

**EFFECT OF TENDON MECHANICAL PROPERTIES ON FORCE
STEADINESS IN YOUNG AND OLD ADULTS**

by

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Abstract

The contribution of the tendon to age-related differences in elbow flexor force steadiness has not been studied. The purpose of this study was to investigate the effect of tendon compliance on force steadiness in young compared with old males during sustained submaximal isometric elbow flexion contractions. Force steadiness and tendon properties were measured in ten young (22.4 ± 3.7 years; 166.9 ± 11.8 cm; 74.3 ± 13.2 kg), and ten old (77.3 ± 5.3 years; 168.9 ± 14.1 cm; 84.6 ± 13.5 kg) healthy physically active males at 6 submaximal forces of 2.5%, 5%, 10%, 20%, 40%, and 60% maximal voluntary contraction (MVC). Muscle-tendon characteristics were assessed by ultrasonography and force steadiness with an isometric dynamometer. Young and old did not differ in height, weight, muscle-tendon, and bone parameters ($p > 0.05$). The main findings of the present study were that a) Young were $\sim 20.4\%$ ($p < 0.001$) stronger than old and this was not due to a difference in voluntary activation ($p > 0.05$), b) Young were steadier (1.1 ± 1.0 CV % MVC) than old (1.9 ± 1.5 CV % MVC) across the 6 submaximal forces ($p < 0.001$), c) Tendon mechanical properties such as stress ($p > 0.07$, $n^2 = 0.19$), stiffness ($p > 0.07$, $n^2 = 0.17$), and Young's Modulus ($p > 0.07$, $n^2 = 0.17$) were moderately less in old than young, and d) Tendon mechanical properties become stiffer as force increases ($p < 0.05$). Tendon displacement, strain, and stress were correlated with force steadiness ($p < 0.001$). These data suggest that tendon properties are one of the primary factors contributing to differences in steadiness across submaximal forces, and these mechanical properties contribute modestly to age-related differences.

Preface

The University of British Columbia Behavioural Research Ethics Board granted ethics approval on April 16th, 2015. The ethics approval certificate number for the current study is H14-00165. To date, the research included in this thesis has not been published in full. Preliminary results were presented at an international conference, European College of Sport Science (ECSS).

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List of Abbreviations

ACh: Acetylcholine

ANOVA: Analysis of variance

BB: Biceps Brachii

Ca²⁺: Calcium

CSA: Cross Sectional Area

CNS: Central Nervous System

CV: Coefficient of Variation

E: Youngs Modulus

FS: Force Steadiness

Ft: Tendon Length

K: Stiffness

Kg: Kilogram

L₀: Resting Tendon Length

LBB: Long Head of biceps Brachii

LHT: Lateral Head of Triceps

MA: Moment Arm

ms: Milliseconds

Na⁺: Sodium

MTJ: Muscle Tendon Junction

MU: Motor Unit

MUDR: Motor Unit Discharge Rate

MUDRV: Motor Unit Discharge Rate Variability

MVC: Maximal Voluntary Contraction

N: Newton

NMJ: Neuromuscular Junction

PNS: Peripheral Nervous System

s: Seconds

SD: Standard Deviation

SBB: Short Head of Biceps Brachii

US: Ultrasound

ϵ : Strain

σ : Stress

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Dedication

The volunteers who made this study possible.

Chapter 1: Introduction

1.1 Organization of the Neuromotor System

When a human being attempts to execute a voluntary movement, electrical impulses are generated in the central nervous system (CNS), passes through the peripheral nervous system (PNS) and finally to the muscle. The CNS includes the brain, ascending and descending tracts within the spinal cord and works with the PNS through nerves that leave the brain stem or the spinal cord. The brain is able to relay information to the body via descending nerve tracts. These nerve tracts exit the brain and move down the spinal cord along two major pathways: 1) Extrapyramidal tract and 2) Pyramidal tract. The brainstem typically controls posture and muscle tone via the extrapyramidal tract. The pyramidal tract activates skeletal muscle primarily through the corticospinal which is under direct cortical control of voluntary movement. The corticospinal tract is the longest and one of the largest in the spinal cord and two thirds of its axons originate in the primary motor cortex of the forebrain and end in the spinal cord (Figure 1.0). In the spinal cord by means of direct routes and interconnected neurons, these nerves ultimately excite the alpha motor neurons (α MN) whose cell bodies are located in the grey matter of the anterior horn of the spinal cord. When a single α MN is activated, it excites many individual muscle fibres and this constitutes the motor unit (MU) (McArdle, Katch and Katch, 2010). One motor neuron can innervate fewer than 10 and up to 3000 muscle fibres, depending on the size, degree of control and strength required by the muscle. Muscles that control fine and precise movements of low strength have fewer than 10 fibres per MU, whereas the larger muscles that control gross movements and require a high level of strength may

innervate as many as 2000 or 3000 fibres per MU (Enoka, 1995; MacIntosh, Gardiner, & McComas, 2006).

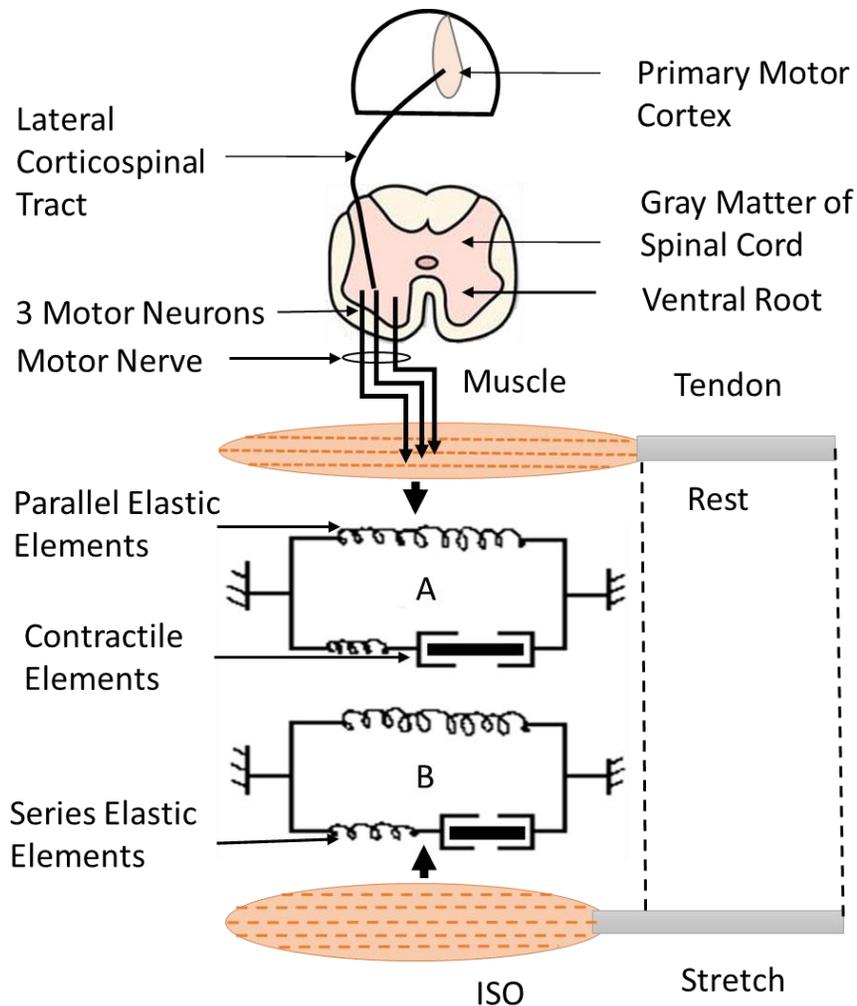


Figure 1.0: In order to generate isometric contraction electrical signal from the primary motor cortex travels from the motor cortex down the spinal cord by corticospinal tract, synapse with alpha motor neuron to excite the muscle fibers. Actin and myosin are called contractile elements. Due to interaction of actin and myosin, force is produced. Before this force transmits to the bone, non-contractile elements such as elastic elements need to stretch fully. When elastic component is stretched the passive force is generated. Therefore, the total force of a muscle is made up of three elements: i) Parallel elastic elements ii) Contractile elements, and iii) Series elastic elements. Hence, the sum of the passive force and the active force represents the overall strength of the muscle. ISO, isometric.

The MU is the final common pathway (; Denslow & Hassett, 1942; Sherrington, 1906) and serves as a link for transmission of information between the brain and the muscle to control the force of muscle contraction. In the MU, the alpha motor neuron branches and the terminal ends connect with extrafusal muscle fibres forming the neuromuscular junction (NMJ) and specifically the motor end plate. The NMJ consists of the presynaptic plasma membrane of the motor nerve, the synaptic cleft or space between the motor nerve and muscle, and the postsynaptic membrane which is located on the sarcolemma of the muscle fibre. The terminal portion of the nerve has numerous sac-like vesicles containing a neurotransmitter known as acetylcholine (ACh). When the α MN is at rest, it has a resting membrane potential of approximately -70 mV. This negative electrical potential means that the cell's interior has a negative charge compared with the surrounding extracellular fluid. This polarized state is created by a high concentration of positively charged sodium ions (Na^+) outside the cell and a lower concentration of positively charged potassium ions (K^+) as well as negatively charged protein inside the cell. Due to an electrical stimulus arriving at the nerve cell, Na^+ rushes into the cell, shifting that part of the membrane toward a less-negative potential, causing depolarization where an action potential is generated at a threshold of approximately -55 mV. This depolarization through the subsequent activation of voltage-gated sodium channels passes down the axon and at the synaptic bouton causes voltage-gated calcium (Ca^{2+}) channels to open. The Ca^{2+} causes release of the neurotransmitter (ACh) from the synaptic vesicles into the synaptic cleft by exocytosis. At this level the electrical signal (nerve impulse) turns into a chemical signal (released neurotransmitter). The ACh binds to the specialized receptors (neurotransmitter receptor) on the ligand-gated channels on

the postsynaptic membrane to open the channels and allows selective cations to flow across the sarcolemma. Inward flow of Na^+ causes depolarization in the postsynaptic membrane of the muscle fibre and propagates as a postsynaptic membrane potential along the sarcolemma. At this level the chemical signal (released neurotransmitter) turns into an electrical signal (postsynaptic potential). The signal continues along the sarcolemma and down a series of transverse tubules (T tubules) within the muscle. At the T tubules, an action potential is propagated into the interior of the cell. Ultimately Ca^{2+} is released from the sarcoplasmic reticulum and results in movement of troponin and tropomyosin and this enables the myosin molecule heads to grab and swivel their way along the thin actin filament and causes muscle contraction (McArdle, Katch & Katch, 2010).

Two important proprioceptors, the muscle spindles and the Golgi tendon organs, both play important roles in motor control. They promptly convey the message to the CNS about the movement behaviour of the muscle and limb so that the brain is consistently aware of muscle and limb position (McArdle, Katch and Katch, 2010). The muscle spindle is enclosed within a capsule and contains specialized muscle fibres called intrafusal fibres. They are found throughout the body of a muscle, in parallel with the extrafusal fibres. These intrafusal fibres are innervated by gamma motor neurons that exit through the ventral root of the spinal cord and function to maintain the sensitivity of the muscle spindle to stretch. The necessary output information is detected by the muscle spindle and travels via group Ia and the group II sensory axons to the spinal cord. Both sensory neurons are excitatory to the agonist muscles or its synergists; however, group Ia afferents are inhibitory through an interneuron to the antagonist muscles (MacIntosh,

Gardiner, & McComas, 2006). Golgi tendon organs provide further information about the change of muscle force. These organs are located at the musculotendinous junction (MTJ) and are fewer in number than the muscle spindle. When higher levels of force are generated, sensory information from the tendon organs is transmitted by Ib afferent fibres. This axon inhibits the motor neurons of the agonist muscle through an inhibitory interneuron, and excites those of the antagonists which causes a decrease in muscle contraction and a decrease in force and ultimately helps to protect the muscle from damage (MacIntosh, Gardiner, & McComas, 2006). Thus, muscle spindles and Golgi tendon organs have complementary functions of informing the CNS through reflex feedback during muscle contraction.

1.2 Voluntary Muscle Force and Force Steadiness

The development of adequate voluntary force necessitates appropriate communication and activation between the primary motor cortex, descending pathway, motor neurons and muscle fibres with the integration of afferent feedback. Ultimately, the release of Ca^{2+} , its binding with troponin to open actin-myosin binding sites will enable force production at the level of the single muscle fibre. The stimulation of muscle fibres is initiated through activation of Mus, and forces can be generated from minimal to maximum output by recruiting more MUs or by up-regulating the frequency of MU discharge rate (MUDR) (MacIntosh, Gardiner, & McComas, 2006). A maximal voluntary contraction (MVC) is achieved when all the MUs are recruited and MUDR are at their highest level (De Luca et al., 1982).

Motor units not only contribute to the absolute force produced but the steady control of force, which is enabled through adaptations in recruitment and discharge rates

(Enoka et al., 2003). The ability to control force, known as force steadiness (FS) is the consistency of maintaining an isometric contraction around a given target force. Deviation from this target force is a measure of force steadiness and expressed as a coefficient of variation (CV) the standard deviation of force divided by average isometric force (Brown et al., 2010; Enoka et al., 2003; Tracy & Enoka, 2002). Coefficient of variation is inversely related to the steadiness therefore, the higher the value the less steady the contraction. The variability of firing of the action potential is expressed as MU discharge rate variability (MUDRV). Motor unit discharge rate variability is a primary means in controlling steady contractions and generally MUDRV is inversely proportionate to FS across a wide range of muscle forces (Enoka et al., 2003; Tracy et al., 2005).

Force steadiness depends on different factors such as the task, muscle group, and intensity of the contraction (% of MVC) and usually appears as an inverted U shape function across low to high levels of force (Danion & Gallea, 2004; Enoka et al., 2003; Slifkin & Newell, 1999; Tracy & Enoka, 2002) (Figure 1.1). Force is steadiest at intermediate force levels (30–40% MVC) because muscle force can be adjusted by the contribution of both MU recruitment and MUDR whereas below this region, at low forces, MU recruitment is the main mechanism to generate and control force (Slifkin & Newell, 1999). Force steadiness is also position dependent, for instance, during isometric elbow flexion, force was steadiest in the neutral and supinated positions compared with pronated (Brown et al., 2010) (Figure 1.1). Position dependency in force steadiness is attributed to factors of absolute force and MUDR variability.

