate PROM directed to young patients needs to be used or developed. Such a tool would help both physiotherapists and researchers to unveil the effectiveness of rehabilitation practices. (Part 1)
- This research found that patients do compensate during movements. Further study is required to monitor the compensatory movements and whether patients adopted the compensatory movements in more ADLs and whether they adopted them pre-operatively and to what extent compensatory movements impact the post-surgery rehabilitation outcomes. (Part 2)
- Differences between bilateral and unilateral groups might be of interest, especially for the movement compensation found, and patients might adopt a new strategy when two hips are affected. (Part 2)

- Future research needs to compare a patient's muscle strength, ROM and gait by taking into consideration different surgical approaches. In addition, future research might add a control group with conservative treatment in postoperative rehabilitation. (Part 2)
- Role of feeling unsatisfied on rehabilitation outcomes post-operatively should be investigated, especially given that 40% of the respondents did not see themselves returning to a high level of activities in the future. (Part 3)
- Further research is needed on the interesting findings found regarding patients' rehabilitation experiences, in relation to, for example, rehabilitation period, rationale for the chosen exercises and monitoring the effectiveness of the exercises prescribed. In addition, it was not clear from these findings why each patient sought additional exercises, which can be explored in future research as well. (Part 3)
- Therapists could be invited for interview, as an example of future research, in order to measure their knowledge, what they are offering to patients with DDH and what are the barriers and enablers presented to patients with DDH during rehabilitation. (Part 3)

It is hard for a single researcher or group to aim to achieve all of the suggested future research, and, therefore, other researchers are encouraged to contribute in order to deliver high-quality healthcare services.

Chapter Seven: Conclusion

This research has attempted to provide essential information regarding the postoperative rehabilitation of patients with DDH. This research shed light on the available research evidence in the literature, explored compensatory movements during three functional activities, illustrated the patients' rehabilitation experiences by using both a motion capture system (Part 2) and exploring patients' values (Part 3).

In Part 1, even with the combination of the available research articles in the literature, and hospital guidelines that were linked and rationalised in the previous chapter and the initial results of this project, it was difficult to draw a definitive conclusion regarding what best practice would be. Lack of evidence-based research in the literature and the fact that the rehabilitation process was not delivered based on research evidence but rather based on the healthcare provider knowledge, borrowing from adjacent hip conditions and experience, raises the most challenging issue. Lack of evidence, clinical variation and the possibility of delivering low quality healthcare are the issues identified after systematic searching of the literature were the main findings concluded at the end of Part 1. Unfortunately, there is very limited research around the rehabilitation of patients with DDH, which limits the ability to compare, contrast or even combine the results of this research. Patients with DDH would benefit from guided systematic rehabilitation protocols. Delivering low quality healthcare, an unnecessary variety of exercises, and an unidentified priority of the main goal of the rehabilitation are potential problematics expected from unguided and non-evidence-based practices.

Part 2's significant findings found between the DDH and control groups were related to patients' gait, less significant findings during squat and even less significant findings during SLB. Patients' operated hip showed the most altered movement, as expected post PAO, compared to the control group and patients' non-operated leg. Patients showed different trunk lateroflexion and rotation movement patterns post-PAO as well. Postoperative DDH participants had better hip joint biomechanics; however, the differences between postoperative hip joint and normal leg movements were evident. The influence of asymmetry and the altered biomechanics between the two limbs needs to be measured to inform rehabilitation programmes. If patients tend to compensate in the affected hip to overcome a certain movement pattern, then therapists should counter that by re-educating them on proper movement. Patients had significant compensatory movements during their gait, squat and SLB. The compensatory movements led to altered trunk and lower limb movements during functional activities in certain joints, which can be expected to lead to further complications for unaffected joints. In addition, these results suggest the importance of investigating more functional exercises where patients might adopt new strategies to avoid pain by compensatory movements which could be missed or unsafe. Based on the findings of Part 2, it has been found that patients were compensating over the three exercises.

Based on patients' values explored in this research in Part 3, patients were not satisfied with their rehabilitation experiences. Identifying the patients' goals and issues, aiming towards patient satisfaction with the rehabilitation experience and delivering high quality research would lead the achievement optimal postoperative rehabilitation. Moreover, variation of exercises delivered was noticeable and it seems that the timeline for rehabilitation differs from one patient to another; some patients did not receive rehabilitation at all, and some patients were continuing to do their rehabilitation over a year. In addition, when patients reported their rehabilitation experience, nearly half felt that their rehabilitation journey was not sufficient. Interestingly, there were certain types of recommended exercises such as hydrotherapy, cycling and other exercises to avoid such as high impact sports, without clear rationale/evidence. Two-thirds of the patients sought others outside the rehabilitation team for additional exercises. Nearly half of the patients thought that they would never get back to a high level of activities. Lack of perceived opportunity and motivation could play a crucial role and needs to be investigated further.

During integration of the results of Part 1, Part 2 and Part 3, from the data available in the literature and the data gathered, the researcher managed to show that there was not a clear picture of what the best service would look like or how it should be framed, and this would be an area to be improved. The known general facts, approved in the literature, might act as raw material to build upon to hopefully reach the best service delivery possible.

This doctoral thesis has explored the available research evidence in the literature, compensatory movements during three functional activities and patients' values. Despite the limitations, this research, based on the literature search, is one of the first studies to investigate the available evidence in the literature around DDH, observe functional exercises and to have investigated patients with DDH rehabilitation experiences post PAO. It was shown by this research data that the literature around DDH lack strong evidence regarding rehabilitation, raising a concern whether participation of patients with DDH postoperative is adequately measured, and patients may not be sufficiently achieving their goals in this domain. Finally, at this point, it was suggested that further work is indeed needed in order to achieve significant progress comparable to results achieved for rehabilitation for other hip conditions, such as hip arthroplasty. The long-term aim of DDH rehabilitation postoperative would be to deliver optimal rehabilitation services and improve each patient's quality of life. Providing results from different domains exploring patients with DDH post-PAO will enrich the area of rehabilitation and enrich our understanding of the rehabilitation process these patients go through. The clinical guidelines found in the literature could be adopted at the clinics, however, with caution, patients with DDH post PAO show compensatory movements across walking, squat and less compensatory movements during SLB which might be better targeted during rehabilitation. Finally it seems that patient with DDH have poor satisfaction regarding rehabilitation received post-operative.

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Appendices

Appendix 1 (First area)

Database	Search strategy	Results
Medline	hip dysplasia OR congenital hip dislocation OR developmental dysplasia of the hip OR DDH AND hip dislocation OR subluxation OR Adults Hip AND Surgery/osteotomy OR PAO/periacetabular OR Surgical treatment OR Operation OR Surgical procedure OR Hip preservation surgery AND Adult OR Adolescence OR Old OR Women and men	9
PEDro		0
CINAHL		815
ASSIA		10
EMBASE		22
AMED		1
Total records identified through database search		857

Appendix 1 (Second area)

Database	Search strategy	Results
Medline	hip dysplasia OR congenital hip dislocation OR developmental dysplasia of the hip OR DDH OR hip dislocation OR subluxation OR Adults Hip AND Biomechanics OR kinematics OR kinetics OR Gait OR Mobility OR Gait analysis OR Dynamic OR movement OR pattern OR Ambulation/locomotion AND Adult OR Adolescence OR Old OR Women and men	101
PEDro		2
CINAHL		122
ASSIA		3
EMBASE		448
AMED		4
Total records identified through database search		680

Appendix 1 (Third area)

Database	Search strategy	Results
Medline		26

PEDro	hip dysplasia OR congenital hip dislocation OR developmental dysplasia of the hip OR DDH OR hip dislocation OR subluxation OR Adults Hip AND Physiotherapy OR Physical therapy OR Rehabilitation OR Treatment/Therapy OR Abductor muscle strengthening exercise OR Exercise OR activity OR activity levels OR sport AND Adult OR Adolescence OR Old OR Women and men	12
CINAHL		31
ASSIA		29
EMBASE		175
AMED		3
Total records identified through database search		276

Appendix 2

School of Healthcare Sciences
Head of School and Dean Professor David Whittaker

Ysgol Gwyddorau Gofal Iechyd
Pennaeth yr Ysgol a Deon Yr Athrawes David Whittaker

15 November 2018

Cardiff University
Eastgate House
13th Floor
35 – 43 Newport Road
Cardiff CF24 0AB

Tel Ffon: +44 (0)29 20 688559
Email E-bost HCAREEthics@cardiff.ac.uk

Prifysgol Caerdydd
13ed Llawr
Ty Eastgate
35 – 43 Heol Casnewydd
Caerdydd CF24 0AB

Fawaz Alrasheedi
Cardiff University
School of Healthcare Sciences

Dear Fawaz

Hip dysplasia: Patients movement patterns during walking, single limb stance and squatting and patients' experience of rehabilitation: mixed method study

At its meeting of ***13 November 2018***, the School's Research Ethics Committee considered your research proposal. The decision of the Committee is that your work should:

Proceed subject to the resubmission and approval of minor amendments made by the Committee Chair.

