A COMPARATIVE STUDY OF TENDINOUS INTERCONNECTION IN THE FOREARM AND HAND OF HUMAN CADAVERS AND LIVE SUBJECTS

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Submitted in accordance with the requirements for the degree of

Master of Philosophy

2013

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ABSTRACT

Certain complex hand functions such as playing musical instruments, buttoning and writing require the action of the long flexor tendons. Repeated movements of these tendons cause inflammatory changes resulting in an increase in the Tendon Cross Sectional Area (TCSA), and, subsequently, tendinous interconnections (occurs in approximately 20% of the general population, commonly between the flexor pollicis longus [FPL] and index finger flexor digitorum profundus [FDP] - Linburg-Comstock syndrome). Coupled with an anatomically congested space at the wrist, such interconnections may compress the median nerve resulting in carpal tunnel syndrome. This study evaluated the prevalence of tendinous interconnection amongst 200 medical students at Cardiff University by a series of structured hand movements (n=12) in controlled setting. The findings were corroborated using Ultrasound Scan (USS) (n=4) and Magnetic Resonance Imaging (MRI) (n=1). The muscle mass, fibre length, density, angle of pennation and tendon length were ascertained by studying hands and forearms (n=30) of embalmed human cadavers. The data was used to determine the Physiological Cross Sectional Area (PCSA) and calculate the relation between PCSA and TCSA. Simple linear regression established the direct relation of PCSA to TCSA, muscle mass and tendon length. A direct relation between the TCSA of FPL and index finger FDP was identified. The cross sectional area of the median nerve increases as it traverses the carpal tunnel. The PCSA had no bearing on density and angle of pennation. USS was found to be more dynamic and sensitive than MRI in identifying tendinous and tenosynovial interconnections, as the tenosynovial interconnections <1 mm thick could be recognised. The study also (i) identified a lower percentage of tendinous interconnection (compared to the literature) in a randomly selected group of individuals, (ii) detected the limitation of photograpic measurements to study angles of finger movements and (iii) highlighted the disadvantage of calculating PCSA in cadavers.

ACKNOWLEDGEMENTS

This research and dissertation would not have materialised without the guidance and advocacy of several individuals who in one way or another contributed and extended their valuable assistance during the various stages.

Foremost, I would like to express my most sincere gratitude to my supervisor Dr Alan Watson for his steadfast support, prudence and direction. His steer greatly helped me to successfully complete my research and write this dissertation. In addition to supervising and guiding me, he patiently read all drafts and provided inestimable suggestions.

Special thanks are owed to Dr Hannah Shaw, Ms Lisa Mead and Mr Swaran Yarnell for providing relevant technical and scientific support towards specific aspects of the research. They were always willing to help and provide constructive criticism, albeit in a humorous and friendly manner.

I would also like to thank Professor John Woodcock (Medical Engineering Department, University Hospital of Wales) and Dr Sridhar Kamath (Consultant Musculoskeletal Radiologist, University Hospital of Wales) for helping me with the pertinent aspects of the research.

I would like to thank my family for their love and encouragement all these years. For my parents, who raised me with a love of science and supported me in all my pursuits. And most of all for my loving, supportive, encouraging and patient husband whose unconditional support throughout this journey is much appreciated. Last but not the least, I would like to thank our lovely children, Tanya, Keziah and Kristan who always cheer me up and bring a smile to my face at the end of a hard day at work!

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LIST OF ABBREVIATIONS USED IN THE DISSERTATION

APB	Abductor Pollicis Brevis
APL	Abductor Pollicis Longus
CMC	Carpo-metacarpal
CSA	Cross-sectional Area
CTS	Carpal Tunnel Syndrome
DIP	Distal Inter-phalangeal
ECRB	Extensor Carpi Radialis Brevis
ECRL	Extensor Carpi Radialis Longus
ECU	Extensor Carpi Ulnaris
EDC	Extensor Digitorum Communis
EDM	Extensor Digiti Minimi
EIP	Extensor Indicis Proprius
EPB	Extensorr Pollicis Brevis
EPL	Extensor Pollicis Longus
FCR	Flexor Carpi Radialis
FCSA	Functional Cross-sectional Area
FCU	Flexor Carpi Ulnaris
FDP	Flexor Digitorum Profundus
FDS	Flexor Digitorum Superficialis
FPB	Flexor Pollicis Brevis
FPL	Flexor Pollicis Longus
FT	Flexor Tenosynovitis
IP	Inter -phalangeal
MCP	Metacarpo-phalangeal
MCSA	Mean Cross-sectional Area
MP	Metacarpo-phalangeal
MRI	Magnetic Resonance Imaging
NHS	National Health Service
OP	Opponens Pollicis
PB	Phosphate Buffer

PCSA	Physiological Cross-sectional Area
PL	Palmaris Longus
PRMD	Playing Related Musculoskeletal Disorders
SD	Standard Deviation
SEM	Standard Error of Mean
TCSA	Tendon Cross-sectional Area
USS	Ultrasound Scan
WRMD	Work Related Musculoskeletal Disorders

Chapter 1

INTRODUCTION

1.1 Introduction to the dissertation

Constant and repetitive movements involving the flexor tendons of the thumb and the fingers whilst typing, playing sports, playing string and keyboard-based instruments can result in tenosynovitis (inflammation of the outer synovial sheath that covers the tendon - tenosynovium) and tendonitis (inflammation of the tendon). This leads to an increase in the tendon cross sectional area (TCSA), which subsequently contributes to the development of tendinous interconnections (Katz *et al.*, 2002). These interconnections, coupled with an anatomically congested carpal tunnel at the wrist, may lead to compression of the median nerve resulting in carpal tunnel syndrome (Slater, 2001). Aside from being acquired, interconnections may also be developmental or inherited (Karalezli *et al.*, 2006a).

Tendinous interconnections are estimated to occur in about 20% of the general population (Rennie *et al.*, 1998). Although string music players present with symptoms associated with tendinous interconnections and, consequently, considered to have a higher incidence, there is insufficient evidence in the literature that conclusively establishes higher incidence in this group. Studies by Miller *et al.* (2003) and Karalezli *et al.* (2006b) corroborate the above observation.

This study attempted to evaluate the prevalence of tendinous interconnection amongst first year medical students at Cardiff University, some of whom played string and key-based musical instruments. The prevalence of these interconnections was established by studying live human volunteers. The findings from the human volunteer study were corroborated using Ultrasound

Scan (USS) and Magnetic Resonance Imaging (MRI). Cadaveric dissection of the upper limb was used to ascertain the muscle mass, angle of pennation, muscle fibre length, muscle density and tendon dimensions (length, width and breadth). These measurements were obtained by reflecting, dissecting or removing the muscle along with its tendon from the forearm, wrist and hand. (The methods involved in dissection are explained in chapter 2). The data were used to calculate the Physiological Cross Sectional Area (PCSA) and Tendon Cross Sectional Area (TCSA).

Chapter 1 provides a background to the structure of the hand with particular reference to the muscles and tendons, essential developmental embryology, carpal tunnel and movements at the wrist, pathogenesis of tendinous interconnections, and the fundamentals and principles behind undertaking the studies in this dissertation. A sound understanding of the anatomy of the hand and the flexor tendons is essential to decipher the mechanics of development of these tendinous interconnections and hence described in detail.

1.2 Overview of the hand

The human hand, an intricate and prehensile part of the body, is capable of a wide range of movements involving extreme precision and exactitude. The hand is the region of the upper limb distal to the wrist joint. Its skeleton consists of carpal bones, metacarpals and phalanges. The soft tissue covering the skeleton consists of tendon and its coverings, small muscles of the hand and neurovascular structures. These structures cover (envelope) the phalanges to form the digits. The five digits consist of the laterally positioned thumb and

medial to the thumb the four fingers the index, middle, ring and little fingers. The hand has a volar (anterior or palmar) and dorsal (posterior) surface.

The ability to use the hands has evolved over time, starting with primitive gestures such as grabbing objects to more precise and highly dexterous activities such as threading a needle that warrants accurate hand-eye coordination. Fine motor skills require controlled use of the small muscles of the hand, fingers and the thumb, in conjunction with forearm muscles and wrist movements. The development of these skills allows humans to undertake complex tasks such as typing, writing, buttoning, sewing, and playing certain musical instruments (such as the guitar, violin and piano).

1.3 Skeleton of the hand

The bones of the hand can be divided into three well defined groups:

- Phalanges (bones of the digits) - three each in the four fingers and two in the thumb
- Five metacarpal bones (each related to one digit)
- Eight carpal bones

1.4 Fingers and thumb

Each metacarpal consists of base, shaft and the head (from proximal to distal). All the bases articulate with the carpal bones and with the bases of adjacent metacarpal bones. The heads articulates with the proximal phalanx of the digits. The head of first metacarpal bone articulates with the proximal phalanx of the thumb (distally) while the second to the fifth articulates with the proximal phalanx of the index, middle, ring and the little fingers respectively. The joint between the first metacarpal and the trapezium is a saddle type of

joint thus imparting a wide range of mobility to the thumb (discussed in detail in subsequent session) while that formed by the metacarpophalangeal joint (MCPJ) is a condylar joint thus permitting flexion and extension (Standring, 2005c). The phalanges are the bones of the digits - the thumb has two (proximal and distal) while the other digits have three (proximal, middle and distal). Similar to metacarpals, these phalanges have a base, shaft and the head. The base articulates with the head of the respective metacarpal bone thus forming the MCPJ. The fingers can perform adduction and abduction at the MCPJ, which is defined with respect to the long axis of the middle finger, and flexion and extension at the interphalangeal joint (IPJ).

1.5 Thumb

The thumb exhibits a wide range of mobility at the carpometacarpal (CMC) joint. The different movements at this joint include: flexion, extension, adduction, abduction, rotation and circumduction (Standring, 2005a). Of these movements, flexion and extension occur parallel to the palmar plane while the adduction and abduction occur at right angles. Circumduction is a combination of adduction, abduction, extension and flexion. The thumb has evolved to perform another unique movement called the opposition - a composite position of the thumb achieved by the flexion of the first metacarpal at the CMC joint, internal rotation at the MCPJ, and minimal flexion of the IPJ (**Figure 1.1**) (Standring, 2005a). The thumb is the only digit on the human hand that is able to oppose against the other four fingers and thus enables the hand to perform precise motor skills such as writing and gripping. The grips are classified as tip pinch and lateral (or key) pinch (McMinn, 1994) (**Figure 1.2**). In anatomical position, the long axis of the thumb is rotated 90° to the

rest of the digits so that the pad of the thumb faces medially. Consequently, movements of the thumb are defined at right angles to the movements of the other digits of the hand (Standring, 2005b).

1.6 Intrinsic muscles of the hand

The intrinsic muscles originate and insert within the hand, and execute precision movements such as ‘precision grip’. These are divided into the three groups namely: general, thenar and hypothenar muscles. The general intrinsic muscles are the Palmaris Brevis (PB), Dorsal Interossei (DI), Palmar interossei (PI), lumbricals and Adductor Pollicis (AP). The thenar muscles are Abductor Pollicis Brevis (APB), Flexor Pollicis Brevis (FPB) and Opponens Pollicis (OP). The hypothenar muscles are Opponens Digiti Minimi (ODM), Abductor Digiti Minimi (ADM) and Flexor Digiti Minimi Brevis (FDMB). The origin, insertion, action and innervation of the thenar and hypothenar muscle groups are shown in **Tables 1.1, 1.2 and Figure 1.3**.

1.7 Extrinsic muscles of the hand

Extrinsic muscles are classified according to their action at the phalanges of fingers thumb and wrist joint. These include the Flexor Digitorum Superficialis (FDS) and Flexor Digitorum Profundus (FDP) to the fingers, and the Flexor Pollicis Longus (FPL) to the thumb. Tendinous interconnections commonly develop between the tendons of FPL and FDP to the index finger. The FDS attaches to the sides of the proximal phalanges of all fingers, the FDP to the volar surface of the base of the distal phalanges of all fingers and the FPL to the volar surface of the base of the distal phalanx of the thumb. Together, and in conjunction with the small muscles of the hand, they bring about the 'power grip' as when making a tight fist (Drake *et al.*, 2007e). The power grip is used when the fingers (and sometimes palm) grip on an object with the thumb makes counter pressure such as gripping a hammer and opening a jar using both your palm and fingers. These muscles are shown in **Figure 1.4.**

1.8 Flexor tendons of the wrist

These include the Flexor Carpi Ulnaris (FCU) and Flexor Carpi Radialis (FCR). FCU and FCR perform flexion as well as ulnar deviation (adduction) or radial deviation (abduction) of the wrist respectively (Standring, 2005e). The origin, insertion, action and innervation of all flexor tendons to the thumb, fingers and wrist are shown in **Table 1.3**.

1.9 Pulley system of the hand

Pulleys (**Figure 1.5**) are tough, fibrous structures found in the palmar aspect of the hand and fingers. They mainly help to maintain the flexor tendons of the

hand in steady relationship with the joint axes and encourage effective finger flexion (Doyle, 1989).

The pulley system is composed of the flexor retinaculum (transverse carpal ligament), the palmar aponeurosis pulley and the digital flexor pulley system. The digital pulley system comprising of cruciate and annular pulleys is the most significant for finger flexion. In their normal position, the pulley system is stable and can accommodate a large arc of motion of fingers without bowstringing of the tendons. Loss of a pulley results in an increased tendon movement to generate the same arc of motion. As the force generated by the muscle is directly proportional to the muscle fibre length, the efficiency of tendon excursion (active range) is reliant on maintenance of the crucial relationship between pulleys and the adjacent joints axes (Lieber, 1992 and Doyle, 1989). Reconstruction of this system following injury is dependent on knowledge of the anatomy and an understanding of the functional significance of each component of the system (Doyle *et al.*, 2001e).

1.10 Histology of the flexor tendons

The normal histology of the flexor tendons consists of densely packed collagen fibrils running parallel to each other. A dense connective tissue called the endotendineum separates collagen fibrils from each other. The blood vessels and nerves run through the endotendineum in a longitudinal fashion. The capillary wall is composed of lining endothelium resting on a basal lamina and sub-endothelial connective tissue. The ground substance (the extracellular space between collagen fibrils) consists of polysaccharides and extra-cellular fluid. Groups of endotendinuem may be reorganised to form larger functional units by thicker connective tissue to form the peritendineum. The group of peritendineum are surrounded by dense irregular connective tissue to form epitendineum. The nucleus of the longitudinal elongated fibroblasts lies in the widest portion of the cell and these are scattered between the collagen fibril bundles. Within these collagen fibres also lie elongated and flattened nuclei of inactive fibrolast (tendinocytes) (Ross and Pawlina, 2005). This is shown in **Figure 1.6** and the arrangement of different layers of tendon is shown in **Figure 1.7**.

1.11 Histology of the tenosynovium

To protect the epitendineum layer of the tendon from friction they are surrounded on the outside by two layers of flattened synovial cells of mesenchymal origin. Of these two layers, one of the layers is attached to the tendon while the other one is attached to the neighbouring structures. The space (tendon sheath space- TSS) between the two layers contains a viscous fluid that is composed of water, protein and hyaluronate (Stevens and Lowe, 2005). This is shown in **Figure 1.8.**

1.12 Carpal Tunnel

The carpal bones are arranged at the wrist in two rows of four bones each. The proximal row, from radial to ulnar, consists of scaphoid, lunate, triquetrum and pisiform. The distal row, again from radial to ulnar, consists of trapezium, trapezoid, capitate and hamate. The fibrous band known as the flexor retinaculum is attached medially to the pisiform and the hook of hamate and the laterally to the scaphoid and the trapezium, thus converting the carpal arch **(Figure 1.9)** in to a tunnel called the carpal tunnel. Thus, the sides and the floor of the carpal tunnel are formed by the carpal arch while the flexor retinaculum forms the roof.

1.13 Structures passing through the Carpal Tunnel (Contents of the Tunnel)

The carpal tunnel contains the median nerve and all the long flexor tendons to the digits and the thumb (FDP, FDS and FPL). The median nerve is the most superficial structure in the carpal tunnel (Rotman *et al.,* 2002). The motor branch of the median nerve in hand arises from the main trunk under or just distal to flexor retinaculum, and winds around the distal border of retinaculum to reach thenar muscles (including the APB, FPB and OP) and the first two lumbricals. The sensory branches of the median nerve innervate the skin over the lateral three and 1/2 digits including the nail bed and dorsal surface of the distal phalanx (can be up to distal half of the middle phalanx) (Standring, 2005). A cross section through the carpal tunnel is shown in **Figure 1.10**.

Within the carpal tunnel, the alignment, shape and relationship of the median nerve to the flexor tendons varies depending on wrist movements. Using US scan, Zeiss and colleagues (1989) noted that during flexion of the wrist, the nerve lies anterior to the FDS (index) tendon and during extension the nerve became interposed between the superficial flexor tendons of the index finger and FPL of the thumb or between the FDS of the middle and ring fingers. It was also noted that the area of the nerve changed with wrist movements. During flexion the nerve flattened antero-posteriorly whilst it became rounded during extension.

There is an inverse relation between the width and the thickness of the median nerve as it passes through the carpal tunnel. As the width increase from an average of 6.1 mm (at the middle portion of the tunnel) to 7.7 mm (at the exit of the tunnel), the thickness of the nerve decreases from an average of 2.1 mm (at the middle portion of the tunnel) to 1.9 mm (at the exit of the tunnel) (De Krom *et al.,* 1987). Thus the median nerve flattens during its course through the carpal tunnel. This may be to easily pass through the tunnel and to accommodate the accompanying flexor tendons (Allmann *et al.,* 1997). Similar findings have also been established using US scan by Buchberger and colleagues in 1991. The increase in the area of the nerve is due to increased density of the intraneural connective tissue especially within the epineurial layers (Castelli *et al*., 1980). There is also an increase in the thickness of the arteriole wall and the venules due to endo proliferation (Armstrong *et al.*, 1984). This change to the vessel wall is regarded as an adjunct protective feature that opposes increased intra-tunnel pressure during wrist movements

and reduces the chances of vascular collapse (Castelli *et al.*, 1980). **Figure 1.11** shows the different layers of the peripheral nerve.

1.14 Structures superficial to the Carpal Tunnel

The tendon of Palmaris Longus (PL) passes over the flexor retinaculum to continue as the palmar aponeurosis. The palmar cutaneous branch of the median nerve, which innervates skin over base of thenar eminence, arises a short distance proximal to the flexor retinaculum. The superficial branch of the radial artery also runs superficial to the flexor retinaculum and ends by anastomosing with the deep branch of the ulnar artery thus completing the superficial palmar arch. The ulnar neurovascular bundle lies superficial to the carpal tunnel as they enter the palm through the 'Guyon's canal'.

1.15 Structural changes in the Carpal Tunnel during wrist movements

An animation of the movements at the wrist joint is seen in the attached Power Point presentation (Courtesy of Dr Alan Watson).

Movements such as normal flexion and extension of the wrist and fingers affect the width and dynamic pressure within the carpal tunnel. Flexing the wrist causes the flexor retinaculum to move closer to the radius which considerably decreases the cross section of the proximal opening of the tunnel and also the distal end of the capitate moves into the opening. In extreme extension the lunate constricts the passage as it is pressed toward the interior of the tunnel (Schmidt, 2004).

During ulnar deviation of the wrist, the triquetrum glides distally across the hamate. This movement causes the triquetrum to move into extension resulting in reduced height of the ulnar aspect of the wrist. In addition, during this movement, the hamate approaches the ulnar styloid and the lunate rotates antero-medially along with it into extension (Schmidt, 2004). During radial deviation, the distal row of carpal bones migrate radially whilst the proximal

row, mainly the scaphoid and lunate, move towards the ulnar styloid. The capitate along with trapezoid moves more towards the radial styloid in relation to the scaphoid and lunate movements (Kaufmann *et al*. 2005, Mac Conaill, 1941).

During forceful flexion of the fingers (such as when making a fist), the lumbrical muscles migrate proximally into the carpal tunnel and increase the pressure within the carpal tunnel from about 2.5 mmHg to 31 mmHg at the most constricted part of the tunnel (at the level of hook of hamate) (Gelberman *et al.*, 1981). The cross sectional area (CSA) of the carpal tunnel is found to increase during flexion of the wrist. This is to accommodate the lumbrical muscles that move into the carpal tunnel during flexion. This adjustment causes overall reduction in the space within the carpal tunnel and may result in compression of the median nerve (carpal tunnel syndrome is discussed later in this chapter). The other adjustments that occur during flexion of the wrist include compression of the fat, flattening and displacement of the median nerve, and pressure on the superficial and deep flexor tendons (Ham *et al.*, 1996). During wrist extension, the cross-sectional area of the carpal tunnel increases at the level of the hook of hamate thus decreasing the pressure within the tunnel (Horch *et al*, 1997).

1.16 Essential embryology

1.16.1 Upper limb

In humans, the upper limb develops by the end of the first month of intrauterine life. At this stage, the limb bud appears as a mesenchymal core (which is a type of undifferentiated loose connective tissue derived mostly from the mesoderm - one of the three primary germ cell layer) covered by a

thin layer of epithelium (Seyfer *et al.,* 1989). The hands and the fingers are well developed by the end of second month of intrauterine life. The differentiation of the tendons at the end of muscle belly begins between the seventh and eighth week (Ippolito, 1990). Limb fibroblasts and tenoblasts (tendon cells) primarily originate from the somatopleura, which is formed from the outer layer of the lateral plate mesoderm found at the periphery of the embryo (Kienv and Chevallier 1979).

1.16.2 Development of flexor tendons and pulleys

Limb muscles are formed by myogenic precursor cells that migrate into the limb buds and differentiate into myoblasts. The myogenic precursor cells are derived from the dorsolateral muscle-forming region of the somites (which are bilaterally paired segments of mesoderm that are arranged along the anterior-posterior axis of the developing embryo) (Moore *et al*, 2008). In humans, they migrate into the limb buds during the fourth week of development. Following migration of the mesodermal cells into the limbs, the axons of the nerve from the corresponding rami of the spinal cord follow them proximally to distally (Sadler, 2000). These mesodermal cells unite into two common muscle masses which later splits to form the extensor and flexor compartment respectively. The myoblasts hypertrophy and fuse into myotubules; every muscle is recognizable by seven weeks (Beatty, 2000). The basic embryology of the limb is shown in **Figure 1.12.**

Shellswell and Wolpert (in 1977) demonstrated that tendons (which are somatopleuric in origin) develop independent of the muscle bellies. The tendinous and muscle blastemae (the formative, undifferentiated material from

which muscles and tendons develop) start to develop separately from one another and join up secondarily. In chick embryo study, it has been found that the tendons start to develop earlier and anterior to the future forearm muscles, despite the absence of these muscles. However, for their maintenance and further development the tendons require connection to at least one muscle belly or the whole muscle group. Further to this observation, experiments by Kieny and Chevallier (1979) demonstrated that if the dorso-ventral axis of the limb were to be inverted the tendons developed normally but joined with the wrong muscles *i.e.*, ventral tendons matched with dorsal muscle group and vice versa. This is illustrated in **Figure 1.13**. This establishes that the attachment to a muscle is necessary for the further development of the tendon. The pulley system is recognised by week nine as condensing mesenchyme. The pulleys are well-developed by the 12^{th} week of intra-uterine life (Linscheid, 2000) and are identifiable around the flexor tendon in positions similar to that found in the adult hand (Sbernardori *et al.*, 2000).

1.17 Work Related Musculoskeletal Disorders (WRMD)

Work related musculoskeletal disorders cause pain, disability and loss of employment for workers in many occupations (Silverstein *et al.,* 1986). Musculoskeletal problems are considered significant health factors for performing artists, especially instrumentalists. Use of the hand in continuous and repeated activities such as typing, playing string- or key-based musical instruments places an increased degree of stress and strain on the soft tissue structures including the tendons. In the long-term, this can lead to reduced functional efficiency of the involved digits and/or the hand, resulting in inability to perform the task that requires a very high degree of dexterity. The symptoms of this condition include pain, weakness of the hand, tingling and stiffness (Zaza *et al.,* 1998), which might be related to the tendonitis, tenosynovitis or carpal tunnel syndrome (Hiner *et al.,* 1997). Common playing-related musculoskeletal disorders (PRMDs) of musicians include overuse problems, such as tendonitis, and peripheral nerve entrapment syndromes (Zaza, 1997).

In musicians, repetitive movements at the wrist such as flexion, extension, radial and ulnar deviation of the wrist may cause tenosynovitis of the long flexor tendons, which in the long-term contribute to the formation of tendinous interconnections mainly within the carpal tunnel (Leijnse *et al.,* 1997a). These interconnections can either be fine tendinous linkages or strong adherent sheets of tenosynovium, both of which may be very resistant to stretch. Tenosynovium helps with the smooth gliding of the tendon with the least amount of friction. Interconnections at the level of tenosynovium act as

adhesions that prevent movements of the tendon and causes tension during finger movements. Whilst playing a musical instrument, these may become the potential sites for pain and inflammation (Leijnse *et al.*, 1992). The postulated pathophysiology for development of tendinous interconnection is discussed in detail in subsequent sections.

The risk factors that have been identified for PRMD include the type of instrument that the musician frequently plays, their gender, age, duration and intensity of playing, and individual physical characteristics such as the hand size (Brandfonbrener, 2003). Abréu-Ramos and colleagues (2007) demonstrated that PRMD is more common in adult musicians (mean age: 22-29 years) than in adolescents as this age group played the musical instrument for longer hours and with fewer breaks in between playing (28.7 hours/week). Similarly, in 1992, Pratt and colleagues identified that the prevalence of PRMD was approximately 39% to 47% in adults compared to 17% in secondary school music students. They also found that PRMD is more common in female string- and keyboard players compared to their male counterparts. Some of the proposed theories concerning the difference are smaller hand size along with decreased arm strength and more flexibility and joint laxity of the hand in females. However, these theories have not been investigated sufficiently to derive concrete conclusions (Brandfonbrener, 1990; Chong and Chesky, 2001). There is strong evidence to suggest that the musicians who play an instrument for more than four hours a day and more than 60 minutes without a break are more prone to clinical signs and symptoms of PRMD (Roach *et al.,* 1994; Bruno *et al*, 2008).

PRMD results in loss of speed, precision and grip such that the musician loses their ability to play the instrument effectively (Caldron *et al.*, 1986). Furthermore, symptoms may get aggravated soon after playing the instrument due to the gradual build-up of inflammatory material in the tenosynovium leading to transient tenosynovial swelling (Winspur and Parry, 1997; Hansen *et al.*, 2006). PRMD can be physically, emotionally and financially distressing for the musicians since it can hamper their ability to play the instrument either professionally or as a leisure pursuit (Zaza *et al.*, 1998; Zaza 1998).

Prevention of PRMDs includes recognition of both internal (e.g., musicians strength and flexibility of the musician's body) and external factors involved (e.g., anatomical and functional position whilst playing an instrument, instrument size and techniques of holding the instrument involved); that is, the interface between the musicians, their instruments and the playing environment (e.g., rest breaks or hours of practice) (Foxman *et al.*, 2006, Miller *et al.*, 2002).

1.18 Common types of tendinous interconnections in musicians

In 1979, Richard Linburg and Brian Comstock identified an anomalous interconnection between the FPL and FDP of index finger at the level of carpal tunnel that restricted independent flexion of these digits. The patient presented with pain in the distal forearm. Now popularly known as the ***Linburg-Comstock anomaly,*** it is characterised by simultaneous flexion of the distal IP joint of the index finger with flexion of the IP joint of the thumb and the inability to actively flex the IP joint of the thumb without simultaneously

flexing the distal IP joint of the index finger (Spaepen *et al.*, 2003). Linburg-Comstock syndrome causes functional impediment in musicians (Karalezi *et al.*, 2006a) by reducing the independent movement of the FDP (index) when the thumb is flexed (Hamitouche *et al.*, 2000). The presence of these interconnection and similar anomalies have been subsequently identified and reiterated by a number of studies both amongst musicians and non-musicians (Leijnse *et al.*, 1997a; Allieu *et al.*, 1998; Miller *et al.*, 2003).