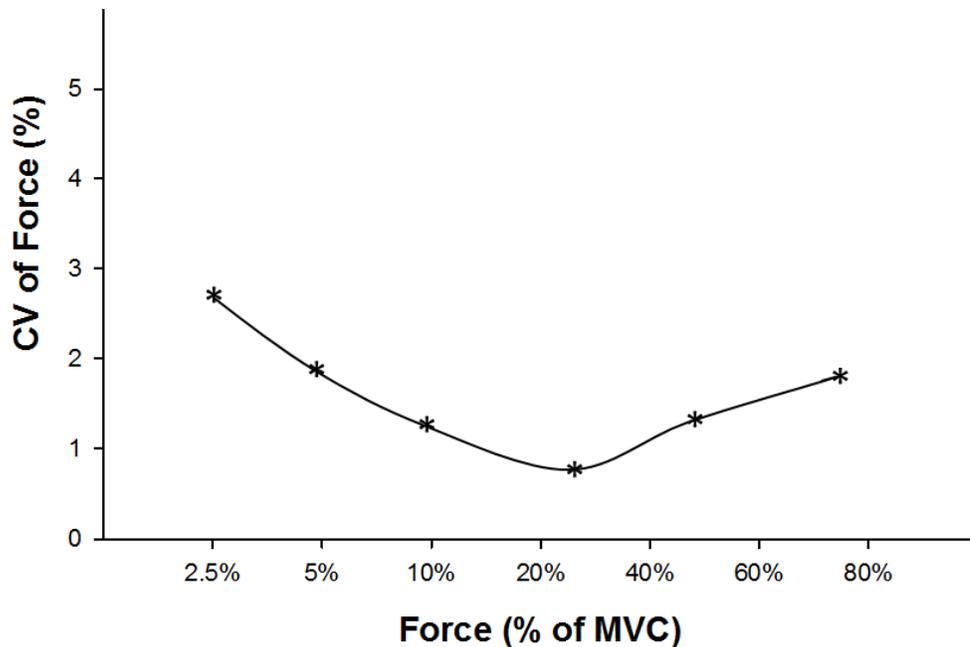


Figure 1.1: Relationship between force and force steadiness. In the neutral forearm position the U shape feature suggests that CV of force is highest (least steady) at low (<5% MVC) as well as high (<75% MVC) relative force levels; however, at intermediate force levels (20-40% MVC) contractions are steadiest (adapted from Brown et al., 2010, Enoka et al., 2003, Tracy & Enoka, 2002). %CV, percentage of coefficient of variation of force; %MVC, percent maximal voluntary contraction.

Males are generally steadier than females and this is primarily due to muscle strength being higher in males (Brown et al., 2010). The ability to control force differs between muscle groups and is also attributed to maximal strength. For example, in older adults compared with young adults, FS was 19% lower for elbow flexors and 37% lower for knee extensors (Tracy et al., 2007). It is well established that older adults are less able to maintain a steady force during isometric and dynamic contractions (Christou & Carlton, 2001; Hortobagyi et al., 2001; Tracy & Enoka, 2003) in the first dorsal interosseous (Laidlaw et al., 2000), tibialis anterior (Dewhurst et al., 2007), and quadriceps (Carville et al., 2007). These same studies also found differences in MVC with younger adults being

stronger than older adults. Contrary to this, force steadiness in old adults was similar to young adults in the elbow flexors when strength was similar between the two age groups (Graves et al., 2000; Tracy et al. 2007). This suggested that the decrease in steadiness was associated with an age-related decline in muscle strength (Carville et al., 2007; Tracy et al., 2002) whereby enhancing muscle strength improved force steadiness (Hortobágyi et al., 2001; Tracy et al., 2004). Therefore, muscle weakness is likely a strong factor in decreased steadiness (Brown et al., 2010), and increasing strength could be a primary means to enhance force steadiness. However, muscles and tendons work as a unit to generate force (Earp et al., 2011; Roberts, 2002) and in older adults the more compliant tendon associated with decrease in postural balance (Onambele et al., 2006) and increased sway (Baudry et al., 2012). The contribution of the tendon to sway in lower limbs suggests that the compliance of the tendon also contributes to the production of steadier contractions in the upper limb. Overall, force control requires coordination between neural and muscular aspects of the MU as well as the tendon and the latter has been overlooked across studies to date.

1.3 Tendon characteristics

Muscles have elastic elements that can further enhance muscle flexibility. Muscle is encircled by epimysium, a dense layer of collagen fibre that extends from the deep fascia, perimysium that encloses the bundles of muscle fibres, and endomysium that surrounds individual muscle fibres. These three layers of connective tissue extend beyond the muscle fibre to form a tendon (McArdle, Katch & Katch, 2010). Each muscle has two tendons; one proximal and one distal. These correspond to attachment points on the bone. The area in which the muscle joins the tendon is called the muscle tendon

junction (MTJ) and the point at which a tendon connects with the bone is called the osteotendinous junction. Healthy tendons are white in colour and viscoelastic in nature. They consist of elastic fibres such as collagen (65-80%) and elastin (1-2%), ground substances such as proteoglycans, glycosaminoglycan, inorganic molecules, and different types of cells such as fibroblasts, macrophages, plasma cells, white blood cells, mast cells and fat cells (Kannus, 2000). The elastic fibres undergo length changes called deformations that are directly proportional to the applied forces. The ground substance has viscous properties which are characterized as time-dependent and rate change-dependent (Watkins, 2010). Collagen and elastin elements are produced by tenoblasts and tenocytes. Collagen is a connective tissue which is made up of protein molecules such as amino acid, and the coupling of amino acids forms an alpha chain. Three alpha chains coil to form collagen molecules which are encircled by a thin layer of proteoglycans and glycosaminoglycans. The collagen molecules link to form a tropocollagen molecule which is soluble. Soluble tropocollagen molecules form cross-links to create insoluble collagen molecules, which then collectively form microfibrils. The microfibrils are surrounded by proteoglycans and glycosaminoglycans. Within the microfibrils each collagen molecule aligns in a quarter staggered array and forms collagen fibrils. The collagen fibril is the smallest tendon structural unit. A group of collagen fibrils forms primary fibre bundles, a group of primary fiber bundles forms the secondary fibre bundles, and a group of secondary fiber bundles forms the tertiary fibre bundles. Each of these three fibre bundles are encircled by an endotenon. Finally, a group of tertiary fibres form the tendon covered by an epitenon (Kannus, 2000). This hierarchical structure of the

tendon arranges the fibre bundles with the long axis of the tendon and creates tensile force from the tendon (Wang, 2006).

Tendons are mechanically responsible for transmitting forces produced by the contractile elements of muscle, and make movement possible through the joint's range of motion. The mechanical properties refer to the ability of tendon to alter their structure in response to muscle loads. Due to advances in the application of real-time ultrasonography, characterization of the mechanical properties of human tendons *in vivo* is possible (Maganaris & Paul, 2002). The parameters of the mechanical properties are tendon strain (ϵ), stress (σ), Young's modulus (E), and stiffness (K), and these can be measured *in vivo* during voluntary isometric contractions (Narici, Maffulli, & Maganaris, 2008; Onambele et al., 2006; 2007). The change in tendon length is expressed as strain. Strain is a measure of the ratio of the deformation of a tendon upon force application from its resting length, and stress is a measure of the ratio of the tendon force and the cross sectional area. Young's modulus is measured from the relationship of stress and strain which is non-linear (Heinemeier & Kjaer, 2011). Young's modulus depends on the material properties of the tendon, therefore when the value is high the Young's modulus indicates a stiffer tendon (Heinemeier & Kjaer, 2011). Stiffness is a measure of tendon deformation in relation to force generated at the tendon. How much the tendon will deform is dependent on tendon CSA and its length, thus the change in tendon length is inversely proportional to the CSA (Heinemeier & Kjaer, 2011). As stiffness depends on the material properties and the tendon dimension, stiffer tendons are able to transfer muscle force to the bone more rapidly than compliant tendons (Heinemeier & Kjaer, 2011; Wang et al.,

2012, Narici et al., 2006, Onambele et al., 2006), as a more compliant tendon requires a longer time to be stretched than a stiffer tendon (Wilkie, 1949).

1.4 Integrated function between muscle and tendon

Muscle force is generated under a tight interaction between actin and myosin molecules at the level of the sarcomere to generate active force. Before this force transmits to the bone elastic elements such as titin need to stretch fully. Passive force is a resistive force generated by the elastic components of muscle fibres and is largely developed by the elastic protein titin (Granzier, & Labeit, 2004; Horowitz et al., 1986). Therefore, the total force of a muscle is made up of three components: 1) the parallel elastic component (PEC; epimysium, endomysium, and perimysium) which, represents the elasticity of the passive elements of the muscles and ligaments 2) the contractile component (actin, myosin), which determines the behaviour of active elements of the muscle, and 3) the elastic components connected in series (cytoskeleton, and, tendons) (Figure 1.0) (Hof & Van Den Berg, 1981). The sum of the passive force and the active force represents the overall strength of the muscle as a function of its length (Herzog & Leonard 2002; Rassier et al. 1999). Thus, any change in elastic properties can affect the functional properties of the entire musculotendinous unit which ultimately can affect the force-length relationships of the muscle fibres (Alexander, 2002; Fukunaga et al., 2002; Magnusson et al., 2003; Reeves et al., 2004). For example, in the force-length relationship of muscle, maximum force is produced in the plateau region due to optimal overlap of contractile elements. Beyond this region, shortening or lengthening of the sarcomere on the ascending or descending limb of the force-length curve decreases force production (Gordon et al. 1966). A more compliant tendon leads to muscle fibre

shortening causing the muscle to operate at shorter sarcomere lengths; thus, a more compliant tendon would produce less muscle force than a stiffer tendon (Kubo et al., 2006; Narici et al., 2005; Oda et al., 2007). As a consequence, knowledge of the mechanical properties of human tendons is important in understanding the contribution of the muscle–tendon unit to force production.

The mechanical properties of the tendon are influenced by aging (Narici et al., 2008, 2007), sex (Onambele et al., 2007), disuse (Maganaris et al., 2006), and training (Reeves et al. 2003). For example, resistance training results in increased tendon stiffness in old and young adults (Reeves et al., 2003). Also with both short term rest (12 wk of bed rest) (Reeves et al., 2005) and long term (1.5-25 yr) disuse (Maganaris et al., 2006), the tendon becomes compliant in young and old adults alike. Tendons of females are less stiff than males (Kubo et al., 2003; Onambele et al., 2007) due to the female hormone estrogen and the tendon becomes less stiff with increased age (Onambele et al., 2006).

1.5 Contribution of Biceps Brachii Muscle to Movements

During isometric elbow flexion in a neutral wrist position, the main contributors to force production are the brachialis, brachioradialis, and biceps brachii (Buchanan, Rovai, & Rymer, 1989). As the name of the biceps brachii (BB) muscle implies, it has two heads (long head of the biceps (LBB), short head of the biceps (SBB)) and both are located in the anterior aspect of the arm (Figure 1.2 bottom left). The LBB arises from the supraglenoid tubercle of the scapula and passes through the intertubercular (bicipital) groove of the humerus (Figure 1.2 top) to join with the SBB that arises from the coracoid process of the scapula at the level of the deltoid tuberosity to form a single muscle belly

(Figure 1.2 top). Distally this muscle belly forms a single flat tendon about 7 cm above the elbow joint with the flat surface of the tendon facing anteriorly (Skaf et al., 1999). The tendon crosses the elbow joint and inserts on the tuberosity of the radius (Figure 1.2 bottom right). On average the length of the BB tendon is 2.3 cm from the articular margin of the radial head to insertion (Athwal, Steinmann, & Rispoli, 2007). It also attaches to the bicipital aponeurosis, which descends medially to insert onto the deep fascia of the forearm (Tortora & Derrickson, 2009). The tendon and the bicipital aponeurosis are often palpable in the anterior cubital fossa. Real-time ultrasound (US) makes imaging in the longitudinal and transvers axial planes of the BB tendon *in vivo* possible (Brasseur, 2012; Chew, & Giuffrè, 2005) (Figure 1.2 longitudinal view).

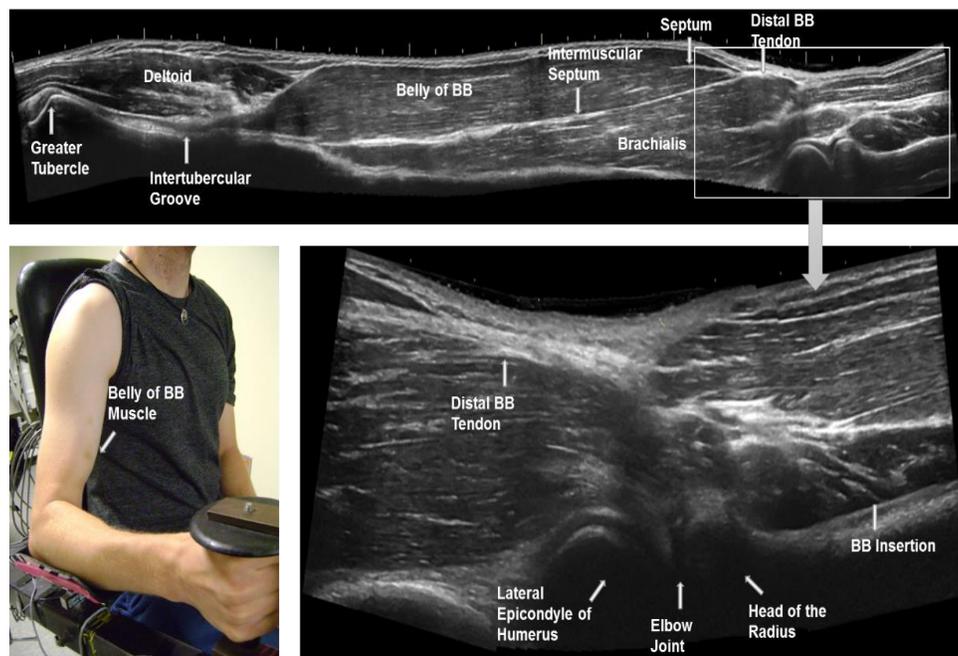


Figure 1.2: Anatomy of the BB muscle and tendon *in vivo*. A longitudinal ultrasonic image of the BB muscle at rest (top). The prominent BB muscle at the anterior aspect of the arm (bottom left). Ultrasonic view of the anterior cubital fossa showing the structures of the distal aspect of the BB tendon, lateral epicondyle of the humerus, and head of the radius (bottom right). The BB tendon is inserted on the radial tuberosity (bottom right).

As BB tendons of both heads cross the shoulder joint anteriorly, the BB also contributes to shoulder flexion. However, its primary action is to flex the forearm at the elbow (Tortora & Derrickson, 2009) where its contribution to elbow flexion force is ~47% (Kawakami et al., 1994). In addition, the BB assists with forearm supination and pronation at the radioulnar joint (Tortora & Derrickson, 2009). The MU activity of the BB is position dependent and differs between two heads. For example, Harwood et al., (2010) stated that at a low level of isometric elbow flexion MUDR was higher in the supinated forearm position compared with the neutral and pronated. These investigators reported that the SBB had higher MUDR than LBB, and the SBB only exhibited greater MUDRV in the pronated position. They also demonstrated that the position-related change in the forearm did not show any difference in MUDR activity between young and old adults. Brown et al., (2010) reported that during isometric elbow flexion, neutral and supinated position were steadier than pronated and at those positions both were equally strong and steady.

1.6 Tendon Properties and Force Steadiness with Increased Age

The relationship between tendon displacement and CSA determines the stiffness of a tendon. An increase in tendon CSA would likely restrict tendon displacement thereby uncoupling the relationship between muscle and tendon length. Magnusson et al., (2003) demonstrated that older females had an ~ 22% greater Achilles tendon cross-sectional area compared with young females and this increase in size may reduce the risk of injury to the tendon in older adults. Irrespective of CSA, other investigators have suggested that tendon compliance increased with age (Karamanidis & Arampatzis, 2005; Onambele et al., 2006). This mechanical change of the tendon with aging is thought to be due to a

combination of an increase in elastic content and non-reducible collagen cross-linking, as well as a decrease in the collagen fibril crimp angle, extracellular water and mucopolysaccharide content making the tendon more compliant (less stiff) with increased age (Narici & Maganaris, 2006).