The Committee has asked that the lead reviewers' comments be passed onto you and your supervisor, please see attached.

The proposal, amended in the light of the above points and in discussion with your supervisor, should be emailed to me for consideration by the committee Chair. You should email your response to HCAREEthics@cardiff.ac.uk

When resubmitting your revised proposal you should provide a covering letter highlighting how and where you have amended the revised proposal, in the light of the above comments. You should clearly indicate the page number and line number/s, and you might find the following table a means of reporting the amendments you have made to the proposal. In addition, the changes should be highlighted in the revised documentation using the track changes facility.

Comment/Amendment required.	**My Response is;**	**Location in text i.e. page and line number.**

Please do not hesitate to contact me if you have any questions.

Yours sincerely

Mrs Liz Harmer – Griebel
Research Administration Manager

Cc : Tina Gambling, Robert van Deursen

Appendix 3

PARTICIPANT INFORMATION SHEET

Study Title

Hip dysplasia: Patients movement patterns during walking, single limb stance and squatting and patients' experience of rehabilitation: mixed method study

Invitation paragraph

- This is an invitation to involve in our study. A full description of the study aims and its contents are described in detail in this sheet. Feel free to ask the any part of our team if anything is not clear or need more clarification. You have the rights to have enough time to think about it and then you can decide whether to participate or not. This study will review and analyse the exercises chosen to determine which is the most effective in facilitating hip joint biomechanics and whether the patients tends to compensate during these exercises.

What is the purpose of the study?

- To recommend, based on the results, exercises that might be beneficial for DDH patients in order to maximise the benefits of rehabilitation program received.
- To compare between hip dysplastic joint with normal hip joint to see whether the exercises prescribed are suitable for DDH patients and to investigate what exercise is the most common/challenging among the exercises prescribed to DDH population.
- To explore patients' overall experience of rehabilitation.

Why have I been invited?

- You are being invited to join this study since you are diagnosed with Developmental Hip Dysplasia (DDH) and already have done the surgery. The researcher selected participants through contacting two popular charities, STEP and DDH UK.

Do I have to take part?

- As a matter of fact, taking part of this study is up to you. It is your choice to join this study or refuse. All the information regarding this study is either described in this sheet or orally, if preferred. If agreed, you will be given a consent form to sign in that you want to take part of this study. You can withdraw at any point of this research without notice ahead.

What will happen to me if I take part?

- After deciding to take part of the study, you are required to sign the consent form. It needs to be noted that if you felt uncomfortable you can withdraw at any point of the study. Your participation in this study will require you to do five different exercises on treadmill at Research Centre for Clinical Kinesiology (RCCK), School of Healthcare Science (HCARE) at Cardiff University. The session might last for approximately 90 to 120 minutes.

What will I have to do?

- At the beginning you will be asked to change to appropriate sport tight clothes so that the markers can fit (preferably shorts). There is a changing room and a toilet in the laboratory. You will be asked at the beginning about your medical condition and status, age, and other relevant information stated in the inclusion criteria will be asked/obtained in order to make sure that you meet the inclusion criteria. Then you will be given a consent form that explains the procedure of each exercise and the possible risks and you will be asked to sign it if you agree. The purpose of the study will be explained; if you need further clarification, it is your right to ask at any time. After receiving the signed consent form the data collection, the study will start. At the beginning, anthropometric data will be measured in order to setup the software to collect the data. Then, the participant will be asked to wear appropriate clothes in order to set the marker clearly and shoes. The markers set according to Vicon Plug-in-gait model and the targeted areas are pelvis, hip, knee and ankle. You will be asked to wear a safety harness that will protect you from falling while walking on the treadmill.

  You will be asked to do the three exercises while standing on treadmill or over ground. Exercises are walking at normal speed, single limb balance and double limb squat. A clear voice command will be given at the beginning of each exercise. Five trials will be calculated and the average of these trials will be considered during the data analysis. The final stage will be the removal of all the equipment from you.

What are the possible disadvantages and risks of taking part?

A form to assess the risk assessment of the laboratory that will be used on this research project can be found in the appendices below. As far as the researcher knows, there will be no side effect regarding using the treadmill except if the virtual environment will be used, then a dizziness might happen due to the screen. In order to avoid that, the researcher will either turn off the screen and carry on the exercise. Alternatively, give the patient enough time between the trials. Falls is a risk that might happen. However, acceptable lighting and a dry floor will be ensured prior to conducting any investigation. Perimeter will keep people at safe distance from the operating system. This acts as further control measure to decrease the probability of falling.

-

What are the possible benefits of taking part?

- We hope to be able to better understand the rehabilitation process for patients with DDH.
- We hypothesised and found that persons with DDH would show superior directed hip joint contact force as a movement compensation to alleviate pain by increasing ankle pronation and decreased hip extension. Therefore, we hypothesise that patients with hip dysplasia would compensate during the rehabilitation process by adapting new positions to avoid aggravating positions.

  However, for participants in this research study no benefit is expected during this study.

Will my taking part in the study be kept confidential?

- At the time you consent all the information given at any point of this study will be confidential. All personal details if given will be removed so that no one could identify you. The confidentiality of the participants is guaranteed.

What will happen if I don't carry on with the study?

- As mentioned above, you have the right to withdraw at any point of this study. According to Cardiff University guidelines all the collected information will be strictly confidential.

What will happen to the results of the research study?

- We hope that the analysed data will help us to identify the DDH patients' movement and whether the exercises in the clinics are considered appropriate or if these exercises should be changed. This research will help us building the base for future researches. In addition, if publication approval is received the participants will be notified.

What if there is a problem?

- In order to conduct this study smoothly you will be politely asked to follow and co-operate with the given instructions. If you want to complain about any concern that you have, any mistreatment or are approached in non-appropriate way, please directly contact Dr Kate Button the Director of Research Governance via email: buttonk@cardiff.ac.uk OR Fawaz Alrasheedi via email on: Alrasheedifd@cardiff.ac.uk

- If you think that the complaint is not handled well or not taken seriously, you can formally contact the faculty of Healthcare at Cardiff University or contact the Postgraduate research director DR. Tina Gambling at gamblingts@cardiff.ac.uk

Appendix 4

Consent Form

Hip dysplasia: Patients' movement patterns during walking, single limb stance and squatting and patients' experience of rehabilitation: mixed method study

Please Initial box

1- I confirm that I have read the information sheet dated .... for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2- I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my legal rights being affected. ☐

3- I understand that all data recorded including photographs or videos will be stored securely for a minimum of 10 years following the end of the study. ☐

4- I do agree/do not agree (delete as applicable) for you to share anonymised information with external collaborators. ☐

5- I understand that the information collected about me will be used to support other research in the future, and may be shard anonymously with other researchers. ☐

6- I do allow the use of anonymised videotapes and/or still pictures of myself for:

A. Teaching and Research Presentation ☐

B. Research Publications ☐

7- I agree to take part in the above study ☐

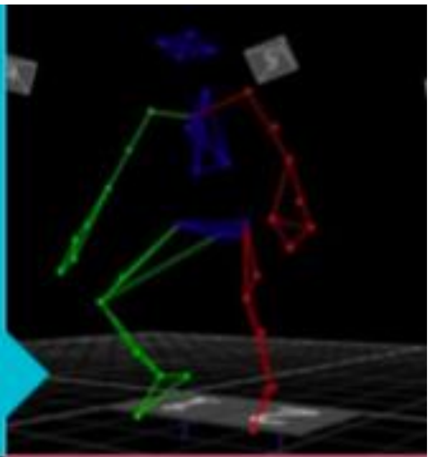
Name of Participant	Date	Signature

Name of Person taking consent	Date	Signature

<u>Subject Identification Number for this Investigation: ……………………</u>

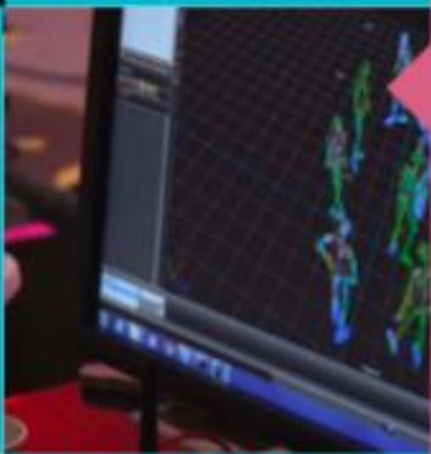
MOTION ANALYSIS

Gait laboratory is considered as one of the most accurate and objective ways to measure patient's movement.
Gait laboratory will help us assess your musculoskeletal system to predeict and prevent injuries.