Any movement against interconnection causes pain (usually of tearing in nature) on the palmar aspect of the hand, radial side of the wrist or in the distal part (mainly the distal one-thirds) of the forearm (Miller *et al.*, 2003). These interconnections have been identified just proximal to the radiocarpal joint or the distal forearm (Karalezli *et al.*, 2006c).

Miller and colleagues (2002 and 2003) have classified the manifestations of FPL and FDP interconnections. This classification is based on the level of the interconnection and the degree of mechanical impediment. These are: (1) synkinesis (involuntary movement of hand or muscles associated with a voluntary movement) (2) synkinesis and positive Linburg-Comstock test results (i.e., pain and discomfort during flexion of the thumb to the base of the little finger while the index finger is held in extension by the examiner), and (3) pain and deformity following continuous use. They also observed that amongst string players, the symptoms were more prevalent in the left hand and this tended to decrease from the radial to the ulnar side of the hand. This is due to the fact that the left hand is involved in free finger and thumb movements when playing bowed or string instruments. The static thumb

posture with active finger movements, as in string instrument players, leading to tenosynovitis over time has been suggested to lead to this anomalous interconnection (Miller *et al.*, 2003).

1.19 Pathogenesis of tendinous interconnections

The recognized concept of a synovial sheath (tenosynovium) is that of a two-layered structure surrounding the tendon with the presence of lubricating fluid between these layers. The inner layer holds on to the tendon, and is attached by areolar tissue to the outer layer that adheres to the surroundings. These layers slide relative to each other and the loose connective tissue sandwiched between them is stretched only with larger than physiological tendon displacements. The purpose of the sheaths is to reduce friction of the tendons relative to the environment or other tendons, and they are constructed in a manner that allows nerves and vessels to reach the tendons undamaged. However, within the carpal tunnel, the synovial sheaths comprise many layers of thin membranes (in contrast to the 'classical' two layered tendon sheaths arrangement (e.g., in the digits), the synovial mass in the carpal region will be referred to here as 'synovial membranes' (Leijnse *et al*, 1997a). These membranes enclose all flexor tendons (FDS, FDP and FPL) collectively as well as the individual tendons. Synovial membranes, in general, do not adhere to the superficial tendons, except sometimes in the case of those of the little finger as numerous thin tendon strands (Leijnse *et al,* 1997a). However, within the carpal tunnel they often adhere strongly to the deep flexor tendons. When they are attached to two adjacent tendons, they may form interconnections.

There are differences in the morphology of the superficial and deep flexor tendons. The superficial flexor tendons have tightly packed tendon strands giving it a round and smooth appearance, while the deep flexor tendons (especially, the three on the ulnar side) are a collection of loosely packed tendon strands. However, distal to the distal border of the flexor retinaculum where the lumbrical muscles originate, the deep flexor tendons assume a round and smooth appearance. In the carpal tunnel where the deep flexor tendons are loosely packed tendon strands, the synovial membrane gets trapped between the individual tendon strands predisposing to the formation of interconnections (Leijnse *et al.*, 1997a) (**Figure 1.14).** The interconnection between the tendons of FPL and FDP (index) might be due to the anatomic proximity coupled with the large mean PCSA of the FDP tendons. In addition, although the FPL and FDP tendons are independent of each other, due to the common mesodermal mass from which these tendons are derived, the interconnection could occur as a congenial anomaly (Mangini, 1960; Kaplan, 1984). These tendinous interconnections together with adhesive synovial membranes may provide strength to resist the *in vivo* forces that generate the opposite displacements of the connected tendons (Leijnse *et al.*, 1997a).

In musicians, repetitive trauma would expose the musculoskeletal tissue frequent to low-magnitude forces that might result in damage at the microscopic level. In chronic tendon disorders, the structure of the tendon is disturbed by the collagen fibres gliding past one another, leading to rupture of their cross-linked structure and denaturising of the collagen. Clinically, this may present as inflammation, oedema and pain. Consequently, frequent

clinically identifiable manifestations of overuse tendon injury are tendonitis and tenosynovitis (Kannus, 1997).

1.20 Genetic basis for tendinous interconnections

There is no study, to date, that relates genetic factors predisposing to the formation of tendinous interconnections. Thus, it was worthwhile to look at genetic links to other inherited connective tissue disorders such as Ehler-Danlos syndrome (EDS) (also known as hypermobility syndrome). Tendon disruptions (including complete loss of flexor tendon or some tendons appearing small and rudimentary) have also been described in patients with EDS in which there is mutation of collagen I gene (COL1A1) (Mao and Bristow, 2001). Collagens are molecules that give structure and strength to connective tissues throughout the body. *COL1A1* provide instructions for making proteins that are used to assemble different types of collagen.

Collagens begin as pro-collagen molecules. Each pro-collagen molecule consists of three rope like chains: two pro-α1(I) chains and one pro-α2(I) chain. The two pro-α1(I) chains are produced from the *COL1A1* gene, while the pro-α2(I) chain is produced from the *COL1A2* gene. Mutation to *COL1A1* gene leads to lack of production of a pro-α1(I) chain. The absence of this segment interferes with the assembly, processing and basic structure of type I collagen molecules thus forming a weaker collagen chain. Tissues such as skin, bones, and tendons, which are rich in Type 1 collagen are most affected by this change. These defects weaken connective tissues such as bones and tendons (in classical EDS) resulting in the characteristic features of this condition including hyper mobility and frequent dislocations (Mao and Bristow, 2001).

It is thought that the scleraxis (*Scx*) gene, encoding a basic helix–loop–helix (bHLH) transcription factor, is a distinct marker for tendon and ligament progenitors (Cserjesi *et al.,* 1995). Experiments on mice with mutant Scx gene (*Scx*$^{-/-}$) have shown disruption in differentiation or complete loss of the flexor tendons thus leading to the limited use of the forelimb paw including lack of grip power and decreased force transmission as the dorsal extension is not counteracted by the flexor tendon activity due to complete absence, or smaller and rudimentary FDP tendons (Murchison *et al*., 2007). In humans, although this may not be life-threatening it may compromise the health related quality of life. It could manifest as a disability to carry out day-to-day activities involving grip such as writing, buttoning, combing hair and feeding. It may also affect their professions if their job involves activities that require grip and precision.

Scx$^{-/-}$causes lack of differentiation of the tendons thus predisposing to tendinous interconnections (Murchison *et al*, 2007). *Scx*$^{-/-}$*also leads to disruption of the histology of the tenosynovium of the tendons including the FDP*. Normally, the tenosynovium is made up of continuous layer of flat cells enmeshed with filamentous fibrils *while following mutation the cells appear greatly disorganised and fail to form a continuous layer* (D'Souza a*nd Patel, 1999). Due to the break in the tenosynovium, it may* get trapped between the individual FDP tendon strands predisposing to the formation of interconnections (Leijnse *et al.,* 1997b).

The extracellular matrix protein tenascin C plays an important role in collagen fibre alignment and orientation. Lack of tenascin C in patients with EDS mimics microtrauma to the tendon, leading to disruption in the orientation of

the collagen fibres thus predisposing to tendinous interconnections (Murchison et al., 2007).

Thus the individuals with mutation of collagen I gene (COL1A1) or those with $Scx^{-/-}$ or lack of tenascin C protein may present with EDS as these genes and protein help with organisation, alignment and orientation of the tenosynovium and the collagen fibres. Lack of $Scx^{-/-}$ and tenascin C protein also predisposes the individual to tendinous interconnections as they form discontinuity of the flat layered orientation thus causing breaks in the tenosynovium which may cause the individual tendon strands to get trapped in these breaks. Thus these patients may present with congenital or hereditary tendinous interconnections.

1.21 Tenosynovitis and Carpal Tunnel Syndrome in musicians

The synovium that wraps the flexor tendons contains a lubricant fluid that aids in the smooth movement of the tendon within the sheath. Constant and repetitive movement at the wrist causes tendonitis and tenosynovitis (inflammation of the synovium). As a response to injury, there is an increase in collagen fibre size, fibroblast density, and vascular proliferation within the tendon (Ettam *et al*., 2004). This leads to the enlargement of the tendon (Biundo *et al.,* 1997). As an inflammatory change, the fluid within the synovium becomes viscous and affects the smooth sliding of the flexor tendons. This leads to increased friction of the tendon-sheath complex which prompts more inflammation. The enlargement of the tendon-sheath complex exerts pressure upon the median nerve in the uncompromising tunnel resulting in symptoms of carpal tunnel syndrome (Jameson *et al.*, 1998).

The second cause of CTS in musicians is the misalignment of the carpal bones that form the boundary of the carpal tunnel. This can occur following the contraction and relaxation of the forearm flexors and intrinsic hand muscles (hypothenar and thenar muscles) that are attached to the pisiform, scaphoid and the tubercle of the trapezium carpal bones. Repeated and overuse of the thumb and other fingers, as in string- and key-based players, may lead to misalignment of the carpal bone and thus compression of the median nerve (Jameson *et al.*, 1998).

1.22 Common variations in and around the Carpal Tunnel

Anatomical variations may occur in the carpal tunnel region. These include anomalous origin muscles, presence of accessory muscle bellies and tendons, proximal origin of the lumbricals, and variation in the course and branches of the neurovascular bundle in its vicinity. Accessory muscles are anatomical variants representing additional distinct muscles that are encountered along with the normal muscles. Although these accessory muscles may remain asymptomatic, they can lead to clinical symptoms due to compression of the adjacent structures such as nerves, vessels, or tendons (Sooker *et al.,* 2008). Awareness of these variations within the carpal tunnel is important both during the clinical examination and during its release as failure to identify them can result in inadequate decompression (Puroshothaman *et al.,* 2009). Some of the important and recognised variations are discussed in the section below.

1.22.1 Nerve Anomalies

Although ulnar nerve runs in the Guyon's canal, on rare occasions, the nerve may lie within the carpal tunnel. The patient may present with symptoms of both CTS and ulnar nerve compression including wasting of the small muscles of the hand and paresthesia along the little finger and the ulnar half of the ring finger (Papanastasiou *et al.,* 2004 and Galzio *et al.,* 1987). Small muscle wasting along with weakness of the hand can affect the speed, power and fine motor movements of the fingers that affect the musician's ability to play string or key-based instruments (Caldron *et al.,* 1986).

1.22.2 Muscle anomalies

The lumbrical to the index finger may originate proximally on the FDP within the carpal tunnel. Thus, these can mimic space occupying lesion and can lead to median nerve compression and symptoms of CTS (Butler *et al,* 1971).

1.22.3 Flexor muscle variation

The accessory head of FPL (Gantzer's muscle) has been described in 52% of population. In the study by Al-Qattan and colleagues (1996), the authors identified that the Gantzer's muscle arises from the medial humeral epicondyle in 85% and had a double origin from the epicondyle and coronoid process in the rest. In some cases, the accessory head of FPL also arose from beneath the FDS. Compression of the anterior interosseous nerve can lead to spastic contraction of the deep muscles of the forearm (Hemmady *et al,* 1993). Such spastic contraction can cause clawing of the middle and index fingers thus affecting the musician's ability to play the instrument efficiently.

Another variation consists of the FDS muscle including a digastric muscular component with a part of the muscle located in the forearm and another part located in the palm. In these cases involving a digastric component, extension of the middle phalanx causes the FDS muscle belly of the forearm to be pulled to the carpal tunnel thus causing compression of the median nerve (Elias *et al*, 1985, Christensen, 1977). Kono (2003) documented the presence of an accessory muscle belly of FDS (index) that extends into the carpal tunnel. In these patients, symptoms of CTS may be due to compression of the median nerve by the accessory muscle belly.

1.22.4 Variations of muscles of hand

Accessory ADM occurs in approximately 24% of general population (Zeiss *et al.*, 1996). It may originate from the inter-compartmental septum on the medial side of the forearm just proximal to the wrist joint, coursing anterior to the ulnar neurovascular structures in the Guyon canal and inserting into the ADM or separately onto the ulnar aspect of the base of the proximal phalanx (Wahba *et al.*, 1998). Alternatively, the accessory muscle may originate from the palmaris longus tendon in the lower third of the forearm. The presence of the accessory muscle presents with symptoms associated with the compression of the ulnar nerve thus leading to wasting of small muscles of the hand consequently affecting fine motor skills that are required for playing musical instruments (Sooker *et al.*, 2008). **Figures 1.15 (A-C)** illustrate a few common variations and interconnections (indicated with ★) that have been recorded in the dissection room at the School of Biosciences, Cardiff University (courtesy of Mr. Robert Colliver).

1.22.5 Tendon Anomalies

Rennie and colleagues (1998) found tendinous connections between FPL and FDS tendons in 25% of subjects unilaterally and in 6% bilaterally. Although this interconnection is rarely problematic, it may mimic symptoms of carpal tunnel syndrome by causing median nerve compression through the development of tendonitis.

1.22.6 Arterial Anomalies

Median Artery

The median artery usually regresses after the eighth week of intrauterine life, but in some cases it may persist into adulthood (Natsis *et al.*, 2009). It passes through the carpal tunnel of the wrist, accompanying the median nerve and may terminate at one or more of the palmar arches. It is thought to occur in about 5-8% of individuals (Rodríguez-Niedenführ *et al.,* 1999). Several studies have reported the occurrence of carpal tunnel syndrome due to an anomalous and persistent median artery (Eid *et al.,* 2011, Boughton *et al.,* 2010, Pierre-Jerome *et al.,* 2009).

1.23 Relevant pathologies involving the flexor tendons

1.23.1 Non-pyogenic flexor tenosynovitis

Non-pyogenic flexor tenosynovitis is an inflammatory process affecting the flexor tendon system that leads to disruption of the normal flexor tendon function in the hand. In musicians, repetitive flexion and extension of the fingers result in microtrauma to the tendon and tendon sheath. The protective inflammatory process within the tendon sheath interferes with the gliding mechanism, leading to adhesions and scarring. Chronic non-pyogenic flexor

tenosynovitis may predispose to trigger finger (Fulcher *et al.,* 1998; Verdon, 1996).

1.23.2 Trigger finger

Trigger finger is characterised by locking of the involved flexor tendon at the finger. The common clinical presentations include pain, dysfunction and difficulty in flexing or extending the involved digit (classically 'locking'). This condition commonly involves the A1 pulley (first annular pulley - arises from volar plate of MP joint, beginning 5 mm proximal to the MP joint and ending at the base of the proximal phalanx) due to the disparity in size between the flexor tendon and the surrounding retinacular pulley system. The condition is labeled so because when the finger unlocks, it pops back suddenly, as if releasing a trigger on a gun (Makkouk *et al.*, 2008).

1.24 Relevant pathologies in and around the wrist

1.24.1 Carpal Tunnel Syndrome (CTS)

CTS is a collection of characteristic symptoms and signs that occurs following entrapment or compression of the median nerve within the carpal tunnel. This can occur due to a number of different conditions. As the area of the wrist through which the median nerve passes is very narrow, any swelling (tumours), accumulation of fluid in the area (related to obesity, pregnancy, hypothyroidism), change in the bony wall of the tunnel (arthritis and fractures of the carpal bones) and inflammation of the tendon (tendonitis or

tenosynovitis) which increases the flexor tendon size and leads to pressure on the median nerve. This pressure will ultimately interfere with the nerve's ability to function normally (Katz *et al.,* 2002). The condition is more prevalent in women (10:1) due to a lower average cross sectional area of the carpal tunnel (Dekel *et al.,* 1980). The common clinical presentations include tingling and numbness, paresthesia, and pain along the distribution of the median nerve territory. These symptoms may or may not be accompanied by objectively determinable changes in sensation and strength of median-innervated muscles in the hand especially the APB (Atroshi *et al,* 1990). In musicians, the symptoms may not be apparent on initial clinical examination but may appear after a period of playing due to swelling of the tendon sheaths (Winspur and Parry, 1997).

1.24.2 Guyon's canal syndrome

Guyon's canal syndrome is a nerve compression affecting the ulnar nerve as it passes through the Guyon's canal. Presenting symptoms may vary from mild paraesthesia in the ring and little finger to clawing of these digits and severe intrinsic muscles atrophy (Zimmerman *et al.,* 2009*).* The patient may complain of pain at the wrist that radiates into the hand. Early fatigue or weakness may be noticed if work requires repetitive hand motions (Dunselman *et al.,* 2008). The risk factors for Guyon's canal syndrome include fractures of the hamate, rheumatoid arthritis, and overuse of the wrist including flexion and extension as often seen in musicians who play string instruments such as violin and guitar. During hyperextension of the wrist, the

ulnar nerve is pulled taut across the carpal bones, thus aggravating the symptoms (Ginanneschi *et al.,* 2008).

1.25 Physiological Cross-sectional Area (PCSA)

The mechanical effects of a muscle are associated with its mass and its position relative to the joint it acts on. For more than a century, researchers have evaluated muscle mass and the force it produces by calculating its PCSA. Muscle mass (and therefore any expression of PCSA) varies significantly from person to person, even in individuals of similar weight and height (Brand *et al.,* 1986). PCSA is calculated by using the equation: $(m.\cos\alpha)/lp$ where 'm' is the muscle mass in grams, 'α' is the average angle of pennation for the muscle fibre in degrees, 'l' is the length of the muscle fibre in centimetres and 'p' is the muscle density in $g.cm^{-3}$. It is a significant anatomical measurement because the maximum force that a muscle can generate is directly related to its PCSA and the tendon cross-sectional area (Leijnse *et al.,* 1997)

PCSA describes the area of the transverse section of the muscle. The maximum force that a muscle can generate is directly related to its PCSA (van Eijden *et al.,* 1995; Bamman *et al.,* 2000). Thus, bigger the muscle, bigger the tendon cross sectional area and thus there are more chances of the tendon to rub against each other in a confined space such as the carpal tunnel. The recurring trauma of constant rubbing with each other during movements may cause the collagen fibres to glide past one another, causing a split of their cross-linked structure and thus abnormal tendon interconnections (Kannus, 1997).

The properties of a muscle depend not only on its individual fibres, but also on the architectural arrangement within muscle. The cross sectional areas of muscle are directly dependent on the number of muscle fibres (Ikai and Fukunaga, 1968). Fibres seldom run the whole length of the muscle, tending rather to slant at an angle to the muscle's central tendon thus forming an angle called the angle of pennation. Due to this arrangement, more muscle fibres can be accommodated thus producing larger force with smaller range of movement (Gans, 1982; Otten, 1998). During muscle contraction, the pennated fibres pull the central tendon at an angle to create a force. The force exerted on the tendon can be calculated by cosine of the angle of insertion. During rest, the angle of insertion is less than 10° which does not have a marked effect on the force produced. The angle of pennation needs to be calculated to find which muscle is more forceful during contraction and produces the greatest muscle fibre shortening (Roy and Edgerton, 1992). Brown and colleagues (2003) noted that the muscles with long fibres have low pennation angles while those with short fibres had larger angle of pennation. The muscles with larger angle of pennation (short fibres) contracted slowly and produced more force during contraction and thus were more powerful muscles (Mc Ardle *et al.,* 1996).

The velocity of contraction generated by the muscle is directly proportional to the mean fibre length and PCSA (Lieber, 1992). The PCSA indicates the probable tension the muscle can generate (An *et al.,* 1991).

1.26 Tendon Cross-sectional Area (TCSA)

Tendons transmit force generated by the skeletal muscles that are essential in all voluntary movement. Such movement can influence the gross morphology of tendon depending on the action of the tendon across the joint (Heinemeier, *et al.,* 2011). An and colleagues (1991) concluded following live human volunteer study that the TCSA of the muscle is directly proportional to its PCSA. Higher muscle mass may be due to the type of work they perform across the joint, or the power the muscle generates or may be due to hypertrophy of the muscle fibre. Heavier and bulkier the muscle, greater is the TCSA and thus the greater the risk for these tendons to abrade against each other, especially in a congested space such as the carpal tunnel. Constant and repetitive movements at the wrist would expose the musculoskeletal tissue to low-magnitude trauma that might result in structural damage to both the epitendineum and tenosynovium (Stevens *et al*., 2005). As tendinous tissue is relatively avascular, injury to the tendon results in tendinosis, delayed healing and repair (Bunata *et al*., 2007).

Light microscopy studies have established that repair following tendon injury is associated with changes within the collagen, matrix and tenocytes (Ja¨rvinen *et al*., 1997; Khan *et al*., 1999). Some collagen fibres separate and lose their parallel orientation, with a decrease in fibre diameter and in overall density. Collagen micro tears also occur, and these tears may be surrounded by red blood cells and fibrin deposits. Within the matrix, the collagen fibres become unequal and show irregular crimping with an increased waviness. This arrangement is in contrast to the normal tight, parallel, bundled appearance

(Movin *et al*., 1998, Khan *et al*., 1999). All these pathological changes results in denaturising of the collagen and may predispose to tendinous interconnections (Kannus, 1997).

TCSA may increase following pathology such as tenosynovitis where in the TCSA would increase and could in turn lead to the compression of the median nerve (Katz *et al,* 2002).

1.27 Investigative strategies that can be used to study tendinous interconnections

1.27.1 Previous studies

The tendon architecture and the hypothesis for interconnecting strands between the tendons have been mainly established by macroscopic dissection of arms in cadavers, measuring the cross-section of wrists at the level of carpal tunnel on human volunteers and by designing finger models (Leijnse *et al.*, 1992; Leijnse, 1997). Karalezli and colleagues (2006) carried out clinical examinations on live subjects presenting with pain and restricted movements of the fingers as a method to establish the interconnections. Currently, however, there is no established method to accurately determine the anatomical extent and nature of these interconnections. Neither is there a method to establish the associated loss of function and long-term morbidity.

1.27.2 Human cadaveric dissection

Cadaveric dissection has been the cornerstone in the understanding of the human body, and, consequently, an essential component of medical training

since the Renaissance (Parker, 2002). Dissection of the bodies provides one of the best methods to identify and evaluate tendinous interconnections in general population. In live humans however, exploratory surgery is rarely an option for determining the presence of anomalous tendinous interconnections. The following imaging methods are frequently used to study and locate these interconnections.

1.28 Aims of this dissertation

- To record the tendinous interconnections in and around the Carpal Tunnel in cadavers
- In the light of the possibility that increase in tendon diameter may increase the susceptibility to CTS, to calculate and analyse the relation between the PCSA and TCSA
- To evaluate anatomical variations of different muscles of the forearm and hand in human cadavers
- To investigate the efficacy of MRI and USS as a means to identify tendinous interconnections in affected hands of human subjects.

1.29 Hypothesis

It could be hypothesised that**:**

- tendinous interconnections are more prevalent in females
- heavier muscles would have a larger PCSA and TCSA. Thus, the muscles with larger TCSA have more chance to abrade against each other in congested spaces such as the carpal tunnel predisposing to tendinous interconnections

- the TCSA of FDP (index) finger would be greater than all the other FDP tendons. A direct relationship may exist between the TCSA of FPL and FDP (index). This would reduce the space between the FDP (index) and FPL and predispose to tendinous interconnections
- the area of median nerve increases as it travels through different anatomical points within the carpal tunnel
- PCSA is inversely proportional to muscle fibre length. This arrangement would allow more muscle fibres to be packed into a smaller unit space thus influencing the PCSA
- PCSA is directly proportional to the angle of pennation.

Chapter 2

MATERIALS AND METHODS

2.1 Introduction

This chapter outlines the materials and methods that were employed in recording and calculating the PCSA, and associated components such as mass, angle of pennation, fibre length and density. It also summarises how the calculations were undertaken to study the angle of flexion of the MCP and IPJ of the thumb in relation to the dependent fingers. Finally, the usage of MRI and the USS scan on volunteers to study the tendinous interconnection are also discussed.

2.2 Dissection of cadavers

The foremost part of the research included cadaveric dissection and examination. The bodies (mean age of 86.25 years in females and 78.7 years in males) were bequeathed following a complete informed consent prior to death. Once the bodies were bequeathed, the bequethal officer brought the bodies to the Anatomy Department at Cardiff University. The dissection was carried out in the dissecting room under the regulation of the Human Tissue Act (2004) which strictly governs the dissected materials.

These cadavers were largely used by the medical, dental and the basic science students in their dissection. This study was commenced subsequent to their dissection of the upper limb. Finer dissection and recording of the measurements were carried out. Although forty bodies were obtained by the department, dissection could be carried out in only thirty upper limbs (which included the dental, medical and the basic sciences cadavers), since in the remaining, either (i) the bodies were poorly dissected by the students, or (ii) the hands were dried significantly and presented with claw which could not be stretched, or (iii) some of the hands had to be used for other teaching purposes.

2.3 Categorising the muscles

The muscles FCU, FCR, FPL, FDS and FDP were identified on the 15 cadavers (30 upper limbs) – (denoted as C1-C15 in the appendices tables). These muscles were categorised as unipennate, bipennate or multipennate according to the macroscopic arrangement of the muscle fiber (**Figure 2.1**). Unipennate muscle is defined as a muscle whose muscle fibres are attached or inserted at an angle (obliquely) to one side of the tendon. Bipennate muscle is defined as a muscle which has a central tendon on to which the muscle fibres converge from either side. A multipennate muscle is defined as a muscle with several intermediate tendons joining onto form a central tendon. The muscle fibres converge on to these tendons. Out of the muscle under study, FPL and FCU were categorised as unipennate muscles; FCR was bipennate while FDP and FDS were multipennate muscles.

2.4 Instruments, measurements and calculations

A Vernier calliper (with an error of ± 0.02 millimetres) was used measure the tendon width and thickness while a Crocraft digital Vernier Calliper was used to measure the the thickness of the tenosynovial interconnection. To record the angle of pennation both helix and ordinary protractors (with an error of ± 3º) were used, to record the length of the muscle and the muscle fibre and a flexible tape (error of ± 0.02 cms) was used a 300 ml capacity cylindrical beaker (error of ± 2.0ml) was used to calculate the density. The muscles were weighed on an electronic digital scale, which had an error of ± 0.001 grams.

2.5 Identifying the flexor tendons

The fibrous band running over the wrist joint was identified to be the flexor retinaculum and the space underneath as the carpal tunnel. Once the carpal tunnel was recognised, the long flexors of the fingers were either traced form the tunnel to their insertion (proximal to distal approach) or from their insertion (on to the phalanges) to the carpal tunnel (distal to proximal approach). The FPL tendon was identified by dissecting the distal phalanx of the thumb. Once the tendon was identified, the tendon was traced back on to the carpal tunnel. In the same manner, the tendon of FDS and FDP were identified by tracing back from their insertion at the middle or distal phalanx of the respective fingers. The relative inferior anatomical relation of FDP to the FDS tendons was used to confirm the tendons at the palm of the hand. FCU was identified by passive flexion of the wrist and by following the muscle belly and the tendon up to its insertion onto the pisiform bone. The same method was followed for identifying the tendon of FCR with its insertion onto the base of second and third metacarpals. **Figure 2.2** shows the anatomical relations of these five tendons.

Further to identifying these tendons, the width, thickness and the distance between the FPL and FDP of index finger before, at, and after the carpal tunnel were recorded with the hand held in anatomical position using a wooden board and strings.

2.6 Calculating the TCSA

For the calculation of TCSA, the cross sectional shapes of the tendons were taken to be elliptical (based on their gross appearance) and the formula below was used.