With increased age, fascicle length decreases and fewer sarcomeres in series have been proposed as the cause (Narici et al., 2003), thus it would be logical that the relative tendon length would increase in older adults to operate in the optimal level of force in the sarcomere length–tension relationship. Onambele et al., (2006) reported that the tendon becomes compliant with increased age and compliant tendons lengthen easier which facilitates shortening of muscle fibres (Kubo et al., 2006; Narici et al., 2005). It is also likely that the decrease in fascicle length (Kubo et al. 2003; Narici et al., 2003) and increased tendon compliance in older adults also contribute to less force being produced (Reeve et al., 2004). Moreover, a compliant tendon may cause relatively slow transmission of forces from muscle to bone which might affect force output. For instance, Onambele et al., (2006) suggested that the decline of postural balance was due to an increase in tendon compliance which decreased the rate of the “catch and throw” (Loram et al., 2002) which is the time between force production and transfer. A small delay of transfer of force output from the muscle to bone is likely to have a negative effect on force control, similar to the detriment it has on postural balance. Hence, force transmission response of the compliant tendon in older adults would likely increase force variability in old adults. This postulation is further supported by observations that strength training increases tendon stiffness (Reeves et al., 2003), and also improves force steadiness

(Hortobágyi et al., 2001; Tracy et al., 2004) of old and young adults; yet the role of the tendon in force steadiness has not been studied.

1.7 Summary

Muscle and tendon works as a unit to produce desirable force. Tendon transmits force to the bone and that impact on control of force output. Control of force, expressed as force steadiness, varies with age, sex, contraction intensity, contraction type, and training. These have been studied extensively in the literature (Brown et al., 2010; Enoka et al., 2003). The effect of tendon mechanical properties has received minimal attention; however, an age-related difference in tendon mechanics, notably lower stiffness, has been observed (Karamanidis & Arampatzis, 2005; Onambele et al., 2006). Because older adults are weaker it is likely that a more compliant tendon transferring a lesser amount of force would contribute to the age-related reduction in force steadiness. To date no investigation has quantified tendon mechanical properties of the BB relative to force steadiness in young and old adults. The present study aimed to identify the contribution of muscle-tendon mechanical properties to force steadiness in young and old adults.

Chapter 2: Purpose and Hypotheses

2.1 Purpose

The purpose of this study was to investigate the contribution of tendon parameters to force steadiness in young compared with old adults.

2.2 Hypotheses

It was hypothesized that:

1. Strength would be less in old compared with young males.
2. Coefficient of variation of force steadiness would be greater in old compared with young, which indicates the older males would be less steady.
3. The tendon would be more compliant in old compared with young males.
4. There would be a relationship between force steadiness and tendon mechanical properties.

Chapter 3: Methods

3.1 Subjects

Ten young (22.4 ± 3.7 years) and ten old (77.3 ± 5.3 years) males that were similar in height (166.9 ± 11.8 cm, young; 168.9 ± 14.1 cm, old) and weight (74.3 ± 13.2 kg young; 84.6 ± 13.5 kg old) were recruited to participate from the University of British Columbia Okanagan campus and surrounding communities. Subjects were tested in the morning between 8am-12pm as tendon stiffness decreases from the morning to evening (Pearson & Onambele, 2006). Subjects were physically active, right hand dominant, free of orthopedic injury to the right arm and wrist and self-reported no neurological, cardiovascular or cognitive impairments. As well, subjects did not participate in resistance training. Upon meeting with a potential subject, a letter of initial contact was presented that introduced the researcher and explained the study. When the subject decided to participate they were given a consent form further specifics of the research protocol and their rights as a volunteer participant. Following recruitment 32 old and 18 young males demonstrated interest and were contacted, among them 12 old and 10 young participated. Two old male were excluded due to their age (>70 years old). Following informed written consent a lifestyle questionnaire which detailed physical activity was filled out. This study was approved by the University of British Columbia Behavioural Research Ethics Board (H14-00165).

3.2 Experimental Setup

Subjects were seated in a custom-designed chair which was adjusted to the subject's height with the hip and knee angle set at 90° . The right elbow rested in a padded support with the joint positioned to 110° of flexion (full extension is 180°) with the forearm

and wrist in a neutral position and the shoulder abducted at 15°. Underneath the wrist apparatus, a MLP-150 linear calibrated force transducer (68kg) (Transducer Techniques, Temecula, CA, USA) was positioned. Visual feedback of force was provided with a 52.1 cm (20.5 inch) monitor screen located 1 metre in front of the subject. The force dynamometer was grounded through a Coulbourn Instruments Unit (Coulbourn Electronics, Allentown, Pennsylvania, USA) and force signals were amplified (100Hz) and filtered (10Hz - 20Hz) and sampled at 496Hz with a 16-bit 1401 plus A/D converter (Cambridge Electronic Design (CED), Cambridge, England) and stored for off-line analysis using Spike2 software (Version 7, CED, Cambridge, England) (Figure 3.0).

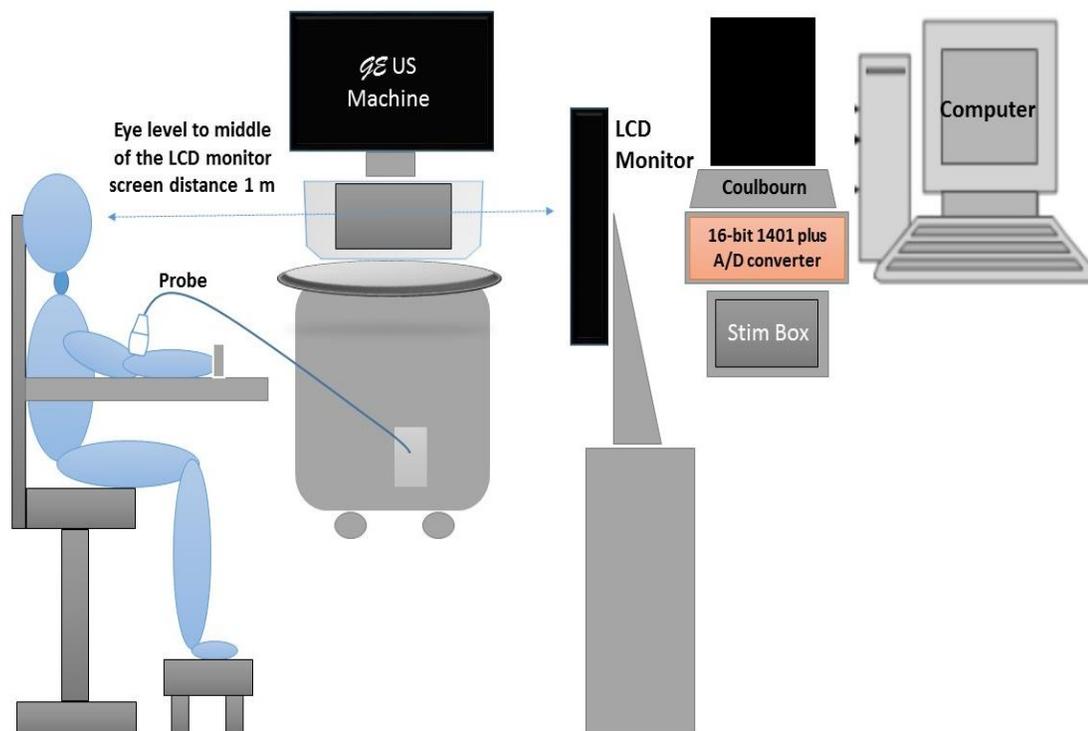


Figure 3.0: *Experimental set-up. Subjects sat on the custom made chair with the right elbow positioned to 110° of flexion with the wrist in a neutral position. The LCD monitor was placed 1 m in front of the subjects to provide visual feedback. The ultrasound machine was beside the subject and the probe was fixed over the tendon in two different orientations to record the musculotendinous junction (MTJ) and cross sectional area (CSA). Electrical stimulation was applied to the elbow flexors to assess voluntary activation.*

A real time B-mode US (GE LogiQ E9, USA) was used to obtain muscle tendon characteristics *in vivo*. The US screen was set up with the frame rate 29Hz, gain 44, and depth of 450 mm (4.5 cm). A ML6-15 probe (4.5-15.0MHz linear array, 13 x 58 mm footprint, 50 mm field of view, 80 mm (8 cm) depth of field, LOGIQView, GE©) was placed in a custom designed encasement to ensure secure and consistent probe placement. The probe was positioned at 90⁰ to the arm and localized on the skin at the muscle tendon junction (MTJ) to record the tendon displacement and tendon cross sectional area (CSA) during the force steadiness task. Tendon displacement measurements were taken at 110⁰ elbow angle and at this position the probe was fixed on the MTJ on the skin vertically. The probe was consistently positioned and held firmly across experiments in the custom designed case that was secured to the arm with fabric straps (Figure 3.1 Left). A three mm wide and 160 mm long echo absorptive marker was positioned to identify consistent probe placement. To measure CSA of the tendon the probe was fixed on the MTJ on the skin horizontally. The probe was secured with straps (Figure 3.1 right).

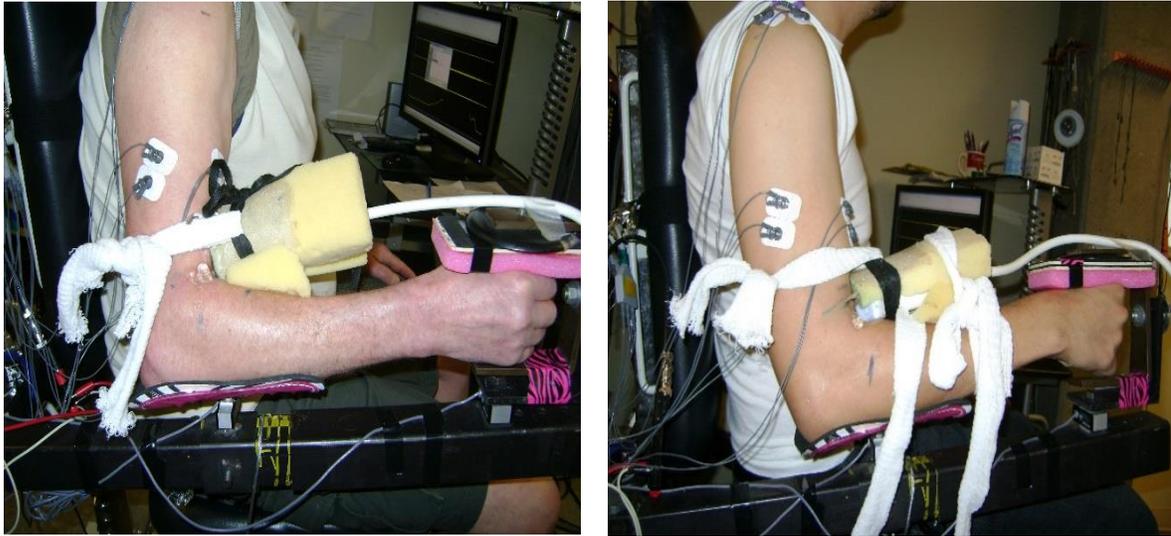


Figure 3.1: *Ultrasound probe placement. Ultrasound probe placement for tendon elongation (Left) with the probe (15 MHz wave frequency) fixed vertical to the arm using a custom designed case that was positioned with fabric straps to the skin surface over the MTJ. CSA of the tendon (Right) was measured at the same location but the probe was fixed horizontal to the arm. Additional triangular foam inserts were added when support was necessary to position the probe at a 90° angle to the arm.*

3.3. Experimental Design

Two assessments were performed an, 1) Anatomical assessment, and 2) Physiological assessment. Following anatomical measurements of muscle length, muscle CSA, tendon length and tendon CSA, subjects performed three MVCs with the twitch interpolation technique (see section 3.5.1 for details). The highest force achieved was used to calculate the submaximal forces of 2.5%, 5%, 10%, 20%, 40%, and, 60% for the FS task (Figure 3.2). Tendon displacement (mm) and tendon CSA (mm²) were recorded across the submaximal contractions with real-time ultrasound (GE LogiQ E9, USA). Ultrasound videos were time-locked with force. The submaximal contractions were executed twice to record the tendon displacement and CSA. The order of displacement

and CSA recordings were randomized between subjects and the target forces (2.5%, 5%, 10%, 20%, 40% and 60% of MVC) were also randomly assigned. After executing the twelve FS trials (6 force levels for 2 probe positions), an additional elbow flexion MVC as well as an extension MVC without twitch interpolation was executed to monitor for fatigue (Figure 3.2).

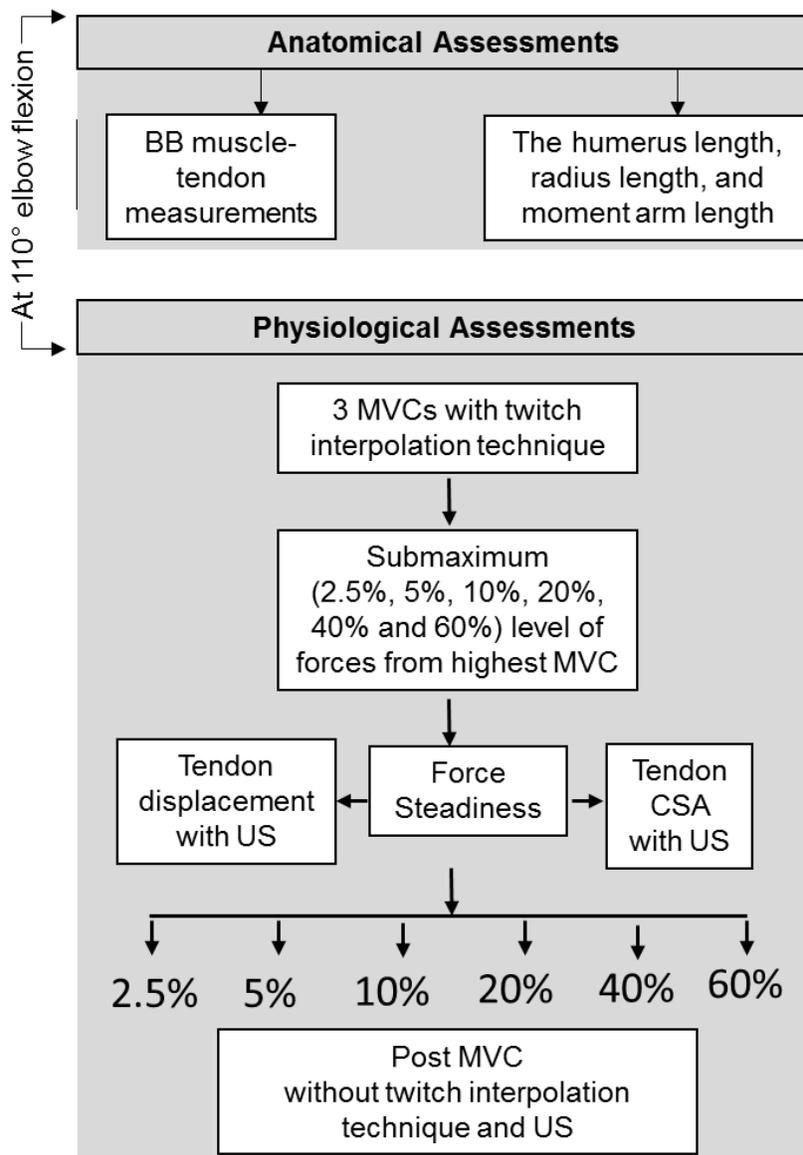


Figure 3.2: Schematic representation of protocol and measures.