THE GOAL OF THIS RESEARCH

We hope by doing this research is to be able to recommend exercises benficial for U.

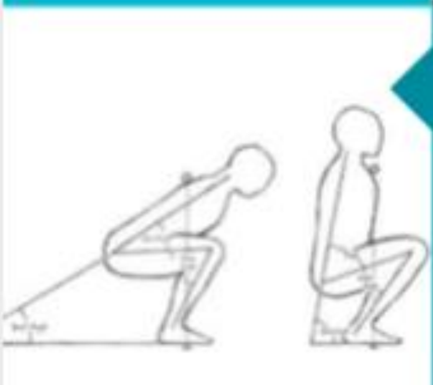


WHATS THIS STUDY ABOUT

1-To compare between hip dysplastic joint and normal hip joint.

2-To investigate what exercises are the most common/chllenging among the exercises perscribed.

3-To explore patients overall experience of rehabilitaaiton.



WHOSE INVOLVE

If you are adult whom

- Diagnosed with hip dysplasia and underwent a hip preservation surgery.

- Unilateral Hip Dysplasia

- Healing evident on x-rays
- No major surgery in the last 6 months (excluding hip surgery)

WHAT TO DO:

Yoy will attend one session that includes:
- Assessment and measurements
- Doing three exercises (walking, squat and one leg baance).

How to contact us?
1- Fawaz Alrasheedi
AlrasheediFD@cardiff.ac.uk
2-Dr.Tina Gambling
GamblingTS@cardiff.ac.uk
3-Prof. Robert Van Deursen
vandeursenr@cardiff.ac.uk
Telephone: +44 (0)29 206 87555

Scan the logos below to see Cardiff Hip Pain accounts and ask if you have inquiry:

Appendix 6-A

A. Laboratory Risk Assessment Form (GRAIL system)

Location: Research Centre for Clinical Kinesiology (RCCK)

Equipment/system: Gait Real-time Analysis Interactive laboratory (GRAIL) contains:

Instrumented treadmill; D-Flow software; Vicon motion capture system; 180° semi-cylinder projection system; safety harness system.

Task being assessed: Walking

Name of investigator: ______________________ **Date:** __________________

Please Contact: 1- Fawaz Alrasheedi. School of Healthcare Sciences, East Gate House, Cardiff University
AlrasheediFD@cardiff.ac.uk
2- Prof. Robert Van Deursen, School of Healthcare Sciences, Cardigan House, Cardiff University
vandeursenr@cardiff.ac.uk

Risk assessment *

Hazard	Preventive safety measures	Persons who may be harmed	Further control measures	Degree of risk (1-5) (See Table 1)				
				1 Rare	2	3	4	5 Almost certain
1.Electric shock	Connect to a supply main with protective earth. If fault or damaged parts are detected, then GRAIL system should be stopped immediately and step away from the system.	Operator/Subject	Make sure that the system is switched off electrically. System daily and monthly inspection. Perimeter (would keep people at safe distance from the operating system)	1				
2.Tripping over wires.	Number of wires reduced to a minimum and those remaining are moved out of the way.	Operator/Subject	Visitors will be warned of their presence when entering the laboratory and after each task.		2			
3.Failure of the safety harness.	Subject's weight should be under 135 kg or 300 lbs. Make sure that each subject is wearing the harness fit his/her size. Safety harness and life line protect against falling. The safety harness secured with a life line to the celling.	Subject	Daily system check and monthly system check FOR the safety harness.	1				

Hazard	Preventive safety measures	Persons who may be harmed	Further control measures	Degree of risk (1-5) (See Table 1)				
				1 Rare	2	3	4	5 Almost certain
4. Tripping or falling while stepping on/off the treadmill.	The operator will guide the subject while stepping on and off the treadmill.	Subject	Protective side panels added; however, no one is allowed to step on these panels.		2			
5. Failure of the side bars.	Side bars support the subject who cannot fully standalone until the subject leaves the treadmill safely.	Subject	Daily system check and monthly system check FOR the side bars.	1				
6. Damage of eyesight, reflective surface may cause irregularities in applications.	Subjects will be asked to take a rest for at least 3-5 minutes before performing the next exercise.	Operator/Subject	If the area surrounding the system has reflective materials/surfaces, the surrounding area will be covered or removed.	1				
7. Dizziness might be experienced with use of the 3D environment.	During the assessment the patient will be asked if diagnosed with visual impairment and will be excluded if the answer is yes.	Subject	Enough time will be given to the patient before carrying on the next exercise.	1				

*Please see **Table 1** below for the classification used above.

DECLARATION

I have carried out all risk assessment to the best of my ability and training and in accordance with the procedure given in this University Guide Note

Name and signature of person completing the form:

Name: Signature: Date:

Name and signature of person agreeing to remedial measures and target dates:

Name: Signature: Date:

Emergency procedures:

1. Make sure that the subject is safe and outside the system's operating area.
2. Support the subject if help needed to step of the treadmill.
3. Remove loose parts from operating area and check for any damages.
4. After everything is checked and the subject wants to carry on then, clear the suspension state and the system is ready to use.

Likelihood score (L)

Likelihood score	**1**	**2**	**3**	**4**	**5**
Descriptor	**Rare**	**Unlikely**	**Possible**	**Likely**	**Almost certain**
Frequency How often might it /does it happen	This will probably never happen/recur	Do not expect it to happen/recur but it is possible it may do so	Might happen or recur occasionally	Will probably happen/recur but it is not a persisting issue	Will undoubtedly happen/recur. Possibly frequently.

Appendix 6-B

B. Laboratory Risk assessment (Vicon over-ground motion capture system)

Location: Research Centre for Clinical Kinesiology (RCCK)

Equipment: Vicon motion capture system

Task being assessed: Single limb balance and double limb squat.

Name of investigator: ______________________ **Date:** __________________

Please Contact: 1- Fawaz Alrasheedi. School of Healthcare Sciences, East Gate House, Cardiff University
AlrasheediFD@cardiff.ac.uk
2- Prof. Robert Van Deursen, School of Healthcare Sciences, Cardigan House, Cardiff University
vandeursenr@cardiff.ac.uk

Risk assessment *

Hazard	Preventive safety measures	Persons who may be harmed	Further control measures	Degree of risk (1-5) (See Table 1)				
				1 Rare	2	3	4	5 Almost certain
1. Slips and falls	Acceptable lighting and a dry floor will be ensured prior to conducting any investigation.	Participant/investigator	Perimeter (would keep people at safe distance from the operating system)	1				
2. Tripping over wires.	Number of wires reduced to a minimum and those remaining are moved out of the way. The investigator will guide the participant throughout the whole duration of different exercises.	Participant/investigator	Visitors will be warned of their presence when entering the laboratory and after each task.		2			
3. Risk of infection resulting contact with equipment/surf-ace.	A cleaning regime has been put in place to clean all equipment before and after use.	Participant/investigator	School cleaning crew to clean in regular bases weekly.	1				

Hazard	Preventive safety measures	Persons who may be harmed	Further control measures	Degree of risk (1-5) (See Table 1)				
				1 Rare	2	3	4	5 Almost certain
4. Damage of eyesight, reflective surface may cause irregularities in applications.	Subjects will be asked to take a rest for at least 3-5 minutes before performing the next exercise.	Participant	If the area surrounding the system has reflective materials/surfaces, the surrounding area will be covered or removed.	1				
5. Skin irritation because of the double-sided tape	During the assessment the participants will be asked if they are allergic or not.		Hypoallergenic tape will be used.					

*Please see **Table 1** below for the classification used above.

DECLARATION

I have carried out all risk assessment to the best of my ability and training and in accordance with the procedure given in this University Guide Note

Name and signature of person completing the form:

Name: Signature: Date:

Name and signature of person agreeing to remedial measures and target dates:

Name: Signature: Date:

Likelihood score (L)

Likelihood score	**1**	**2**	**3**	**4**	**5**
Descriptor	**Rare**	**Unlikely**	**Possible**	**Likely**	**Almost certain**
Frequency How often might it /does it happen	This will probably never happen/recur	Do not expect it to happen/recur but it is possible it may do so	Might happen or recur occasionally	Will probably happen/recur but it is not a persisting issue	Will undoubtedly happen/recur. Possibly frequently.