Area of ellipse = π x 1/2 (width x thickness)

For those muscles tendons that crosses the carpal tunnel and reach the hand (FPL, FDS for middle, ring and little fingers, FDP for middle, ring and little fingers) the width and thickness were recorded two centimetres above the carpal tunnel. While for FCU and FCR the cross sectional area was calculated two centimetres above their insertion.

2.7 Identifying the median nerve

At the proximal wrist, the median nerve was identified by its relation between the tendons of FDS and FCR before entering the carpal tunnel as seen in **Figure 2.3**. The shape of the nerve before, at, and after the tunnel was noted and the cross sectional area calculated. The shape of the nerve was taken to be elliptical (based on gross appearance) and the formula below was used to calculate its cross sectional area.

Area of ellipse = π x 1/2(width x thickness)

2.8 Calculating the tendon length

The tendon lengths of all these muscles were documented. The tendon length was accurately measured from the distal end of insertion of the muscle onto the tendon (**Figure 2.4**) to the bony insertion of the tendon. For FCU and FCR, the tendon lengths were measured from the point it exits the muscle to the point of insertion. For multipennate muscles such as the FDS and FDP, the mean of each tendon from the distal end of insertion of the muscle onto the tendon until its entry to the tunnel was recorded **(Figure 2.5).** The whole tendon length for FDS, FDP and FPL (until its insertion onto their respective phalanges) could not be recorded as in many of the hands the tendons were removed or destroyed by the student dissectors.

2.9 Calculating the angle of pennation

The angle of pennation was recorded with the muscles *in situ* at the midpoint of the muscle belly (midpoint between the origin and the distal end of the muscle belly). If the muscle is multipennate – mean of the all the lateral and medial side angles were taken (shown in **Figure 2.6**). This point was determined by using a flexible measuring tape. The angle of pennation is defined as the angle formed between the direction of the muscle fibres and the direction of the line connecting the muscle's point of attachment. This angle was recorded with an instrument (**Figure 2.7**) designed by the principal investigator. Named the '***pennator***', it consists of an elastic band with pins attached at two ends 'A' and 'B'. A thread runs from the pin 'B'. A thin cardboard is slipped underneath the muscle, the pin 'A' is fixed at the beginning of the muscle while the pin 'B' is inserted at the lower end of the muscle. The thread is adjusted along the angle of pennation of the fibre. Once the angle of the fibre is adjusted, the pin is inserted through the muscle fibre such that the pin would leave a mark on the cardboard underneath. This point is taken as 'C'. The cardboard is withdrawn once

the recording of the angle is complete. The three points are joined and the angle of pennation measured with a protractor.

The angle of pennation was evaluated by a protractor with a precision of ± 3º. The angle was recorded for individual muscle according to the arrangement of the muscle fibre. In case of FDS and FDP, the angle of pennation was taken to be the mean of all the angles of the fibres on the medial and lateral side inserting at each intermediate tendon.

2.10 Weighing the muscle

Once the cross sectional area of the tendon and the angle of pennation were calculated, the muscles of the forearm were identified at their origin and removed meticulously taking care to preserve all the muscle tissues. All the extra tendinous tissue was discarded (leaving the inter and the intramuscular tendon intact) and each muscle weighed (**Figure 2.8**). The following muscles were investigated: FDS, FDP, FCU, FCR and FPL. Each muscle was weighed with an electronic digital scale with a measurement precision of ± 0.001gms. FDS and FDP were weighed in groups whereas FCU, FPL and FCR were weighed individually.

2.11 Calculating the fibre length

For evaluating muscle fibre length, the muscles were immersed overnight in plastic containers with warm Biocide solution. This helped to dissolve the fat and separate the muscle fibre thus making it easier to dissect. Just prior to dissection, the muscles were dabbed dry using tissue paper. A small bundle of muscle fibre was dissected from the main muscle using a pair of forceps. The muscle fibre length was measured by placing the muscle bundle against the flexible measuring tape. Mostly, the muscle fibres were uniform but if they were non-uniform, the mean length was calculated.

2.12 Calculating the volume and density

Muscle density for each muscle was calculated by using the Archimedes principle (an object immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced by the object). This is:

Density =mass/volume

where, mass is the weight of the muscle in grams and volume (in centimetres^3).

Muscle volume was determined using a submersion method, whereby the apparent weight of an object immersed in water decreases by an amount equal to the weight of the volume of the water displaced. As 1 ml of water has a mass of approximately 1 g, the difference between the two masses (in grams) equals the volume (in ml) of the immersed muscle (Archimedes' Principle) (Brown *et al.*, 2003).

With all the above data, the PCSA was calculated using the formula:

PCSA=(m.cosα)/lp)

Where, 'm' is the muscle mass in grams, 'α' is the average angle of pennation of muscle fibres in degrees, 'l' is the muscle fibre length in centimetres and 'p' is the muscle tissue density in $g.cm^{-3}$.

The summary of the dissection procedures are shown in **Table 2.1** and **Figure 2.9**.

2.13 Ultrasound Scans (USS)

Ultrasound imaging is based on the principles that when a sound wave strikes an object, it bounces back or echoes. By measuring these echo waves it is possible to determine how far away the object is and its size, shape, and consistency. Ultrasound travels freely through fluid and soft tissues but is reflected by more solid or dense surfaces. For example, the ultrasound will travel freely though blood in a heart chamber, but when it hits a valve, a lot of the ultrasound echoes back. Thus, when ultrasound 'hits' different structures in the body of different density, it sends back echoes of varying strength (Robertson and Baker, 2001). Echo signals that are sent back are amplified electronically and displayed on a monitor in shades of grey (from black to white), stronger reflectors appear as brighter shades of grey and appear white (such as tendons) in an image while those with no echoes (such as muscle) will appear black (Sprawls, 1993).

For this study, ultrasound scanner with a resolution of 0.3-1.0 mm and a 12–14 MHz variable frequency probe was used as this is the standard resolution used to study the musculoskeletal system.

2.14 Magnetic Resonance Imaging (MRI)

Magnetic Resonance Imaging, developed in the late 1980s, works on the principle that many atomic nuclei exhibit the property of spin (i.e., they are constantly turning around an axis). Upon application of an external static magnetic field, the protons of water molecules will be aligned with the magnetic field. When they are disturbed by a second alternating magnetic field, at certain radio frequency, they begin to resonate. When a person is in the scanner, the hydrogen nuclei (i.e., protons), found in abundance in the human body in water molecules and align with the strong magnetic

field. Since protons in different tissues of the body (e.g., fat, muscle, bone, and tendons) realign at different speeds, the different tissues of the body can be distinguished (Young, 1998).

Although the sensitivity of the MRI machine was 2mm-10mm thick slices, 3.5 mm thick slice was used during pilot study. These are the standard specifications used to study any musculoskeletal pathology.

2.15 Advantages of USS over MRI

Ultrasound has certain advantages over MRI scans as it is non-invasive, less expensive, portable and is well tolerated by most patients (even the patients with cardiac pacemakers and metallic implants as it does not have strong magnetic field like MRI scan). Furthermore, it is useful in patients who are claustrophobic to the MRI setting.

The dynamic, real-time nature of sonography allows personal interaction with the patient, often resulting in a more directed examination, specific for each individual (Alder *et al.*, 1999). The live images allow the patient to carry out movements and stress the structure under study thus making it possible to localise and visualise the pathology and locate the cause of pain as in muscle or tendon tear (Robertson and Baker, 2001). Samuels and colleagues in 2010 concluded that the diagnosis and study of the pathology may be quicker and can be conveniently performed at the bedside or in clinic. A comparison with the other limb can also be undertaken in the same sitting.

2.16 Advantages of MRI over USS

MRI has an advantage over ultrasound in studying pathologies of the bones. Ultrasound has difficulty in penetrating the bones and thus can only visualise the outer surface of the bone. Thus for the study of pathologies that arise or affect the internal structures of bones or certain joints MRI is commonly used. As the clarity of the USS images are hazy, the final diagnosis and understanding of the pathology is highly subjective and observer dependent.

2.17 Volunteer study

To study the tendinous interconnection, volunteers were selected by asking them to perform pertinent movements such as flexion, extension; adduction, abduction and opposition of the thumb in relation to other fingers and the palm of the hand. The extent of restricted hand movements and flexion of the dependent digit(s) at proximal or distal phalanx(s) were observed. Following the movements, they were selected to enter the study if the angle of flexion of the IPJ of the thumb was >40º (on gross observation) and if this angle of flexion was accompanied by the dependent flexion of the DIPJ of the index and/or middle fingers. Using these criteria 12 volunteers with a mean age of 18.6 years (females) and 20.5 years (males) (referred to as volunteer 1 – volunteer 12 in appendices) were identified from the 2009-10 batch of year one medical course. Following informed consent, a series of photographs of the affected hand / hands were taken in two planes (supination and mid-prone) and four positions (rest, early movement, mid-position and fully flexed). The camera was set at a fixed height of five feet (eye level of the principle observer) at a distance of one meter from the hands of the volunteer and an angle of approximately 45 º **(Figure 2.10).** Once the photographs were taken, they were downloaded and placed on a grided PowerPoint slide. Following printing, the angles of flexion were drawn on these

photographs. Both the planes were used to measure the angle of flexion at the MCPJ and the IPJ of the thumb and the dependent fingers. The choice of the joint and the plane was made depending on the clarity of the printed image.

The summary of criterion for volunteer selection is shown in **Table 2.2**.

To study the angle of flexion of the IPJ of the thumb, a baseline was drawn passing vertically through the IPJ crease. Another line was drawn horizontally passing through the top of the IPJ and another point was drawn from the midpoint of the tip of the thumb. The angle of flexion of the IPJ was determined by joining these points. To study the angle of flexion of the MCP joint of the thumb, a baseline was drawn vertically through the skin crease of the MCP joint. Another horizontal line was drawn horizontally through the top of the MCP joint and the third line was drawn through the point of flexion of the thumb at the MCP joint. The angle of flexion of the DIPJ of the fingers was studied by drawing a vertical line along the crease of the DIPJ of the affected index or middle finger. Another horizontal line was drawn along the base of the DIP and the third line was drawn along the middle of the finger. The volunteer hands showing how these angles are measured is shown below in

Figures 2.11 and 2.12.

2.18 USS study

Ultrasound scan was performed by a single operator, using an Toshiba ATL HDI 5000 model ultrasound scanner which has a spatial resolution (ability of the scan to differentiate two structures as separate) of 0.3-1.0 mm, penetration depth (how much the ultrasound waves can penetrate into the body and get reflected) of 6cms and a 12–14 MHz variable frequency probe. The probe was placed sagittally, axially or obliquely distal (± 0.4-0.8 cms) to the distal transverse line on the flexor side of the wrist as this line corresponds to the proximal border of the flexor retinaculum. The scanner used conventional greyscale to detect the tendinous interconnections.

Depending on the angle measurement from the printed photographs, volunteers whose angle of flexion at the MCPJ of the thumb between 30-45˚, IPJ of thumb between 45-55˚and flexion of DIP of dependent finger between 20-45˚ were accepted for the USS study (n=4). Interconnections were found on the left hand of three volunteers while the result remained inconclusive in one volunteer.

2.19 MRI study

For the pilot study Artoscan 0.2T dedicated MR scanner was used. This machine had the following specifications: sensitivity of the machine was 2 mm-10 mm thick slices although 3.5 mm thick slice was used during pilot study. TR (Repetition Time) (the time between repetitions of the basic sequence in an imaging sequence) which was 400.0 seconds. TE (Echo Time) (represents the time in an imaging sequence between the initial pulse and the maximum in the echo) which was 16.0 milliseconds. These are the standard specifications used to study any musculoskeletal pathology.

2.20 Repeatability and reliability

2.20.1 Cadaveric study

(Cadavers are referred to as R1-R4 in the appendices)

The above instruments and methods were followed to check the repeatability and reliability of the experiment using for calculating the factors influencing the PCSA. Dissection was carried out on eight upper limbs of the cadavers (two males and two females). The mean age of the male cadavers were 79.8years while of the females were 82.6 years.

The principle observer dissected on one male and one female cadaver while a first year medical student volunteered to dissect on the other male and the female cadaver. Both the summary, pictoral representation of the procedure and the word document of the material and method were made available to the volunteer. Prior to dissection the volunteer was briefed on how to use the Vernier callipers.

The exact procedure was followed meticulously and the results are discussed in Chapter 3.

2.20.2 Confirming reliability of the cadaveric results using Image Pro-Plus

The five flexor tendon (FCU, FCR, FPL, FDS and FDP) and median nerve from RI cadaver was used to study the accuracy of the results of the cross sectional area. The tendons of were cut and removed at the exact site were the TCSA was measured (2cms above the insertion of FCU and FCR and 2cms above the carpal tunnel for FDS, FDP and FPL) seen in **Figure 2.13**. For median nerve, the samples were taken from three anatomical points: before, at and after the carpal tunnel. The cut tendons and the nerve were mounted vertically on a box and photographs were taken with a measuring tape in the background **(Figure 2.14)**. The TCSA and the nerve cross sectional area were calculated using the Image Pro-Plus software. During

measurement it was confirmed that the cross section of these structures were elliptical. The results are discussed in Chapter 3.

2.20.3 Volunteer study

(Referred to as VR1-VR3 in the appendices)

To study the repeatability and reliability of the materials and methods used, volunteers were selected by asking them to perform pertinent movements such as flexion, extension; adduction, abduction and opposition of the thumb in relation to other fingers and the palm of the hand. The extent of restricted hand movements and flexion of the dependent digit(s) at proximal or distal phalanx(s) were observed. Following the movements, they were selected to enter the study if the angle of flexion of the IPJ of the thumb was >40º (on gross observation) and if this angle of flexion was accompanied by the dependent flexion of the DIPJ of the index and/or middle fingers. Using these criteria three volunteers (two females and one male with a mean age of 19.5 years and 19 years respectively) was identified from the 2012-13 batch of year one medical course.

The original (mentioned in session 2.17) materials, methods, criteria and strategies were used. The procedure was repeatable but the reliability was enhanced by using fixed reference points while positioning the hand. The method is discussed overleaf.

2.20.3.1 Methodology using fixed reference points

Angle of flexion was conducted by a volunteer under the supervision of the principle observer. The volunteer's hand was held against a graduated background. The hand was held in anatomical position such that the crease of the MCPJ of the thumb corresponding to 0° (Point C) at the scale on the background. The ulnar side of the hand rested against the baseline (Point A) and the middle finger placed corresponding to point B as seen in **Figure 2.15 and attached video**. The MCPJ and the IPJ of the thumb and the DIPJ of the dependent fingers were highlighted with skin marker pens. The distance between the volunteer's hand and the camera was maintained consistently at one meter and 45º inclination. The angles of flexion are shown in **Figures 2.16 and 2.17**.

These movements of the thumb and dependent fingers were compared against a control hand (seen in attached video).

Following informed consent, a series of photographs of the affected hand / hands were taken in two planes (supination and mid-prone) and four positions (rest, early movement, mid-position and fully flexed). Once the photographs were taken, they were downloaded and placed on a grided PowerPoint slide. Following printing, the angles of flexion were drawn on these photographs. Both the planes were used to measure the angle of flexion at the MCPJ and the IPJ of the thumb and the dependent fingers. The choice of the joint and the plane was made depending on the clarity of the printed image.

2.20.4 Volunteer study and ultrasound

The same ultrasound machine used in the initial study was used for this repeatability and reliability study. The probe was placed sagittally, axially or obliquely distal (± 0.4-0.8 cms) to the distal transverse line on the flexor side of the wrist as this line corresponds to the proximal border of the flexor retinaculum. The scanner used conventional greyscale to detect the tendinous interconnections. Volunteer 1 (VR1) was accepted on to the USS study and a tendinous interconnection was localised in the left hand.

Chapter 3

RESULTS

3.1 Introduction

The results obtained from the following studies are outlined in this chapter:

1. Initial cadaveric dissection study comprising of 30 upper limbs from 15 cadavers (seven males and eight females; mean age 84.8 years and 89.5 years respectively).
2. Volunteer study involving 12 volunteers with tendinous interconnections (10 females and two males; mean age 18.6 years and 20.5 years respectively).
3. USS study of four volunteers with interconnections (all females; mean age 18.6 years).
4. Studies that undertook factors influencing the PCSA such as TCSA, mean mass, mean tendon length, mean density and angle of pennation.
5. Relations and significance of the data obtained from the cadaveric study were analysed by using simple linear regression and one-way ANOVA test.
6. Results obtained during the repeatability and reliability test by the dissection of eight upper limbs from four cadavers (two males and two females; mean age 79.8 years and 82.6 years respectively).
7. Results obtained from Pro-Image Plus software were used to confirm the shape and cross sectional area of the flexor tendons and median nerve.
8. Results obtained during the repeatability and reliability study of three volunteers with tendinous interconnections (two females and one male; mean age 19.5 years and 19 years respectively).
9. Result of USS study of the male volunteer (mean age 19 years) from the above study.

3.2 Interpretation of the results

3.2.1 Calculating the simple linear regression

To calculate the relation between various variable, simple linear regression graph was plotted.

Simple linear regression is a simple statistical tool that is used to study the relation and dependency of one or more descriptive variables. This type of linear regression attempts to find a straight line that best fits the data, where the variation on the real data above and below the line is minimised.

The significance of data is interpreted on the following observations:

- R – represents the degree of the relationship between the two variables.
- R^2- is the measure of the variability that can be accounted for between the two variables. Closer the R^2 value to 1, significant the data.
- Probablity value (p value) –states that the values are not derived by chance. If $p<0.05$**,** there is a significant relationship between the variables in the linear regression model (Bowker and Randerson, 2007).

3.2.2 Calculating with one-way ANOVA test

One-way ANOVA test was considered to find whether there are any significant differences between the means of independent (unrelated) data. As the one-way ANOVA compares the means between the groups and determines whether any of those means are significantly different from each other. In this dissertation, it was used to find the significance of the mean area of the median nerve at three anatomical points as it passes through the carpal tunnel (i.e., before, at and after the tunnel). It was also used to find the significance between the mean mass and the mean PCSA of the individual muscles.

3.2.3 Calculating the area of the tendon and median nerve using the Pro-Image Plus

The cross sectional area of the median nerve and the long flexor tendons were confirmed using the Image Pro-Plus. The software was used to confirm the shape and area of the cross sections of median nerve and flexor tendons.

3.3 Cadaveric details

	Males (n=7)	**Females (n=8)**
Mean age	84.8	89.5
Interconnections	6	5
Side of interconnection	Right =9	Left=2
Muscles and tendons dissected	FPL, FCU, FCR, FDS and FDP	FPL, FCU, FCR, FDS and FDP

3.4 Results for PCSA

PCSA in cm^2	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	0.52	1.11	0.69	1.02	2.08
STDEV	0.17	0.33	0.30	0.23	0.23
SEM	0.03	0.06	0.05	0.04	0.04

Thus, the mean PCSA for FPL was the least while FDP had the highest PCSA. As a result the muscles arranged in the order of increasing PCSA are: FPL, FCR, FCU, FDS and FDP. The raw data is shown in **Figure 3.1 and Appendices table: 3.1A**

3.5. Analysis of the relationship between the PCSA and mean mass

The comparative analyses of the relationship between the mean PCSA and mass of the different flexor muscles are shown in **Figure 3.2 and Table 3.2B of appendices.**

Mean mass in gms	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	4.30	14.31	5.31	5.54	17.59
STDEV	0.56	1.03	0.80	0.87	0.98
SEM	0.10	0.18	0.14	0.15	0.18

The muscles arranged in the increasing order of weight are as follows: FPL, FCR, FCU, FDS and FDP. Thus, FPL was the lightest muscle of the five flexors; while FDP was the heaviest.

PCSA in cm^2	FPL	FDS	FCR	FCU	FDP
Mean	0.52	1.11	0.69	1.02	2.08
STDEV	0.17	0.33	0.30	0.23	0.23
SEM	0.03	0.06	0.05	0.04	0.04

Thus, the mean PCSA for FPL was the least while FDP had the highest PCSA.

With the help of regression graph it was concluded that there was a direct relationship between the PCSA and the mean mass as p was 0.02 and R^2 was 0.95.

3.5.1 Statistical significance

Using one way ANOVA test it was concluded that the area of the mean mass and PCSA were statistically. **(Table:3.3C of appendices)**

3.6. Analysis of relationship between the mean TCSA and mean mass

The comparative analyses of relationship between the mean TCSA and mean mass of the different flexor muscles are shown in **Figure 3.3 and Table 3.4D of appendices**.

TCSA in cm^2	FPL	FDS	FCR	FCU	FDP
Mean	0.02	0.12	0.05	0.10	0.18
STDEV	0.01	0.01	0.02	0.02	0.01
SEM	0.00	0.00	0.00	0.00	0.00

Thus, the mean TCSA for FPL was the least while FDP had the highest.

Mean mass in gms	FPL	FDS	FCR	FCU	FDP
Mean	4.30	14.31	5.31	5.54	17.59
STDEV	0.56	1.03	0.80	0.87	0.98
SEM	0.10	0.18	0.14	0.15	0.18

The muscles arranged in the increasing order of weight are as follows: FPL, FCR, FCU, FDS and FDP. Thus, FPL was the lightest muscle of the five flexors; while FDP was the heaviest.

With the help of regression graph it was concluded that there is a direct relation between the TCSA and the mean mass as p was 0.01 and R^2 was 0.96.

3.7. Analysis of relationship between the mean PCSA and mean fibre length

The comparative analyses of relationship between the mean PCSA and fibre length of the different flexor muscles are shown in **Figure 3.4 and Table 3.5E of appendices**.

PCSA in cm^2	FPL	FDS	FCR	FCU	FDP
Mean	0.52	1.11	0.69	1.02	2.08
STDEV	0.17	0.33	0.30	0.23	0.23
SEM	0.03	0.06	0.05	0.04	0.04

Thus, the mean PCSA for FPL was the least while FDP had the highest PCSA.

Mean fibre	FPL	FDS	FCR	FCU	FDP

length					
Mean	6.19	1.51	7.17	4.26	4.13
STDEV	0.17	0.21	0.47	0.34	0.42
SEM	0.03	0.03	0.08	0.06	0.07

Thus, the FDP had the shortest muscle fibre while FCR the longest muscle fibre.

With the help of regression graph it was concluded that there is no direct relation between the PCSA and the mean fibre length as p was 0.06 and R^2 was 0.10.

3.8. Analysis of the relationship between PCSA and the mean density

The comparative analyses of the relationship between the PCSA and mean density in the different flexor muscles are shown in **Figure 3.5 and Table 3.6F of appendices**.

PCSA in cm^2	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	0.52	1.11	0.69	1.02	2.08
STDEV	0.17	0.33	0.30	0.23	0.23
SEM	0.03	0.06	0.05	0.04	0.04

Thus, the mean PCSA for FPL was the least while FDP had the highest PCSA.

Mean density in gcm^{-3}	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	1.006	1.007	1.047	0.991	1.007
STDEV	0.084	0.019	0.059	0.076	0.027
SEM	0.015	0.003	0.010	0.013	0.004

Thus the mean density of FCU was the least while FCR was the highest.

With the help of regression graph it was concluded that there is no direct relation between the PCSA and the mean density as p was 0.46 and R^2 was 0.28.

3.9. Analysis of the relationship between the mean mass and mean fibre length

The comparative analyses of the relationship between the mass and the fibre length of the different flexor muscles are shown in **Figure 3.6 and Table 3.7G of appendices**.

Mean mass in gms	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	4.30	14.31	5.31	5.54	17.59
STDEV	0.56	1.03	0.80	0.87	0.98
SEM	0.10	0.18	0.14	0.15	0.18

Thus, FPL was the lightest muscle of the five flexors; while FDP was the heaviest.

Mean fibre length in cms	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**

Mean	6.19	1.51	7.17	4.26	4.13
STDEV	0.17	0.21	0.47	0.34	0.42
SEM	0.03	0.03	0.08	0.06	0.07

Thus, the FDP had the shortest muscle fibre while FCR the longest muscle fibre.

With the help of regression graph it was concluded that there is no direct relation between the mean mass and the mean fibre length as p was 0.38 and R^2 was 0.37.

3.10. Analysis of relationship between the mean fibre length and mean density

The comparative analyses of relationship between the mean fibre length and density of the different flexor muscles were are shown in **Figure 3.7 and Table 3.8H of appendices**.

Mean fibre length in cms	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	6.19	1.51	7.17	4.26	4.13
STDEV	0.17	0.21	0.47	0.34	0.42
SEM	0.03	0.03	0.08	0.06	0.07

Thus, the FDP had the shortest muscle fibre while FCR the longest muscle fibre.

Mean density in gcm^{-3}	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	1.006	1.007	1.047	0.991	1.007
STDEV	0.084	0.019	0.059	0.076	0.027
SEM	0.015	0.003	0.010	0.013	0.004

Thus the mean density of FCU was the least while FCR was the highest.

With the help of regression graph it was concluded that there is no direct relation between the PCSA and the mean density as p was 0.79 and R^2 was 0.04.

3.11. Analysis of relationship between PCSA and mean angle of pennation.

The comparative analyses of mean angle of pennation of the different flexor muscles are shown in **Figure 3.8 and Table 3.9I of appendices.**

PCSA in cm^2	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	0.52	1.11	0.69	1.02	2.08
STDEV	0.17	0.33	0.30	0.23	0.23
SEM	0.03	0.06	0.05	0.04	0.04

Thus, the mean PCSA for FPL was the least while FDP had the highest PCSA.

Angle of pennation (in degrees)	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	15.16	7.13	13.06	2.5	11.5
STDEV	2.55	0.03	0.58	0.46	0
SEM	0.467	0.00	0.10	9.93	0

Thus, FPL had the highest angle of pennation while FDS had the lowest.

With the help of regression graph it was concluded that there is no direct relation between the PCSA and the mean angle of pennation as p was 0.08 and R^2 was 0.02.

3.12. Analysis of relationship of tendon cross-sectional area of FDP (Index) and FPL at carpal tunnel

The comparative analysis of the relationship of area of FDP (index) and FPL at carpal tunnel are shown in **Figure 3.9 and Table 3.10J of appendices**.

TCSA in cm^2	**FPL**	**FDP (index)**
Mean	0.13	0.10
STDEV	0.02	0.02
SEM	0.00	0.00

Thus following a linear regression graph it was concluded that TCSA of FDP (index) is directly proportional to the TCSA of FPL as p was 0.07 and R^2 was 0.87.

3.13. The area of median nerve before, at and after the carpal tunnel

The area of median nerve before, at and after the carpal tunnel was calculated. A graph was plotted in this relation (**Figure 3.10 and Table 3.11K of appendices)**

Mean area in cm^2	**Before the tunnel in** cm^2	**At the tunnel in** cm^2	**After the tunnel in** cm^2
Mean	0.14	0.16	0.20
STDEV	0.02	0.04	0.05
SEM	0.00	0.00	0.01

Thus the area of the median nerve increased at it passes through the carpal tunnel.

3.13.1 Statistical significance

Using one way ANOVA test it was concluded that the area of the median nerve is statistically significant after the tunnel while not significant before and at the tunnel **(Table:3.12L of appendices)**

3.14. Relationship between TCSA and PCSA of different flexor tendons

The TCSA of different flexor tendons (FPL, FDS, FCR, FCU, FDP) are shown in **Figure 3.11 and Table 3.13M of appendices**.

Mean TCSA and PCSA in cm²	**FPL PCSA**	**FDS PCSA**	**FCR PCSA**	**FCU PCSA**	**FDP PCSA**
Mean	0.52	1.11	0.69	1.02	2.08
STDEV	0.17	0.33	0.30	0.23	0.23
SEM	0.03	0.06	0.05	0.04	0.04

Mean TCSA and PCSA in cm²	**FPL TCSA**	**FDS TCSA**	**FCR TCSA**	**FCU TCSA**	**FDP TCSA**
Mean	0.02	0.12	0.05	0.10	0.18
STDEV	0.01	0.01	0.02	0.02	0.01
SEM	0.00	0.00	0.00	0.00	0.00

The order of TCSA in the increasing order is as follows: FPL, FCR, FCU, FDS and FDP and the mean PCSA for FPL was the least while FDP had the highest PCSA.