3.4. Anatomical Assessments

3.4.1. Biceps Brachii Muscle and Tendon Structure *in Vivo* at Rest

The length of the BB muscle and tendon of the right dominant arm were quantified with US at a 110° elbow angle. Aquasonic clear ultrasound transmission gel (Parker Laboratories, Inc., New Jersey USA) was applied between the probe and skin which provided acoustic contact. First, a sagittal scan was taken along the belly of the BB muscle to locate the MTJ. This position was marked on the skin surface with a 3 mm thick 160mm long piece of aluminum foil marker that was visible with ultrasound imaging as a dark band. A second sagittal scan was taken to determine the insertion point of the tendon on the radial tuberosity and it was subsequently marked. A longitudinal scan of the biceps tendon from the MTJ to the insertion was performed.

The intertubercular sulcus of the humerus was identified as the proximal point to initiate the muscle scans and this position was also marked on the skin with an echo absorptive marker. A longitudinal scan of the BB muscle from the proximal point to the MTJ was performed at 110°

Transverse BB tendon CSA (mm²) images were obtained with US at the MTJ at 110° of elbow angle. An axial scan was taken to measure CSA of the muscle belly of BB by operating logicView mode.

3.4.2 Moment Arm and Anthropometric Measures

Moment arm and anthropometric measurements were taken with a measuring tape. Humerus length was measured on the skin surface between the greater tubercle of the humerus to the lateral epicondyle of the humerus (Figure 3.3). The radial length was measured as the distance from the lateral epicondyle of the right humerus to the

styloid process of radius and described as lever arm length. A linear edge was placed across the MTJ and insertion point of the BB which was pre-marked on the skin. Moment arm (MA) lengths were measured as the perpendicular distance from the lateral epicondyle of the humerus to the linear edge. To determine the BB muscle belly the subjects were asked to pull upwards against the forearm apparatus and arm circumference was taken from the largest aspect of the BB muscle belly (see Figure 3.3).

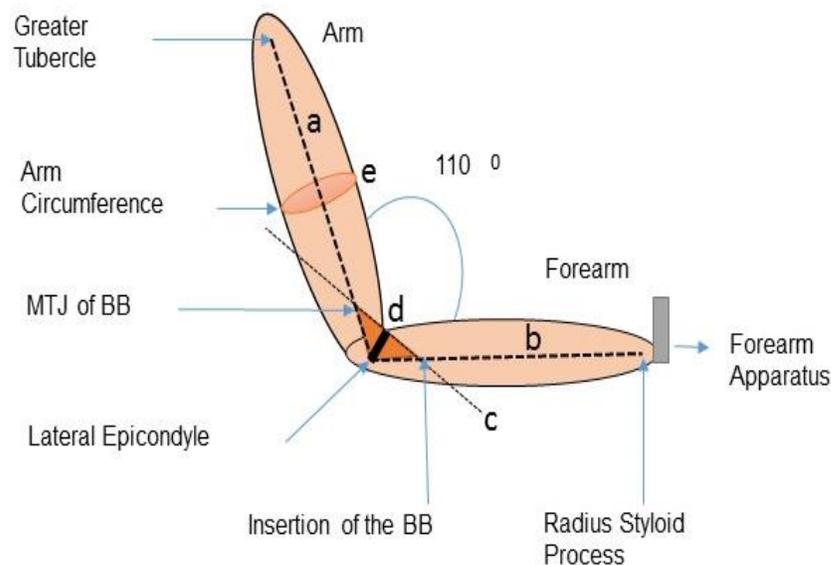


Figure 3.3: A two dimensional geometric representation at 110° elbow angle. The measurements were taken from the lateral aspect of the arm and forearm on the skin surface. Humerus length was taken from the greater tubercle to the lateral epicondyle of the right humerus (a). The radius length was taken from the lateral epicondyle of the right humerus to the styloid process of the radius (b) which was described as the lever arm length. Moment arm length (Thick black line), d) was the perpendicular distance measured from the lateral epicondyle of the humerus to linear edge (c) which was placed on the top of the elbow angle across the arm and forearm. Arm circumference was taken from the largest aspect of the BB muscle belly (e).

3.5. Physiological Assessments

3.5.1 Voluntary Activation

Voluntary activation (VA) was measured by applying an electrical stimulus over the biceps brachii. To assess voluntary activation of the elbow flexors, the twitch interpolation method was used (Allen et al., 1994). To stimulate the elbow flexor muscles, carbon rubber stimulation electrodes (4 x 4.5 cm) were placed diagonally across the arm and tightly bandaged by transpore tape over the upper (anode) and lower (cathode) ridges of the BB. Twitch intensity (200 μ s pulse width, 400 volts) was set to supramaximal by increasing electrical current until a maximal twitch response was reached. Once maximal amplitude was reached the intensity was increased a further 10%. A series of three supramaximal single twitches were applied with a one second interval during MVCs (interpolated twitches) and immediately following the MVC (potentiated twitch) when the muscle was in a relaxed state (Allen et al., 1994; Jakobi & Rice, 2002).

For all attempts at elbow flexion MVC, VA was measured. Subjects were instructed to flex their elbow joint as hard as possible by pulling the wrist apparatus up as fast as possible and to sustain this effort for 4–6 s. Visual feedback and strong verbal encouragement were given for all attempts at MVC. Subjects performed 3 MVCs with 2-3 min rest between efforts. The highest MVC was used to determine MVC and voluntary activation. This value was used to determine submaximal forces for the steadiness protocol.

3.5.2 Force Steadiness Task

Force steadiness was tested by having subjects match linear force targets of 2.5%, 5%, 10%, 20%, 40%, and 60% maximum that was displayed on the LCD monitor. Subjects were instructed to match the targets as precisely as possible. (Figure 3.4). The duration of the steady state for each submaximal force was 5 sec.

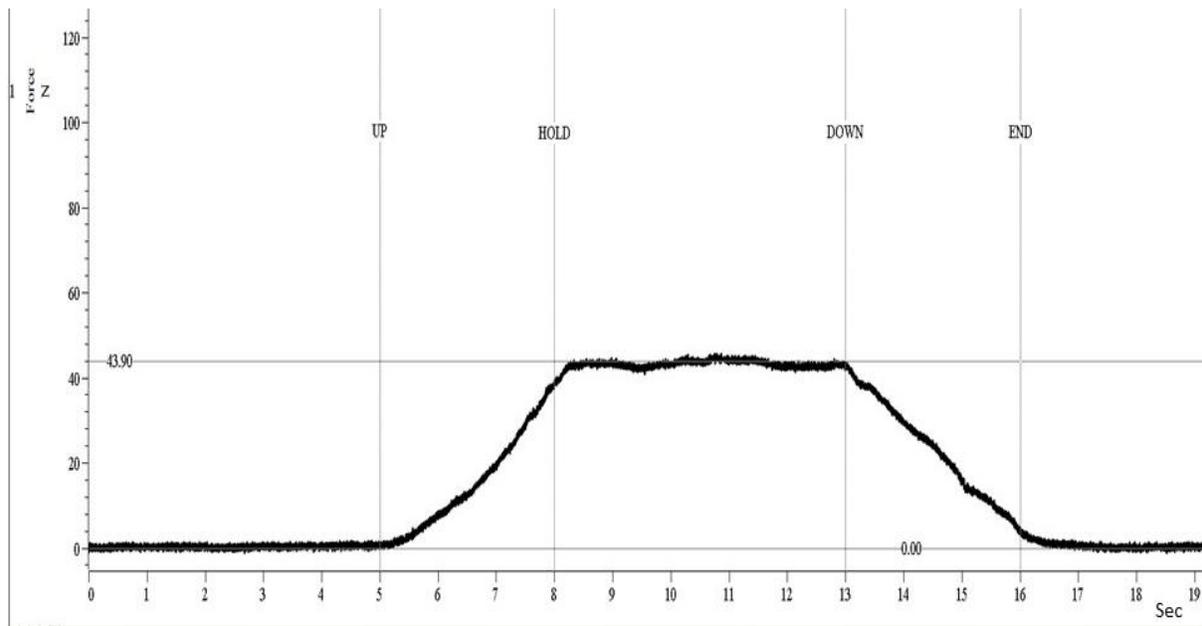


Figure 3.4: Representative visual feedback. Representation of visual feedback for 20% submaximal force. The horizontal axis represents the time in seconds and the vertical axis the contraction force in Newtons. A black tracing line which is the “live” visual feedback represents the contraction force. The target was positioned as a horizontal line. The vertical lines indicate when a contraction starts or changes. The first vertical line which is labelled “UP” indicates when the subject initiated the ramp. The second vertical line is labelled “HOLD” for the subject to maintain the target. The third vertical line is labelled “DOWN” for the subject to begin the relaxation and the fourth vertical line is indicative of the end of the contraction.

There were ~2-3 min rest between each contraction to prevent fatigue. Subjects were familiarized with this experimental procedure through 2-3 practice contractions. The FS tasks were performed for twelve contractions [2 (probe position) x 6 (% of force level)

= 12 contractions] and each contraction was done for each probe positions (vertical and horizontal) to measure tendon displacement and tendon CSA changes, respectively.

3.6 Data Analysis

Offline analysis was conducted by using custom scripts designed for Spike2 (Version 6, CED, Cambridge, England) and pre-programmed measurement tools in the US system (LOGIQView, GE©). The plateau of each isometric submaximal force (2.5%, 5%, 10%, 20%, 40%, and 60% of MVC) was analysed to quantify force steadiness. The first and last second were excluded to ensure that the subject was holding the steady state contraction without anticipation of the force transition, thus the analysis was made over the middle three seconds. For US measurements, the steady state plateau was also used for measurement of tendon displacements and CSA. The US data were recorded in cm and converted to mm, similar to previous experiments in this field (Maganaris and Paul, 2002)

3.6.1 Voluntary Activation and Force Steadiness

Voluntary activation was estimated by using the formula: % activation = $[(1 - \text{superimposed twitch} / \text{potentiated twitch}) \times 100]$ (Allen et al., 1994). Steadiness was calculated as the coefficient of variation of force for each submaximal level of contraction. Force steadiness was an average of the values achieved for the two US recordings (MTJ and CSA of tendon).

3.6.2 Muscle and Tendon Measures

To identify the muscle and tendon structure ~ 2-3 US scans and video were recorded for each contraction and the best image and video were analysed. *In vivo* length of the BB was measured with the open spline trace (mm) preprogrammed within the GE

platform. Measures were made from the proximal to distal MTJ (Figure 3.5). Muscle thickness was measured as the vertical distance in mm between the superficial and deep aponeurosis (Figure 3.5). Resting muscle CSA (Figure 3.6) and resting tendon CSA (Figure 3.7) were measured with the area trace function.

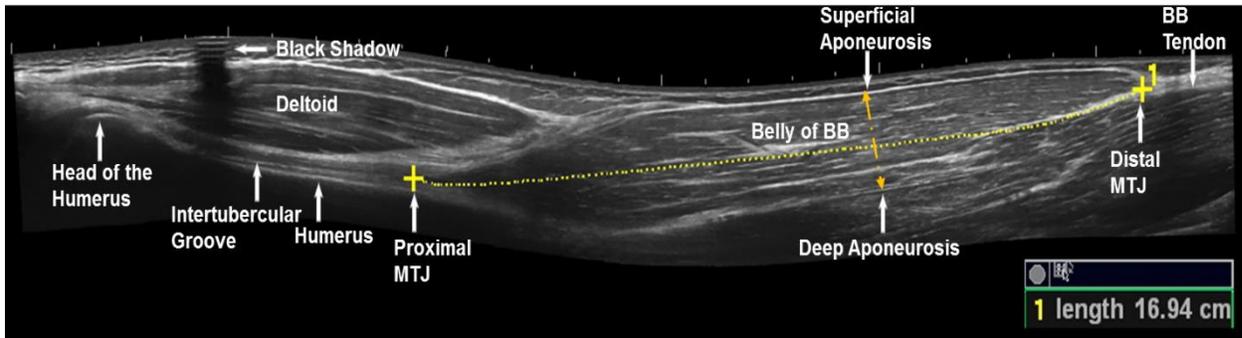


Figure 3.5: The BB muscle in vivo at 110° outlined for a young subject. BB is measured from the proximal to distal MTJ with the open spline trace which is shown as a yellow line. The recorded measurement is displayed at the right corner of the image. Muscle thickness was measured as vertical distance between superficial aponeurosis and deep aponeurosis at the BB belly.

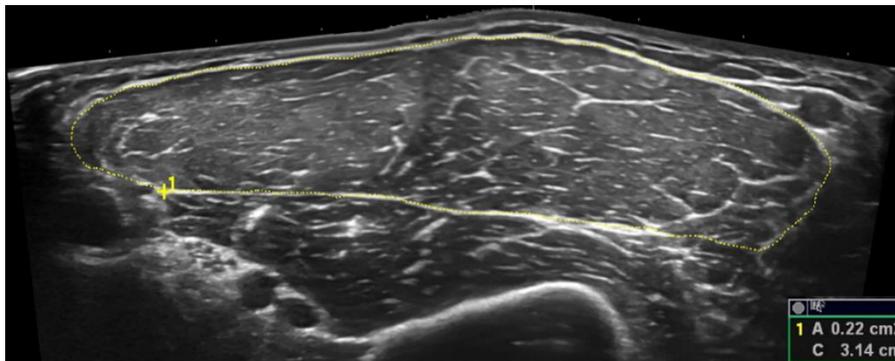


Figure 3.6: BB muscle CSA in vivo at 110° for a young subject. The CSA was measured with area trace displayed at the right corner of the image.