Appendix 6-C

A. Laboratory Risk Assessment Form (Biodex)

Location: Research Centre for Clinical Kinesiology (RCCK)

Equipment/system: Biodex

Task being assessed: Muscle strength

Name of investigator: ________________________ **Date:** ____________________

Please Contact: 1- Fawaz Alrasheedi. School of Healthcare Sciences, East Gate House, Cardiff University
AlrasheediFD@cardiff.ac.uk
2- Prof. Robert Van Deursen, School of Healthcare Sciences, Cardigan House, Cardiff University
vandeursenr@cardiff.ac.uk

Risk assessment

Hazard	Preventive safety measures	Persons who may be harmed	Further control measures	Degree of risk (1-5) (See Table 1)				
				1 Rare	2	3	4	5 Almost certain
1. Electric shock	The system is checked by the Biodex technical support team on a yearly basis to check that the equipment is safe and fit for purpose. Connect to a supply main with protective earth. If fault or damaged parts are detected, then Biodex system should be stopped immediately and step away from the system.	Operator/Subject	Make sure that the system is switched off electrically. System daily and monthly inspection before operation with subject. Perimeter (would keep people at safe distance from the operating system)	1				
2.Tripping over wires.	Number of wires reduced to a minimum and those remaining are moved out of the way.	Operator/Subject	Visitors will be warned of their presence when entering the laboratory and after each task.	1				
3. Tripping or falling while stepping on/off the chair.	The operator will guide the subject while stepping on and off the chair. Access to the	Subject	None	1				

	equipment does not require subjects to step over any wires.							
4. Muscle injury	Subjects will be asked to increase their muscle contraction gradually coached by the operator so that the strength test is executed safely. Subjects take a rest for at least 10 seconds rest between sets and 2 minutes rest between measuring different muscles.	Operator/Subject	If the patient felt exhausted or increased pain the test stops immediately.	1				
5. Delayed onset of muscle soreness (DOMS)	Repeated strong contractions are kept to a minimum to avoid setting the conditions for DOMS. The number of repetitions were limited to three.	Subject	Subjects take a rest for at least 10 seconds rest between sets and 2 minutes rest between measuring different muscles.	1				

DECLARATION

I have carried out all risk assessment to the best of my ability and training and in accordance with the procedure given in this University Guide Note

Name and signature of person completing the form:

Name: Signature: Date:

Name and signature of person agreeing to remedial measures and target dates:

Name: Signature: Date:

Emergency procedures:

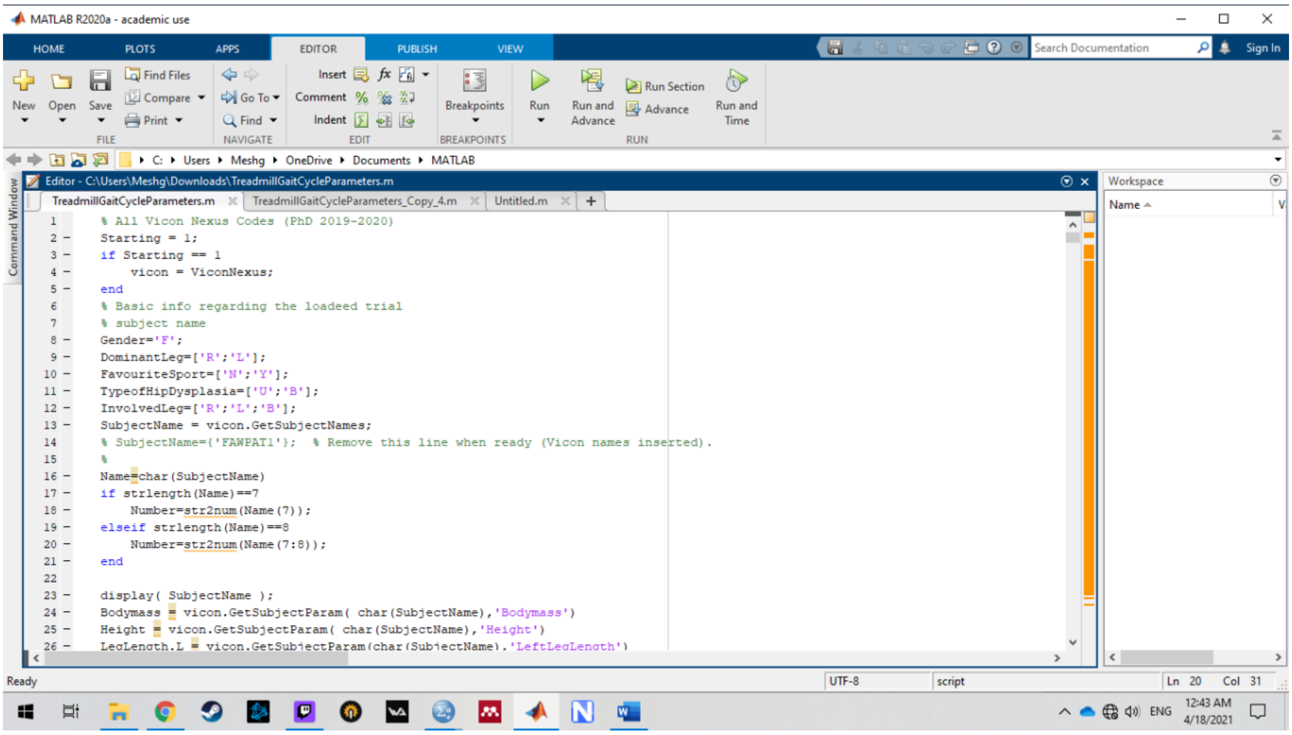
5. Make sure that the subject is safe and outside the system's operating area.

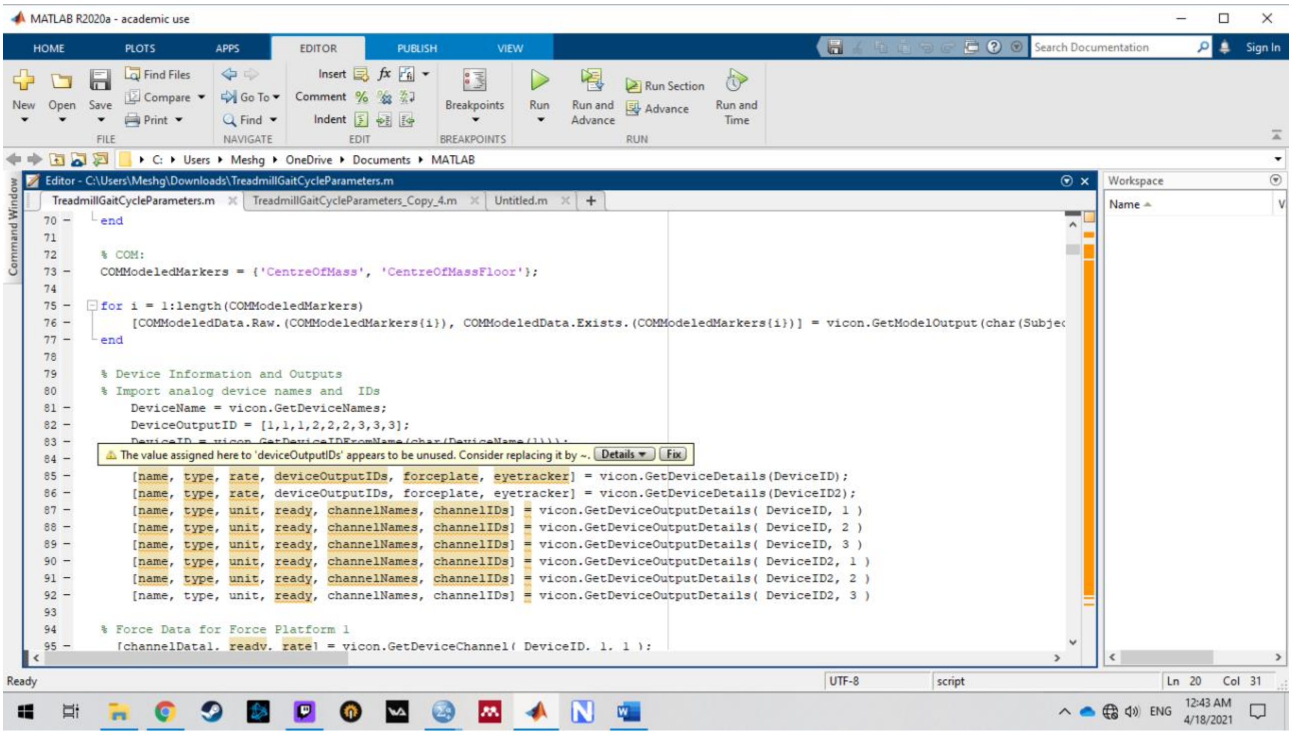
6. Support the subject if help needed to step of the treadmill.
7. Remove loose parts from operating area and check for any damages.
8. After everything is checked and the subject wants to carry on then, clear the suspension state and the system is ready to use.