Thus with the help of a simple linear regression graph it was concluded that TCSA is directly proportional to PCSA as the R^2 was 0.94 while p was 0.03.

3.15. Relation between PCSA and the mean tendon lengths of different flexor tendons

The comparative relationship between PCSA and tendon length are shown in **Figure 3.12 and Table 3.14N of appendices**

PCSA in cm²	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	0.52	1.11	0.69	1.02	2.08
STDEV	0.17	0.33	0.30	0.23	0.23
SEM	0.03	0.06	0.05	0.04	0.04

The mean PCSA for FPL was the least while FDP had the highest PCSA.

Tendon length in cms	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	5.24	5.46	8.763	6.373	2.55
STDEV	0.789	0.795	1.34	1.252	0.918
SEM	0.144	0.145	0.245	0.228	0.167

Thus, FCR had the longest tendon while FDP had the shortest.

Thus with the help of a simple linear regression graph it was concluded that PCSA is related to tendon length as the R^2 was 0.87 while p was 0.04.

3.16: Thickness of cadaveric tendinous and tenosynovial interconnections

The mean tendon thickness of the cadaveric tendinous interconnection was 0.33 cm (SEM 0.04: SD ± 0.23). One of the cadavers had tenosynovial interconnection with a thickness of 0.09 cm. The information is shown in **Appendices Table 3.15O**

Age in years	Sex	Hand with interconnection	Tendon thickness(in cm)
93	F	R	0.32
94	F	L	0.55
81	M	R	0.50
81	M	L	0.31
90	F	R	0.34
92	F	R	0.24
89	M	R	0.34
95	M	R	0.02
78	M	R	0.03
85	F	R	0.82
Mean			**0.33**
Standard Deviation			**0.23**
Standard error of mean			**0.04**
85	M	R (Tenosynovial interconnection)	**0.09**

3.17 Conclusion of the dissection results

- The muscles in the increasing order of PCSA and TCSA are FPL, FCR, FCU, FDS and FDP. It was established that PCSA is directly proportional to TCSA. It was also established that mass has a direct relation with TCSA and PCSA.
- There was a direct relation between PCSA and the tendon length of different flexor tendons.
- At the carpal tunnel, TCSA of FPL was directly proportional to the TCSA of FDP (index) and the area of the median nerve increased at it passes through the tunnel.
- There was no conclusive relation between PCSA and the mean fibre length, mean density, the mean fibre length of the muscle, mean tendon length and the mean angle of pennation.

3.18. Tendinous interconnection established during dissection

Thirty forearm and hands were dissected and eleven were found to have interconnections or anatomical variations. The details of the age, sex, involved upper limb, extend and dimensions of interconnections can be seen in **Table 3.16P of appendices**. The observed interconnections (indicated with ★) extended between:

- the right FDS (ring) and right FDS (little) fingers in the hand(**Figure 3.13**)
- the right FDS (index) and the first right lumbrical in the hand (**Figure 3.14**)
- the right FPL and the right FDP (index) in the forearm (**Figure 3.15**)
- between main belly of right FDP and right FPL in the forearm (**Figure 3.16**)

- the right FDS (ring) and right FDS (index) in the forearm (**Figure 3.17**)
- the main bellies of left FDS and FDP in the forearm (**Figure 3.18**)
- **Figure 3.19** demonstrates an intermediate tendon in the right FDS (index) in the forearm
- the left pronators teres and left FDS in the forearm **(Figure 3. 20)**
- the right Extensor Carpi Radialis Brevis and Abductor Pollicis Brevis in the forearm **(Figure 3.21)**
- the right FCU and FDS in the forearm **(Figure 3.22)**
- the right flexor retinaculum and FDS in the forearm **(Figure 3.23)**

3.19 Analysis of results of volunteer study

Volunteer details

Total student's studied (n)=200	
Number of males with interconnections (n=2)	Number of females with interconnections (n=10)
Male:female=1:5	
Mean age 20.5 years	Mean age 18.6 years
Right hand interconnection	8 volunteers
Left hand interconnection	7 volunteers
Bilateral interconnections	3 volunteers

3.19.1 Analysis of the general information of the volunteers: (**Appendices [Table 3.17Q]**)

To study the tendinous interconnection, 200 first year medical students (2009-10 batches) were randomly picked by asking them to perform pertinent movements **such as** flexion, extension; adduction, abduction and opposition of the thumb in relation to other fingers and the palm of the hand. **T**he extent of restricted hand movements and flexion of the dependent digit(s) at proximal or distal phalanx(s) were observed. Following the movements, they were selected to enter the study if the angle of flexion of the IPJ of the thumb was >40º (on gross observation) and if this angle of flexion was accompanied by the dependent flexion of the DIPJ of the index and/or middle fingers. Out of these, 12 (10 females and 2 males with average age of 18.60 years and 20.50 years respectively) were identified to have tendinous interconnection between the FPL and FDS of other fingers. Of these 12 volunteers, three presented with bilateral tendinous interconnection (25%) while nine (75%) presented with unilateral interconnection. Ten out of the twelve volunteers played musical instruments for an average of 3.7 hours/week (average of half an hour/day). Most of the volunteers were right handed (10 volunteers) while one was ambidextrous and the other was left handed. Majority of the right handed volunteers (8 volunteers) played string instruments while one played wind instrument and the other did not play any instruments. **Table 3.1** shows the general statistics of the volunteers.

3. 19.2 Analysis of clinical examination of volunteers (Right hand): (**Appendices [Table 3.18R**)

- Five (one male and four females) volunteers had interconnection between the FPL (thumb) and FDP (index) finger on the right hand. They played the musical instrument (drums and violin) for an average of 3 hours/week.
- One female volunteer presented with interconnection between the FPL (thumb) and FDP (middle) finger. She played the piano for an average of 3 hours/week.
- One male and one female volunteer presented with interconnection between the FPL (thumb) and the FDP (index and middle) fingers. They also played (saxophone and guitar) for an average of 3 hours/week.

3. 19.3. Analysis of clinical examination of the volunteers (Left hand): (Appendices [Table 3.19S])

1. Three female volunteers had interconnection between the FPL (thumb) and FDP (index) finger on the left hand. They played the musical instrument (harp and violin) for an average of 2.80 hours/week.

2. Three volunteers (one male and two females) presented with interconnection between the FPL thumb and the FDP (middle) finger. They played the musical instrument (piano and guitar) for an average of 2.50 hours/week.

3. Two female volunteers presented with interconnection between the FPL (thumb) and the FDP (index and middle) fingers. They also played (piano and guitar) for an average of 2.5 hours/week.

3. 19.4 Analysis of angle of flexion between the thumb and the dependent fingers for all the volunteers are inserted below (Appendices [Table 3.20T]) and Figure 3.24

Following analysis of angle of flexion between the thumb and the dependent fingers, it was concluded that the angle of flexion increases with the flexion of the thumb at the distal interphalangeal joint (DIP). The angle of flexion was maximum when the thumb was flexed at the metacarpophalangeal (MCP) joint. Video of the movements and angle of flexion of the fingers are also attached.

3.19.5 Overall conclusion concerning the interconnections in the right and the left hands

Out of all these 12 volunteers, seven presented with right hand interconnections between the thumb and other dependent fingers (index and middle). These volunteers spend an average of 3 hours/week playing the musical instrument compared to 2.5 hours/week by the volunteers with tendinous interconnections in the left hand.

3.19.6 Overall conclusion for gender based interconnection in both cadavers and live volunteers

Cadaveric study(n=15)	**Males (n=7)**	**Females (n=8)**
Mean age	84.8	89.5
Interconnections	6	5
Side of interconnection	Right =9	Left=2
Male: female=1:1		
Volunteer study (n=200)	**Males (n=2)**	**Females (n=10)**
Mean age	20.5 years	Mean age 18.6 years
Side of interconnection	Right hand = 8	Left hand = 7
Bilateral interconnections		3 volunteers
Male: female=1:5		

3.20 Results for the ultrasound scan

Depending on the angle measurement from the printed photographs, volunteers whose angle of flexion at the MCPJ of the thumb between 30-45˚, IPJ of thumb between 45-55˚and flexion of DIP of dependent finger between 20-45˚ were accepted for the USS study (n=4). Four female volunteers (two with bilateral tendinous interconnection and two with interconnection on the left hand) were chosen and imaged by USS as they had very clear evidence of interconnection. Out of the two volunteers with bilateral interconnections, one played the piano and the other played no musical instrument while out of the other two volunteers with left tendinous interconnection, one played the violin and the other played the piano.

USS (oblique view) just distal to the carpal tunnel demonstrated interconnections in the left hand of three volunteers who played a musical instrument while no such interconnection was identified in the volunteer who did not play an instrument. In two volunteers (2 and 3) it was concluded that there was a tenosynovial interconnection due to hypo-echogenic (black) band between FDP and FPL (index). While for volunteer 12 there was a clear tendinous interconnection as there was a hyperechogenic patch (white) between the FPL and FDP (index). For volunteer 9, the results were inconclusive as the probable musculo-tendinous interconnection had hypo-echogenicity which was characteristic of muscle and on close examination muscle fibres could be seen clearly. It is therefore thought that this might be an accessory muscle belly from either FPL or FDS (index) rather than a tendinous interconnection.

The ultrasound images of the volunteers are shown in **Figures 3.25- 3.28.** The labels on these images were provided by the radiologist while the line indicating the interconnection was added later on (with exception to volunteer 9 –whose label was

added on to the power point slide with the consultation of the radiologist). The dimensions of the tendinous interconnections are shown in **Appendices Table 3.21U.**

	Thickness of the tendinous interconnection (**cm$^{2)}$**	
Volunteer 2	0.2	
Volunteer 3	0.1	
Volunteer 12	0.2	
Volunteer 9	0.2	
	Mean	**0.175**
	STDEV	**0.05**
	SEM	**0.025**

3.21 Problem encountered during volunteer study

Prior to obtaining ethical approval, the working condition of the small bore MRI machine was evaluated and was found to be satisfactory. When the pilot study was carried out (in normal hands), the images were clear and the quality was considered sufficient for the purpose of this study (**Figure 3.29**). After careful consideration of the working of the MRI machine and evaluation of the quality of images (it generated), ethical approval was obtained from Cardiff University and The Institute of Medical Engineering and Medical Physics. Following ethical approval, attempt was made to carry out the study on the volunteer with Linburg-Comstock anomaly. The volunteer with bilateral Linburg-Comstock anomaly was identified by a series of simple tests that included movements of the thumb and index finger at different planes and angles. The volunteer agreed to take part in the MRI study at the Institute of Medical Engineering and Medical Physics, School of Engineering, Cardiff University.

However, when the study on the volunteer was undertaken, unfortunately, the quality of images generated by the MRI machine was poor with numerous artefacts. It was not possible to differentiate the tendon from the muscle (**Figure 3.30**). Hence it was felt that this MRI machine was not suitable to undertake this study. No other MRI machines were available in the department. It was not possible to identify another MRI machine in the university for the purposes of this study and obtaining an MRI machine from the National Health Service (NHS) would have taken long time due to the lengthy ethical application process involved. After a careful consideration of the options, it was decided to abandon MRI evaluation for the study and was decided to substitute them with USS study and images. This whole process resulted in unforeseen delay in the completion of this study.

3.22 Problems encountered during obtaining photographs

Twelve volunteers in whom the angle of flexion of the IPJ of the thumb was >40ºand angle of flexion of the IPJ of the thumb was accompanied by the dependent flexion of the DIPJ of the index and/or middle finger were chosen for further study such as taking series of photos.

To study the angle of flexion, series of photographs were taken in two planes - in mid-prone and in supine positions and printed to draw the different angles of flexion. The volunteers were comfortable with the movements at the mid-prone position; however, they found it hard to flex their phalanges in the supine position. This may be due to the fact that were tired or had become conscious of the being constantly monitored. These reflected as variations in angle of flexion, artefacts and artificial movements due to conscious flexion of other fingers. The movements were further exacerbated when the volunteers were asked to repeat even after a break of 15 minutes.

The volunteers also found it difficult to flex the thumb naturally at MCPJ. This was clearly seen in volunteer number '4' (**seen in the video**). In supine position, there was flexion of the left little finger that was not seen in any other views. When taking images in supine position, volunteer number '5' could not rest her hand in anatomical position at image '0' but could do so with initial movement.

These artefacts and artificial movements are evident during the finger movements of volunteer number '6' wherein there was constant flexion of the DIPJ of the middle finger on flexion of the IPJ of the thumb. After much effort, the volunteer was unable to flex the thumb at the MCP joint and this brought about conscious flexion of the other fingers. The volunteer also found it difficult to keep the hand steady and had to constantly shake the hand before and after the images were taken in each view.

Volunteer number ‘9’ was conscious of the exercise that there is clear voluntary flexion of the little finger in supine position which is absent in mid-prone position.

3.23 Reliability and repeatability

The following sections outlines the results obtained during the repeatability and reliability test obtained by the dissection of eight upper limbs from four cadavers (2 males and 2 females with a mean age of 79.8 years and 82.6 years respectively). It also discusses the results of the three volunteers who were studied for tendinous interconnections (two females and one male with a mean age of 19.5 years and 19 years respectively). Finally, the result of USS study of the male volunteer (mean age of 19 years) is discussed.

3.24 Interpretation of the results

3.24.1 Simple linear regression and one way ANOVA test

The relation results were calculated using the linear regression graphs while the one way ANOVA test was used to calculate the significance of the mean area of the median nerve at three anatomical points as it passes through the carpal tunnel (i.e., before, at and after the tunnel). It was also used to find the significance between the mean mass and the mean PCSA of the individual muscles.

3.24.2 Calculating the area of the tendon and median nerve using the Pro-Image plus

The cross sectional shape and area of the median nerve and the long flexor tendons were confirmed using the Image Pro-Plus software.

3.25 Dissection based

3.25.1 Cadaveric dissection

Cadaveric dissection using the same procedure discussed in chapter 2 was followed and dissection was carried out on eight upper limbs of two male and two female cadavers (R1-R4). The mean age of the male cadavers were 79.8years while for the females were 82.6 years.

	Males (n=2)	**Females (n=2)**
Mean age	79.8 years	82.6 years
Interconnections	None	None
Muscles and tendons dissected	FPL, FCU, FCR, FDS and FDP	FPL, FCU, FCR, FDS and FDP

The results are as follows:

3.25.2 Results for PCSA

PCSA in cm^2	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	0.38	1.00	0.68	0.80	2.20
STDEV	0.22	0.31	0.35	0.05	0.17
SEM	0.07	0.11	0.12	0.02	0.06

Thus, the mean PCSA for FPL was the least while FDP had the highest PCSA. As a result the muscles arranged in the order of increasing PCSA are: FPL, FCR, FCU, FDS and FDP. The data is shown in **Figure 3.31 and appendices Table 3.21a**

3.25.3 Analysis of the relationship between the PCSA and mean mass

The comparative analyses of the relationship between the mean PCSA and mass of the different flexor muscles are shown in **Figure 3.32 and appendices Table 3.22b.**

The results of the one-way nova test are in **Appendices table 3.23c:**

Mean mass in gms	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	4.69	13.77	5.88	4.99	17.55
STDEV	0.70	0.93	0.62	0.62	0.57
SEM	0.24	0.32	0.22	0.22	0.20

The muscles arranged in the increasing order of weight are as follows: FPL, FCR, FCU, FDS and FDP.

Thus, FPL was the lightest muscle of the five flexors; while FDP was the heaviest.

PCSA in cm^2	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	0.38	1.00	0.68	0.80	2.20
STDEV	0.22	0.31	0.35	0.05	0.17
SEM	0.07	0.11	0.12	0.02	0.06

Thus, the mean PCSA for FPL was the least while FDP had the highest PCSA.

With the help of regression graph it was concluded that there was a direct relationship between the PCSA and the mean mass as p was 0.02 and R^2 was 0.89.

3.25.4 Analysis of relationship between the mean TCSA and mean mass

The comparative analyses of relationship between the mean TCSA and mean mass of the different flexor muscles are shown in **Figure 3.33 and Table 3.24d of appendices**.

TCSA in cm^2	FPL	FDS	FCR	FCU	FDP
Mean	0.09	0.12	0.25	0.15	0.18
STDEV	0.01	0.01	0.01	0.01	0.00
SEM	0.25	0.43	0.21	0.22	0.27

Thus, the mean TCSA for FPL was the least while FDP had the highest.

Mean mass in gms	FPL	FDS	FCR	FCU	FDP
Mean	4.69	13.77	5.88	4.99	17.55
STDEV	0.70	0.93	0.62	0.62	0.57
SEM	0.24	0.32	0.22	0.22	0.20

The muscles arranged in the increasing order of weight are as follows: FPL, FCR, FCU, FDS and FDP. Thus, FPL was the lightest muscle of the five flexors; while FDP was the heaviest.

With the help of regression graph it was concluded that there is a direct relation between the TCSA and the mean mass as p was 0.04 and R^2 was 0.92.

3.25.5 Analysis of relationship between the mean PCSA and mean fibre length

The comparative analyses of relationship between the mean PCSA and fibre length of the different flexor muscles are shown in **Figure 3.34 and Table 3.25e of appendices**.

PCSA in cm^2	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	0.38	1.00	0.68	0.80	2.20
STDEV	0.22	0.31	0.35	0.05	0.17
SEM	0.07	0.11	0.12	0.02	0.06

Thus, the mean PCSA for FPL was the least while FDP had the highest PCSA.

Mean fibre length	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	6.35	3.95	6.95	4.47	1.42
STDEV	0.19	0.51	0.48	0.18	0.18
SEM	0.06	0.18	0.17	0.08	0.06

Thus, the FDP had the shortest muscle fibre while FCR the longest muscle fibre.

With the help of regression graph it was concluded that there is no direct relation between the PCSA and the mean fibre length as p was 0.08 and R^2 was 0.54.

3.25.6 Analysis of the relationship between PCSA and the mean density

The comparative analyses of the relationship between the PCSA and mean density in the different flexor muscles are shown in **Figure 3.35 and Table 3.26f of appendices**.

PCSA in cm^2	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	0.38	1.00	0.68	0.80	2.20
STDEV	0.22	0.31	0.35	0.05	0.17
SEM	0.07	0.11	0.12	0.02	0.06

Thus, the mean PCSA for FPL was the least while FDP had the highest PCSA.

Mean density in gcm^{-3}	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	0.97	0.96	0.98	0.95	0.97
STDEV	0.14	0.05	0.06	0.05	0.04
SEM	0.05	0.01	0.02	0.01	0.01

Thus the mean density of FCU was the least while FCR was the highest.

With the help of regression graph it was concluded that there is no direct relation between the PCSA and the mean density as p was 0.36 and R^2 was 0.56.

3.25.7 Analysis of the relationship between the mean mass and mean fibre length

The comparative analyses of the relationship between the mass and the fibre length of the different flexor muscles are shown in **Figure 3.36 and Table 3.27g of appendices**.

Mean mass in gms	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	4.69	13.77	5.88	4.99	17.55
STDEV	0.70	0.93	0.62	0.62	0.57
SEM	0.24	0.32	0.22	0.22	0.20

Thus, FPL was the lightest muscle of the five flexors; while FDP was the heaviest.

Mean fibre length in cms	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	6.35	3.95	6.95	4.47	1.42
STDEV	0.19	0.51	0.48	0.18	0.18
SEM	0.06	0.18	0.17	0.08	0.06

Thus, the FDP had the shortest muscle fibre while FCR the longest muscle fibre.

With the help of regression graph it was concluded that there is no direct relation between the mean mass and the mean fibre length as p was 0.47 and R^2 was 0.45.

3.25.8 Analysis of relationship between the mean fibre length and mean density

The comparative analyses of relationship between the mean fibre length and density of the different flexor muscles were are shown in **Figure 3.37 and Table 3.28h of appendices**.

Mean fibre length in cms	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	6.35	3.95	6.95	4.47	1.42
STDEV	0.19	0.51	0.48	0.18	0.18
SEM	0.06	0.18	0.17	0.08	0.06

Thus, the FDP had the shortest muscle fibre while FCR the longest muscle fibre.

Mean density in gcm^{-3}	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	0.97	0.96	0.98	0.95	0.97
STDEV	0.14	0.05	0.06	0.05	0.04
SEM	0.05	0.01	0.02	0.01	0.01

Thus the mean density of FCU was the least while FCR was the highest.

With the help of regression graph it was concluded that there is no direct relation between the PCSA and the mean density as p was 0.08 and R^2 was 0.35.

3.25.9 Analysis of relationship between PCSA and mean angle of pennation

The comparative analyses of mean angle of pennation of the different flexor muscles are shown in **Figure 3.38 and Table 3.29i of appendices.**

PCSA in cm^2	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	0.38	1.00	0.68	0.80	2.20
STDEV	0.22	0.31	0.35	0.05	0.17
SEM	0.07	0.11	0.12	0.02	0.06

Thus, the mean PCSA for FPL was the least while FDP had the highest PCSA.

Angle of pennation (in degrees)	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	15.5	7.31	12.87	9.25	11.5
STDEV	2.67	0.45	0.64	2.96	0
SEM	0.94	0.16	0.22	1.04	0

Thus, FPL had the highest angle of pennation while FDS had the lowest.

With the help of regression graph it was concluded that there is no direct relation between the PCSA and the mean angle of pennation as p was 0.06 and R^2 was 0.56.

3.25.10 Analysis of relationship of tendon cross-sectional area of FDP (Index) and FPL at carpal tunnel

The comparative analysis of the relationship of area of FDP (index) and FPL at carpal tunnel are shown in **Figure 3.39 and Table 3.31j of appendices**.

TCSA in cm^2	**FPL**	**FDP (index)**
Mean	0.14	0.108
STDEV	0.00	0.00
SEM	0.00	0.00

Thus following a linear regression graph it was concluded that TCSA of FDP (index) is directly proportional to the TCSA of FPL as p was 0.03 and R^2 was 0.94.

3.25.11 The area of median nerve before, at and after the carpal tunnel

The area of median nerve before, at and after the carpal tunnel was calculated. A graph was plotted in this relation (**Figure 3.40 and Table 3.32k of appendices)**

Median nerve area in mm^2	**Before the tunnel in cm^2**	**At the tunnel in cm^2**	**After the tunnel in cm^2**
Mean	0.14	0.15	0.18
STDEV	0.03	0.04	0.03
SEM	0.00	0.00	0.00

Thus the area of the median nerve increased at it passes through the carpal tunnel.

3.25.11.1 Statistical significance

One-way ANOVA test identified that the change in cross-sectional area of the median nerve during its course in the carpal tunnel was not statistically significant. Following the consultation with the statistician, it was concluded that this might be due to the small sample size (n=8) since the minimum sample size required was 30 in order to give sufficient power to the study and eliminate the Type I error. This is seen in **(appendices Table:3.33l)**

3.25.12 Relationship between TCSA and PCSA of different flexor tendons

The TCSA of different flexor tendons (FPL, FDS, FCR, FCU, FDP) are shown in **Figure 3.41 and Table 3.34m of appendices**

PCSA in cm^2	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	0.38	1.00	0.68	0.80	2.20
STDEV	0.22	0.31	0.35	0.05	0.17
SEM	0.07	0.11	0.12	0.02	0.06

TCSA in cm^2	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	0.09	0.12	0.25	0.15	0.18
STDEV	0.01	0.01	0.01	0.01	0.00
SEM	0.25	0.43	0.21	0.22	0.27

The order of TCSA in the increasing order is as follows: FPL, FCR, FCU, FDS and FDP and the mean PCSA for FPL were the least while FDP had the highest PCSA.

Thus with the help of a simple linear regression graph it was concluded that TCSA is directly proportional to PCSA as the R^2 was 0.90 while p was 0.03.

3.25.13 Relation between PCSA and the mean tendon lengths of different flexor tendons

The comparative relationship between PCSA and tendon length are shown in **Figure 3.42 and Table 3.35n of appendices**

PCSA in cm^2	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	0.38	1.00	0.68	0.80	2.20
STDEV	0.22	0.31	0.35	0.05	0.17
SEM	0.07	0.11	0.12	0.02	0.06

The mean PCSA for FPL was the least while FDP had the highest PCSA.

Tendon length in cms	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
Mean	4.56	5.13	8.91	6.83	2.47
STDEV	1.03	0.59	1.09	1.24	0.87
SEM	0.36	0.20	0.38	0.43	0.30

Thus, FCR had the longest tendon while FDP had the shortest.

Thus with the help of a simple linear regression graph it was concluded that PCSA is directly related to tendon length as the R^2 was 0.85 while p was 0.03.

3.25.14 Conclusion of the dissection results for repeatability and reliability test

- The results for the repeatability and reliability test was exactly the same as the original test and are as follows:
- The dissection findings following repeatability and reliability test was the same as the initial experiment. Thus it can be concluded that the procedure undertaken were both reliable and repeatable. The results are as follows:
- The muscles in the increasing order of PCSA and TCSA are FPL, FCR, FCU, FDS and FDP. It was established that PCSA is directly proportional to TCSA. It was also established that mass has a direct relation with TCSA and PCSA.
- There was a direct relation between PCSA and the tendon length of different flexor tendons.
- At the carpal tunnel, TCSA of FPL was directly proportional to the TCSA of FDP (index) and the area of the median nerve increased at it passes through the tunnel.
- There was no conclusive relation between PCSA and the mean fibre length, mean density, the mean fibre length of the muscle, mean tendon length and the mean angle of pennation.

3.25.15 Confirmation of cross sectional area using Image Pro-Plus software

3.25.15.1 Confirmation of TCSA and area of median nerve using Image Pro-Plus software

Tendons and median nerve Cadaver R1 was used

Tendons dissected	**FPL**	**FDS**	**FCR**	**FCU**	**FDP**
TCSA by Image Pro-Plus	1.81	1.8	2.65	2.93	2.1
TCSA by dissection	0.9	1.2	2.5	1.5	1.8

These results confirm that the crosses sectional shape of the tendon is elliptical and the results derived are accurate.

3.25.15.2 Confirmation of the area of the median nerve by Image Pro-Plus software

Cadaver R1 was used

Tendons dissected	**Before the tunnel (cm^2)**	**At the tunnel**	**After the tunnel**
Cross sectional area by Image Pro-Plus	0.14	0.20	0.21
Cross sectional area by dissection	0.14	0.15	0.18

3.26 Volunteer study

Total number of volunteers (n)=3	
Number of male with interconnections (n=1)	Number of female with interconnections (n=2)
Mean age in male 19 years	Mean age in females 19.5 years
Male:female=1:2	
Right hand interconnection	2
Left hand interconnection	1

Following analysis of angle of flexion between the thumb and the dependent fingers, it was concluded that the angle of flexion increases with the flexion of the thumb at the DIP joint. The angle of flexion was maximum when the thumb was flexed at the MCP joint. The graph showing these results is seen in **Figure:3.43 and Table 3.36o of appendices**.

3.26.1 USS imaging of the volunteer's hand

Depending on the angle measurement from the printed photographs, volunteer whose angle of flexion at the MCPJ of the thumb was >30-45º, IPJ of thumb between >45-55º and flexion of DIP of dependent finger was between >20-45º was accepted on to the USS study. One male volunteer (with unilateral tendinous interconnection and on the left hand) was chosen and imaged by USS.

The dimension of the tendinous interconnection is below:

	Thickness of the tendinous interconnection (**cm**)	
Volunteer 1	**Mean**	**0.2**
	STDEV	**0.0**
	SEM	**0.0**

USS (oblique view) just distal to the carpal tunnel demonstrated interconnections in the right hand. This is seen in **Figure 3.44**.