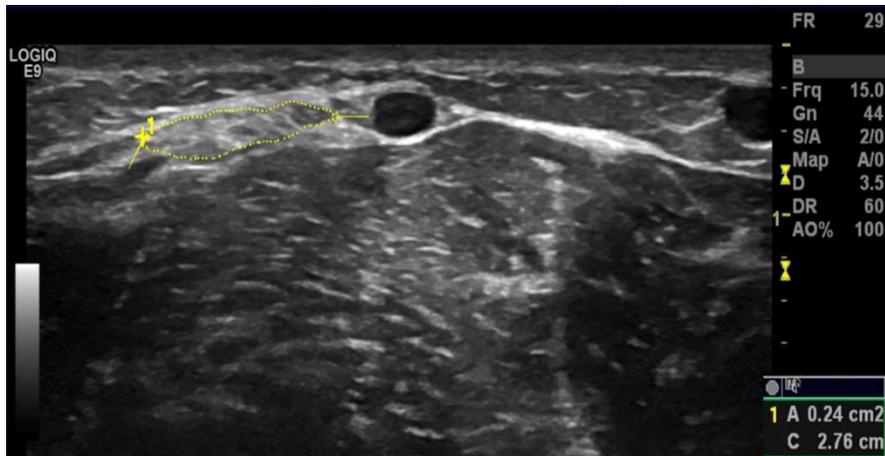


Figure 3.7: BB tendon CSA in vivo at 110° for a young subject. The measure is displayed at the right bottom corner. The right panel depicts the optimization control tools. FR, frame rate; B, B mode ultrasound; Frq, frequency of sampling; Gn, brightness of the ultrasound image; D, depth;

3.6.3 Mechanical Properties of tendon

To calculate Young's Modulus and tendon stiffness, tendon force (Ft) was determined (Figure 3.10) from muscle moment and moment arm (Figure 3.3 for moment arm measures) ($F_t = \text{Muscle moment} \times \text{moment arm}$). Muscle moment was calculated from the submaximal voluntary contraction (% of MVC) and the lever arm length (Muscle moment = submaximum forces \times lever arm length). Lever arm length was measured as the length of the radius bone in mm. (Figure 3.3).

To calculate Young's Modulus (E) the relationship between stress (σ) and strain (ϵ) were plotted (Figure 3.10) ($E = \sigma/\epsilon$). Stress was calculated from the ratio of tendon force and the CSA ($\sigma = F_t/\text{CSA}$), and tendon strain was calculated as the relative displacement (Figure 3.8) of resting length (Murata et al., 2009) which was calculated by using the following equation:

$$\text{Strain\% } (\epsilon) = [\text{Tendon displacement } (\Delta L) / \text{resting tendon length } (L_0)] * 100$$

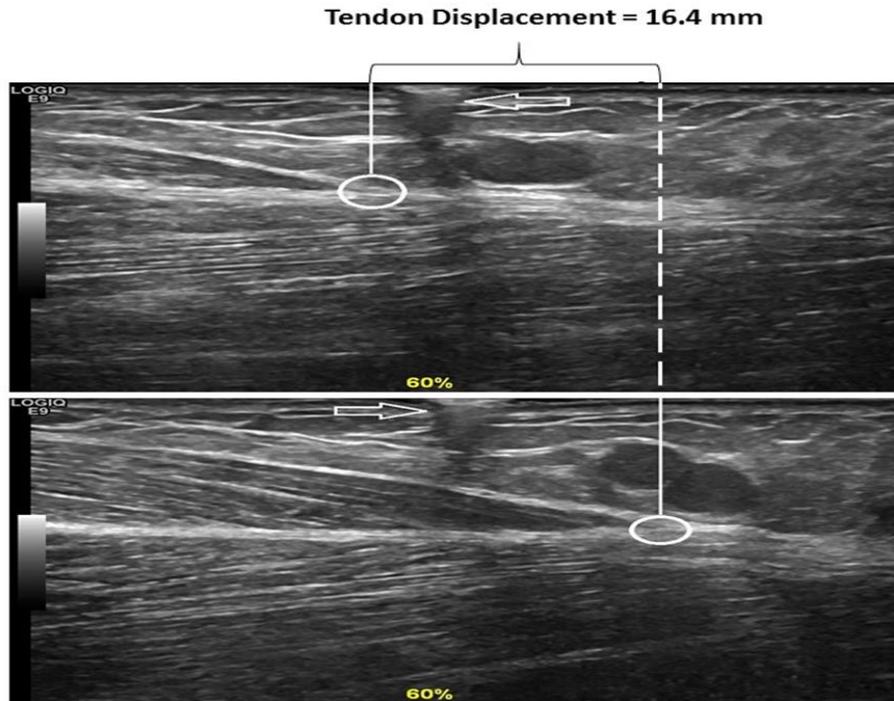


Figure 3.8: Tendon displacement in vivo for an old subject. In vivo sagittal-plane sonographs over the BB musculotendinous junction before contraction (on top), and steady state contraction at 60% of MVC (bottom). The black shadow indicated by a white arrow was generated by the echo absorptive marker. The visual image of the tendon was measured before contraction from the edge of the screen to the MTJ junction (on top) and then the shift in the displacement of the MTJ to the right during steady state contraction was measured (from rest 0 N to 134.28 N 60% MVC force). The distance traveled by the tendon during 60% of MVC force was defined as tendon displacement ($\Delta L = 16.4$ mm).

Tendon CSA was measured over the mid portion of the submaximal isometric contraction. Resting tendon length (L_0) was measured from the distance between its insertion on the radial tuberosity and the BB MTJ by using a spline trace as it is a non-linear distance (Figure 3.9).

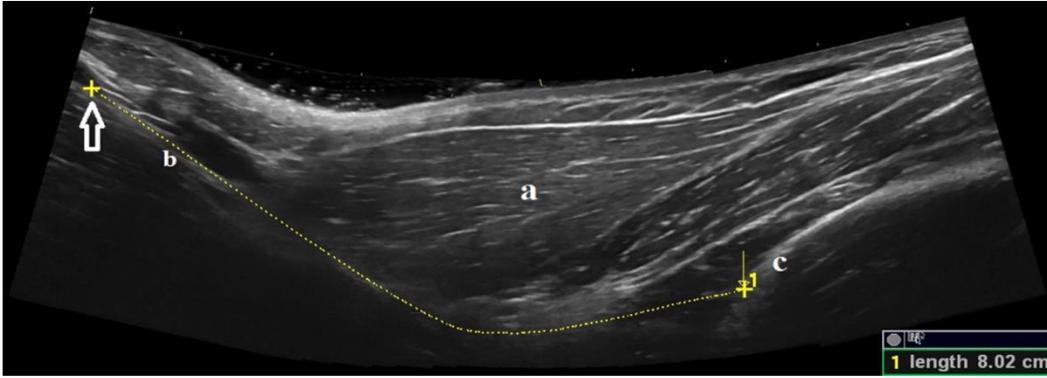


Figure 3.9: A scanned ultrasonographic image of the resting BB tendon at 110° elbow angle from a young subject. Muscles are hypoechoic (a, darker gray), BB tendon also appears hyperechoic with no striations (b, white on the screen), and bone appears anechoic with a bright hyperechoic rim (c, typically darker black). Resting tendon length was measured from the MTJ (white arrow) to the insertion (+1, adjacent to letter c) with a spline trace (dotted yellow line). The measure is displayed in the right bottom corner.

Tendon stiffness (K) was measured as tendon elongation relative to tendon force ($K = Ft / \Delta L$) (Figure 3.10).

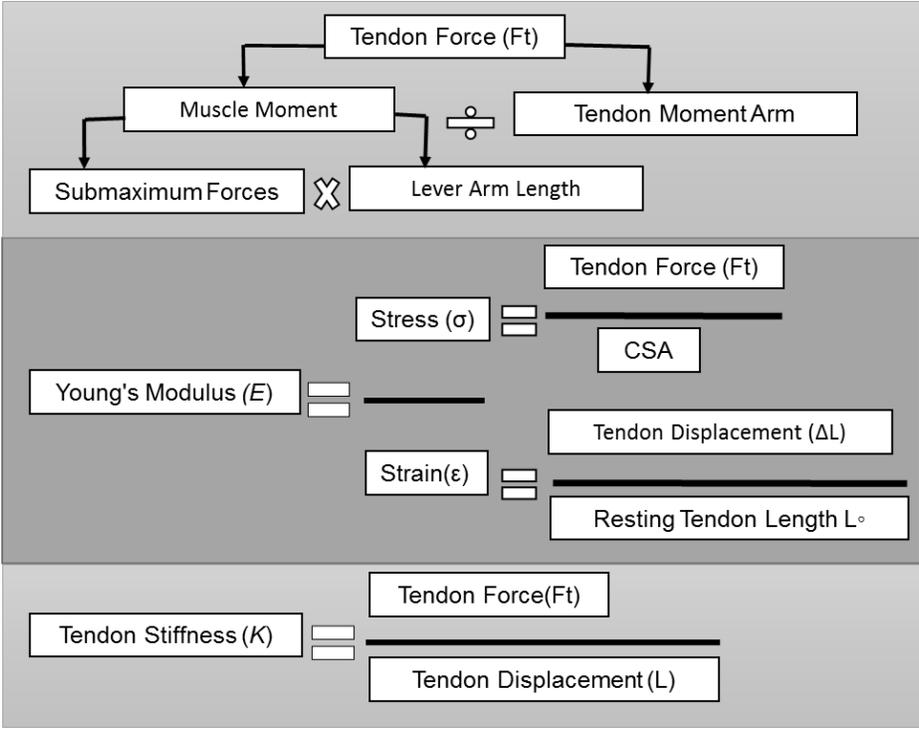


Figure 3.10: Measurements for calculation of tendon mechanical properties.

3.7 Statistical Analysis

Data was analyzed using Statistical Package for Social Science (SPSS) version 20.0 and Microsoft Excel (version 2013). Independent sample t-tests were conducted to evaluate differences in subject characteristics, and right arm muscle-tendon and right arm anatomy between young and old males. Age-related differences in force steadiness and tendon measures (CSA, displacement, stiffness, strain, Young's modulus) were assessed with a 2 (age; young, old) x 6 (force level; 2.5%, 5%, 10%, 20%, 40% & 60% MVC force) two way ANOVA. Regression analysis was employed to compare the degree of association between force steadiness and tendon properties (displacement, strain, stress, Young's modulus, stiffness) using a second order polynomial. Significance was estimated at $p \leq 0.05$. Tukey Post Hoc tests were used to compare significant interactions. All data and tables in text presented as mean \pm standard deviation (SD), and graphs presented as mean \pm standard error.

Chapter 4: Results

4.1 Subject Characteristics

Young and old males did not differ in height, weight, and BMI (Table 4.0). There were also no differences in voluntary activation ($p > 0.05$). Elbow flexion MVC were ~20.4% lower in old compared with young ($p \leq 0.05$).

Table: 4.0 Subject Characteristics

	Young (n=10)	Old (n=10)
Age (Years)	22.4 ± 3.7*	77.3 ± 5.3
Height (m)	166.9 ± 11.8	168.9 ± 14.1
Weight (Kg)	74.3 ± 13.2	84.6 ± 13.5
BMI (Kg/m²)	26.7 ± 3.9	29.8 ± 4.3
Elbow Flexor MVC (N)	265.7 ± 52.7*	211.5 ± 40.4
Voluntary Activation (%)	98.3 ± 3.4	96.9 ± 5.7

*Values are means ± SD. * significantly different from old; %, percent; N, newton; m, meter; Kg, kilogram.*

4.2 Force Steadiness

There was no two-way interaction for force x age ($p=0.45$); however, main effects for age ($p=0.001$) and force ($p=0.001$) were found. Old males (1.9 ± 1.5 CV % MVC) were less steady than young males (1.1 ± 1.0 CV % MVC) (Figure 4.0A). As force increased the CV decreased, indicating that at higher forces, irrespective of age, force production was steadier. The least steady contraction was 2.5% (3.6 ± 1.8 CV % MVC) and the steadiest contraction was at the 40% target force (Figure 4.0B). The CV of force did not differ between target forces of 20% - 60% ($p \geq 0.33$).

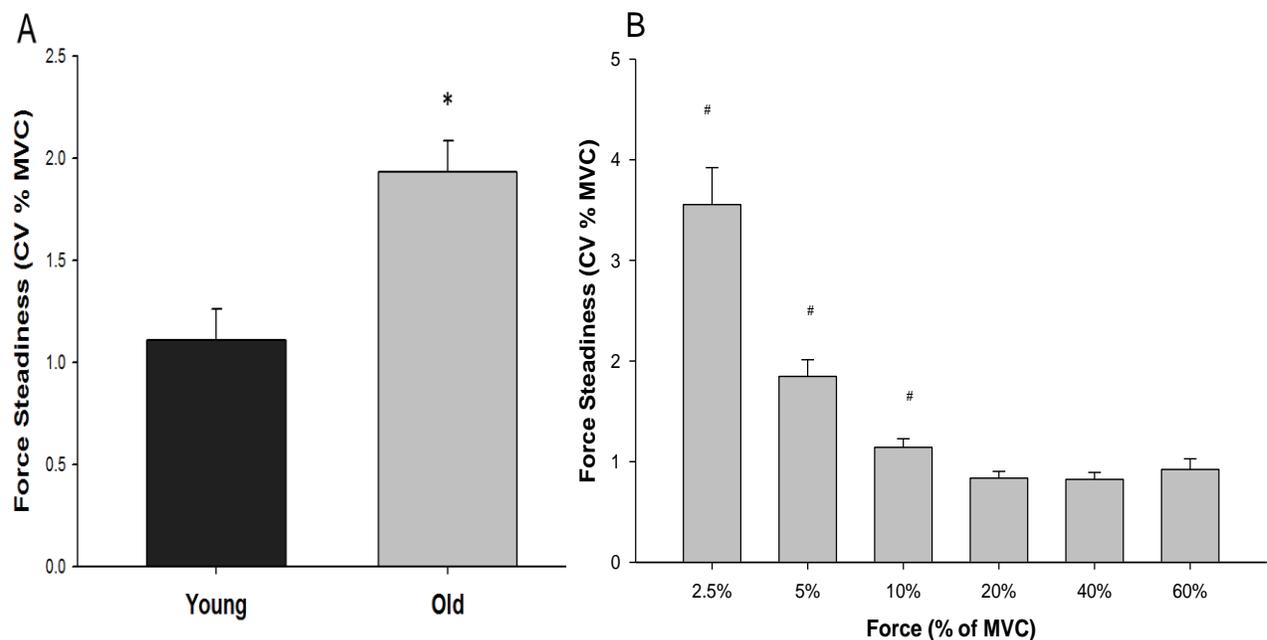


Figure 4.0: Force steadiness between age groups (A) and across force levels (B). Old were less steady than young and force steadiness increased (decrease in CV) with force level. *, force steadiness less in old. #, Force steadiness differed from all other forces. MVC, maximal voluntary contraction; CV, coefficient of variation, N, Newton; %, percentage; *, #, significance ($p \leq 0.05$).

4.3 Muscle-Tendon and Humerus-Radius Characteristics

There were no significant differences between young and old males in anatomical characteristics of either the muscle-tendon or bone (Table 4.1).

Table 4.1 Bone, Muscle, and Tendon Measures

Parameters	Young (n=10)	Old (n=10)
Humerus Length (mm)	313.1 ± 16.5	316.3 ± 18.4
Radius Length (mm)	276.6 ± 13.1	277.2 ± 17.0
Arm Circumference (mm)	314.3 ± 27.3	299.0 ± 41.4
Muscle Length (mm)	138.0 ± 11.7	144.3 ± 15.67
Muscle Thickness (mm)	21.7 ± 3.2	20.2 ± 2.6
Muscle CSA (mm²)	1111.2 ± 455.8	1107.3 ± 212.5
Moment Arm (mm)	56.9 ± 4.1	55.7 ± 5.78
Resting Tendon Length (mm)	83.7 ± 7.9	86.4 ± 4.7
Tendon CSA (mm²)	23.9 ± 4.9	25.0 ± 4.2
Tendon Length/Muscle Length	0.6 ± 0.1	0.6 ± 0.1

Values are means ± SD, MVC, maximum voluntary contraction; CSA, cross sectional area; *mm*, millimeter.