Likelihood score (L)

Likelihood score	**1**	**2**	**3**	**4**	**5**
Descriptor	**Rare**	**Unlikely**	**Possible**	**Likely**	**Almost certain**
Frequency How often might it /does it happen	This will probably never happen/recur	Do not expect it to happen/recur but it is possible it may do so	Might happen or recur occasionally	Will probably happen/recur but it is not a persisting issue	Will undoubtedly happen/recur. Possibly frequently.

Appendix 7-A


MATLAB R2020a - academic use
Editor - C:\Users\Meshg\Downloads\TreadmillGaitCycleParameters.m
TreadmillGaitCycleParameters.m
TreadmillGaitCycleParameters_Copy_4.m
Untitled.m
% All Vicon Nexus Codes (PhD 2019-2020)
Starting = 1;
if Starting == 1
vicon = ViconNexus;
end
% Basic info regarding the loadeed trial
% subject name
Gender='F';
DominantLeg=['R';'L'];
FavouriteSport=['N';'Y'];
TypeofHipDysplasia=['U';'B'];
InvolvedLeg=['R';'L';'B'];
SubjectName = vicon.GetSubjectNames;
% SubjectName={'FAWPAT1'}; % Remove this line when ready (Vicon names inserted).
%
Name=char(SubjectName)
if strlength(Name)==7
Number=str2num(Name(7));
elseif strlength(Name)==8
Number=str2num(Name(7:8));
end
display(SubjectName);
Bodymass = vicon.GetSubjectParam(char(SubjectName),'Bodymass')
Height = vicon.GetSubjectParam(char(SubjectName),'Height')
LegLength.L = vicon.GetSubjectParam(char(SubjectName),'LeftLegLength')
Ready
Ln 20 Col 31
12:43 AM
4/18/2021


MATLAB R2020a - academic use
Editor - C:\Users\Meshg\Downloads\TreadmillGaitCycleParameters.m
end
% COM:
COMModeledMarkers = {'CentreOfMass', 'CentreOfMassFloor'};
for i = 1:length(COMModeledMarkers)
[COMModeledData.Raw.(COMModeledMarkers{i}), COMModeledData.Exists.(COMModeledMarkers{i})] = vicon.GetModelOutput(char(Subjec
end
% Device Information and Outputs
% Import analog device names and IDs
DeviceName = vicon.GetDeviceNames;
DeviceOutputID = [1,1,1,2,2,2,3,3,3];
The value assigned here to 'deviceOutputIDs' appears to be unused. Consider replacing it by ~. Details Fix
[name, type, rate, deviceOutputIDs, forceplate, eyetracker] = vicon.GetDeviceDetails(DeviceID);
[name, type, rate, deviceOutputIDs, forceplate, eyetracker] = vicon.GetDeviceDetails(DeviceID2);
[name, type, unit, ready, channelNames, channelIDs] = vicon.GetDeviceOutputDetails(DeviceID, 1)
[name, type, unit, ready, channelNames, channelIDs] = vicon.GetDeviceOutputDetails(DeviceID, 2)
[name, type, unit, ready, channelNames, channelIDs] = vicon.GetDeviceOutputDetails(DeviceID, 3)
[name, type, unit, ready, channelNames, channelIDs] = vicon.GetDeviceOutputDetails(DeviceID2, 1)
[name, type, unit, ready, channelNames, channelIDs] = vicon.GetDeviceOutputDetails(DeviceID2, 2)
[name, type, unit, ready, channelNames, channelIDs] = vicon.GetDeviceOutputDetails(DeviceID2, 3)
% Force Data for Force Platform 1
[channelData1, ready, rate] = vicon.GetDeviceChannel(DeviceID, 1, 1);
Ready
Ln 20 Col 31
12:43 AM
4/18/2021

Appendix 7-B

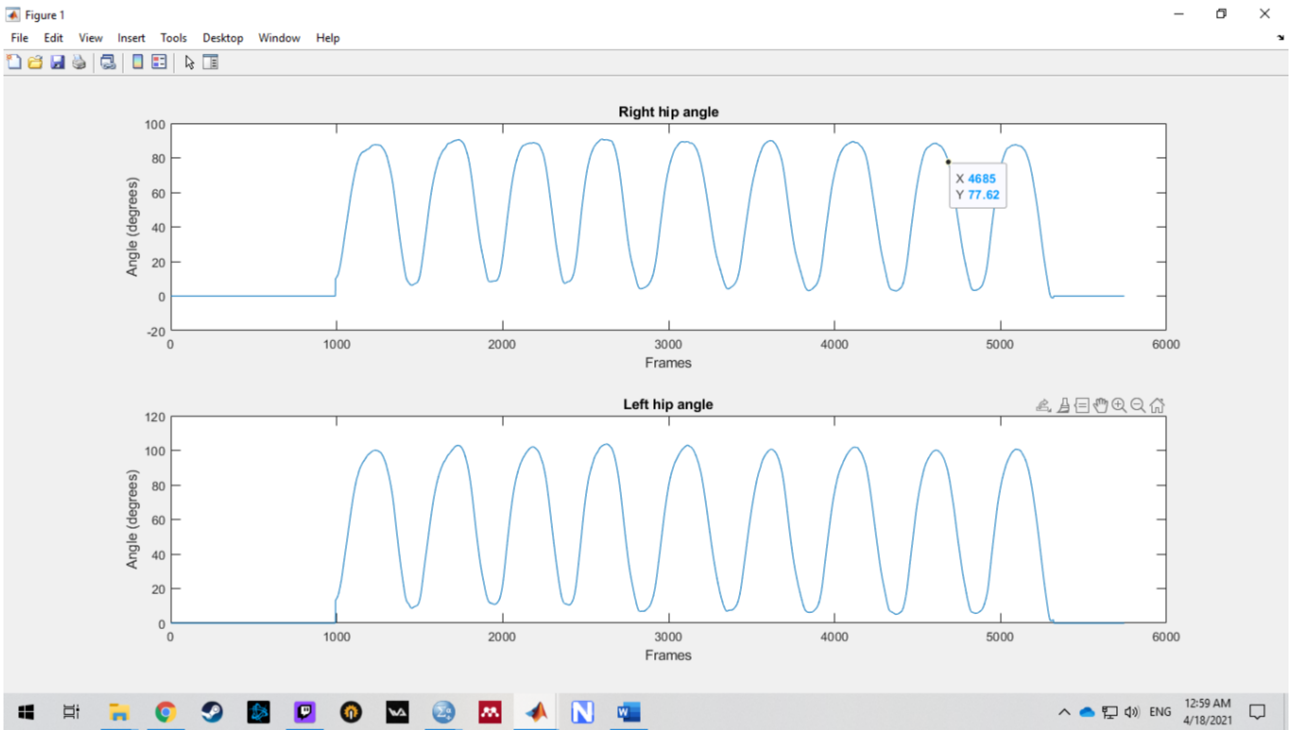


Figure 1
File Edit View Insert Tools Desktop Window Help
Right hip angle
Angle (degrees)
Frames
X 4685
Y 77.62
Left hip angle
Angle (degrees)
Frames
ENG
12:59 AM
4/18/2021