Chapter 4

DISCUSSION

4.1 Introduction

This chapter discusses the results observed during the study of tendinous interconnections following cadaveric dissection and trials in live volunteers. It also evaluates the limitations and problems encountered whilst undertaking these studies. The current study has tried to establish the relation between TCSA and PCSA. **In the light of the possibility that increase in tendon diameter may increase the susceptibility to CTS due to compression and pressure on the median nerve**. In addition, it reviews the literature comparing the imaging options available to study upper limb tendinous interconnections, and also discusses the advantages of using US scan in calculating the angle of pennation *in vivo* and thus the PCSA.

4.2 Tendon healing and interconnections

Table 4.1 shows the pathophysiology of tendon healing and how scarring can lead to tendinous interconnections. Factors that influence tendon healing include the anatomical location, extend of injury, vascularity and amount of rest. Ingraham and colleagues (2003) identified that micro trauma to the tendon leads to disruption of the normal parallel alignment of the collagen fibre. This results in activation of the tenocytes from the epitenon and endotenon layers of the tendon. During proliferative stage of tendon healing, there is an increase in the size of the tenocytes and proliferation of the capillaries leading to an increase in the TCSA. Sharma and colleagues (2005) described that an increase in the tendon cross sectional area would lead to recurrent injury to the tendon due to constant abrasion with the adjacent tendon(s). This in turn inhibits the remodelling phase of healing leading to scarring and subsequent interconnections.

4.3 Proven hypotheses

4.3.1 Interconnections are more prevalent in females

In the volunteer study, two males and ten females presented with interconnections (5:1). This finding concurred with the literature that reports a higher incidence in women compared to men (3:1) (Hamitouche *et al*., 2000). Although the reason remains unknown it is thought that in musicians, it might be due to smaller hand size along with decreased arm strength and more flexibility and joint laxity. This may lead to stretching of the flexor tendons while performing string instruments such as the violin. Overstretching and frequent movements at the wrist would lead to trauma and tearing of the tenosynovium, predisposing to tendinous interconnections. However, these theories have not been investigated sufficiently to derive concrete conclusions (Brandfonbrener, 1990; Chong and Chesky, 2001)

4.3.2 Relation between PCSA, TCSA and tendinous interconnections

TCSA is the cross sectional area of the tendon. From the present study, it can be concluded with the help of a linear regression graph that TCSA of individual muscle tendons are directly proportional to the corresponding PCSA. This finding is in accordance with previous reports in the literature (An *et al*., 1991). Thus the hypothesis made in chapter 1 has been proven. This relationship is important for understanding the aetiologies of acquired tendinous interconnections at the carpal tunnel as muscles with larger PCSA would have larger TCSA thus creating a greater change for these tendons to rub against each other. At the carpal tunnel, the deep flexors tendons of the fingers consist of loosely arranged tendon strands. Consequently, the tenosynovium may get trapped between these individual tendon strands and predispose to the formation of tendinous interconnections (Leijnse *et al.*, 1997a). This may result in carpal tunnel syndrome as these interconnections may

behave like space occupying lesions (Rennie and Muller, 1998; Rotman *et al*., 2002). This postulation was established by Linburg and Comstock in 1979 (four cases) and by Lombardt and colleagues in 1988 (33 cases). In the above two studies, surgical excision of the anomalous tendinous interconnections resulted in resolution of the patient's symptoms.

4.3.3 Relation between TCSA of FDP (index) and FPL

The data gathered from the cadaveric dissection were analysed using simple linear regression and it was concluded that the TCSA of FDP (index) and FPL were directly proportional. Thus it may be espied that as the TCSA of FDP (index) increase the TCSA of FPL also increases, which would in turn reduce the space between the two tendons within the carpal tunnel. Thus during constant and repetitive wrist movements the tendons may rub against each other causing micro trauma. Furthermore, following injury, there may be an increase in the collagen fibre size, fibroblast density and vascular proliferation within the tendon and tendon sheath, which further increases the TCSA. This in turn increases the pressure within the carpal tunnel leading to the compression of the median nerve (Crevier-Denoix *et al*., 1998, Ettem *et al*., 2004 and Yoon *et al*., 2005). Thus the hypothesis made in chapter 1 has been proven.

4.3.4 Relation between mean mass and PCSA

Following the study, it was established that the muscles FPL, FCR, FCU, FDS and FDP – had PCSA, and mean mass in the increasing order *i.e* FDP having the highest PCSA and mean mass while FPL the least. Thus it was recognized that PCSA is directly proportional to the mass of the muscle. Thus, FDP was the heaviest muscle with the largest PCSA, while FPL had the lowest mean weight with lowest PCSA.

Therefore FDP is a stronger muscle than FPL as the strength of each muscle is proportional to the PCSA (An *et al.*, 1991). Hence, a thick muscle with large PCSA can produce great amount of force (MacIntosh *et al.*, 2006). Based on this study, the hypothesis made in chapter 1 that the mean mass of the muscle has a direct effect on the PCSA has been proven.

4.3.5 Relation between mean tendon length and PCSA

From the results of the current study, it can be concluded that the FDP had the longest tendon while FPL had the shortest. The study also concluded that there is a direct relation between the PCSA, TCSA, mean mass and tendon length. Previous studies suggest that long and tendinous muscles can form pulley systems thus allowing large external movement like grasping with the fingers with relatively small movements of the muscles and tendons (MacIntosh *et al*., 2006). Thus muscles such as FDS and FDP are used for finer movements such as writing and sewing in association to other intrinsic muscles of the hand.

4.3.6 Mean cross sectional area of median nerve

The cross sectional area of the median nerve was calculated at three points during its path along the carpal tunnel. The cross sectional area of the median nerve was the smallest before it entered the tunnel and largest as the nerve exit the tunnel. Thus during the course of the median nerve through the carpal tunnel, it flattens out and increases in area. This may be to easily pass through the tunnel and to accommodate the other flexor tendons that pass with it (Allmann *et al.,* 1997). In the past, these findings have been established by USS scan (Buchberger *et al.*, 1991)

4.4 Null hypotheses

4.4.1 No relation between mean fibre length and PCSA

Previous studies have shown that PCSA has an inverse relation to the fibre length, thus, the longer the muscle fibre, smaller the PCSA of the muscle. It may be due to the fact that longer the muscle fibre, fewer muscle fibre would be accommodated in a given unit area and this would reduce the PCSA (Alexander *et al.*, 1975). But following this study it was noted that there is no relation between the mean fibre length and the PCSA. Although Lieber in 1992 suggested that muscle velocity is proportional to muscle fibre length thus it could be concluded that FCR produced a high velocity of contraction compared to other muscles that were studied.

4.4.2 No relation between mean density and PCSA

The density of the muscle had no bearing on the PCSA of the muscle, nor was there any bearing between the muscle fibre length. Brown and colleagues (2003) reported the density for all the muscles were taken to be a constant of 1.075 $g.cm^{-3}$. Therefore when used in the formula for PCSA it do not seem to influence the final results.

4.4.3 No relation between mean angle of pennation and PCSA

In a pennated muscle (such as FPL, FDS, FDP, FCU and FCR), the muscle fibres are inserted to the central tendon at an angle. Within the muscle, the fibres are arranged parallel to the central tendon. Due to this arrangement, more muscle fibres can be accommodated thus producing larger force with smaller range of movement (Otten, 1998). During muscle contraction, the pennated fibres pull the central tendon at an angle to create a force. The force exerted on the tendon can be calculated by cosine of the angle of insertion. During rest, the angle of insertion is less than 10° which does not have a marked effect on the force production. To find out which muscle is powerful and contracts the most, the angle of pennation needs to be calculated during

muscle contraction as the angle changes considerably during contraction (Roy and Edgerton, 1992). Alexander and colleagues in 1975 and Narici and colleagues in 1992 found that in the pennated muscles, PCSA is always larger than TCSA while in this study it was directly proportional. Brown and colleagues in 2003 noted that the muscles with long fibres has low pennation angles while those with short fibres were highly pennated while in this study there was no relation between the angle of pennation and the length of the individual muscle fibre nor with PCSA. Thus the theory regarding pennated muscle fibre arrangement and force created cannot be concluded following this study as it would involve active movements of the respective muscles and the joints.

4.5 Limitations of dissection study

4.5.1 Technical difficulties

4.5.1.1 Problem due to embalming techniques

The first part of this study involved cadaveric dissection and collection of morphometric data from the long flexor muscles that act at the wrist and fingers. The cadavers were preserved with formaldehyde-based embalming fluid, resulting in the tissues becoming hard, rigid and often difficult to dissect; similar difficulty has been encountered by other researchers (MacBride 1998). Previous studies have identified that following embalming the cadaveric muscle may shrink thus affecting the PCSA (Narici *et al*., 1996, Cutts, 1998).

In 1995 Narici and colleagues studied the PCSA and force generated by human gastrocnemius in live volunteers. PCSA was calculated using the formula = (m/pLf)cosθ where ‘m’ is muscle mass, ‘p’ is muscle density (1.050 g cm-3), ‘V’ is muscle volume, ‘θ’ is the angle of pennation and ‘Lf’ is fibre length. The parameters

for the formula were calculated using both MRI and US scan. Following the above study they concluded that the angle of pennation, fibre length and PCSA changed from rest to contraction thus affecting the PCSA. The PCSA increased (while contracting) by 34.8%. Taking into account the fact that PCSA changes during rest and contraction, the PCSA derived from cadavers may not be accurate.

Suggested improvements

Similar to the above study and from the results observed in this dissertation it can be stated that the cadaveric study may not be the best method for calculating the PCSA. This is because parameters such as angle of pennation, fibre length change with movements and passive movements cannot be undertaken in the cadaver. Likewise, recording the movements with an US or MRI scan is not possible. Thus imaging techniques such as US and MRI scans are better at calculating the PCSA and in understanding the relation between PCSA, muscle force and muscle strength.

4.5.1.2 Analysing muscle fibre length and angle of pennation

In cadavers, the muscle fibre lengths and angles of pennation were only measured at selected and specific sites within each muscle and these locations were consistent within the same muscles in all the limbs. Furthermore, the variability in muscle fibre length and angle of pennation expressed as one standard deviation (SD) from the mean reflects measurement error variability based on measurement location within a muscle and variability among limbs. For example, the deep digital flexor muscle displayed a large SD in fibre length this error being attributable to the range of muscle

fibre lengths recorded across various locations within the muscle. The other limitation relates to the measurement of tendon length at rest. The length of tendon of each muscle was measured from the muscle's distal fibres to its insertion, and no account was made of the intra muscular tendon that can extend far into the muscle belly. Adding the length of the intra muscular tendon to measured tendon length at rest would lead to a considerable increase in overall tendon length at rest and this factor ought to be taken into consideration (Brown *et al.*, 2003).

Cutts (1998) documented the effects of formaldehyde-based embalming methods on muscle architecture. He stated that formaldehyde-based solutions are most likely to cause shrinkage of the muscle fibre. The muscle fibre length may vary from live volunteers as the cadaveric muscle is fixed when they are in a state between relaxation and contraction. Thus, results of cadaveric studies cannot accurately reflect what would be found in living subjects (Thompson *et al*., 2002). Sacks and Roy (1982) stated that the shortening or elongation of muscle tissue due to chemical fixation can be expected to be less than 5%. However in this study, the muscle fibre length was measured after they were removed from the muscle and this might have caused some changes to the muscle fibre length mainly the shortening of the muscle fibre as the fibre may have been destroyed during removal.

The final limitation of this study was the potential lack of adequate perfusion of the muscles by the embalming fluid. As some of the FDP muscles were not adequately perfused with the embalming fluid, the fibres tore easily when teased. Although I could isolate single fibres to measure fibre lengths, it was difficult to confirm with certainty their intactness (whole length). This affected the accuracy of the muscle

fibre length and thus the PCSA. A similar problem was encountered by Friedrich and Brand (1990) while recording the muscle fibre architecture in the human lower limb.

Studies on human tibialis anterior and medial gastrocnemius muscles in live volunteers by Herbert and colleagues (2002) using US scan showed that with passive movement of these muscles, the muscle fascicles underwent much smaller changes in length than whole muscle-tendon units (i.e, origin-to-insertion length). Thus when resting muscles are stretched (e.g, by contraction of their antagonists) much of the increase in muscle-tendon length occurs in the tendon. The intramuscular and the intermediate tendons also undergo changes (such as shortening) during contraction. This is due to the presence of elastin in the extracellular matrix (elastin causes stretching and shortening of the tendon) (Lieber *et al*., 2000). The above studies also concluded that the angle of pennation also decreased during muscle contraction.

Suggested improvements

In the cadavers the muscles are in a partially contracted state and some of the tendons in the hand were curled up. Thus it was difficult to establish the exact tendon length in the relaxed state nor was it possible to note the changes of angle of pennation during various movements across the joints. Thus imaging techniques (such as MRI and USS) are much better at recording, comparing the tendon length (both intra and extra muscular) and in studying the changes in angle of pennation during rest and during active and passive movements across the joints.

4.5.1.3 Age of the cadavers and lack of specific cadaveric information

Narici and colleagues (2003) found that the muscle architecture is significantly altered by aging. The age-related changes include shortening of muscle fibre length and

decrease in angle of pennation (Narici, 1998). The decrease in angle of pennation is due to decrease in fibre number secondary to disuse atrophy (Lexell, 1988). As the fibre number and angle of pennation influences the TCSA and PCSA, it was not possible to compare the dissection results with that of a younger cadaver as the mean age of the cadavers studied were between 78.7 (male) and 86.2 (female) years. In this dissertation, pertinent medical history couldn't be obtained nor was any information available to indicate possible fibre atrophy, hypertrophy or development anomalies; the accuracy of PCSA thus could not be substantiated.

Needless to say, studies using cadaver muscles are usually from an older age group and hence it is not practical to accurately evaluate the fibre number and angle of pennation in young individuals (from cadaver studies). This limitation has been previously highlighted by Friedrich and colleagues (1990) who identified the challenge to be further related to unknown health histories, varying methods of fixation and shrinkage in muscle volume following death. Furthermore, as the cadavers may have had muscle wasting following a period of inactivity due to their age or illness before death, the PCSA would be lesser than in active, healthy subjects (Cutts *et al*., 1991). Locke and colleagues (2010) also encountered this problem when they studied the muscle fibre cross sectional area in cadavers with claw toes.

There is an increase in fat and connective tissue, and corresponding reduction in muscle mass (due to motor neuron unit degeneration as a result of degeneration of nerves) and decreased activity in the elderly (>80 years old) (Inokuci *et al*., 1975). Hooper and colleagues (1983) recorded that there is a variation in the fibre size in an ageing muscle due to atrophy that leads to muscle fibre degeneration and loss of muscle fibre. This process of atrophy is followed by compensatory hypertrophy

wherein the remaining muscle fibre increases in size to compensate for the loss of function brought on by the atrophied muscle fibre. This may be due to decreased perfusion of the tissues due to compromised arterial supply secondary to atherosclerosis. Lack of blood supply affects the healing of the muscle fibre which may be injured even following moderate physical activity, resulting in the loss of the muscle fibre. In order to carry out the same activity, there would be compensatory hypertrophy of the existing muscle fibres. These factors can affect PCSA.

In the study by Morse and colleagues (2005), cross sectional area of lateral head of gastrocnemius muscle of the elderly (mean age of 73.8 years) were studied *in vivo* to find the effect of ageing on muscle force and PCSA. The formula used to calculate PCSA *in vivo* was muscle volume/fascicle length. Muscle volume was calculated by multiplying anatomical cross sectional area (derived by the use of complex scanning and imaging software) by slice thickness (obtained by taking series of slices eight mm thickness and gap of two mm from origin to the insertion of the lateral head of gastrocnemius muscle using MRI).

Suggested improvements

As the estimation of force requires active dynamic movement of the joint and simultaneous recording using MRI and US scans, it was not possible to undertake this experiment in this study that used cadavers. In addition, apart from the presence of live volunteer and the chance to inquire relevant medical history, *in vivo* studies using MRI and US scans have the added advantage of sophisticated software for data gathering and analysis, and the possibility of using other limb as a control.

4.5.1.4 Change in the area and shape of the tendons and median nerve

In the current study the cross sectional area of the flexor tendons and the median nerve were taken to be elliptical. This is in accordance to previous studies done by Ikeda and colleagues (1996). It is thought that the tendons and nerves tend to flatten especially if they pass through congested space such as the carpal tunnel. The shape of these structures also depends on the position of the wrist during embalming.

Suggested improvements

USS studies by and Henderson colleagues in 2012 found that the shape and position of the median nerve and the flexor tendons change with wrist movements. These include the movement of the flexor tendons superiorly towards the palm while the median nerve moves radially from flexion to extension. Zeiss and colleagues (1989) noted that during flexion of the wrist, the nerve lies anterior to the FDS (index) tendon and during extension the nerve became interposed between the superficial flexor tendons of the index finger and FPL of the thumb or between the FDS of the middle and ring fingers. It was also noted that the area of the nerve changed with wrist movements. During flexion the nerve flattened antero-posteriorly whilst it became rounded during extension. Thus USS studies are found to be superior to other imaging techniques in recording the changes to the TCSA and cross sectional area due to their dynamic nature.

4.6. Significance of tendinous interconnection in the palmar surface of the hand and wrist in volunteers

4.6.1. Introduction

The prevalence of Linburg-Comstock anomaly amongst general population is highly variable. According to some reports, the occurrence of the interconnection is around 20% (Miller *et al*., 2003) while others have described a higher incidence of around

30-32% (Linburg *et al*., 1979, Slater, 2001; Puroshothaman *et al*., 2009; Old *et al*., 2010). These studies were carried out in Caucasian population of varying ages and both genders. All the above studies used clinical examination (active flexion of the IPJ of the thumb resulting in passive simultaneous flexion of the DIPJ of the index finger) to determine the anomaly and this relatively subjective assessment may explain the wide range in the observed prevalence. However, the lower incidence noted by Miller and colleagues (2003) could be due to the fact that they took associated symptoms into consideration (pain or discomfort during flexion of the thumb while the examiner held the index finger in extension).

4.6.2 Limitations of the volunteer study

Out of 200 first year medical students at the School of Biosciences, Cardiff University, 12 (bilateral in three) were identified to have tendinous interconnection between the FPL and FDP of index or middle fingers. Thus the results from this study demonstrate that six percent of the population in this age group (mean age of 18.6 years) have Linburg-Comstock anomaly although a selection of arbitrarily selected medical students might not be a true reflection of the general population. This is because the students entering professional studies in science might have had different exposure in their formative years to those pursuing a mechanical or vocational degree. Nevertheless, this study might have, perhaps serendipitously, provided information on the prevalence of Linburg-Comstock anomaly in a professional student population.

4.6.3 Limitations of obtaining photographs and measuring angle of flexion

To study the angle of flexion, a series of photographs were taken in two planes - in mid-prone and in supine position. The volunteers could do the movements at the mid-prone position without difficulty. However, when the study was done with the hand in supine position, it was observed that most volunteers found demonstration of the different finger movements difficult either because their hands were tired or they were more conscious of the being constantly monitored. This resulted in artefacts and artificial movements, which in turn affected the variation in the angle of flexion between the fingers and the thumb. The movements were exacerbated when the volunteers were asked to repeat after a break of 15 minutes.

For measuring the angle of flexion of the IPJ, MCP of the thumb and DIPJ of the fingers, lines were drawn on the skin creases made by these joints thus they are not fixed reference points and are not same for all the volunteers. These points may vary according to the different views of the photograph and the clarity of the image and prominence of these joints in each image. As the angle of flexion of MCPJ of the thumb and the IPJ of the thumb and fingers were not measured against a fixed plane or against a fixed reference point, this may have affected the overall angle of flexion.

Similar problems with unclear reference points on the skin were faced by Fioretti in 1994 wherein the hand and finger movements were observed from the outside (with the help of cameras) to create a 3D hand kinetics model. Also by Fischer and colleagues in 1998 while attempted to visually measure the joint angles of the fingers while building a robotic hand using data from human hand movements. All the above studies, however, suffer from the problem that they do not use fixed reference points on the hand, but rather use a specific point on the skin as a stable reference point. From the above studies it can be postulated that all of the methods using markers on

the hand are therefore rather imprecise; rather than measuring the motion of the whole finger, they measure the motion of one or more points on the skin, being subject to both active and passive influences (Stillfried and van der Smagt, 2010).

Suggested improvements

The limitations brought on by using reference points on the skin were overcome during the 'repeatability and reliability' test that was carried out on the hands of three volunteers with tendinous interconnections. In this test, three reference points were used and the hand held against these points, which made the reading reliable and accurate. The IPJ and MCPJ of the thumb, and the DIP of the index and middle fingers were highlighted with skin marker pens. This made it easier to measure the angle of flexion and greatly improved the accuracy as well as eliminating the limitations caused by the clarity of the photography. As this appears to be first study using the above method, no reference to this could be found in the literature.

Stillfried and van der Smagt (2010) overcame the above limitations when they obtained a static *in vivo* bony reference point to study the movement of the bones in the hand using high resolution $(0.38\ mm)^3$ MRI machines to create 3D images of the different joint movements of the fingers. Thus it can be concluded that MRI is the viable method to precisely measure hand and finger kinematics.

Conclusion

MRI scan has an advantage over US scan in measuring the angle of flexion of phalangeal joints for the following reasons:

(i) MRI scan images can be evaluated objectively (US scan is operator dependent)

(ii) In MRI scan, the bony prominences can be used as a fixed reference points in the generated images

(iii) Images from MRI scan have higher clarity and resolution

(iv) A fixed position of the hand can be obtained (as opposed to movements in position of the hand during an US study)

4.7 Future studies

4.7.1 Possible hereditary/genetic link to tendinous interconnections

Incidentally, it was observed that two volunteers (both females) reported their mothers to have similar interconnection. As one of the volunteer did not play any musical instrument, it is enticing to postulate that there might be a hereditary element to this condition but this remains merely speculative with no corroborative studies.

4.7.2 Embryological basis for tendinous interconnections

Studies of chick embryos indicate that the limb muscles and tendons are derived from the dermomyotome of somites, (Christ *et al*., 1977; Kieny and Chevallier, 1979; Kardon, 1998, Ordahl and Le Douarin, 1992). The dermatomyotome consists of medial and lateral lip. Proliferation and elongation of cells along the medial lip gives rise skeletal muscles of the back while proliferation of the lateral lip dermatomyotome gives rise to body wall and limb musculature (Ordahl and Le Douarin, 1992).

The limb bud (precursor of limb) is a protrusion of somatic mesoderm (which develops into muscles, nerves, and blood vessels) and lateral plate mesoderm (which develops into bone, cartilage, and tendon) into the overlying ectoderm. Almost immediately after the establishment of the limb bud, chondrogenesis core (cartilage precursor cells) accumulate in the center, and precursors of tendons and muscles accumulate in the periphery (Johnson and Tabin 1997).

Morphogenesis of tendon is the least understood aspect of musculoskeletal development. Pretendinous mesenchymal cells (also known as tendon blastema- are derived from the somatopleuric cells) condense on the mesenchymal lamina (a glycoprotein rich extracellular matrix which develops beneath the ectodermal layer) both dorsally and ventrally to the chondrogenic rays (precursor to cartilages). The extensor tendons develop from the dorsal tendon primordial while the flexor tendons develop from the ventral tendon primordial (Al-Qattan *et al*., 2009).

Similar to the pretendinous mesenchymal cells, premyogenic mesenchymal cells derived from the dermomyotome condenses on the mesenchymal lamina to form dorsal and ventral muscle masses. These muscle masses split later to form the muscles of the extensor and flexor compartments, respectively (Seyfer *et al*.,1989). By the seventh week of intrauterine life, upper limb muscle is identifiable and contains muscle fibres. The differentiation of the tendons at the end of muscle belly begins between the seventh and eighth week (Ippolito, 1990).

Every muscle is identifiable by seven weeks of intra-uterine life. In the flexor compartment of the forearm muscles are arranged in superficial and deep groups. The superficial flexor compartment consists of pronator teres, FCR, palmaris longus, FDS and FCU while the deep group consists of FDP, FPL and pronator quadratus (Standring, 2005). The deep flexor muscles are more extensive and thicker than the superficial group. The differentiation of the flexor muscles of the forearm occurs from superficial to deep and from distal (from the digits) to proximal (towards the carpal bones). As FDP and FPL are located in the deep forearm and as they more extensive and thicker than the superficial muscles these are amongst the last ones to

differentiate. Presence of interconnections (both tendinous and muscular) is common at the site of carpal tunnel as the distal to proximal differentiation may fail to complete at this level (Lewis, 1910, Jones *et al*., 1997).

As the long flexors of the fingers and the wrist are derived from a common mesodermal mass, a tendinous connection can exist between them presenting as a congenital anomaly (Mangini 1960, Kaplan 1984). There is very limited literature to support the existence of congenital tendinous interconnections as they mostly remain asymptomatic (Rennie *et al*., 1998).

Conclusion

In this dissertation, as the results are based on cadaveric dissection, it was not possible to establish whether the interconnections were congenital or acquired as the relevant family history or occupational history were not available.

4.7.3 Genetic basis for tendinous interconnections

Although, there is evidence of genetic link for the development of tendinous interconnection in conditions such as EDS such investigations were not within the limit of this study. However, exploration of the genetic basis for tendinous interconnections should be considered if opportunity permits to undertake similar studies in the future.

4.7.4 Measurement of angle of flexion

In the future studies, the angle of flexion of the MCPJ and the IPJ of the thumb and the dependent fingers could be measured with the help of goniometer. This would eliminate the limitations caused by clarity of the photographs.

4.8 . USS versus MRI to diagnose musculoskeletal pathologies

Musculoskeletal ultrasound scan uses high-frequency sound waves to image soft tissues (such as muscle, tendons) and bony structures in the body for the purposes of diagnosing pathology (Smith *et al.,* 2009). Technological advances, improved portability and reduced costs have made US scans affordable and useful over MRI scans. Modern day US scan machines provide exquisitely detailed images of the musculoskeletal system, delivering sub-millimeter resolution that is superior to comparative MRI scans (Kremkau, 2002 and Smith *et al.*, 2009). US provide hands on, dynamic, real time and interactive examination with instant patient feedback (Khoury, 2007). Ultrasound is generally unaffected by metallic artefacts and delivers no radiation to patient or the user, an important consideration while evaluating females of child bearing age group. Unlike radiographs, CT and MRI, ultrasound can be readily used to complete a comparative examination of the contralateral extremity when clinically indicated. Ultrasound provides a very high quality picture of a relatively small area (Smith *et al*., 2009).

Disadvantages of ultrasound include limited resolution at greater depths and inability to penetrate bones (Kremkau, 2002). Unlike MRI, US scan is operator dependent and to successfully integrate diagnostic or interventional musculoskeletal ultrasound into clinical practice, the practitioner must acquire the necessary training (Smith *et al*., 2009).

MRI has an advantage over ultrasound in that it can cover a wider anatomical area. The area covered depends on the specifications of the machine and the magnetic bore used. For example, hand imaging uses a bore diameter of 33cms (length) x 16 cms (height) while whole body imaging uses a bore of 205cms x 50cms.

In the current study the ultrasound scan was performed by a single operator with a 12–14MHz variable frequency probe, which had a spatial resolution of 0.3-1.0 mm (ability of the scan to differentiate two structures as separate) and penetration depth of 6 cms (how much the ultrasound waves can penetrate into the body and get reflected back). During dynamic movements of the wrist the tenosynovium could be distinguished from the flexors tendons. The structures that moved less during wrist and finger movements were recognised to represent tenosynovium (which is usually < 1mm thick), while the flexor tendons moved more with movements (Bruno *et al*., 2006).