4.4 Muscle Moment

The two-way interaction of force x age ($p=0.03$) as well as main effects of age ($p=0.001$) and force ($p=0.03$) were observed for muscle moment. Young males ($8090.4 \pm 7589.89 \text{ N/mm}^2$) had greater muscle moment than old males ($6424.2 \pm 5820.93 \text{ N/mm}^2$) across all forces other than 2.5% ($p \leq 0.03$). Muscle moment increased significantly across all forces for old males ($p \leq 0.001$); however, in young males muscle moment increased after 5% MVC ($p \leq 0.001$) with no difference observed between 2.5% and 5% ($p=0.31$) (Figure 4.1).

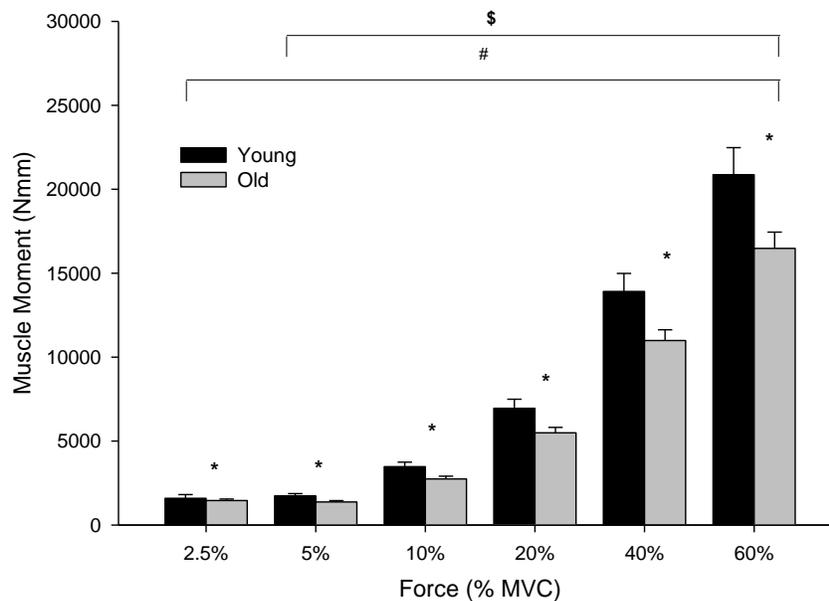


Figure 4.1: Muscle moment across force levels and age groups. Muscle moment was greater in young than old and increased significant between all force levels for old and in young the increase was evident at 5% MVC. *, young greater than old; #, significant increase between forces for old; \$, significant increase with force for young. MVC, maximal voluntary contraction; N, Newton; %, percentage; mm, millimeter; *, #, \$, significance ($p \leq 0.05$).

4.5 Tendon Force

A two-way interaction of force x age was observed for tendon force ($p = 0.03$). No differences were found between young and old males ($p = 0.06$; $n^2 = 0.17$); however, there was a main effect of force ($p = 0.001$). In the old males tendon force increased significantly between forces ($p < 0.001$) whereas in young males tendon force did not differ between 2.5-5% MVC ($p \geq 0.3$) and thereafter increased significantly between all forces ($p \leq 0.001$) (Figure 4.3).

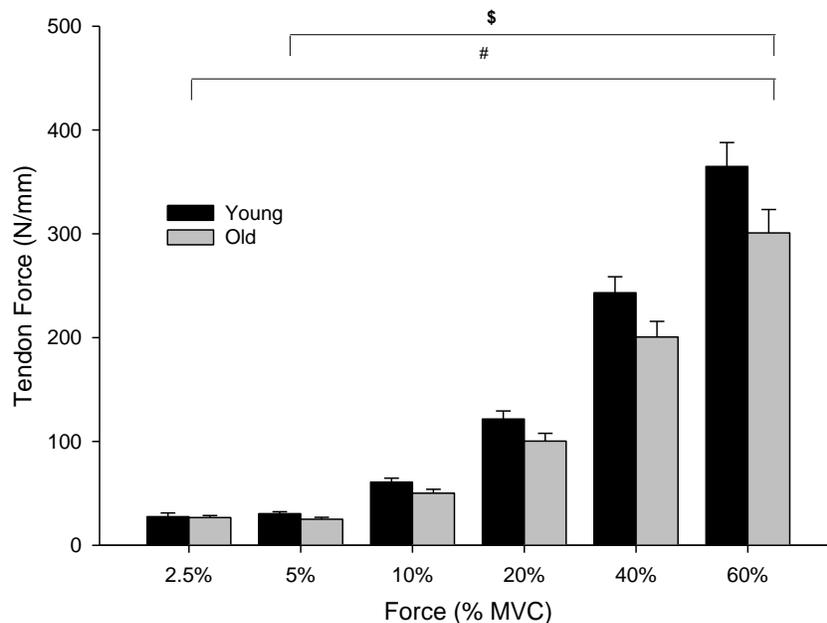


Figure 4.2: Tendon force between age groups and across force levels. In old males tendon force increased significantly between all force levels and in young the increase was evident at 5% MVC. #, significant difference between forces for old; \$, significant increase between forces for young. MVC, maximal voluntary contraction; N, Newton; %, percentage; mm, millimeter; *, #, \$, significance ($p \leq 0.05$).

4.6 Tendon Dimensions and Mechanical Properties

No two-way interaction (age x force level) or main effect of age were found for tendon CSA ($p = 0.24$; $p = 0.34$), tendon displacement ($p = 0.76$; $p = 0.29$), strain ($p = 0.76$; $p = 0.39$), stress ($p = 0.42$; $p = 0.06$, $n^2=0.19$). Young's Modulus ($p = 0.11$; $p = 0.07$, $n^2=0.17$) and tendon stiffness ($p = 0.29$; $p = 0.07$, $n^2=0.17$) trended towards old having more compliant tendons than young. There was a main effect of force ($p \leq 0.001$) for all tendon variables.

CSA was highest at 2.5% ($22.1 \pm 4.8 \text{ mm}^2$) and 5% ($22.3 \pm 4.0 \text{ mm}^2$) of MVC and lowest at 60% ($19.4 \pm 3.8 \text{ mm}^2$) of MVC. Tendon CSA decreased as force level increased; however, CSA at 2.5% did not differ from 5% ($p = 0.13$), 10% ($p = 0.06$), and 20% ($p = 0.10$) of MVC. CSA at 60% differed from all force levels other than 40% (Figure 4.3A). Tendon displacement and strain increased significantly with force level ($p < 0.05$) (Figure 4.3C, 4.3D). Stress did not differ between 2.5% ($1.26 \pm 0.44 \text{ N/mm}^2$) and 5% ($1.28 \pm 0.07 \text{ N/mm}^2$) ($p = 0.67$); however, there was a significant increase between all other forces ($p \leq 0.001$) (Figure 4.3D). Young's Modulus was greatest at 60% MVC ($2.0 \pm 1.4 \text{ N/mm}^2$) and lowest at 5% ($0.37 \pm 0.2 \text{ N/mm}^2$) of force. Young's Modulus increased significantly between forces of 5% and higher ($p \leq 0.01$) and differed significantly between 2.5% and 5% and 40% and 60% ($p \leq 0.02$) (Figure 4.3E). Tendon stiffness was greatest at 60% ($44.8 \pm 29.5 \text{ N/mm}$) and lowest at 5% ($21.4 \pm 12.5 \text{ N/mm}$) of force. Tendon stiffness did not differ between 2.5% and 10% ($p=0.06$) as well as 20% ($p=0.46$) (Figure 4.3F).

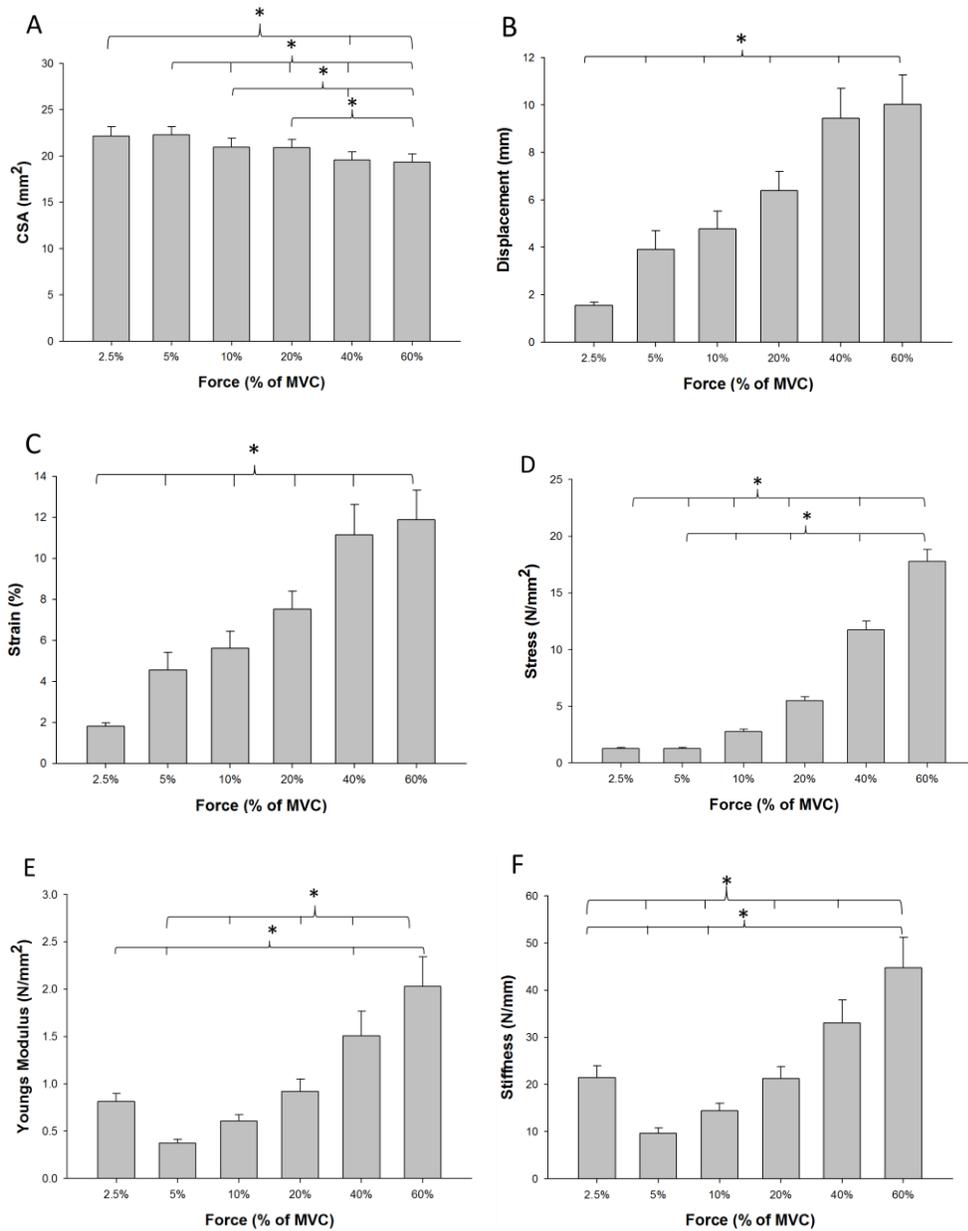


Figure 4.3: Tendon dimensions across force levels. (A) CSA decreased as force level increased, (B) Tendon displacement and (C) Strain increased significantly as force increased. (D) Stress did not differ between 2.5% and 5% MVC but increased significantly between all other forces. (E) Young's modulus at 2.5% did not differ from 10% and 20% MVC, but differed from all other forces. At 5% YM differed between all forces (F) Tendon stiffness at 2.5% did not differ from 20% and 40% MVC, all other comparisons were significantly different. *, CSA, cross-sectional area; MVC, maximal voluntary contraction; N, Newton; %, percentage; mm, millimeter; *, significance ($p \leq 0.05$).

4.7 Correlation and Regression Analysis

In the regression analysis force steadiness was the dependent factor and the tendon mechanical parameters of 1) strain, 2) stress, 3) Young's Modulus, and 4) tendon stiffness were the independent variables. When data were evaluated across all submaximal forces there was a moderate correlation between force steadiness and tendon displacement (young $r^2 = 0.51$, $p \leq 0.001$, old $r^2 = 0.58$, $p \leq 0.001$) (Figure 4.4A), strain (young $r^2 = 0.44$, $p \leq 0.001$, old $r^2 = 0.62$, $p \leq 0.001$) (Figure 4.4B), stress (young $r^2 = 0.60$, $p \leq 0.001$, old $r^2 = 0.53$, $p \leq 0.001$) (Figure 4.4C); however, there were no significant correlations for CSA (young $r^2 = 0.002$, $p = 0.71$, old $r^2 = 0.05$, $p = 0.07$) (Figure 4.4D), stiffness (young $r^2 = 0.09$, $p = 0.02$, old $r^2 = 0.002$, $p = 0.75$) (Figure 4.4E) and Young's Modulus (young $r^2 = 0.08$, $p = 0.03$, old $r^2 = 0.03$, $p = 0.75$) (Figure 4.4F).