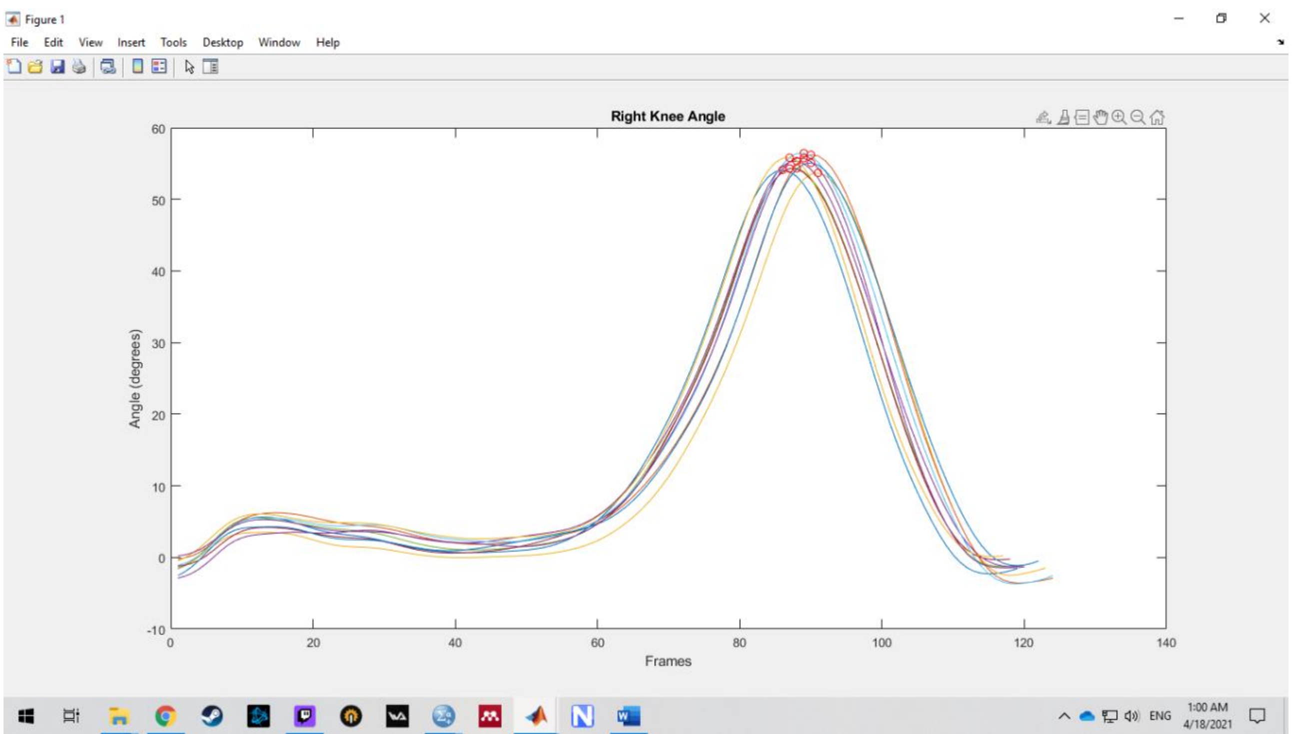


Figure 1
File Edit View Insert Tools Desktop Window Help
Right Knee Angle
Angle (degrees)
Frames
ENG
1:00 AM
4/18/2021

Appendix 8

Questionnaire for DDH patient rehabilitation post-operative

p. 1 Questionnaire overview

Thank you for agreeing to take part in the Hip Dysplasia Experience of Rehabilitation Questionnaire. This questionnaire should only take around 10 minutes to complete. Be assured that all answers you provide will be kept confidential.

Questionnaire Aim

To understand how physiotherapists manage patients with hip dysplasia post operatively, we are aiming to investigate the common exercises prescribed by physiotherapists within clinics and the home. We would like to investigate the duration, frequency, and intensity of the physiotherapy programme postoperatively.

CONESNT

Participation

Your participation in this survey is voluntary. You may refuse to take part in the research or exit the survey at any time without penalty.

Benefits

You will receive no direct benefits from participating in this research study. However, your responses may help us learn more about Hip Dysplasia.

Confidentiality

Your survey answers will be sent to a link at: https://admin.onlinesurveys.ac.uk where data will be stored in a password protected electronic format. The website onlinesurveys.ac.uk does not collect identifying information such as your name, email address, or IP address. Therefore, your responses will remain anonymous. No one will be able to identify you or your answers, and no one will know whether or not you participated in the study.

Please select your choice below. Clicking on the “Yes” button indicates that:

- You have read the above information
- You voluntarily agree to participate
- You are 18 years of age or older
- Diagnosed with hip dysplasia

I consent to participate in this survey

- Yes
- No

p. 2 Demographic Data

2 Age: …………

3 Gender:

- Male
- Female
- Prefer not to say

4 Dominant Leg:

- Right
- Left

5 Involved Leg (operated leg):

- Right
- Left
- Both

6 Type of surgery:
- Hip preservation surgery
- Hip arthroplasty
- I don't know
- If you selected Other, please specify:

p. 3 Rehabilitation/physiotherapy program
The first section explores the physiotherapy process immediately after the surgery.
7 How many times have you attended physiotherapy sessions per week?
- Once
- Twice
- Three times
- Daily

8 How long does each session last for?
- 30 minutes
- 30-60 minutes
- Other

If you selected Other, please specify:

9 What exercises have you been doing (did you do) immediately postoperative in the clinic or at home?
- Walking training with crutches
- Bed exercises for the affected leg
- Range of motion exercises
- Other

If you selected Other, please specify:

10 What exercises have you been doing (did you do) after you received full weight bearing clearance (able to stand on your operated leg)? Name or describe them

11 How many non-weight bearing exercises and weight-bearing exercises are recommended by your therapist? Weight-bearing exercises (supporting your own weight) such as: walking, hiking and dancing. Non-weight-bearing exercises (without supporting your own weight) such as: swimming and lifting weight.
a Describe the non-weight bearing exercises and the weight-bearing exercises are recommended by your therapist.

12 How long did it take physiotherapists to stop therapy sessions and recommend home exercises only?
- Two weeks
- Three weeks
- One month
- Not applicable
- Other

If you selected Other, please specify:

13 What exercises that have been (were) recommended for you to do at home? (if not recommended just write not applicable)

14 How many times have you have been asked to do these exercises at home by your physiotherapist?
- Daily

- Five times a week
- Three times a week
- One time per week
- Not applicable

15 Do you think that the exercises recommended to you by your therapists are helping (helped) the progress of your rehabilitation process?

- Strongly agree
- Agree
- Neither agree or disagree
- Disagree
- Strongly disagree

16 Have you been doing any additional exercises?

- Yes
- No

If you selected yes, please specify or describe them:

17 Which source of information that has led you to do these additional exercises?

- Expert in rehabilitation team different from your main therapist
- Medical journal/website
- Google
- YouTube
- Word of mouth (for example other patients)
- Other
- If you selected Other, please specify:

18 What are the benefits that you gain when you did these additional exercises?

- Improved hip movement
- Decreased pain
- Increased walking time
- Not applicable
- Other

If you selected Other, please specify:

19 Do you think further exercises should have been included in your rehabilitation program that may have been suggested by friends, private therapist etc.…?

- Yes
- No

20 What is your overall opinion about the rehabilitation process after being discharged from the hospital?

- Excellent
- Normal
- Not efficient enough
- Not applicable
- Other

If you selected Other, please specify:

21 Do you consider yourself able to compete to a high level of activities? such as skiing, tennis, jogging etc...

- Yes
- No
- Maybe sometime in the future

p. 4 New movement pattern/new strategies to overcome the issue of feeling the pain
Further questions added to investigate the possible limitation and movement compensation that might happen when neglecting certain muscles strengthening exercises.

22 Prolonged setting affects my hip condition
- Strongly agree
- Agree
- Neither agree or disagree
- Disagree
- Strongly disagree

23 Prolonged standing affects my hip condition
- Strongly agree
- Agree
- Neither agree or disagree
- Disagree
- Strongly disagree

24 Can you step over a small box on the floor with ease?
- Yes
- No

25 Do you experience any hip pain when you pick up an object of the floor?
- Yes
- Sometimes
- No

26 Did you come up with a new strategy to avoid pain? For example, have you identified any strategies that you had used to modify the exercises you have been doing OR any movement that you asked to do?
- Yes
- No

If you selected Yes, please specify the new strategy:

27 If you are in a hurry and need to walk faster, do you find it uncomfortable taking longer steps?
- Yes
- Sometimes
- No

p. 5 University of California, Los Angeles (UCLA) activity score
28 Check one box that best describes current activity level.
1- Wholly inactive, dependent on others, and cannot leave residence.
2- Mostly inactive or restricted to minimum activities of daily living.
3- sometimes participate in mild activities such as walking limited housework and limited shopping.
4- Regularly participate in mild activities.
5- sometimes participates in moderate activities such as swimming or could do unlimited housework or shopping.
6- Regularly participate in moderate activities.
7- Regularly participates in active events such as bicycling.
8- Regularly participates in active events such as golf or bowling.
9- Sometimes participates in impact sports such as jogging, tennis, skiing, acrobatics, ballet heavy labour or backpacking
10- Regularly participates in impact sports

p. 6 The modified Harris hip score (mHHS)
Please answer the following questions as they pertain to your hip:
29 Pain
- None/able to ignore it
- Slight, occasional, no compromise in activity
- mild, no effect on ordinary activity, pain after usual activity, use aspirin/ibuprofen/Tylenol
- Moderate tolerable makes concessions occasional narcotics
- Marked serious limitations
- Totally disabled

Function: Gait
30 Limp
- None
- Slight
- Moderate
- Sever
- Unable to walk

31 Support
- Cane for long walks
- Cane all the time
- Crutch
- 2 canes
- 2 crutches
- Unable to walk

32 Distance Walked
- Unlimited
- 6 Blocks
- 2-3 block
- Indoors only
- Bed and chair

Functional activities
33 Stairs
- Can go up/down normally
- Can go up/down normally with banister
- Any method
- Unable

34 Socks/shoes
- With ease
- With difficulty
- Unable

35 Sitting
- Any chair, 1 hour
- High chair, 1/2 hour
- Unable to sit, 1/2 hour, any chair

36 Public Transportation
- Able to enter public transportation
- Unable to use public transportation (such as bus, or airport transportation)

37 Please write down your email if you are agreeing to be contacted to participate in the second phase of this project (movement analysis).

p. 7 Final page
Thanks a lot
Thank you for taking the time to complete this survey. We truly value the information you have provided.
If you have something in your mind that we haven't asked you about or you have any further information wanted to add please contact us on the email:
GamblingTS@cardiff.ac.uk OR AlrasheediFD@cardiff.ac.uk

Appendix 9

Questionnaire for activity Assessment: Activity level was assessed with the University of California, Los Angeles (UCLA) activity score (1 to 10)

UCLA Activity Score	Hip ID:
	Study Hip: ☐ Left ☐ Right
	Examination Date (MM/DD/YY): / /
	Subject Initials: |___|___|___|
	Medical Record Number:

Interval: _____________

Check one box that best describes current activity level.