In US scan, the tendons appear as markedly hyper-echoic (white) fibrillar structure inside a thick hypo-echoic (grey/black) sheath depending on the acoustic interface of the structure. Acoustic interface is the amount of sound wave energy that is reflected back while some of it passes through the structure. If a large amount of sound wave energy is reflected back (as in bones and tendons) the structure appears brighter (white) whereas, if the wave pass through the structures (as in synovium and body fluids) they appears darker (grey or black) (Kremkau, 2002).

Fornage (1989) concluded that a high resolution US probe is sensitive to identify both tendinous and tenosynovial interconnections that are <1mm thick. It was hence established that the tendinous and tenosynovial interconnections that were dissected

during cadaver study would be adequately imaged as their mean thickness was 0.33cm (SEM 0.042: SD ± 0.23) and 0.02cm for tenosynovial interconnection.

Another advantage of US scan over MRI is that it can be used to calculate the angle of pennation of muscle fibre *in vivo*. The angle of pennation is calculated by drawing along the orientation of the muscle fibre. Muscle fibres are hypoechoic (black) appearance. The perimysium creates interfaces between the fibres that appear as linear echogenic grey or white reflections within a black muscular background (Middleton *et al*., 2001). Thus, the angle of pennation is drawn along the central tendon with the perimysium joining the tendon at varying angles (mostly acute, usually ranging from 6 – 18 degrees). All studies that calculated either PCSA or cross sectional areas of the muscle *in vivo* have used US scans to document angle of pennation (Rutherford 1992, Aagaard *et al*., 2001, **Brorsson 2008)**.

Previously, Karalezi and colleagues (2006) used a 1.5T MRI machine scan capable of 2.5 mm to 3 mm slice thickness to identify and localise Linburg-Comstock anomaly. Although the above scanner would localise the cadaveric tendinous interconnections (mean 3.3mm), if employed for the current study, it would have failed to image the cadaveric tenosynovial interconnection as the mean thickness was only 0.9 mm and also volunteer interconnections as the mean thickness 1.75 mm. The MRI scan used during the pilot study was capable of slicing images at 2 mm thick. Since US scan can record interconnections <1 mm thick, this investigative modality was found to be superior to identify them. Coupled with its sensitivity and dynamic imaging, US scan was the method of choice for studying interconnections in this dissertation since MRI scan, if used, would have missed the tenosynovial interconnection. Currently, a MRI spatial resolution (slice thickness) of <1mm is used to study soft tissue tumours (e.g.,

breast malignancies) but there is no literature that specifies the resolution to study tendinous/tenosynovial interconnections.

Based on the available evidence, it can be concluded that US is the investigation of choice to study musculoskeletal- tendinous pathologies.

Chapter 5

CONCLUSION

This dissertation has proven that parameters such as TCSA, mean tendon length and mean muscle mass influence the PCSA. The mechanical effects (such as force generated and strength) of a muscle are related to the size (bulk) of the muscle and to its relative location to the joint it crosses. Thus, PCSA is an important anatomical parameter in calculating the maximum force that a muscle can produce. In future studies, it may be worthwhile to compare the factors influencing PCSA in cadavers and compare the same parameters on live volunteers to see the effect of PCSA on muscle strength and force generated. The current study also demonstrated that the TCSA of FDP (index) and FPL are directly proportional and FDP has the largest PCSA. Bigger the muscle, bigger the tendon cross sectional area and thus more chance for the tendon to abrade against each other. The recurring micro-trauma of steady abrasion with each other during movements may cause the collagen fibres to glide past one another, causing a split of their cross-linked structure and thus abnormal tendon interconnections.

The precise microscopic basis for tendinous interconnections in the palmar surface of the hand is not established yet and the exact sequence of development of the interconnection remains a matter of conjecture at present. However, its macroscopic presence and its strong predilection in the hands of musicians playing string instruments cannot be disputed. In the current study, following the cadaveric dissection and linear regression analysis it was concluded that PCSA has a direct relation to TCSA and muscle mass. The TCSA of FDP (index) was found to be directly proportional to the TCSA of FPL. Thus in an anatomically congested space such as the carpal tunnel, the proximity of large muscles such as the FDP and FPL could result in constant rubbing of the tendons during repetitive wrist and finger movements. This may cause micro trauma to the tendon sheath thus predisposing to

tendinous interconnections. Although the tendinous interconnection appears to be an acquired condition, the role of any causative genetic or hereditary factors cannot be discounted and may be the subject of future investigative strategies. This dissertation has established US scan to be the investigation of choice in localising and identifying tendinous interconnections. It should thus be the first choice of investigation while managing patients presenting with this condition.

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APPENDICES 1

ETHICAL APPROVAL

Cardiff School of Engineering
Director of School: Professor P R Thomas BSc MSc DIC PhD DSc FEng CEng FIChemE FCGI
Research Office
Deputy Director of School-Research: Professor A J Tasker BSc PhD

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ETHICAL APPROVAL

Title of Project: Anatomical Variations and Physiological Aspects Regarding Tendon Variations in the Hands of Musicians

Researcher: Dr Shiby Stephens

Supervisor: Dr Alan Watson

On behalf of the Cardiff School of Engineering Research Committee, I approve the attached application.

Professor A. Porch
Chair – ENGIN Research Committee

20th September 2009

CONSENT FORM

The aim of my research is to study the anatomical variations and physiological aspects regarding tendon variations in the hands of string playing musicians. This research mainly looks into the incidence of tendon interconnects in the hands of

musicians and general population. The study will involve careful analysis of the common tendon interconnection that may exist in the palmar surface of the hand and the forearm. I am interested in studying the interconnection between the tendons of the thumb (Flexor pollicis longus) and index finger (Flexor digitorum profundus). These interconnections along with few clinical presentations are called the Linburg-Comstock syndrome. Occasionally tendinous interconnection may exist between thumb and other fingers, in these instances the interconnections will be studied as rare occurrence.

The study will consist of conducting a series of simple, uncomplicated and pain free examinations of the fingers of the both the hands. The examiner will guide you as to what movements need to be done. If there is any indication of any tendinous interconnection, series of photographs or video of the fingers at different angle will be taken and the angle of inter dependence will be calculated at a later time. Once the tendinous interconnections are established, the person will be requested to take part in medical imaging using an ultrasound.

The examination of the fingers should not take more than 15 minutes. Your data will be dealt with in the strictest confidential manner and you may withdraw at any time without giving any reason, without my medical care or legal rights being affected.

Your help and time is much appreciated:

Dr. Shiby Stephens

Study Number:

Title of Project: Evaluation of anatomical variation and loss of function in hands of string and key based musical palyers

Name of Researcher:

I confirm that I have read and understand the information sheet dated ..... for the above study.

CONSENT FORM FOR RESEARCH STUDY	**Please tick to confirm**

• I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.	•
• I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected.	•
• I understand that relevant sections of any of my medical notes and data collected during the study may be looked at by responsible individuals from Cardiff University, where it is relevant to my taking part in this research. I give permission for these individuals to have access to my records.	•
• I understand that any information I provide is confidential, and that no information that could lead to the identification of any individual will be disclosed in any reports on the project, or to any other party. No identifiable personal data will be published. The identifiable data will not be shared with any other organisation.	•
• I agree to take part in the above research study.	•

Name of the volunteer:……..

Date:…….

Signature:……..

Name of the researcher::……..

Date:…….

Signature:……..

PROFORMA

General

Age:

Sex: M / F

What musical instrument do you play?

How many hours / days per weeks do you play?

Are you professional or amateur?

Grade

Dominant hand: R / L

Do you play any other musical instrument?

Hobbies:

Medical history:

1. History of smoking: Y /N

(If yes, how many cigarettes per day? Or if quit, how long ago was that and how long did you smoke for?)

2. History of trauma to hand or forearm: Y / N

3. Family history of any congenital hand deformities: Y / N

4. Relevant past or present medical history related to upper limb:

Examination proper:

RIGHT HAND:

1. Can the thumb be held in anatomical position? Y/ N

2. Can the thumb be held in anatomical position independent of the index / middle / ring / little finger? Y/ N

If No: Why?

3. Is there normal range of flexion at the interphalangeal / metacarophalangeal joint of the thumb? Y/ N

If No: Why?

4. Can the subject opponise the thumb? Y/ N

If No: Why?

5. Does the index/ middle / ring / little finger flex with thumb flexion? Y/ N

6. Does the proximal / middle/ distal phalanx of index/ middle / ring / little finger flex with the interphalangeal joint of the thumb?

7. Does the proximal / middle/ distal phalanx of index/ middle / ring / little finger flex with the metacarpophalangeal joint of the thumb?

8. Associated pain at:

The ulnar side of the forearm: Y/ N

The radial side of the forearm: Y/ N

9. Is there any weakness in the movement of the thumb against resistance? Y/ N

10. Is there any weakness in the movement of the index/ middle / ring / little finger against resistance? Y/ N

11. Is there any altered sensation along the thenar eminence or first two fingers? Y/ N

12. Is there any pain during extension or flexion of the wrist? Y/ N

LEFT HAND:

1. Can the thumb be held in anatomical position? Y/ N

2. Can the thumb be held in anatomical position independent of the index / middle / ring / little finger? Y/ N

If No: Why?

3. Is there normal range of flexion at the interphalangeal / metacarophalangeal joint of the thumb? Y/ N

If No: Why?

4. Can the subject opponise the thumb? Y/ N

If No: Why?

5. Does the index/ middle / ring / little finger flex with thumb flexion? Y/ N

6. Does the proximal / middle/ distal phalanx of index/ middle / ring / little finger flex with the interphalangeal joint of the thumb?

7. Does the proximal / middle/ distal phalanx of index/ middle / ring / little finger flex with the metacarpophalangeal joint of the thumb?

8. Associated pain at:

The ulnar side of the forearm: Y/ N

The radial side of the forearm: Y/ N

9. Is there any weakness in the movement of the thumb against resistance? Y/ N

10. Is there any weakness in the movement of the index/ middle / ring / little finger against resistance? Y/ N

11. Is there any altered sensation along the thenar eminence or first two fingers? Y/ N

12. Is there any pain during extension or flexion of the wrist? Y/ N

Physiological cross sectional area

Cadaver number	SEX and SIDE of hand dissected	FPL	FDS	FCR	FCU	FDP
C1	F (Right)	0.51	1.75	0.82	0.82	2.40
	F (Left)	0.48	0.78	0.85	0.76	2.28
C2	M (Right)	0.32	1.01	0.14	0.83	2.51
	M (Left)	0.33	0.91	0.11	0.81	2.16
C3	F (Right)	0.09	0.98	0.83	0.92	2.03
	F (Left)	0.08	0.94	0.78	0.82	2.08
C4	M (Right)	0.63	0.90	0.88	0.74	2.08
	M (Left)	0.67	0.76	1.05	0.76	2.10
C5	F (Right)	0.90	0.83	0.73	0.69	1.80
	F (Left)	0.66	1.29	0.69	0.96	1.71
C6	F (Right)	0.42	1.96	0.83	0.81	1.87
	F (Left)	0.56	0.87	0.91	0.84	1.88
C7	M (Right)	0.64	0.96	0.14	1.19	1.86
	M (Left)	0.63	1.31	0.14	1.14	2.19
C8	F (Right)	0.75	1.26	0.70	0.99	2.03
	F (Left)	0.59	0.95	0.77	0.81	1.96
C9	F(Right)	0.51	2.17	0.65	0.98	1.78
	F(Left)	0.46	1.09	0.64	0.97	1.82
C10	M (Right)	0.44	1.14	0.95	1.07	1.84
	M (Left)	0.54	1.05	0.93	1.02	2.05
C11	F (Right)	0.47	1.09	0.89	1.19	2.12
	F (Left)	0.49	1.11	0.86	1.03	2.45
C12	M (Right)	0.70	1.32	1.01	1.40	2.42
	M (Left)	0.50	1.02	0.11	1.38	2.35
C13	F (Right)	0.45	0.90	0.12	1.24	2.24
	F (Left)	0.43	0.90	0.82	1.39	2.31
C14	M (Right)	0.44	0.98	0.69	1.63	1.77
	M (Left)	0.48	1.27	0.68	1.24	1.90
C15	M (Right)	0.71	0.86	0.92	1.11	2.44
	M (Left)	0.70	0.84	0.93	1.09	2.01
	Mean	**0.52**	**1.11**	**0.69**	**1.02**	**2.08**
	STDEV	**0.17**	**0.33**	**0.30**	**0.23**	**0.23**
	SEM	**0.03**	**0.06**	**0.05**	**0.04**	**0.04**

Table 3.1A: (Corresponding to figure 3.1)-Physiological cross sectional area of different flexor muscles

Relationship between PCSA and the mean mass

Cadaver number	SEX and SIDE of hand dissected	FPL (Mass in gms)	FPL (PCSA in cm^2)	FDS (Mass in gms)	FDS (PCSA in cm^2)	FCR (Mass in gms)	FCR (PCSA in cm^2)	FCU (Mass)	FCU (PCSA in cm^2)	FDP (Mass in gms)	FDP (PCSA in cm^2)
C1	F (Right)	3.84	0.51	14.32	1.75	4.38	0.82	5.33	0.82	16.69	2.40
	F (Left)	3.23	0.48	14.22	0.78	4.34	0.85	5.22	0.76	16.52	2.28
C2	M (Right)	3.56	0.32	14.32	1.01	5.35	0.14	4.22	0.83	17.33	2.51
	M (Left)	3.62	0.33	14.54	0.91	4.22	0.11	4.35	0.81	17.24	2.16
C3	F (Right)	4.68	0.09	12.66	0.98	4.38	0.83	4.25	0.92	18.46	2.03
	F (Left)	4.52	0.08	12.34	0.94	4.26	0.78	5.38	0.82	18.46	2.08
C4	M (Right)	4.12	0.63	13.54	0.90	4.00	0.88	5.46	0.74	18.48	2.08
	M (Left)	4.22	0.67	13.48	0.76	4.36	1.05	4.6	0.76	18.36	2.10
C5	F (Right)	4.84	0.90	14.77	0.83	5.25	0.73	4.77	0.69	16.91	1.80
	F (Left)	4.86	0.66	14.48	1.29	5.16	0.69	4.61	0.96	16.99	1.71
C6	F (Right)	3.96	0.42	12.46	1.96	5.52	0.83	5.18	0.81	17.22	1.87
	F (Left)	3.87	0.56	12.34	0.87	5.76	0.91	5.28	0.84	17.46	1.88
C7	M (Right)	4.12	0.64	13.99	0.96	6.80	0.14	5.93	1.19	18.5	1.86
	M (Left)	4.62	0.63	13.45	1.31	6.8	0.14	5.66	1.14	18.31	2.19
C8	F (Right)	5.54	0.75	14.33	1.26	5.97	0.70	4.39	0.99	17.62	2.03
	F (Left)	5.78	0.59	14.34	0.95	5.81	0.77	4.12	0.81	17.42	1.96
C9	F(Right)	4.32	0.51	15.66	2.17	5.26	0.65	5.66	0.98	16.48	1.78
	F(Left)	4.11	0.46	15.43	1.09	5.34	0.64	5.52	0.97	16.29	1.82
C10	M (Right)	4.10	0.44	15.72	1.14	5.54	0.95	6.63	1.07	16.89	1.84
	M (Left)	4.01	0.54	15.64	1.05	5.33	0.93	6.54	1.02	16.77	2.05
C11	F (Right)	3.71	0.47	15.4	1.09	6.69	0.89	6.98	1.19	17.56	2.12
	F (Left)	3.65	0.49	15.54	1.11	6.52	0.86	5.76	1.03	17.88	2.45
C12	M (Right)	4.95	0.70	14.54	1.32	5.33	1.01	6.40	1.40	20.01	2.42
	M (Left)	4.87	0.50	14.39	1.02	5.24	0.11	6.43	1.38	20.21	2.35
C13	F (Right)	4.11	0.45	13.43	0.90	5.46	0.12	6.66	1.24	17.59	2.24
	F (Left)	4.01	0.43	13.48	0.90	5.46	0.82	6.54	1.39	17.36	2.31
C14	M (Right)	4.61	0.44	15.62	0.98	4.48	0.69	6.88	1.63	16.77	1.77
	M (Left)	4.32	0.48	15.48	1.27	4.36	0.68	6.58	1.24	16.25	1.90
C15	M (Right)	4.44	0.71	14.58	0.86	5.91	0.92	5.58	1.11	17.83	2.44
	M (Left)	4.43	0.70	14.82	0.84	5.99	0.93	5.44	1.09	17.54	2.01
	Mean	**4.30**	**0.52**	**14.31**	**1.11**	**5.31**	**0.69**	**5.54**	**1.02**	**17.59**	**2.08**
	STDEV	**0.56**	**0.17**	**1.03**	**0.33**	**0.80**	**0.30**	**0.87**	**0.23**	**0.98**	**0.23**
	SEM	**0.10**	**0.03**	**0.18**	**0.06**	**0.14**	**0.05**	**0.15**	**0.04**	**0.18**	**0.04**

Table 3.2B: (Corresponding to figure 3.2)- Comparative relationship between PCSA and the mean mass of different flexor muscles

Table:3.3C: Comparing the significance of PCSA and mean mass

Relationship between TCSA and mean mass

Cadaver number	SEX and SIDE of hand dissected	FPL TCSA in cm^2	FPL (Mass in gms)	FDS TCSA in cm^2	FDS (Mass in gms)	FCR TCSA in cm^2	FCR (Mass in gms)	FCU TCSA in cm^2	FCU (Mass in gms)	FDP TCSA in cm^2	FDP (Mass in gms)
C1	F (Right)	0.07	3.84	0.13	14.32	0.12	4.38	0.13	5.33	0.22	16.69
	F (Left)	0.07	3.23	0.13	14.22	0.13	4.34	0.13	5.22	0.20	16.52
C2	M (Right)	0.09	3.56	0.12	14.32	0.12	5.35	0.11	4.22	0.24	17.33
	M (Left)	0.10	3.62	0.12	14.54	0.13	4.22	0.17	4.35	0.21	17.24
C3	F (Right)	0.06	4.68	0.13	12.66	0.13	4.38	0.11	4.25	0.18	18.46
	F (Left)	0.06	4.52	0.14	12.34	0.12	4.26	0.09	5.38	0.20	18.46
C4	M (Right)	0.09	4.12	0.08	13.54	0.11	4.00	0.10	5.46	0.20	18.48
	M (Left)	0.07	4.22	0.12	13.48	0.11	4.36	0.11	4.68	0.19	18.36
C5	F (Right)	0.08	4.84	0.12	14.77	0.12	5.25	0.15	4.71	0.18	16.91
	F (Left)	0.09	4.86	0.12	14.48	0.11	5.16	0.14	4.61	0.19	16.99
C6	F (Right)	0.09	3.96	0.12	12.46	0.11	5.52	0.13	5.18	0.19	17.22
	F (Left)	0.08	3.87	0.12	12.34	0.10	5.76	0.14	5.28	0.18	17.46
C7	M (Right)	0.09	4.12	0.13	13.99	0.13	6.80	0.16	5.93	0.18	18.56
	M (Left)	0.08	4.62	0.11	13.45	0.13	6.81	0.16	5.66	0.19	18.32
C8	F (Right)	0.08	5.54	0.13	14.33	0.12	5.92	0.14	4.39	0.18	17.62
	F (Left)	0.08	5.78	0.13	14.34	0.11	5.82	0.14	4.12	0.19	17.42
C9	F(Right)	0.11	4.32	0.15	15.66	0.14	5.25	0.16	5.66	0.18	16.48
	F(Left)	0.12	4.11	0.12	15.43	0.13	5.35	0.17	5.52	0.19	16.29
C10	M (Right)	0.09	4.10	0.13	15.72	0.13	5.54	0.16	6.63	0.16	16.89
	M (Left)	0.10	4.01	0.12	15.64	0.13	5.33	0.18	6.54	0.18	16.77
C11	F (Right)	0.08	3.71	0.10	15.43	0.10	6.69	0.14	6.98	0.17	17.56
	F (Left)	0.09	3.65	0.10	15.54	0.11	6.52	0.13	5.76	0.17	17.88
C12	M (Right)	0.11	4.95	0.14	14.54	0.21	5.33	0.22	6.40	0.18	20.3
	M (Left)	0.08	4.87	0.14	14.39	0.23	5.24	0.21	6.43	0.20	20.21
C13	F (Right)	0.11	4.11	0.10	13.43	0.15	5.46	0.18	6.66	0.19	17.59
	F (Left)	0.08	4.01	0.09	13.48	0.15	5.46	0.16	6.54	0.16	17.36
C14	M (Right)	0.09	4.61	0.10	15.62	0.10	4.48	0.15	6.88	0.16	16.77
	M (Left)	0.09	4.32	0.08	15.48	0.10	4.36	0.15	6.58	0.15	16.25
C15	M (Right)	0.08	4.44	0.10	14.58	0.15	5.91	0.18	5.58	0.15	17.83
	M (Left)	0.11	4.43	0.08	14.82	0.15	5.99	0.14	5.44	0.17	17.54
	Mean	**0.02**	**4.30**	**0.12**	**14.31**	**0.05**	**5.31**	**0.10**	**5.54**	**0.18**	**17.59**
	STDEV	**0.01**	**0.56**	**0.01**	**1.03**	**0.02**	**0.80**	**0.02**	**0.87**	**0.01**	**0.98**
	SEM	**0.00**	**0.10**	**0.00**	**0.18**	**0.00**	**0.14**	**0.00**	**0.15**	**0.00**	**0.18**

Table 3.4DC (Corresponding to figure 3.3)- Comparative relationship between TCSA and mean mass of different flexor tendons

Relationship between the mean fibre length and PCSA of different flexor muscles

Cadaver number	SEX and SIDE of hand dissected	FPL (Mean fibre length in cms)	FPL (PCSA in cm^2)	FDS (Mean fibre length in cms	FDS (PCSA in cm^2)	FCR (Mean fibre length in cms	FCR (PCSA in cm^2)	FCU (Mean fibre length in cms)	FCU (PCSA in cm^2)	FDP (Mean fibre length in cms)	FDP (PCSA in cm^2)
C1	F (Right)	6.5	0.51	1.9	1.75	7.3	0.82	4.3	0.82	3.3	2.40
	F (Left)	6.5	0.48	1.9	0.78	7	0.85	4.4	0.76	3.4	2.28
C2	M (Right)	6.5	0.32	1.5	1.01	7.5	0.14	4.5	0.83	3.4	2.51
	M (Left)	6.4	0.33	1.6	0.91	7.2	0.11	3.9	0.81	3.9	2.16
C3	F (Right)	6.4	0.09	1.3	0.98	7.2	0.83	3.7	0.92	4.5	2.03
	F (Left)	6.4	0.08	1.4	0.94	7.3	0.78	4.4	0.82	4.4	2.08
C4	M (Right)	6.1	0.63	1.5	0.90	6.1	0.88	4.4	0.744	4.4	2.08
	M (Left)	6	0.67	1.9	0.76	6.1	1.05	4.3	0.76	4.3	2.10
C5	F (Right)	5.9	0.90	1.8	0.83	7.3	0.73	4.5	0.69	4.5	1.80
	F (Left)	5.9	0.66	1.2	1.29	7.5	0.69	3.8	0.96	4.8	1.71
C6	F (Right)	6.1	0.42	1.5	1.96	7.5	0.83	4.5	0.81	4.5	1.87
	F (Left)	6	0.56	1.5	0.87	7.5	0.9	4.6	0.84	4.6	1.88
C7	M (Right)	6	0.64	1.5	0.96	7.3	0.14	4.7	1.19	4.7	1.86
	M (Left)	6.1	0.63	1.1	1.31	7.3	0.14	4.5	1.14	4.1	2.19
C8	F (Right)	6.2	0.75	1.2	1.26	7.5	0.78	4.1	0.99	4.1	2.03
	F (Left)	6.2	0.59	1.6	0.95	6.6	0.76	4.4	0.81	4.4	1.96
C9	F(Right)	6	0.51	1.6	2.17	7.6	0.69	4.6	0.98	4.6	1.78
	F(Left)	6	0.46	1.5	1.09	7.5	0.64	4.4	0.97	4.4	1.82
C10	M (Right)	6.2	0.44	1.4	1.14	7.4	0.95	4.4	1.07	4.4	1.843
	M (Left)	6.2	0.54	1.5	1.05	7.5	0.93	4.5	1.02	3.9	2.00
C11	F (Right)	6.1	0.47	1.5	1.09	6.5	0.89	4.9	1.19	3.9	2.12
	F (Left)	6.1	0.49	1.4	1.11	6.4	0.86	4.5	1.03	3.5	2.45
C12	M (Right)	6.3	0.70	1.1	1.32	7.1	1.01	4.1	1.40	4.1	2.42
	M (Left)	6.2	0.50	1.5	1.02	7.5	0.11	4.2	1.38	4.2	2.35
C13	F (Right)	6.1	0.45	1.6	0.90	6.6	0.12	4.3	1.24	3.7	2.24
	F (Left)	6.1	0.43	1.6	0.90	6.6	0.82	3.7	1.39	3.7	2.31
C14	M (Right)	6.3	0.44	1.6	0.98	7.6	0.69	3.5	1.63	4.5	1.77
	M (Left)	6.3	0.48	1.3	1.27	7.3	0.68	4.2	1.24	4.2	1.90
C15	M (Right)	6.3	0.71	1.7	0.86	7.7	0.92	3.5	1.11	3.5	2.44
	M (Left)	6.3	0.70	1.8	0.84	7.8	0.93	4.1	1.09	4.1	2.01
	Mean	**6.19**	**0.52**	**1.51**	**1.11**	**7.17**	**0.69**	**4.26**	**1.02**	**4.13**	**2.08**
	STDEV	**0.17**	**0.17**	**0.21**	**0.33**	**0.47**	**0.30**	**0.34**	**0.23**	**0.42**	**0.23**
	SEM	**0.03**	**0.03**	**0.03**	**0.06**	**0.08**	**0.05**	**0.06**	**0.04**	**0.07**	**0.04**

Table 3.5E: (Corresponding to figure 3.4)- Comparative relationship between the mean fibre length and PCSA of different flexor muscles

Relationship between the PCSA and mean density

Cadaver number	SEX and SIDE of hand dissected	FPL (PCSA in cm^2)	FPL (Density in gcm^{-3})	FDS (PCSA in cm^2)	FDS (Density in gcm^{-3})	FCR (PCSA in cm^2)	FCR (Density in gcm^{-3})	FCU (PCSA in cm^2)	FCU (Density in gcm^{-3})	FDP (PCSA in cm^2)	FDP (Density in gcm^{-3})
C1	F (Right)	0.51	0.9	1.75	1.0	0.82	1.0	0.82	1.0	2.40	0.9
	F (Left)	0.48	1.0	0.78	1.0	0.85	1.0	0.76	1.0	2.28	0.9