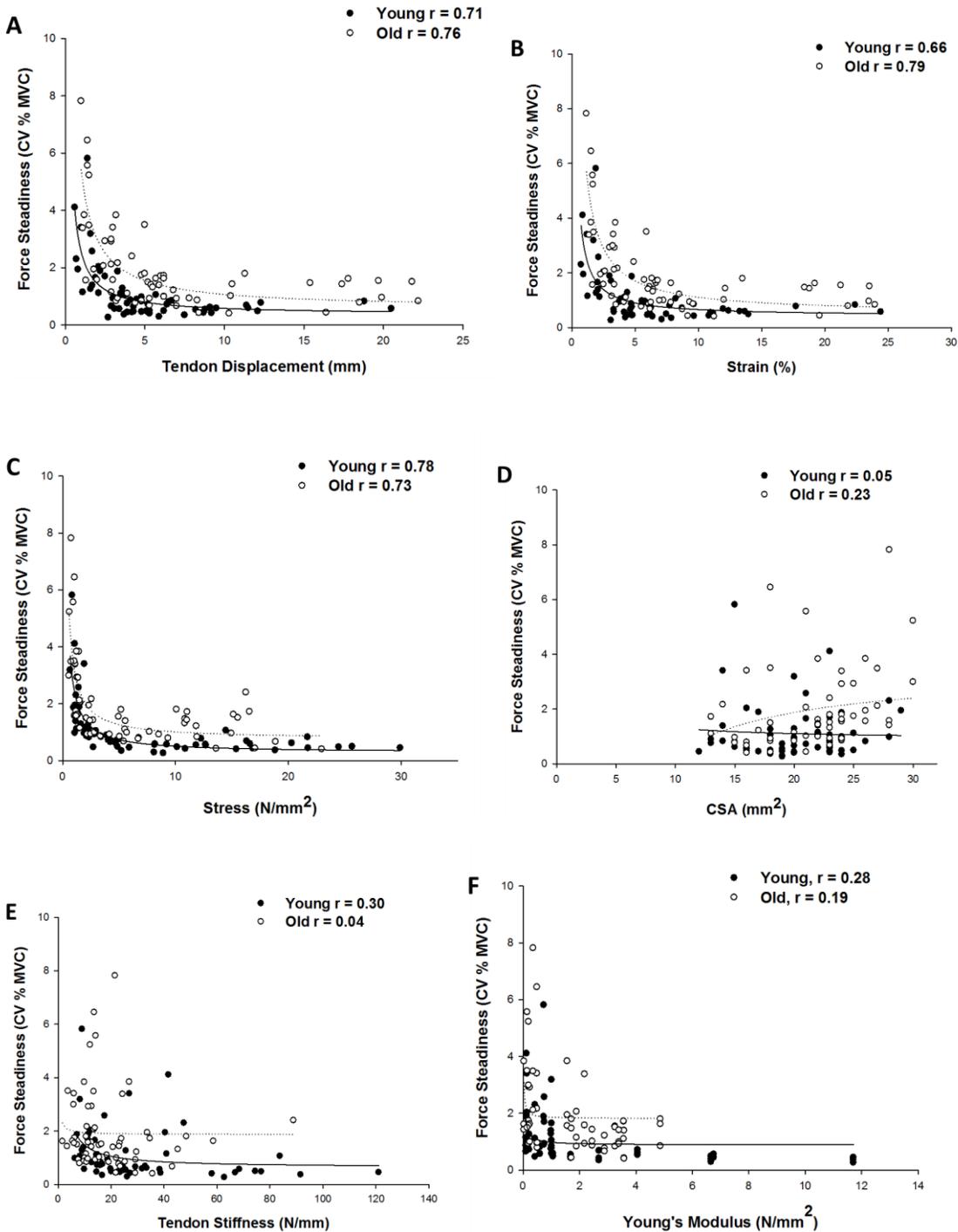


Figure 4.4: Relationship of force steadiness with tendon properties. There was a significant relationship for young and old between with tendon displacement (A) Strain (B) and stress (C). However there was no significant relationship observed between force steadiness and CSA (D) stiffness (E), and Young's modulus (D). CV, coefficient of variation; %, percentage; MVC, maximal voluntary contraction.

Chapter 5: Discussion

The purpose of this study was to examine the effect of tendon properties on FS in young and old males during sustained isometric elbow flexion across a range of force levels. The main findings of the study were that: a) Young were stronger than old; b) Young were steadier than old across all force levels; c) Force steadiness decreased as force increased and then showed the typical increase in CV at higher force levels; d) Mechanical properties of tendon stiffness, and Young's Modulus approached significance between young and old males; and e) Tendon displacement, strain, and stress were moderately correlated with force steadiness. Although, tendon stiffness and Young's Modulus did not have a strong relationship. Hence, BB tendon mechanical properties contribute to the variability in force steadiness between submaximal contractions but are likely to contribute minimally to the age-related declines in force steadiness.

5.1 Age and Tendon Mechanical Properties

Human elastic properties of tendon *in vivo* have primarily been measured in the lower limbs (Kubo et al., 2006; Magnaris & Paul, 2002; Magnusson et al., 2001). Very few studies have reported tendon properties in the upper limbs but stiffness is generally higher compared with the lower limbs (Murata et al., 2008; Otha et al., 2004). To date, no study has measured tendon mechanical properties of the BB between young and old males.

The present study showed muscle moment was greater in young than old and tendon force ($p = 0.07$, $n^2 = .17$) trended to the same effect. Resting tendon length, tendon displacement and CSA are important elements for strain and stress which define the mechanical properties of the tendon. These elements were lower in old compared with young males; however, statistically they did not show significant differences. Because

tendon displacement did not differ, strain was also non-significant between age groups. Moreover, the non-significant difference in tendon force culminated in stress, Young's modulus, and tendon stiffness also trending toward a difference, albeit not achieving statistical significance.

The present study revealed that MVC force in old was significantly lower than young males. Muscle moment was determined from MVC force and lever arm length. In this study, the lever arm was similar ($p=0.93$), therefore the significant muscle moment differences between age groups resulted from young being stronger than old. Tendon force is an expression of the ratio of muscle moment and moment arm. Moment arm has an influence on tendon force, yet in this study the old and young did not differ in moment arm ($p=0.46$). Hence, tendon force only trended towards significance ($p=0.07$) as a consequence of muscle moment ($p = 0.04$) rather than moment arm.

CSA is an important parameter of tendon stress. Tendon stress (measured in newton per square metre) can be expressed as the force transmitted to the tendon during loading divided by its CSA. The higher the tendon CSA the lower the stress value and Magnusson et al., (2002) suggested that this might contribute to reducing risk of falls in older males. However, Onambele et al., (2006) reported a smaller tendon CSA in old compared with young and indicated that this occurred due to aging and that this reduction in size would likely increase risk of falls. Carroll et al., (2008) furthered these studies and indicated that tendon stress at peak force was reduced in old adults and that this difference was primarily related to force rather than age. Elbow flexion force in young was significantly higher than old in the present study, but CSA did not differ between age groups, thus stress differed modestly ($p = 0.07$). Thus, in the BB, it is likely that stress is

largely dictated by strength, but the CSA cannot be discounted. These older adults were healthy and active, thus an age-related differences in stress might be evident in inactive older adults. Young's Modulus gives an indication about the tendon's material properties. Aging generally results in lowering Young's Modulus (Onambele et al., 2006) and this trend was also evident in the BB tendon ($p = 0.07$). The current study indicates that morphological characteristics of the tendon between young and old are modestly different; however, further work is required to address the role of healthy active older adults.

Ohta et al., (2004) studied tendon compliance in young males and the maximal displacement and stiffness values for the BB tendon in the present study were lower than previously reported. These authors showed BB tendon displacement increased to 80% of MVC force, however the current study was performed up to 60% of MVC. Therefore, methodology likely contributed to differences between studies. Tendon stiffness depends on both tendon force and tendon displacement. In the quadriceps, tendon deformation and stiffness did not differ between young and old males (Carroll et al., 2008; Cauppe et al., 2009); however, in the same muscle group others reported that tendon stiffness was lower in the old compared with young adults (Karamanidis et al., 2006, 2008). It is interesting that when the quadriceps and triceps surae muscle groups were studied in old and young males that tendon stiffness was lower in the quadriceps but there was no age-related change in triceps surae (Karamanidis et al., 2006). Thus, age-related changes in tendon are not identical across muscle groups. To our knowledge this is the first study to report tendon mechanical properties in the BB across force levels and identify that tendon displacement does not differ between young and old, but tendon stiffness changes

modestly ($p = 0.07$) and this is likely due to the decrease in muscle strength with increasing age.

5.2 Age and Force Steadiness

Motor unit discharge rate and MUDRV are the properties of MU activity that are typically associated with FS. This study did not address MU activity, but previous studies have reported that old adults exhibit lower MUDR (Barry, et al., 2007; Dalton et al., 2010; Kamen, et al, 1995,) and higher MUDRV (Tracy et al., 2005) which may contribute to an age-related decline in FS (Tracy et al., 2005; Patten & Kamen, 2000). These factors appear to be primary contributors to difference in force fluctuations between young and old (Enoka et al., 2003). Muscle weakness is likely also a key factor in decreased FS and increasing strength is likely a primary means to enhance force steadiness (Brown et al., 2010).

This current study reported age-related reduction of FS in old compared with young for the elbow flexors. Limb position (Brown et al., 2010; Harwood et al., 2010) and visuomotor correction (Tracy et al., 2007) can also influence FS. To avoid these limitations the neutral position with identical visual feedback was used in young and old. As well, strong verbal encouragement was given to produce their maximum elbow flexion force (Jakobi & Rice, 2002) and consistent verbal feedback during the steady state tracking tasks. Furthermore, the twitch interpolation technique was used to ensure young and old were achieving true MVC. Voluntary activation did not differ with age, thus the relative forces executed were similar and visual feedback was appropriately matched, thus these did not contribute to the age-related decline in force steadiness.

5.3 Force Steadiness and Mechanical Properties

Similar to prior reports (Enoka et al., 2003) FS increased with force in this study. Tendon stiffness also increased as force increased (Ito et al 1998; Murata et al., 2009) and in the current study tendon mechanical properties also increased with force. Thus, the current study highlights that in addition to FS being dependent upon age, contraction type and intensity (Enoka et al., 2003), tendon mechanical properties also influence the amount of force produced and thereby influence FS.

Force steadiness is a parameter used to measure how the neuromuscular system controls force output. MU activity is one of the key mechanisms of FS (Enoka et al., 2003). Pasquet et al., (2005) reported that MU recruitment and MUDR in the tibialis anterior were related to the compliance of the muscle-tendon complex. These authors suggested that higher MUDRs were observed at the force level below 10% when the muscle-tendon complex was compliant and as force increased from 10 to 35% MVC the tendon became stiffer and recruitment of additional motor units played a dominant role. The present study revealed that FS and tendon mechanical properties such as stress, strain, Young's Modulus, and tendon stiffness increased as the force increased from 2.5 to 60% MVC. Furthermore, tendon displacement, strain and stress showed moderately strong correlation with FS for both young and old.

In conclusion, Tendon force, stress, Young's Modulus, and tendon stiffness were modestly, albeit not statistically different between young and old. Steadiness was less in old compared with young for isometric elbow flexion at a range of force levels between 2.5% to 60%. Tendon mechanical properties and FS differed across all force levels, therefore, mechanical properties of the tendon influenced FS across submaximal forces.

This influence was primarily evident for tendon displacement, strain and stress which showed moderately strong correlation with FS for both young and old males. It is likely that tendon mechanical properties is one of the factors related to differences in steadiness, but likely contributes only at a minor level to age-related differences in healthy and active young and old males.

Chapter 6: Conclusions and Recommendation

6.1 Conclusions

The objectives of this study were met. The hypothesis that young males were stronger than old males was confirmed. Force steadiness and tendon mechanical properties of the BB were recorded from young males and old males during different levels of sustained isometric contractions. The hypothesis that old males would be less steady than young males was confirmed, but the old did not have a significantly more compliant tendon than young males, albeit this finding trended towards significance. The relationship between FS and tendon mechanical properties of the elbow flexors in young males and old males was established. Although tendon stiffness did not statistically differ between young and old there was a strong moderate correlation with displacement, strain, and stress for both young and old males in relation to FS which highlights that tendon properties do impact FS.

6.2 Implications

These results have important implications for understanding the mechanical properties of tendons and might elucidate underlying factors contributing to FS decreasing with increasing age. It is evident from prior work (Brown et al., 2010) as well as the current investigation that strength occupies a primary role in FS and this is likely in-part due to tendon mechanics. Since strength training is a known contributor to enhancing FS (Hortobagyi et al, 2001; Tracy et al., 2004) and tendon stiffness (Reeves et al., 2003) older males should be encouraged to strength train to preserve muscle strength and tendon stiffness as they age and this will enhance force control.

6.3 Strengths and Limitations

Uniqueness of this study is that it is the first to assess FS and tendon mechanical properties between young and old males in the upper limb. Another major strength of this study was the measurement of the tendon mechanical properties which was undertaken by using ultrasound. To make consistent and accurate measurements the US and force systems were time locked for uniformity. The third strength was the inter-rate reliability for US measurements where the coefficient of determination between the assessed values was $r^2=.99$. The fourth strength was the subject exclusion criteria and the effort made to control bias. For example, all subjects were healthy active, right hand dominant, and no special history of resistance training and/or inactivity as resistance training or inactivity has been shown to influence tendon stiffness and FS. All of the subjects in the study were tested in the morning because tendon stiffness decreases from the morning to evening (Pearson & Onambele, 2006). Ethnicity has an effect on tendon compliance (McCarthy et al., 2006; Shahid et al., 2013) therefore, all the subjects were Caucasian to avoid the effect of ethnicity and all measures were undertaken on males to avoid a sex-effect on FS and tendon stiffness.

The sample size is a limitation of this study. Future studies should include a greater number of subjects to strengthen the findings on age-related difference in mechanical properties of the BB tendon. Another limitation was that tendon stiffness was measured for the BB muscle; however, steadiness was measured as elbow flexion force which also includes the contribution of the brachialis and brachioradialis muscles.

6.4 Future Directions

Given that muscle CSA declines more in old females than old males, and if young females are less steady than young males, it is likely that older females will be less steady than old males; therefore, it would be of interest to quantify the BB tendon mechanical properties in relation to force steadiness between old males and females. Because strength is an important predictor of FS, future studies of FS and tendon stiffness should also test young and old males who are matched for strength. This may have functional implications for movement control in the older adults.

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Appendices

Appendix A: Relevant Tendon Mechanical Parameters

		2.5%	5%	10%	20%	40%	60%
CSA	Y	20.40±5.36	21.40±3.66	19.70±4.22	20.40±3.37	19.40±3.95	19.00±3.43
	O	23.90±3.57	23.20±4.26	22.20±4.44	21.40±4.62	19.80±3.71	19.70±4.22
ΔL (mm)	Y	1.22±0.43	3.14±1.14	4.14±0.93	5.35±1.54	8.43±5.19	9.11±4.62
	O	1.86±0.81	4.69±4.84	5.41±4.58	7.43±4.83	10.44±6.12	10.95±6.24
Strain (%)	Y	1.47±0.54	3.81±1.39	5.06±1.50	6.51±2.10	10.26±6.30	11.12±5.82
	O	2.14±0.88	5.31±5.20	6.17±4.93	8.52±5.19	12.02±6.83	12.62±7.01
Stress (N/mm²)	Y	1.37±0.54	1.46±0.37	3.24±1.00	6.15±1.73	13.16±4.32	19.86±5.56
	O	1.14±0.30	1.11±0.28	2.33±0.64	4.84±1.22	10.29±2.26	15.69±3.94
YM (N/mm²)	Y	1.06±0.50	0.43±0.16	0.69±0.29	1.13±0.75	1.94±1.54	2.46±1.76
	O	0.58±0.17	0.32±0.19	0.52±0.29	0.71±0.37	1.08±0.53	1.60±0.90
Stiffness (N/mm)	Y	26.77±15.20	10.46±2.83	15.55±5.59	26.05±14.78	41.24±27.55	53.21±33.85
	O	16.02±5.93	8.89±6.33	13.25±8.43	16.39±6.66	24.83±13.66	36.30±23.04

Values are means ± SD; CSA, cross sectional area; ΔL, displacement; YM, young's modulus; mm, millimeter. Y, young; O, old.

Appendix B: Ethics Approval



The University of British Columbia Okanagan
 Research Services
 Behavioural Research Ethics Board
 3333 University Way
 Kelowna, BC V1V 1V7 Phone: 250-807-8832
 Fax: 250-807-8438

CERTIFICATE OF APPROVAL - MINIMAL RISK

PRINCIPAL INVESTIGATOR: Jennifer M. Jakobi	INSTITUTION / DEPARTMENT: UBC/UBCO Health & Social Development/UBCO Health and Exercise Sciences	UBC BREB NUMBER: H14-00165				
INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUT:						
<table border="1"> <thead> <tr> <th>Institution</th> <th>Site</th> </tr> </thead> <tbody> <tr> <td>UBC</td> <td>Okanagan</td> </tr> </tbody> </table>		Institution	Site	UBC	Okanagan	
Institution	Site					
UBC	Okanagan					
CO-INVESTIGATOR(S): Afruna Lizu Sharmin Arefin						
SPONSORING AGENCIES: Natural Sciences and Engineering Research Council of Canada (NSERC) - "Spinal Network Adaptability for the Control of Steady Contractions in Men and Women" UBCO Internal Research Funds - "Evaluation of Muscle Length: Technical Advancement in Ultrasound Imaging"						
PROJECT TITLE: A differential comparison of muscular architecture and tendon between sexes and across ages in the assessment of force control.						