☐ 1: Wholly Inactive, dependent on others, and can not leave residence

☐ 2: Mostly Inactive or restricted to minimum activities of daily living

☐ 3: Sometimes participates in mild activities, such as walking, limited housework and limited shopping

☐ 4: Regularly Participates in mild activities

☐ 5: Sometimes participates in moderate activities such as swimming or could do unlimited housework or shopping

☐ 6: Regularly participates in moderate activities

☐ 7: Regularly participates in active events such as bicycling

☐ 8: Regularly participates in active events, such as golf or bowling

☐ 9: Sometimes participates in impact sports such as jogging, tennis, skiing, acrobatics, ballet, heavy labor or backpacking

☐ 10: Regularly participates in impact sports

Appendix 10

The modified Harris hip score (mHHS): the mHHS proven to reflect patient's pain and functional status for active patients.

Name________________________________ Date_________________

MODIFIED HARRIS HIP SCORE

Please answer the following questions as they pertain to your hip:

Pain:
☐None/Able to ignore it
☐Slight, occasional, no compromise in activity
☐Mild, no effect on ordinary activity, pain after usual activity, use aspirin/ibuprofen/Tylenol
☐Moderate, tolerable, makes concessions, occasional narcotic
☐Marked, serious limitations
☐Totally disabled

Function: Gait

Limp
☐None
☐Slight
☐Moderate
☐Severe
☐Unable to walk

Support
☐None
☐Cane for long walks
☐Cane all the time
☐Crutch
☐2 canes
☐2 crutches
☐Unable to walk

Distance Walked
☐Unlimited
☐6 blocks
☐2-3 blocks
☐Indoors only
☐Bed and chair

Functional Activities

Stairs
☐ ☐Can go up/down normally
☐ ☐Can go up/down normally with banister
☐ ☐Any method
☐ ☐Unable

Socks/Shoes
☐☐With ease
☐☐With difficulty
☐☐Unable

Sitting
☐☐Any chair, 1 hour
☐☐High chair, ½ hour
☐☐Unable to sit, ½ hour, any chair

Public Transportation
☐☐Able to enter public transportation
☐☐Unable to use public transportation
(such as bus, or airport transportation)

For Internal Use:

Score__________
Initials__________

Appendix 11

Results of questionnaire piloting study

Results of questionnaire piloting study				
Questions	Patients 3	Patients 4	Patients 5	Patients 6
1) How long did it take you to complete?	10 minutes	15 minutes	15 minutes	10 minutes

2) Were the instructions clear?	Yes	Yes	Yes	Yes
3) Were any of the questions unclear or ambiguous? If so, will you say which and why?	No	Very clear questions	No	No
4) Did you object to answering any of the questions?	No	No	No	No
5) In your opinion, has any major topic been omitted?	No	No	No	No
6) Was the layout of the questionnaire clear/attractive?	Yes	Yes	Yes	Yes
7) Any comments?	No	No	No	No

Results of questionnaire piloting study				
Questions	Patients 7	Patients 8	Patients 9	Patients 10
1) How long did it take you to complete?	Approximately 8 minutes	No more than 10 minutes	15 minutes	Around 10 minutes
2) Were the instructions clear?	Yes	Yes	Yes	Yes
3) Were any of the questions unclear or ambiguous? If so, will you say which and why?	No	No	No	No
4) Did you object to answering any of the questions?	No	No	No	No
5) In your opinion, has any major topic been omitted?	Maybe adding questions around the pain medications that helped after surgery	No	No	No
6) Was the layout of the questionnaire clear/attractive?	Yes	Yes	Yes	Yes
7) Any comments?	No	No	No	No

Results of questionnaire piloting study				
Questions	Patients 11	Patients 12		
1) How long did it take you to complete?	Around 15 minutes	10 minutes		
2) Were the instructions clear?	Yes	Yes		
3) Were any of the questions unclear or ambiguous? If so, will you say which and why?	No	Question number 3 I'm not sure what type of surgery I had		

4) Did you object to answering any of the questions?	No	No		
5) In your opinion, has any major topic been omitted?	Maybe how many times I was referred to physiotherapy department. The reason why I'm saying this is that I have been referred so many times with no real benefit.	No		
6) Was the layout of the questionnaire clear/attractive?	Yes	Yes		
7) Any comments?	No	No		

Appendix 12-A

Invitation to participate in research (Hip Dysplasia group)

Hello

We are a research group that running a project that investigate the rehabilitation of Developmental Dysplasia of the Hip (DDH) patients and investigate the possible effect of the exercises prescribed and whether these exercises are done in a right way that benefits you. This is a PhD project run by Mr Fawaz Alrasheedi, a Physiotherapist, and we are based in **Research Centre for Clinical Kinaesiology (RCCK) at Cardiff University, Cardiff.**

We are aiming by doing this research:

- To compare between hip dysplastic joint with normal hip joint to see whether the exercises prescribed are suitable for DDH patients and to investigate what exercise is the most common/challenging among the exercises prescribed to DDH population.
- To explore patients overall experience of rehabilitation.

The project consists of two parts:

The first phase will be exploring the current experience of rehabilitation in order to understand/explore the rehabilitation process for hip dysplasia patients.

- **How this part will be answered: Online questionnaire will be distributed and will take 10-15 minutes to complete.**
- **What to do: fill the questionnaire and submit it or send it to** AlrasheediFD@cardiff.ac.uk.

The second phase is the new experience that hopefully will enrich the research area around DDH and bring attention to this unsearched area. We will be using a motion capture system that detects your movement during three different exercises: walking, squatting and balance on one leg to detect abnormal patterns, if exist.

- **How this part will be answered: One session consists of quick assessment and measurements, doing three exercises (walking, squatting and balance on one leg) and filling a questionnaire for the first phase if not done before. This session lasts for 1.30-2h**

- **What to do: book for an appointment by sending email to AlrasheediFD@cardiff.ac.uk and bring sport wear. Do the exercises and enjoy the experience.**

You will get:

- **The study results will be sent to your email with explanation of the patterns shared and suggestions after analysing the data.**
- **Voucher of 40£ + Refreshments.**
- **Using Gait Real-time Analysis Interactive Laboratory might reveal things about your body that you have no idea about!!**

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Appendix 12-B

Invitation to participate in research

Hello all

We are a research group running a project that investigates the rehabilitation of Developmental Dysplasia of the Hip (DDH) patients and investigate the possible effect of the exercises prescribed and whether these exercises are done in a right way that benefits the patients. This is a PhD project t run by Mr Fawaz Alrasheedi, a Physiotherapist, and we are based in **Research Centre for Clinical Kinaesiology (RCCK) at Cardiff University, Cardiff.**

We are aiming by doing this research:

- To compare between hip dysplastic joint with normal hip joint to see whether the exercises prescribed are suitable for DDH patients and to investigate what exercise is the most common/challenging among the exercises prescribed to DDH population.
- To explore patients' overall experience of rehabilitation.

The project consists of two parts:

The first phase will be exploring the current experience of rehabilitation in order to understand/explore the rehabilitation process for hip dysplasia patients.

- **How this part will be answered: Online questionnaire will be distributed and will take 10-15 minutes to complete (DDH PATIENTS ONLY).**

The second phase is the new experience that hopefully will enrich the research area around DDH and bring attention to this unsearched area. We will be using a motion capture system that detects the patient movement during three different exercises: walking, squatting and balance on one leg to detect abnormal patterns, if they exist.