C2	M (Right)	0.32	0.8	1.01	1.0	0.14	1.0	0.83	1.0	2.51	1.0
	M (Left)	0.33	0.9	0.91	0.9	0.11	1.0	0.81	0.8	2.16	1.0
C3	F (Right)	0.09	0.9	0.98	0.9	0.83	1.0	0.92	1.0	2.03	1.0
	F (Left)	0.08	0.9	0.94	1.0	0.78	1.0	0.82	1.0	2.08	1.0
C4	M (Right)	0.63	1.0	0.90	0.9	0.88	1.0	0.744	1.0	2.08	1.0
	M (Left)	0.67	1.0	0.76	1.0	1.05	1.0	0.76	0.9	2.10	1.0
C5	F (Right)	0.90	1.2	0.83	0.9	0.73	1.0	0.69	0.7	1.80	0.9
	F (Left)	0.66	1.2	1.29	1.0	0.69	1.0	0.96	0.9	1.71	0.9
C6	F (Right)	0.42	0.9	1.96	1.0	0.83	0.9	0.81	1.0	1.87	1.0
	F (Left)	0.56	0.9	0.87	1.0	0.9	0.9	0.84	1.0	1.88	1.0
C7	M (Right)	0.64	1.0	0.96	0.9	0.14	1.1	1.19	0.9	1.86	0.9
	M (Left)	0.63	0.9	1.31	1.0	0.14	1.1	1.14	0.9	2.19	1.0
C8	F (Right)	0.75	0.9	1.26	1.0	0.78	0.9	0.99	1.0	2.03	0.9
	F (Left)	0.59	0.9	0.95	1.0	0.76	0.9	0.81	1.0	1.96	1.0
C9	F(Right)	0.51	1.0	2.17	0.9	0.69	1.0	0.98	0.9	1.78	1.0
	F(Left)	0.46	1.0	1.09	1.0	0.64	1.0	0.97	0.9	1.82	1.0
C10	M (Right)	0.44	1.0	1.14	0.9	0.95	1.1	1.07	0.9	1.84	0.9
	M (Left)	0.54	1.0	1.05	0.9	0.93	1.0	1.02	0.9	2.00	0.9
C11	F (Right)	0.47	0.9	1.09	1.0	0.89	0.9	1.19	0.9	2.12	0.9
	F (Left)	0.49	0.9	1.11	0.9	0.86	0.9	1.03	0.9	2.45	0.9
C12	M (Right)	0.70	0.9	1.32	0.9	1.01	1.0	1.40	1.0	2.42	1.0
	M (Left)	0.50	0.9	1.02	1.0	0.11	1.0	1.38	1.0	2.35	1.0
C13	F (Right)	0.45	1.0	0.90	1.0	0.12	1.0	1.24	0.9	2.24	0.9
	F (Left)	0.43	1.0	0.90	1.0	0.82	1.0	1.39	0.9	2.31	1.0
C14	M (Right)	0.44	0.9	0.98	0.9	0.69	1.1	1.63	0.9	1.77	0.9
	M (Left)	0.48	1.0	1.27	1.0	0.68	1.0	1.24	0.9	1.90	1.0
C15	M (Right)	0.71	1.1	0.86	0.9	0.92	0.9	1.11	0.9	2.44	0.9
	M (Left)	0.70	1.1	0.84	0.9	0.93	0.9	1.09	1.0	2.01	0.9
	Mean	**0.52**	**1.0**	**1.11**	**1.0**	**0.69**	**1.0**	**1.02**	**0.9**	**2.08**	**1.0**
	STDEV	**0.17**	**0.0**	**0.33**	**0.02**	**0.30**	**0.0**	**0.23**	**0.0**	**0.23**	**0.0**
	SEM	**0.03**	**0.0**	**0.06**	**0.00**	**0.05**	**0.0**	**0.04**	**0.0**	**0.04**	**0.0**

Table 3.6F: (Corresponding to figure 3.5)- Comparative relationship between the PCSA and mean density of different flexor muscles

Relationship between the mean mass and mean fibre length

Cadaver number	SEX and SIDE of hand dissected	FPL (mass in gms)	FPL (Mean fibre length in cms)	FDS (Mass in gms)	FDS (Mean fibre length in cms	FCR (Mass in gms)	FCR (Mean fibre length in cms)	FCU (Mass in gms)	FCU (Mean fibre length in cms)	FDP (Mass in gms)	FDP (Mean fibre length in cms)
C1	F (Right)	3.841	6.5	14.329	1.9	4.381	7.3	5.338	4.3	16.699	3.3
	F (Left)	3.236	6.5	14.221	1.9	4.346	7	5.221	4.4	16.526	3.4
C2	M (Right)	3.569	6.5	14.326	1.5	5.351	7.5	4.229	4.5	17.331	3.4
	M (Left)	3.624	6.4	14.549	1.6	4.221	7.2	4.352	3.9	17.246	3.9
C3	F (Right)	4.687	6.4	12.664	1.3	4.387	7.2	4.252	3.7	18.461	4.5
	F (Left)	4.521	6.4	12.349	1.4	4.269	7.3	5.381	4.4	18.463	4.4
C4	M (Right)	4.128	6.1	13.542	1.5	4.001	6.1	5.461	4.4	18.489	4.4
	M (Left)	4.221	6	13.489	1.9	4.361	6.1	4.68	4.3	18.362	4.3
C5	F (Right)	4.845	5.9	14.776	1.8	5.251	7.3	4.717	4.5	16.914	4.5
	F (Left)	4.863	5.9	14.489	1.2	5.169	7.5	4.612	3.8	16.993	4.8
C6	F (Right)	3.962	6.1	12.469	1.5	5.521	7.5	5.182	4.5	17.221	4.5
	F (Left)	3.874	6	12.344	1.5	5.761	7.5	5.285	4.6	17.461	4.6
C7	M (Right)	4.123	6	13.996	1.5	6.809	7.3	5.931	4.7	18.56	4.7
	M (Left)	4.624	6.1	13.452	1.1	6.81	7.3	5.669	4.5	18.321	4.1
C8	F (Right)	5.546	6.2	14.335	1.2	5.927	7.5	4.393	4.1	17.623	4.1
	F (Left)	5.782	6.2	14.342	1.6	5.821	6.6	4.126	4.4	17.429	4.4
C9	F(Right)	4.324	6	15.665	1.6	5.256	7.6	5.665	4.6	16.483	4.6
	F(Left)	4.118	6	15.431	1.5	5.354	7.5	5.521	4.4	16.291	4.4
C10	M (Right)	4.103	6.2	15.721	1.4	5.542	7.4	6.631	4.4	16.895	4.4
	M (Left)	4.013	6.2	15.643	1.5	5.333	7.5	6.542	4.5	16.773	3.9
C11	F (Right)	3.719	6.1	15.43	1.5	6.699	6.5	6.981	4.9	17.563	3.9
	F (Left)	3.654	6.1	15.544	1.4	6.526	6.4	5.762	4.5	17.884	3.5
C12	M (Right)	4.958	6.3	14.54	1.1	5.331	7.1	6.401	4.1	20.3	4.1
	M (Left)	4.875	6.2	14.391	1.5	5.246	7.5	6.431	4.2	20.211	4.2
C13	F (Right)	4.113	6.1	13.432	1.6	5.461	6.6	6.662	4.3	17.599	3.7
	F (Left)	4.016	6.1	13.489	1.6	5.463	6.6	6.541	3.7	17.361	3.7
C14	M (Right)	4.614	6.3	15.621	1.6	4.489	7.6	6.884	3.5	16.775	4.5
	M (Left)	4.321	6.3	15.48	1.3	4.362	7.3	6.584	4.2	16.259	4.2
C15	M (Right)	4.447	6.3	14.583	1.7	5.914	7.7	5.584	3.5	17.836	3.5
	M (Left)	4.436	6.3	14.822	1.8	5.993	7.8	5.449	4.1	17.542	4.1
	Mean	**4.30**	**6.19**	**14.31**	**1.51**	**5.311**	**7.17**	**5.548**	**4.26**	**17.595**	**4.13**
	STDEV	**0.56**	**0.17**	**1.03**	**0.21**	**0.806**	**0.47**	**0.870**	**0.34**	**0.989**	**0.42**
	SEM	**0.10**	**0.03**	**0.18**	**0.03**	**0.147**	**0.08**	**0.158**	**0.06**	**0.180**	**0.07**

Table 3.7G: (Corresponding to figure 3.6)- Comparative relationship between the mean mass and mean fibre length of different flexor muscles

Relationship between mean fibre length and mean density of different flexor muscles

Cadaver number	SEX and SIDE of hand dissected	FPL (Mean fibre length in cms)	FPL (Density in gcm^{-3})	FDS (Mean fibre length in cms)	FDS (Density in gcm^{-3})	FCR (Mean fibre length in cms)	FCR (Density in gcm^{-3})	FCU (Mean fibre length in cms)	FCU (Density in gcm^{-3})	FDP (Mean fibre length in cms)	FDP (Density in gcm^{-3})
C1	F (Right)	6.5	0.9	3.3	1.0	7.3	1.0	4.3	1.0	1.9	0.9
	F (Left)	6.5	1.0	3.4	1.0	7	1.0	4.4	1.0	1.9	0.9
C2	M (Right)	6.5	0.8	3.4	1.0	7.5	1.0	4.5	1.0	1.5	1.0
	M (Left)	6.4	0.9	3.9	0.9	7.2	1.0	3.9	0.8	1.6	1.0
C3	F (Right)	6.4	0.9	4.5	0.9	7.2	1.0	3.7	1.0	1.3	1.0
	F (Left)	6.4	0.9	4.4	1.0	7.3	1.0	4.4	1.0	1.4	1.0
C4	M (Right)	6.1	1.0	4.4	0.9	6.1	1.0	4.4	1.0	1.5	1.0
	M (Left)	6	1.0	4.3	1.0	6.1	1.0	4.3	0.9	1.9	1.0
C5	F (Right)	5.9	1.2	4.5	0.9	7.3	1.0	4.5	0.7	1.8	0.9
	F (Left)	5.9	1.2	4.8	1.0	7.5	1.0	3.8	0.9	1.2	0.9
C6	F (Right)	6.1	0.9	4.5	1.0	7.5	0.9	4.5	1.0	1.5	1.0
	F (Left)	6	0.9	4.6	1.0	7.5	0.9	4.6	1.0	1.5	1.0
C7	M (Right)	6	1.0	4.7	0.9	7.3	1.1	4.7	0.9	1.5	0.9
	M (Left)	6.1	0.9	4.1	1.0	7.3	1.1	4.5	0.9	1.1	1.0
C8	F (Right)	6.2	0.9	4.1	1.0	7.5	0.9	4.1	1.0	1.2	0.9
	F (Left)	6.2	0.9	4.4	1.0	6.6	0.9	4.4	1.0	1.6	1.0
C9	F(Right)	6	1.0	4.6	0.9	7.6	1.0	4.6	0.9	1.6	1.0
	F(Left)	6	1.0	4.4	1.0	7.5	1.0	4.4	0.9	1.5	1.0
C10	M (Right)	6.2	1.0	4.4	0.9	7.4	1.1	4.4	0.9	1.4	0.9
	M (Left)	6.2	1.0	3.9	0.9	7.5	1.0	4.5	0.9	1.5	0.9
C11	F (Right)	6.1	0.9	3.9	1.0	6.5	0.9	4.9	0.9	1.5	0.9
	F (Left)	6.1	0.9	3.5	0.9	6.4	0.9	4.5	0.9	1.4	0.9
C12	M (Right)	6.3	0.9	4.1	0.9	7.1	1.0	4.1	1.0	1.1	1.0
	M (Left)	6.2	0.9	4.2	1.0	7.5	1.0	4.2	1.0	1.5	1.0
C13	F (Right)	6.1	1.0	3.7	1.0	6.6	1.0	4.3	0.9	1.6	0.9
	F (Left)	6.1	1.0	3.7	1.0	6.6	1.0	3.7	0.9	1.6	1.0
C14	M (Right)	6.3	0.9	4.5	0.9	7.6	1.1	3.5	0.9	1.6	0.9
	M (Left)	6.3	1.0	4.2	1.0	7.3	1.0	4.2	0.9	1.3	1.0
C15	M (Right)	6.3	1.1	3.5	0.9	7.7	0.9	3.5	0.9	1.7	0.9
	M (Left)	6.3	1.1	4.1	0.9	7.8	0.9	4.1	1.0	1.8	0.9
	Mean	**6.01**	**1.0**	**4.13**	**1.0**	**6.01**	**1.0**	**4.26**	**0.9**	**1.51**	**1.0**
	STDEV	**0.17**	**0.0**	**0.42**	**0.02**	**0.470**	**0.0**	**0.34**	**0.0**	**0.21**	**0.0**
	SEM	**0.03**	**0.0**	**0.07**	**0.00**	**0.085**	**0.0**	**0.06**	**0.0**	**0.03**	**0.0**

Table 3.8H: (Corresponding to figure 3.7)- Comparative relationship between the mean fibre length and mean density of different flexor muscles

Relationship between PCSA and mean angles of pennation

Cadaver number	SEX and SIDE of hand dissected	FPL (PCSA in cm^2)	FPL Angle (in °)	FDS (PCSA in cm^2)	FDS Mean of angle (in °)	FCR (PCSA in cm^2)	FCR Mean of the angle (in °)	FCU (PCSA in cm^2)	FCU Angle (in °)	FDP (PCSA in cm^2)	FDP (Mean of the angle (in °)(Medial and Lateral)
C1	F (Right)	0.51	13	1.75	7.5	0.82	13	0.82	7	2.40	11.5
	F (Left)	0.48	13	0.78	7	0.85	13	0.76	7	2.28	11.5
C2	M (Right)	0.32	18	1.01	7	0.14	14	0.83	12	2.51	11.5
	M (Left)	0.33	18	0.91	5	0.11	14	0.81	12	2.16	11.5
C3	F (Right)	0.09	14	0.98	7	0.83	13	0.92	7	2.03	11.5
	F (Left)	0.08	14	0.94	7.5	0.78	13	0.82	7	2.08	11.5
C4	M (Right)	0.63	13	0.90	7	0.88	13	0.74	7	2.08	11.5
	M (Left)	0.67	13	0.76	7	1.05	13	0.76	7	2.10	11.5
C5	F (Right)	0.90	13	0.83	8	0.73	12	0.69	12	1.80	11.5
	F (Left)	0.66	18	1.29	7	0.69	12	0.96	12	1.71	11.5
C6	F (Right)	0.42	18	1.96	7	0.83	13	0.81	12	1.87	11.5
	F (Left)	0.56	13	0.87	7	0.91	13	0.84	12	1.88	11.5
C7	M (Right)	0.64	13	0.96	7	0.14	14	1.19	6	1.86	11.5
	M (Left)	0.63	13	1.31	7	0.14	14	1.14	6	2.19	11.5
C8	F (Right)	0.75	13	1.26	7	0.70	13	0.99	12	2.03	11.5
	F (Left)	0.59	18	0.95	7.5	0.77	13	0.81	12	1.96	11.5
C9	F(Right)	0.51	18	2.17	7.5	0.65	13	0.98	12	1.78	11.5
	F(Left)	0.46	18	1.09	7	0.64	12	0.97	12	1.82	11.5
C10	M (Right)	0.44	18	1.14	7	0.95	12	1.07	7	1.84	11.5
	M (Left)	0.54	12	1.05	7	0.93	13	1.02	7	2.00	11.5
C11	F (Right)	0.47	12	1.09	7	0.89	13	1.19	12	2.12	11.5
	F (Left)	0.49	13	1.11	7	0.86	13	1.03	12	2.45	11.5
C12	M (Right)	0.70	13	1.32	7	1.01	13	1.40	12	2.42	11.5
	M (Left)	0.50	18	1.02	7	0.11	14	1.38	12	2.35	11.5
C13	F (Right)	0.45	18	0.90	7	0.12	14	1.24	12	2.24	11.5
	F (Left)	0.43	18	0.90	7	0.82	13	1.39	12	2.31	11.5
C14	M (Right)	0.44	18	0.98	7	0.69	13	1.63	12	1.77	11.5
	M (Left)	0.48	18	1.27	7	0.68	13	1.24	12	1.90	11.5
C15	M (Right)	0.71	13	0.86	7	0.92	13	1.11	7	2.44	11.5
	M (Left)	0.70	13	0.84	7	0.93	13	1.09	7	2.01	11.5
	Mean	**0.52**	**15.16**	**1.11**	**7.13**	**0.69**	**13.06**	**1.02**	**2.5**	**2.08**	**11.5**
	STDEV	**0.17**	**2.55**	**0.33**	**0.03**	**0.30**	**0.58**	**0.23**	**0.46**	**0.23**	**0**
	SEM	**0.03**	**0.467**	**0.06**	**0.00**	**0.05**	**0.10**	**0.04**	**9.93**	**0.04**	**0**

Angle (in °) =Angle of pennation in (in °)

Table 3.9I: (Corresponding to figure 3.8)- Relationship between PCSA and mean angles of pennation of different flexor tendons

Relationship between the TCSA of FDP (index) and FPL at carpal tunnel

Cadaver number	SEX and SIDE of hand dissected	Area of FPL in cm^2	Area of FDP (i) in cm^2
C1	F (Right)	0.08	0.07
	F (Left)	0.08	0.08
C2	M (Right)	0.09	0.08
	M (Left)	0.10	0.08
C3	F (Right)	0.10	0.08
	F (Left)	0.10	0.08
C4	M (Right)	0.10	0.08
	M (Left)	0.11	0.08
C5	F (Right)	0.11	0.08
	F (Left)	0.11	0.09
C6	F (Right)	0.115	0.09
	F (Left)	0.12	0.09
C7	M (Right)	0.12	0.09
	M (Left)	0.12	0.09
C8	F (Right)	0.13	0.09
	F (Left)	0.13	0.09
C9	F(Right)	0.14	0.10
	F(Left)	0.14	0.10
C10	M (Right)	0.15	0.10
	M (Left)	0.15	0.11
C11	F (Right)	0.15	0.11
	F (Left)	0.15	0.11
C12	M (Right)	0.15	0.11
	M (Left)	0.15	0.13
C13	F (Right)	0.15	0.13
	F (Left)	0.15	0.14
C14	M (Right)	0.16	0.14
	M (Left)	0.16	0.14
C15	M (Right)	0.19	0.16
	M (Left)	0.20	0.16
	Mean	**0.13**	**0.10**
	STDEV	**0.02**	**0.02**
	SEM	**0.00**	**0.00**

Table 3.10J (Corresponding to figure 3.9)- Relationship between the TCSA of FDP (index) and FPL at carpal tunnel

Area of median nerve

Cadaver number	SEX and SIDE of hand dissected	Before the tunnel in mm^2	At the tunnel in mm^2	After the tunnel in mm^2

C1	F (Right)	0.13	0.28	0.35
	F (Left)	0.10	0.13	0.18
C2	M (Right)	0.15	0.16	0.18
	M (Left)	0.16	0.17	0.19
C3	F (Right)	0.16	0.16	0.16
	F (Left)	0.18	0.12	0.15
C4	M (Right)	0.16	0.18	0.20
	M (Left)	0.14	0.15	0.17
C5	F (Right)	0.14	0.16	0.18
	F (Left)	0.16	0.16	0.38
C6	F (Right)	0.19	0.21	0.24
	F (Left)	0.20	0.23	0.24
C7	M (Right)	0.11	0.11	0.15
	M (Left)	0.12	0.13	0.16
C8	F (Right)	0.14	0.15	0.18
	F (Left)	0.13	0.13	0.16
C9	F(Right)	0.12	0.12	0.17
	F(Left)	0.12	0.14	0.15
C10	M (Right)	0.19	0.20	0.22
	M (Left)	0.17	0.17	0.22
C11	F (Right)	0.14	0.14	0.18
	F (Left)	0.12	0.14	0.18
C12	M (Right)	0.13	0.13	0.17
	M (Left)	0.13	0.14	0.15
C13	F (Right)	0.14	0.15	0.18
	F (Left)	0.16	0.13	0.16
C14	M (Right)	0.19	0.12	0.17
	M (Left)	0.20	0.14	0.15
C15	M (Right)	0.13	0.28	0.35
	M (Left)	0.10	0.13	0.18
	Mean	**0.14**	**0.16**	**0.20**
	STDEV	**0.02**	**0.04**	**0.05**
	SEM	**0.00**	**0.00**	**0.01**

Table 3.11K: (Corresponding to figure 3.10)- The area of median nerve before, at and after the carpal tunnel

Table 3.12L One way ANOVA test for the area of median nerve

Relationship between TCSA and PCSA

Cadaver number	SEX and SIDE of hand dissected	FPL TCSA	FPL PCSA	FDS TCSA	FDS PCSA	FCR TCSA	FCR PCSA	FCU TCSA	FCU PCSA	FDP TCSA	FDP PCSA
C1	F (Right)	0.07	0.51	0.13	1.75	0.12	0.82	0.13	0.82	0.22	2.40
	F (Left)	0.07	0.48	0.13	0.78	0.13	0.85	0.13	0.76	0.20	2.28
C2	M (Right)	0.09	0.32	0.12	1.01	0.12	0.14	0.11	0.83	0.24	2.51
	M (Left)	0.10	0.33	0.12	0.91	0.13	0.11	0.17	0.81	0.21	2.16
C3	F (Right)	0.06	0.09	0.13	0.98	0.13	0.83	0.11	0.92	0.18	2.03
	F (Left)	0.06	0.08	0.14	0.94	0.12	0.78	0.09	0.82	0.20	2.08
C4	M (Right)	0.09	0.63	0.08	0.90	0.11	0.88	0.10	0.744	0.20	2.08
	M (Left)	0.07	0.67	0.12	0.76	0.11	1.05	0.11	0.78	0.19	2.10
C5	F (Right)	0.08	0.90	0.12	0.83	0.12	0.73	0.15	0.65	0.18	1.80
	F (Left)	0.09	0.66	0.12	1.29	0.11	0.69	0.14	0.96	0.19	1.71
C6	F (Right)	0.09	0.42	0.12	1.96	0.11	0.83	0.13	0.81	0.19	1.87
	F (Left)	0.08	0.56	0.12	0.87	0.10	0.91	0.14	0.84	0.18	1.88
C7	M (Right)	0.03	0.64	0.13	0.98	0.19	0.14	0.16	1.17	0.18	1.86
	M (Left)	0.00	0.63	0.11	1.33	0.13	0.14	0.16	1.12	0.19	2.19
C8	F (Right)	0.08	0.75	0.13	1.29	0.12	0.70	0.14	0.99	0.18	2.03
	F (Left)	0.08	0.59	0.13	0.93	0.11	0.77	0.14	0.81	0.19	1.96
C9	F(Right)	0.11	0.51	0.15	2.17	0.14	0.65	0.16	0.98	0.18	1.78
	F(Left)	0.12	0.46	0.12	1.09	0.13	0.64	0.17	0.97	0.19	1.82
C10	M (Right)	0.09	0.44	0.13	1.14	0.13	0.95	0.16	1.07	0.16	1.84
	M (Left)	0.10	0.54	0.12	1.05	0.13	0.93	0.18	1.02	0.18	2.00
C11	F (Right)	0.08	0.47	0.10	1.09	0.10	0.89	0.14	1.19	0.17	2.12
	F (Left)	0.09	0.49	0.10	1.11	0.11	0.86	0.13	1.03	0.17	2.45
C12	M (Right)	0.11	0.70	0.14	1.32	0.21	1.01	0.22	1.40	0.18	2.42
	M (Left)	0.08	0.50	0.14	1.02	0.23	0.11	0.21	1.38	0.20	2.35
C13	F (Right)	0.11	0.45	0.10	0.90	0.15	0.12	0.18	1.24	0.19	2.24
	F (Left)	0.08	0.43	0.09	0.90	0.15	0.82	0.16	1.39	0.16	2.31
C14	M (Right)	0.09	0.44	0.10	0.98	0.10	0.69	0.15	1.63	0.16	1.77
	M (Left)	0.09	0.48	0.08	1.27	0.10	0.68	0.15	1.24	0.15	1.90
C15	M (Right)	0.08	0.71	0.10	0.86	0.15	0.92	0.18	1.11	0.15	2.44
	M (Left)	0.11	0.70	0.08	0.84	0.15	0.93	0.14	1.09	0.17	2.01
	Mean	**0.02**	**0.52**	**0.12**	**1.11**	**0.05**	**0.69**	**0.10**	**1.02**	**0.18**	**2.08**
	STDEV	**0.01**	**0.17**	**0.01**	**0.33**	**0.02**	**0.30**	**0.02**	**0.23**	**0.01**	**0.23**
	SEM	**0.00**	**0.03**	**0.00**	**0.06**	**0.00**	**0.05**	**0.00**	**0.04**	**0.00**	**0.04**

Table 3.13M: (Corresponding to figure 3.11)- Comparative relationship between TCSA and PCSA of different flexor tendons

Relationship between PCSA and mean tendon lengths

Cadaver number	SEX and SIDE of hand dissected	FPL PCSA	FPL (in cms)	FDS PCSA	FDS (in cms)	FCR PCSA	FCR (in	FCU PCSA	FCU (in cms)	FDP PCSA	FDP (in

							cms)				cms)
C1	F (Right)	0.51	6.2	1.75	5.85	0.82	9.1	0.82	7.3	2.40	2
	F (Left)	0.48	6	0.78	5.72	0.85	9.3	0.76	7.6	2.28	2.2
C2	M (Right)	0.32	5.7	1.01	5.82	0.14	10.5	0.83	7.3	2.51	2.1
	M (Left)	0.33	5.8	0.91	6.22	0.11	10.2	0.81	7.5	2.16	2.2
C3	F (Right)	0.09	4.6	0.98	4.33	0.83	9.7	0.92	7.9	2.03	3.1
	F (Left)	0.08	4.8	0.94	4.5	0.78	8.2	0.82	7.5	2.08	3.2
C4	M (Right)	0.63	3.2	0.90	4.95	0.88	9.5	0.74	6.1	2.08	2.2
	M (Left)	0.67	3	0.76	5.35	1.05	8.6	0.78	6.4	2.10	2.5
C5	F (Right)	0.90	5.7	0.83	5.1	0.73	10	0.65	8.2	1.80	1.1
	F (Left)	0.66	5.9	1.29	4.95	0.69	10.2	0.96	8.1	1.71	1.3
C6	F (Right)	0.42	4.5	1.96	5.85	0.83	7.2	0.81	5.3	1.87	3.1
	F (Left)	0.56	4.8	0.87	6.02	0.91	7.9	0.84	5.2	1.88	3.3
C7	M (Right)	0.64	5.2	0.98	5.85	0.14	9.4	1.17	7.5	1.86	3.7
	M (Left)	0.63	5	1.33	6.05	0.14	9.6	1.12	7.2	2.19	3.6
C8	F (Right)	0.75	4.4	1.29	4	0.70	8.2	0.99	6.1	2.03	2.7
	F (Left)	0.59	4.8	0.93	3.5	0.77	8.5	0.81	6.7	1.96	2.7
C9	F(Right)	0.51	5.2	2.17	4.67	0.65	8.6	0.98	4.9	1.78	1
	F(Left)	0.46	5.4	1.09	5.27	0.64	8	0.97	4.8	1.82	0.9
C10	M (Right)	0.44	6.1	1.14	4.8	0.95	9.6	1.07	6.5	1.84	3.3
	M (Left)	0.54	6	1.05	5.05	0.93	9.4	1.02	6.7	2.00	2.6
C11	F (Right)	0.47	5.5	1.09	5.57	0.89	8.2	1.19	5.9	2.12	3.9
	F (Left)	0.49	5.8	1.11	4.85	0.86	8.3	1.03	5.5	2.45	3.4
C12	M (Right)	0.70	5.1	1.32	5.87	1.01	4.9	1.40	3.3	2.42	1.1
	M (Left)	0.50	5.6	1.02	6.62	0.11	4.7	1.38	3.1	2.35	1.5
C13	F (Right)	0.45	6.1	0.90	6.02	0.12	9.1	1.24	6.9	2.24	3.7
	F (Left)	0.43	6.2	0.90	6.22	0.82	9.4	1.39	6.4	2.31	3.6
C14	M (Right)	0.44	5.5	0.98	5.95	0.69	9.8	1.63	6.3	1.77	3.7
	M (Left)	0.48	5.4	1.27	5.57	0.68	9.9	1.24	6.2	1.90	2.8
C15	M (Right)	0.71	4.9	0.86	6.9	0.92	8.4	1.11	6.2	2.44	1.9
	M (Left)	0.70	4.8	0.84	6.57	0.93	8.5	1.09	6.6	2.01	2.1
	Mean	**0.52**	**5.24**	**1.11**	**5.46**	**0.69**	**8.763**	**1.02**	**6.373**	**2.08**	**2.55**
	STDEV	**0.17**	**0.78**	**0.33**	**0.79**	**0.30**	**1.34**	**0.23**	**1.252**	**0.23**	**0.918**
	SEM	**0.03**	**0.144**	**0.06**	**0.145**	**0.05**	**0.245**	**0.04**	**0.228**	**0.04**	**0.167**