- **How this part will be answered: One session consists of quick assessment and measurements, doing three exercises (walking, squatting and balance on one leg). This session lasts for 1.30-2 hours.**
- **What to do: book for an appointment by sending email to AlrasheediFD@cardiff.ac.uk and bring sport wear. Do the exercises and enjoy the experience.**

You will get:

- **The study results will be sent to your email with explanation of the patterns shared and suggestions after analysing the data.**

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- **Voucher of 20£ + Refreshments.**
- **Using Gait Real-time Analysis Interactive Laboratory might reveal things about your body that you have no idea about!!**

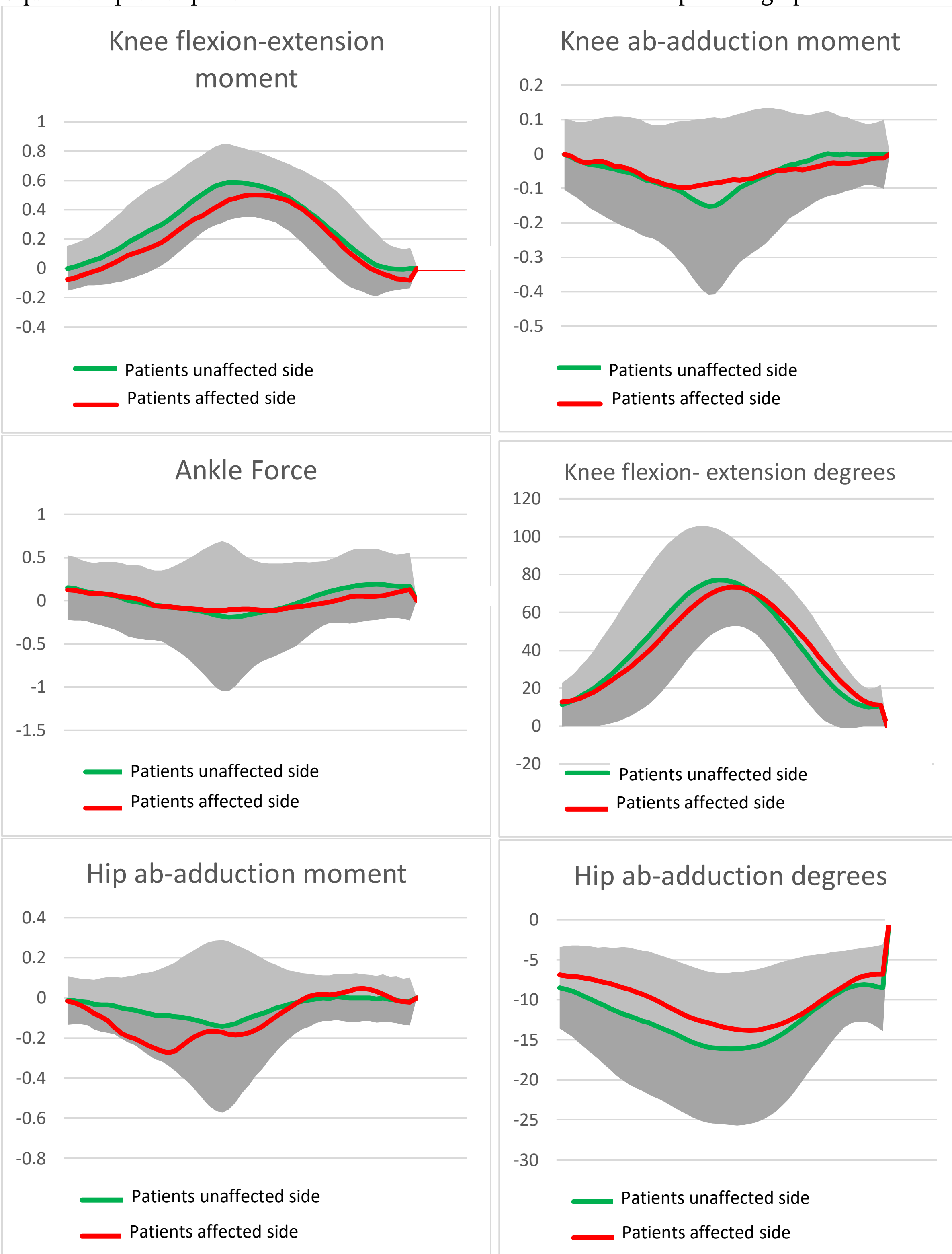
Appendix 13

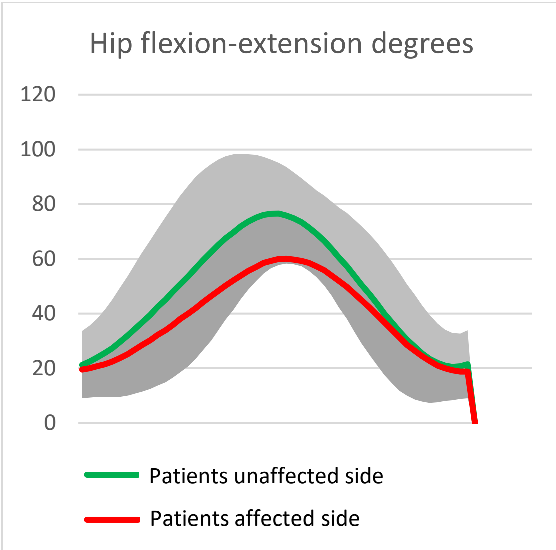
Name	Description	References (number of this word reported)*
10. What exercises have you been doing (did you do) after you received full weight-bearing clearance (able to stand on your operated leg)? Name or describe them.		48
General Exercises	Any exercise that targets the whole body and different muscle groups needs to be active in order to do the exercise (no specific muscle group acts as the prime mover)	13
Cycling	Includes stationary bike and all other variations of cycling	11
Hydrotherapy	All Exercises done at the pool	7
Running	Running exercise	1
Step-up and Stairs	Step-up exercises, variation and stairs exercises.	11
Swimming	Swimming exercise	5
Walking	Walking as an exercise	16
Hip and Pelvis Exercises	Any exercise that targets the hip muscles or the pelvis mainly (hip muscles are the prime mover)	129
Balance Exercises	Any balance exercise that targets the hip muscles group.	22
Bed Exercises	All exercises that are done on bed	1
Isometric Exercises	Isometric exercises that are done on bed	5
Clam	All variations of clam exercises	13
Glutes Exercises	Gluteus Medius muscle is the prime mover for the included Exercises	21
Hip strengthening exercises	Any strengthening exercise that targets the hip muscles mainly (hip muscles are the prime mover)	19

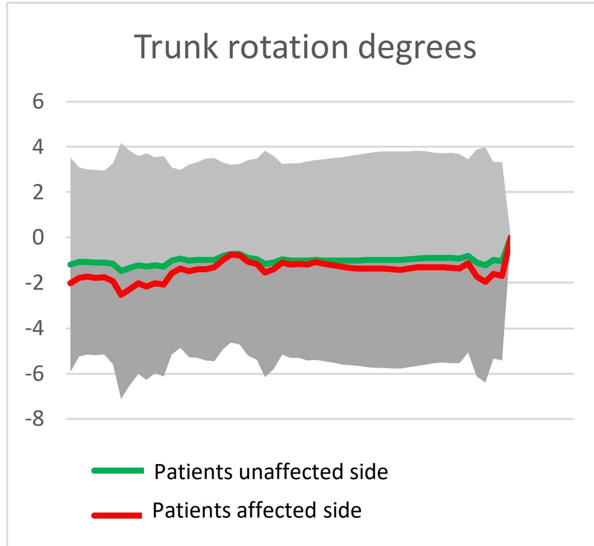
Name	Description	References (number of this word reported)*
Lunges	Lunges exercise	7
Pelvic exercises	Pelvic exercises	1
Range Of Motion (ROM) exercises	Range of motion exercises whether done on bed or while standing	21
Squat	All variations of squat	24
Stretches	Any stretching exercises	8
Whole leg exercises	Any exercise that requires different leg muscles to contract to do the exercises (no specific prime mover)	13
General balance exercises	Any exercise that targets the whole body balance (not specifically for a certain muscle group)	2
Knee exercises	Exercises that target knee muscles mainly	1
Leg strengthening exercises	Any exercise that targets the whole leg and specifically the hip muscles group in order to do the exercise.	10

Appendix 14

Squat: samples of patients' affected-side and unaffected-side comparison graphs




Hip flexion-extension degrees
120
100
80
60
40
20
0
Patients unaffected side
Patients affected side


Trunk rotation degrees
6
4
2
0
-2
-4
-6
-8
Patients unaffected side
Patients affected side

Appendix 15

SLB: samples of patients' unaffected-side and affected-side comparison graphs