Table 3.14N: (Corresponding to figure 3.12)- Comparative relationship between PCSA and mean tendon lengths of different flexor tendons

Tendinous interconnection in cadavers

Age in years	Sex	Hand with interconnection	Tendon thickness(in cm^2
93	F	R	0.32
94	F	L	0.55
81	M	R	0.50
81	M	L	0.31
90	F	R	0.34
92	F	R	0.24
89	M	R	0.34
95	M	R	0.02
78	M	R	0.03
85	F	R	0.82
Mean			**0.33**
Standard Deviation			**0.23**
Standard error of mean			**0.04**
85	M	R (Tenosynovial interconnection)	**0.09**

Table 3.15O: Thickness of tendinous interconnection in cadavers

Type of interconnections related to the age, sex on the hands of cadaver

Age in years	Sex	Side	Interconnection
92	F	Right	FPL and FDP (index)
93	F	Right	FPL and FDP (index)
94	F	Left	FDS and FDP
85	F	Right	FDS (muscle-tendon-muscle)
90	F	Left	Pronator teres and FDS
83	F	Right	Extensor carpi radialis brevis and Abductor pollicis brevis
Mean-89.5 years			

Age in years	Sex	Hand	Interconnection
89	M	Right	FDS middle and little
78	M	Right	1st lumbrical and FDS
95	M	Right	FDS (index) and FDS (ring)
81	M	Right	FCU and FDS
81	M	Right	Flexor retinaculum and FDS
Mean-84.8 years			

Table 3.16P: Statistics on type of interconnections, age, sex on the dissected hand of cadaver

Relevant family history of the volunteers

Volunteer number	Age	Sex	Family history of any tendinous interconnection	Past or present medical history related to the upper limb

1	19	F	None	None
2	18	F	None	None
3.	19	F	None	None
4.	18	F	None	None
5.	19	F	None	None
6.	22	M	None	None
7.	18	F	None	None
8.	18	F	None	None
9.	18	F	Mother has the same condition on the both hands (between thumb and index finger)	None
10.	20	F	None	None
11.	19	M	None	None
12	19	F	Mother has the same condition on the right hands (between thumb and index finger)	None

Table 3.17Q: Relevant family history of the volunteers

Examination history of the volunteers

RIGHT HAND

Volunteer Number	Can the thumb be held in anatomical position independently?	When the IPJ or MCP joint of thumb flexes does the -			
		DIP joint of index flexes	DIP joint of middle flexes	DIP joint of ring flexes	DIP joint of little flexes

1.	Yes	Yes	Yes	No	No
2.	Yes	No	Yes	No	No
3.	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable
4.	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable
5.	Yes	Yes	No	No	No
6.	Yes	Yes	No	No	No
7.	Yes	Yes	No	No	No
8.	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable
9.	Yes	Yes	No	No	No
10.	Yes	Yes	Yes	No	No
11.	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable
12.	Yes	Yes	No	No	No

Table 3.18R: Examination history of the volunteers (Right hand)

Examination History of the volunteers:

LEFT HAND

Volunteer Number	Can the thumb be held in anatomical position independently?	When the IPJ or MCP joint of thumb flexes does the -			
		DIP joint of index flexes	DIP joint of middle flexes	DIP joint of ring flexes	DIP joint of little flexes
1	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable
2.	Yes	Yes	Yes	No	No
3.	Yes	No	Yes	No	No
4.	Yes	Yes	No	No	No
5.	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable
6.	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable
7.	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable
8.	Yes	No	Yes	No	No
9.	Yes	Yes	No	No	No
10.	Yes	Yes	Yes	No	No
11.	Yes	Yes	No	No	No
12.	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable

Table 3.19S: Examination history of the volunteers (Left hand)

Angle of flexion between the thumb and dependent fingers

Volunt. no	M/F	R/L	Image	Flexion of thumb MCP (°)	Flexion of thumb IPJ (°)	Flexion of index DIP with thumb IPJ (°)	Flexion of middle DIP with thumb IPJ (°)
1	F	R	0	0	0	0	0
			1	0	30	12	7
			2	0	82	43	35
			3	69	85	70	62
2	F	L	0	0	0	0	0
			1	0	16	24	12
			2	0	33	34	25
			3	39	43	30	20
2	F	R	0	0	0	0	0
			1	0	21	0	19
			2	0	49	0	23
			3	40	50	0	30
3	F	L	0	0	0	0	0
			1	9	32	0	17
			2	24	42	0	34
			3	40	51	0	31
4	F	L	0	0	0	0	0
			1	0	10	15	0
			2	0	27	25	0
			3	0	35	30	0
5	F	R	0	0	0	0	0
			1	0	22	32	0
			2	0	37	65	0
			3	25	49	83	0
6	M	R	0	0	0	0	0
			1	0	12	25	0
			2	0	38	30	0
			3	29	43	40	38
7	F	R	0	0	0	0	0
			1	0	27	8	0
			2	35	30	17	0
			3	39	40	42	0
8	F	L	0	0	0	0	0
			1	10	30	0	17
			2	22	38	0	37
			3	32	45	0	45
9	F	R	0	0	0	0	0
			1	0	40	25	0
			2	0	47	43	0
			3	38	54	45	0

9	F	L	0	0	0	0	0
			1	0	47	35	0
			2	10	50	40	0
			3	43	55	45	0
10	F	R	0	0	0	0	0
			1	0	33	30	0
			2	0	39	33	18
			3	30	45	29	30
10	F	L	0	0	0	0	0
			1	0	28	16	0
			2	0	43	34	0
			3	23	45	48	10
11	M	L	0	0	0	0	0
			1	0	32	17	0
			2	0	35	50	0
			3	37	40	64	0
12	F	R	0	0	0	0	0
			1	0	35	17	0
			2	0	40	32	0
			3	45	50	49	0

Table 3.20T: Angle of flexion between the thumb (IPJ, MCP) and dip of the dependent fingers during different stages of flexion

Tendinous interconnections in volunteers

	Thickness of the tendinous interconnection (**cm**)	
Volunteer 2	0.2	
Volunteer 3	0.1	
Volunteer 12	0.2	
Volunteer 9	0.2	
	Mean	**0.175**
	STDEV	**0.05**
	SEM	**0.025**

Table 3.21U: The thickness of the tendinous interconnections in volunteers (following US scan)

APPENDICES 2

Repeatability and reliability

Physiological cross sectional area

Cadaver number	SEX and SIDE of hand dissected	FPL PCSA in cm^2	FDS PCSA in cm^2	FCR PCSA in cm^2	FCU PCSA in cm^2	FDP PCSA in cm^2
R1	F (Right)	0.09	0.98	0.83	0.92	2.03
	F (Left)	0.08	0.94	0.78	0.82	2.08
R2	M (Right)	0.32	1.01	0.14	0.83	2.51
	M (Left)	0.63	0.9	0.88	0.74	2.08
R3	F (Right)	0.67	0.76	1.05	0.76	2.1
	F (Left)	0.48	0.78	0.85	0.76	2.28
R4	M (Right)	0.33	0.91	0.11	0.81	2.16
	M (Left)	0.51	1.75	0.82	0.82	2.4
	Mean	**0.38**	**1.00**	**0.68**	**0.80**	**2.20**
	STDEV	**0.22**	**0.31**	**0.35**	**0.05**	**0.17**
	SEM	**0.07**	**0.11**	**0.12**	**0.02**	**0.06**

Table 3.22a: (Corresponding to figure 3.30)-Physiological cross sectional area of different flexor tendons

Relationship between PCSA and the mean mass

Cadaver number	SEX and SIDE of hand dissected	FPL PCSA in cm^2	FPL mass in gms	FDS PCSA in cm^2	FDS mass in gms	FCR PCSA in cm^2	FCR mass in gms	FCU PCSA in cm^2	FCU mass in gms	FDP PCSA in cm^2	FDP mass in gms
R1	F (Right)	0.09	4.84	0.98	14.77	0.83	5.25	0.92	4.77	2.03	16.91
	F (Left)	0.08	4.86	0.94	14.48	0.78	5.16	0.82	4.61	2.08	16.99
R2	M (Right)	0.32	3.96	1.01	12.46	0.14	5.52	0.83	5.18	2.51	17.22
	M (Left)	0.63	3.87	0.9	12.34	0.88	5.76	0.74	5.28	2.08	17.46
R3	F (Right)	0.67	4.12	0.76	13.99	1.05	6.8	0.76	5.93	2.1	18.5
	F (Left)	0.48	4.62	0.78	13.45	0.85	6.8	0.76	5.66	2.28	18.31
R4	M (Right)	0.33	5.54	0.91	14.33	0.11	5.97	0.81	4.39	2.16	17.62
	M (Left)	0.51	5.78	1.75	14.34	0.82	5.81	0.82	4.12	2.4	17.42
	Mean	**0.38**	**4.69**	**1.00**	**13.77**	**0.68**	5.88	**0.80**	**4.99**	**2.20**	**17.55**
	STDEV	**0.22**	**0.70**	**0.31**	**0.93**	**0.35**	0.62	**0.05**	**0.62**	**0.17**	**0.57**
	SEM	**0.07**	**0.24**	**0.11**	**0.32**	**0.12**	0.22	**0.02**	**0.22**	**0.06**	**0.20**

Table 3.23b: (Corresponding to figure 3.31)- Comparative relationship between PCSA and the mean mass of different flexor muscles

3.24c: One way ANOVA test for PCSA and mean mass

Relationship between TCSA and mean mass

Cadaver number	SEX and SIDE of hand dissected	FPL TCSA in cm^2	FPL Mass in gms	FDS TCSA in cm^2	FDS Mass in gms	FCR TCSA in cm^2	FCR Mass in gms	FCU TCSA in cm^2	FCU Mass in gms	FDP TCSA in cm^2	FDP (Mass in gms)
R1	F (Right)	0.09	3.96	0.12	12.46	0.11	5.52	0.13	5.18	0.19	17.22
	F (Left)	0.08	3.87	0.12	12.34	0.10	5.76	0.14	5.28	0.18	17.46
R2	M (Right)	0.09	4.12	0.13	13.99	0.13	6.80	0.16	5.93	0.18	18.56
	M (Left)	0.08	4.62	0.11	13.45	0.13	6.81	0.16	5.66	0.19	18.32
R3	F (Right)	0.08	5.54	0.13	14.33	0.12	5.92	0.14	4.39	0.18	17.62
	F (Left)	0.08	5.78	0.13	14.34	0.11	5.82	0.14	4.12	0.19	17.42
R4	F(Right)	0.11	4.32	0.15	15.66	0.14	5.25	0.16	5.66	0.18	16.48
	F(Left)	0.12	4.11	0.12	15.43	0.13	5.35	0.17	5.52	0.19	16.29
	MEAN	**0.09**	**4.54**	**0.12**	**14**	**0.12**	**5.90**	**0.15**	**5.21**	**0.18**	**17.42**
	STDEV	**0.01**	**0.73**	**0.01**	**1.22**	**0.01**	**0.60**	**0.01**	**0.64**	**0.00**	**0.78**
	SEM	**0.25**	**0.00**	**0.43**	**0.00**	**0.21**	**0.00**	**0.22**	**0.00**	**0.27**	**0.27**

Table 3.25d (Corresponding to figure 3.32)- Comparative relationship between TCSA and mean mass of different flexor tendons

Relationship between PCSA and mean fibre length

Cadaver number	SEX and SIDE of hand dissected	FPL Fibre length in cm	FPL PCSA in cm^2	FDS Fibre length in cm	FDS PCSA in cm^2	FCR Fibre length in cm	FCR PCSA in cm^2	FCU Fibre length in cm	FCU PCSA in cm^2	FDP Fibre length in cm	FDP PCSA in cm^2
R1	F (Right)	6.5	0.09	3.3	0.98	6.5	0.83	4.5	0.92	1.5	2.03
	F (Left)	6.5	0.08	3.4	0.94	6.4	0.78	4.6	0.82	1.1	2.08
R2	M (Right)	6.5	0.32	3.4	1.01	7.1	0.14	4.7	0.83	1.2	2.51
	M (Left)	6.4	0.63	3.9	0.9	7.5	0.88	4.5	0.74	1.6	2.08
R3	F (Right)	6.4	0.67	4.5	0.76	6.6	1.05	4.1	0.76	1.6	2.1
	F (Left)	6.4	0.48	4.4	0.78	6.6	0.85	4.4	0.76	1.5	2.28
R4	F(Right)	6.1	0.33	4.4	0.91	7.6	0.11	4.6	0.81	1.4	2.16
	F(Left)	6	0.51	4.3	1.75	7.3	0.82	4.4	0.82	1.5	2.4
	MEAN	**6.35**	**0.38**	**3.95**	**1.00**	**6.95**	**0.68**	**4.47**	**0.80**	**1.42**	**2.20**
	STDEV	**0.19**	**0.22**	**0.51**	**0.31**	**0.48**	**0.35**	**0.18**	**0.05**	**0.18**	**0.17**
	SEM	**0.06**	**0.07**	**0.18**	**0.11**	**0.17**	**0.12**	**0.08**	**0.02**	**0.06**	**0.06**

Table 3.26e: (Corresponding to figure 3.33)- Comparative relationship between PCSA and mean fibre length of different flexor tendons

Relationship between PCSA and mean density

Cadaver number	SEX and SIDE of hand dissected	FPL density gm/cm $^{-3}$	FPL PCSA in cm^2	FDS density gm/cm^{-3}	FDS PCSA in cm^2	FCR density gm/cm^{-3}	FCR PCSA in cm^2	FCU density gm/cm^{-3}	FCU PCSA in cm^2	FDP density gm/cm^{-3}	FDP PCSA in cm^2
R1	F (Right)	0.8	0.09	1.0	0.98	1.0	0.83	1.0	0.92	1.0	2.03
	F (Left)	0.9	0.08	0.9	0.94	1.0	0.78	1.0	0.82	1.0	2.08
R2	M (Right)	0.9	0.32	1.0	1.01	1.1	0.14	0.9	0.83	0.9	2.51
	M (Left)	0.9	0.63	0.9	0.9	1.0	0.88	0.9	0.74	1.0	2.08
R3	F (Right)	1.0	0.67	1.0	0.76	0.9	1.05	1.0	0.76	0.9	2.1
	F (Left)	1.0	0.48	1.0	0.78	0.9	0.85	1.0	0.76	1.0	2.28
R4	F(Right)	1.2	0.33	1.0	0.91	1.0	0.11	0.9	0.81	1.0	2.16
	F(Left)	1.2	0.51	0.9	1.75	1.0	0.82	0.9	0.82	1.0	2.4
	MEAN	**0.97**	**0.38**	**0.96**	**1.00**	**0.98**	**0.68**	**0.95**	**0.80**	**0.97**	**2.2**
	STDEV	**0.14**	**0.22**	**0.05**	**0.31**	**0.06**	**0.35**	**0.05**	**0.05**	**0.04**	**0.174**
	SEM	**0.05**	**0.07**	**0.01**	**0.11**	**0.02**	**0.12**	**0.01**	**0.02**	**0.01**	**0.06**

Table 3.27f: (Corresponding to figure 3.34)- Comparative relationship between PCSA and mean density of different flexor tendons

Relationship between mean mass and mean fibre length

Cadaver number	SEX and SIDE of hand dissected	FPL Fibre length in cm	FPL mass in gms	FDS Fibre length in cm	FDS mass in gms	FCR Fibre length in cm	FCR mass in gms	FCU Fibre length in cm	FCU mass in gms	FDP Fibre length in cm	FDP mass in gms
R1	F (Right)	6.5	4.84	1.5	14.77	6.5	5.25	4.5	4.77	3.3	16.91
	F (Left)	6.5	4.86	1.1	14.48	6.4	5.16	4.6	4.61	3.4	16.99
R2	M (Right)	6.5	3.96	1.2	12.46	7.1	5.52	4.7	5.18	3.4	17.22
	M (Left)	6.4	3.87	1.6	12.34	7.5	5.76	4.5	5.28	3.9	17.46
R3	F (Right)	6.4	4.12	1.6	13.99	6.6	6.8	4.1	5.93	4.5	18.5
	F (Left)	6.4	4.62	1.5	13.45	6.6	6.8	4.4	5.66	4.4	18.31
R4	M (Right)	6.1	5.54	1.4	14.33	7.6	5.97	4.6	4.39	4.4	17.62
	M (Left)	6	5.78	1.5	14.34	7.3	5.81	4.4	4.12	4.3	17.42
	Mean	**6.35**	**4.69**	**1.42**	**13.77**	**6.95**	**5.88**	**4.47**	**4.99**	**3.95**	**17.55**
	STDEV	**0.19**	**0.70**	**0.18**	**0.93**	**0.48**	**0.62**	**0.18**	**0.62**	**0.51**	**0.57**
	SEM	**0.06**	**0.24**	**0.06**	**0.32**	**0.17**	**0.22**	**0.08**	**0.22**	**0.18**	**0.20**

Table 3.28g: (Corresponding to figure 3.35)- Comparative relationship between mean mass and mean fibre length of different flexor tendons

Relationship between mean fibre length and mean density

Cadaver number	SEX and SIDE of hand dissected	FPL Fibre length in cm	FPL density gm/cm-3	FDS Fibre length in cm	FDS density gm/cm-3	FCR Fibre length in cm	FCR density gm/cm-3	FCU Fibre length in cm	FCU density gm/cm-3	FDP Fibre length in cm	FDP density gm/cm-3
R1	F (Right)	6.5	0.8	1.5	1.0	6.5	1.0	4.5	1.0	3.3	1.0
	F (Left)	6.5	0.9	1.1	0.9	6.4	1.0	4.6	1.0	3.4	1.0
R2	M (Right)	6.5	0.9	1.2	1.0	7.1	1.1	4.7	0.9	3.4	0.9
	M (Left)	6.4	0.9	1.6	0.9	7.5	1.0	4.5	0.9	3.9	1.0
R3	F (Right)	6.4	1.0	1.6	1.0	6.6	0.9	4.1	1.0	4.5	0.9
	F (Left)	6.4	1.0	1.5	1.0	6.6	0.9	4.4	1.0	4.4	1.0
R4	F(Right)	6.1	1.2	1.4	1.0	7.6	1.0	4.6	0.9	4.4	1.0
	F(Left)	6	1.2	1.5	0.9	7.3	1.0	4.4	0.9	4.3	1.0
	MEAN	**6.35**	**0.98**	**1.42**	**0.96**	**6.95**	**0.98**	**4.47**	**0.95**	**3.95**	**0.97**
	STDEV	**0.19**	**0.14**	**0.18**	**0.05**	**0.48**	**0.06**	**0.18**	**0.052**	**0.51**	**0.04**
	SEM	**0.06**	**0.05**	**0.06**	**0.01**	**0.17**	**0.02**	**0.08**	**0.01**	**0.18**	**0.016**

Table 3.29h: (Corresponding to figure 3.36)- Comparative relationship between mean density and mean fibre length of different flexor tendons

Relationship between PCSA and angle of pennation

Cadaver number	SEX and SIDE of hand dissected	FPL Angle of pennation in (º)	FPL PCSA in cm^2	FDS Angle of pennation in (º)	FDS PCSA in cm^2	FCR Angle of pennation in (º)	FCR PCSA in cm^2	FCU Angle of pennation in (º)	FCU PCSA in cm^2	FDP Angle of pennation in (º)	FDP PCSA in cm^2
R1	F (Right)	18	0.09	8	0.98	14	0.83	7	0.92	11.5	2.03
	F (Left)	13	0.08	8	0.94	13	0.78	7	0.82	11.5	2.08
R2	M (Right)	13	0.32	7	1.01	13	0.14	12	0.83	11.5	2.51
	M (Left)	13	0.63	7	0.9	13	0.88	12	0.74	11.5	2.08
R3	F (Right)	13	0.67	7	0.76	12	1.05	12	0.76	11.5	2.1
	F (Left)	18	0.48	7.5	0.78	12	0.85	12	0.76	11.5	2.28
R4	F(Right)	18	0.33	7	0.91	13	0.11	6	0.81	11.5	2.16
	F(Left)	18	0.51	7	1.75	13	0.82	6	0.82	11.5	2.4
	MEAN	**15.5**	**0.38**	**7.31**	**1.00**	**12.87**	**0.68**	**9.25**	**0.80**	**11.5**	**2.2**
	STDEV	**2.67**	**0.22**	**0.45**	**0.31**	**0.64**	**0.35**	**2.96**	**0.05**	**0**	**0.174**
	SEM	**0.94**	**0.07**	**0.16**	**0.11**	**0.22**	**0.12**	**1.04**	**0.02**	**0**	**0.06**

Table 3.30i: (Corresponding to figure 3.37)- Comparative relationship between PCSA and mean angle of pennation of different flexor tendons

Relationship between the TCSA of FDP (index) and FPL at carpal tunnel

Cadaver number	SEX and SIDE of hand dissected	Area of FPL in cm^2	Area of FDP (i) in cm^2
R1	F (Right)	0.14	0.10
	F (Left)	0.14	0.10
R2	M (Right)	0.15	0.10
	M (Left)	0.15	0.11
R3	F (Right)	0.15	0.11
	F (Left)	0.15	0.11
R4	M (Right)	0.15	0.11
	M (Left)	0.15	0.13
	Mean	**0.14**	**0.10**
	STDEV	**0.00**	**0.00**
	SEM	**0.00**	**0.00**

Table 3.31j (Corresponding to figure 3.38)- Relationship between the TCSA of FDP (index) and FPL at carpal tunnel

The area of the median nerve as it passes through the carpal tunnel

Cadaver number	SEX and SIDE of hand dissected	Before the tunnel in mm²	At the tunnel in mm²	After the tunnel in mm²
R1	F (Right)	0.19	0.21	0.24
	F (Left)	0.2	0.23	0.24
R2	M (Right)	0.11	0.11	0.15
	M (Left)	0.12	0.13	0.16
R3	F (Right)	0.14	0.15	0.18
	F (Left)	0.13	0.13	0.16
R4	M (Right)	0.12	0.12	0.17
	M (Left)	0.12	0.14	0.15
	Mean	**0.14**	**0.15**	**0.18**
	STDEV	**0.03**	**0.04**	**0.03**
	SEM	**0.00**	**0.00**	**0.00**

Table 3.32k: (Corresponding to figure 3.39)- The area of median nerve before, at and after the carpal tunnel

Table 3.33.l One way ANOVA test

Relationship between TCSA and PCSA

Cadaver number	SEX and SIDE of hand dissected	FPL TCSA in cm^2	FPL PCSA in cm^2	FDS TCSA in cm^2	FDS PCSA in cm^2	FCR TCSA in cm^2	FCR PCSA in cm^2	FCU TCSA in cm^2	FCU PCSA in cm^2	FDP TCSA in cm^2	FDP PCSA in cm^2
R1	F (Right)	0.09	0.09	0.12	0.98	0.11	0.83	0.13	0.92	0.19	2.03
	F (Left)	0.08	0.08	0.12	0.94	0.10	0.78	0.14	0.82	0.18	2.08
R2	M (Right)	0.09	0.32	0.13	1.01	0.13	0.14	0.16	0.83	0.18	2.51
	M (Left)	0.08	0.63	0.11	0.9	0.13	0.88	0.16	0.74	0.19	2.08
R3	F (Right)	0.08	0.67	0.13	0.76	0.12	1.05	0.14	0.76	0.18	2.1
	F (Left)	0.08	0.48	0.13	0.78	0.11	0.85	0.14	0.76	0.19	2.28
R4	F(Right)	0.11	0.33	0.15	0.91	0.14	0.11	0.16	0.81	0.18	2.16
	F(Left)	0.12	0.51	0.12	1.75	0.13	0.82	0.17	0.82	0.19	2.4
	MEAN	**0.09**	**0.38**	**0.12**	**1.00**	**0.12**	**0.68**	**0.15**	**0.80**	**0.18**	**2.20**
	STDEV	**0.01**	**0.22**	**0.01**	**0.31**	**0.01**	**0.35**	**0.01**	**0.05**	**0.00**	**0.17**
	SEM	**0.25**	**0.07**	**0.43**	**0.11**	**0.21**	**0.12**	**0.22**	**0.02**	**0.27**	**0.06**

Table 3.34m: (Corresponding to figure 3.40)- Comparative relationship between TCSA and PCSA of different flexor tendons

Relationship between PCSA and mean tendon lengths

Cadaver number	SEX and SIDE of hand dissected	FPL Tendon length in cm	FPL PCSA in cm^2	FDS Tendon length in cm	FDS PCSA in cm^2	FCR Tendon length in cm	FCR PCSA in cm^2	FCU Tendon length in cm	FCU PCSA in cm^2	FDP Tendon length in cm	FDP PCSA in cm^2
R1	F (Right)	4.6	0.09	4.33	0.98	9.7	0.83	7.9	0.92	3.1	2.03
	F (Left)	4.8	0.08	4.5	0.94	8.2	0.78	7.5	0.82	3.2	2.08
R2	M (Right)	3.2	0.32	4.95	1.01	9.5	0.14	6.1	0.83	2.2	2.51
	M (Left)	3	0.63	5.35	0.9	8.6	0.88	6.4	0.74	2.5	2.08
R3	F (Right)	5.7	0.67	5.1	0.76	10	1.05	8.2	0.76	1.1	2.1
	F (Left)	5.9	0.48	4.95	0.78	10.2	0.85	8.1	0.76	1.3	2.28
R4	F(Right)	4.5	0.33	5.85	0.91	7.2	0.11	5.3	0.81	3.1	2.16
	F(Left)	4.8	0.51	6.02	1.75	7.9	0.82	5.2	0.82	3.3	2.4
	MEAN	**4.56**	**0.38**	**5.13**	**1.00**	**8.91**	**0.68**	**6.83**	**0.80**	**2.47**	**2.20**
	STDEV	**1.03**	**0.22**	**0.59**	**0.31**	**1.09**	**0.35**	**1.24**	**0.05**	**0.87**	**0.17**
	SEM	**0.36**	**0.07**	**0.20**	**0.11**	**0.38**	**0.12**	**0.43**	**0.020**	**0.30**	**0.06**

Table 3.35n: (Corresponding to figure 3.41)- Comparative relationship between PCSA and mean tendon lengths of different flexor tendons

Angle of flexion between the thumb and dependent fingers

	Volunt. no	M/F	R/L	Image	Flexion of thumb MCP (°)	Flexion of thumb IPJ (°)	Flexion of index DIP with thumb IPJ (°)	Flexion of middle DIP with thumb IPJ (°)
Rest	**VR1**	M	L	0	0	0	0	0
Initial movement				1	0	20	10	7
Mid position				2	0	37	32	25
Fully flexed				3	82	75	70	62
Rest	**VR2**	F	R	0	0	0	0	0
Initial movement				1	0	27	8	0
Mid position				2	35	30	20	0
Fully flexed				3	40	45	42	0
Rest	**VR2**	F	L	0	0	0	0	0
Initial movement				1	10	30	17	0
Mid position				2	25	32	37	0
Fully flexed				3	32	45	45	0

Table 3.36o: (Corresponding to figure 3.42)- Angle of flexion between the thumb (IPJ, MCP) and dip of the dependent fingers during different stages of flexion