CERTIFICATE EXPIRY DATE: March 5, 2016

DOCUMENTS INCLUDED IN THIS APPROVAL:	DATE APPROVED: March 5, 2015	
Document Name	Version	Date
Protocol: Arefin Proposal	01	January 1, 2015
Consent Forms: Consent Form	2	March 4, 2015
Questionnaire, Questionnaire Cover Letter, Tests: Lifetime PA Questionnaire	01	January 30, 2015
Health Questionnaire	01	February 23, 2015
Letter of Initial Contact: Initial Contact _ March 2015	V2	March 4, 2015

The application for ethical review and the document(s) listed above have been reviewed and the procedures were found to be acceptable on ethical grounds for research involving human subjects.

This study has been approved either by the full Behavioural REB of the UBC Okanagan or by an authorized delegated reviewer

Appendix C: Consent Form

THE UNIVERSITY OF BRITISH COLUMBIA | OKANAGAN



Faculty of Health and Social Development
3333 University Way
Kelowna, BC Canada V1V 1V7
Phone: 250-807-9906
Fax: (250) 807 – 9865

LETTER OF CONSENT Force Steadiness and Muscle Architecture

Principal Investigator:

Dr. Jennifer Jakobi, PhD, Associate Professor Health and Exercise Sciences, UBC Okanagan. *Ph:* 250.807.9884; *Email:* jennifer.jakobi@ubc.ca

Co-Investigators

Sharmin Arefin, MSc Student, Interdisciplinary Graduate Studies Health and Exercise Sciences, UBC Okanagan *Ph:* 250-807-9190;
sharmin.arefin@yahoo.com

Afruna Lizu, MSc Student, Interdisciplinary Graduate Studies Health and Exercise Sciences, UBC Okanagan *Ph:* 250-807-9190; afrunalizu@gmail.com

You are being invited to participate in a research study looking at force steadiness and muscle and tendon architecture (anatomy). You must be healthy and between the age of 19-90 years. The purpose of this letter is to provide you with the information you need to make an informed decision about participating in this research.

Voluntary participation and other pertinent information

Your participation in this study is completely voluntary. Should you choose to participate, you will be required to sign the consent form at the end of this information material. However, ***you are free to withdraw from this study at any point in time*** if you wish to discontinue your participation without providing any reasons.

This information will provide you with all necessary facts regarding the study, so please review it with care before you decide if you are going to participate or not.

If you choose not to participate in this study, you will not be penalized in any way, nor do you need to disclose why you have chosen not to participate.

You should only agree to participate if you feel happy that you know enough about the study. If you are participating in another study at this time, please inform the lead study investigator to determine if your participation in this study is appropriate.

Background Information

Ultrasonography is a non-invasive procedure used to measure muscle and tendon structures by taking 'pictures' through the skin. This investigation will use Ultrasound to measure changes in the muscle and tendon in healthy persons during stretching and force producing movements. While your muscle and tendon are measured you will be producing force over a variety of force levels that range from low forces to your best efforts. The measures will be made over a course of 60-120 minutes. The time varies between participants as some images are gathered quickly and others vary between persons anatomy and take longer to record.

Purpose of this study

The aim of this research study is to determine the effect of muscle and tendon architecture on force production and whether this differs in males and females across age.

Who can participate?

If you are a healthy male or female between the ages of 19 and 90 years old, you are welcome to participate in this study. You must be able to speak and read English fluently.

Who should not participate?

You should not participate in this study if you are: (1) Unable to ambulate independently, even with the help of a walking-aid; (2) You have severe cognitive impairment or (3) a neurological disorder; (4) You are unable to read or speak English fluently; (5) You have now, or have previously had major orthopedic surgery.

Procedure for this study

Should you choose to participate in this study, your participation would involve;

completing questionnaires investigating your health and physical activity; performing maximal voluntary contractions and submaximal contractions. Ultrasound will be used to collect data during the duration of this study. This assessment is approximately 60-120minutes or you can visit over a number of occasions for shorter duration.

1. You will come to the Neuromuscular Physiology Lab in Arts and Science 164 at a predetermined time. Upon arrival you will do a health history and physical activity questionnaire. You do not have to answer any questions that you are uncomfortable answering.
2. The graduate student will take initial measurements of your muscle and tendon using ultrasound.
3. The graduate student will operate the dynamometers to record force.
4. The ultrasound will be record throughout the force efforts.

Your responsibilities

It is important that you come to the lab dressed in appropriate clothing. Wearing shorts or loose pants and t-shirts are ideal for comfort. Also, please refrain from exercising the day of testing as it could have an effect on the results of the study.

Risks and discomforts of participation

The risks associated with the proposed research are minimal. Minimal muscle soreness may result from maximal voluntary contractions.

Associated benefits of participation

There are no direct benefits to you, except the results of an assessment of your muscles and tendons.

Results could provide information useful to understanding why force control decreases with increasing age between males and females.

Will I be paid or do I have to pay to participate?

You will not be paid for participating and there is no financial cost to your participation in the described experiments. However, any incurred parking and travel expenses as a result of your participation in this study will be reimbursed, provided receipts are submitted to a member of the research team. **You are free to withdraw from the experiment at any point in time. You do not have to provide a reason for withdrawing from the study if you do not wish to do so**

What to do if you want to withdraw from this study:

Participation in this study is voluntary. You have the right to refuse to participate, refuse to answer any questions or withdraw from the study at any time with no effect on your future (care/academic status/employment). You do not have to provide any reasons to do so. If you choose to enter the study and then decide to withdraw at a later time, all data collected about you during your enrolment in the study will be retained for analysis. This data is to be used for MSc thesis work, which will become a publicly accessible document. No individual will be disclosed in this document and there are no identifiers of person. Data not used in the publication(s) are kept on file, with all data, for approximately 5-years which approximates the funding cycle.

What happens if something goes wrong during the study?

Any adverse event that should arise will be followed-up thoroughly to ensure your safety and health. Background health history and functional assessment parameters will be collected and stored on a computer, while any clinical symptoms will be recorded in the Investigator's laboratory book. All data arising from this study will be archived and stored securely by the Investigators through password protected computer systems and remain confidential. You do not waive any legal rights by signing the consent form.

The researchers of this study will be readily available if you would like to discuss any problems or concerns that may arise. Following completion of the project you will be provided with a feedback sheet explaining the outcomes and any substantive findings.

Can I be asked to leave the study?

If you do not adhere to the study guidelines outlined earlier in this study, you will be asked to leave the study. Also, in the rare event that a medical emergency occurs during the study, you will be automatically withdrawn from the study to ensure your safety and well-being.

After this study is complete:

Results of this project may be published as part of a manuscript, and will be in-part included in graduate student (Sharmin Arefin, Afruna Lizu) theses. Thesis documents are publicly available on the internet. No data will be linked to a specific participant. Your data will be assigned a personal identification number to ensure anonymity in both the analysis and documentation of results. The raw data obtained in this study will only be available to the principle investigator (Dr. Jakobi). As stated earlier, you will be provided with a feedback sheet explaining the outcomes and specific findings of this study.

Privacy and confidentiality

Your confidentiality will be respected. No information that discloses your identity will be released or published without your explicit consent to the disclosure.

However, research records and medical records identifying you may be inspected in the presence of the Investigator or his or her designate by representatives the UBC Behavioural Research Ethics Board for the purpose of monitoring the research. However, no records which identify you by name or initials will be allowed to leave the Investigators' offices.

Personal descriptors (i.e. names) will be coded to a numeric value and data will be kept in a locked cabinet in ASC 164 at the University of British Columbia Okanagan. The data will be made available only to members of the research team, and destroyed in 5 years. The master copy will be stored separate from the coded data in ASC 164 at the University of British Columbia Okanagan.

If you have any concerns about your rights as a research participant and/or your experiences while participating in this study you may contact the Research Participant Complaint Line in the UBC Office of Research Services at 1-877-822-8598 or the UBC Okanagan Research Services Office at 250-807-8832. It is also possible to contact the Research Participant Complaint Line by email (RSIL@ors.ubc.ca).

CONSENT FORM FOR PARTICIPANTS

I have read and understand the information sheet concerning this project. All my questions have been answered to my satisfaction. I understand that I am free to request further information at any stage. I know that:

1. My participation in the project is entirely voluntary, and I am free to withdraw from this study at any time without any disadvantage.
2. The data on which the results of the project depend will be retained in secure storage for five years, after which they will be destroyed.
3. I will be required to complete initial assessments and the protocol of approximately 2-hour in duration.
4. The experimental session will involve the following measurements:
 - Demographic & health history questionnaires, physical activity questionnaires, and measures of strength by performing maximal voluntary contractions.
 - Assessment of tendon and muscular changes as well as force.
5. The results of the project will be published as part of a thesis and may be published as part of a manuscript and will be available in the University of British Columbia Okanagan Library but every attempt will be made to preserve anonymity.
6. I will receive a signed and dated copy of this consent form.

I agree to take part in this project

..... Printed
name of Subject

..... Signature
Date

..... Printed
name of principal investigator

..... Signature
Date

Appendix D: Health History Form

General Information

Participant:

CODE: _____

Sex:

Male Female

Occupation:

Position _____ Employer _____

Address _____

Phone _____

Present Health History

Check those questions to which you answer yes (leave the others blank).

Has a doctor ever said your blood pressure was too high?

Do you ever have pain in your chest or heart?

Are your ankles often badly swollen?

Do cold hands or feet trouble you even in hot weather?

Do you suffer from frequent cramps in your legs?

Do you get out of breath long before anyone else?

Have you ever had a joint surgery?

Comments: _____

Do you now have or have you recently experienced:

Swollen or painful knees or ankles?

Swollen, stiff or painful joints?

Pain in your legs after walking short distances?

Foot problems?

Back problems?

Significant vision or hearing problems?

Significant unexplained weight loss?

A deep vein thrombosis (blood clot)?

A hernia that is causing symptoms?

Persistent pain or problems walking after you have fallen?

Women only answer the following. These questions are asked as hormones influence muscle force, thus we account for hormones in our statistical analysis. Do you have:

Experienced or are undergoing Menopause?
Are you on any type of hormone replacement therapy?
Are you on any type of birth control?

Comments: _____

Men and women answer the following:

List any prescription medications you are now taking: _____

List any self-prescribed medications, dietary supplements, or vitamins you are now taking: _____

Date of last complete physical examination: _____

- Normal Abnormal Never Can't remember

Date of last chest X-ray: _____

- Normal Abnormal Never Can't remember

Date of last electrocardiogram (EKG or ECG): _____

- Normal Abnormal Never Can't remember

Date of last dental check up: _____

- Normal Abnormal Never Can't remember

List any other medical or diagnostic test you have had in the past two years: _____

List hospitalizations, including dates of and reasons for hospitalization: _____

List any drug allergies: _____

Past Medical History

Check those questions to which your answer is yes (leave others blank).

- Heart attack if so, how many years ago? _____
- Rheumatic Fever
- Heart murmur
- Diseases of the arteries
- Varicose veins
- Arthritis of legs or arms
- Diabetes or abnormal blood-sugar tests
- Phlebitis (inflammation of a vein)
- Dizziness or fainting spells
- Epilepsy or seizures
- Stroke
- Diphtheria
- Scarlet Fever
- Infectious mononucleosis
- Nervous or emotional problems
- Anemia
- Thyroid problems
- Pneumonia
- Bronchitis
- Asthma
- Abnormal chest X-ray
- Other lung disease
- Injuries to back, arms, legs or joint
- Broken bones
- Jaundice or gall bladder problems

Comments: _____

Family Medical History

Father:

Alive Current age _____

My father's general health is:

Excellent Good Fair Poor

Reason for poor health: _____

Deceased Age at death _____

Cause of death: _____

Mother:

Alive Current age _____

My mother's general health is:

Excellent Good Fair Poor

Reason for poor health: _____

Deceased Age at death _____

Cause of death: _____

Siblings:

Number of brothers _____ Number of sisters _____ Age range _____

Health problems _____

Familial Diseases

Have you or your blood relatives had any of the following (include grandparents, aunts and uncles, but exclude cousins, relatives by marriage and half-relatives)?

Check those to which the answer is yes (leave other blank).

- Heart attacks under age 50
- Strokes under age 50
- High blood pressure
- Elevated cholesterol
- Diabetes
- Asthma or hay fever
- Congenital heart disease (existing at birth but not hereditary)
- Heart operations
- Glaucoma
- Obesity (20 or more pounds overweight)
- Leukemia or cancer under age 60

Comments: _____

Other Heart Disease Risk Factors

Smoking

Have you ever smoked cigarettes, cigars or a pipe?

Yes No

(If no, skip to diet section)

If you did or now smoke cigarettes, how many per day? _____ Age started _____

If you did or now smoke cigars, how many per day? _____ Age started _____

If you did or now smoke a pipe, how many pipefuls a day? _____ Age started _____

If you have stopped smoking, when was it? _____

If you now smoke, how long ago did you start? _____

Diet

What do you consider a good weight for yourself? _____

What is the most you have ever weighed (including when pregnant)? _____

How old were you? _____

My current weight is: _____

One year ago my weight was: _____

At age 21 my weight was: _____

Number of meals you usually eat per day: _____

Number of times per week you usually eat the following:

Beef _____ Fish _____ Desserts _____

Pork _____ Fowl _____ Fried Foods _____

Number of servings (cups, glasses, or containers) per week you usually consume of:

Homogenized (whole) milk _____ Buttermilk _____ Skim (nonfat) milk _____

2% (low-fat) milk _____ 1% (low-fat) milk _____ Coffee _____

Tea (iced or not) _____ Regular or diet sodas _____ Glasses of water _____

Do you ever drink alcoholic beverages?

- Yes No

If yes, what is your approximate intake of these beverages?

Beer:

- None Occasional Often If often, _____ per week

Wine:

- None Occasional Often If often, _____ per week

Hard Liquor:

- None Occasional Often If often, _____ per week

At any time in the past, were you a heavy drinker (consumption of six ounces of hard liquor per day or more)?

- Yes No

Comments: _____

Do you usually use oil or margarine in place of high cholesterol shortening or butter?

- Yes No

Do you usually abstain from extra sugar usage?

- Yes No

Do you usually add salt at the table?

- Yes No

Do you eat differently on weekends as compared to weekdays?

- Yes No

Comments: _____

Appendix E: The Lifetime Total Physical Activity Questionnaire

Description of Occupational Activity	Age Started	Age Ended	No. of Months/Year	No. of Days/Week	Time/Day		Intensity of Activity (1, 2, 3, 4)*
					Hours	Minutes	
1.							
2.							
3.							
4.							
5.							
6.							
7.							

Description of Exercise/Sports Activities	Age Started	Age Ended	No. of Months/Year	No. of Days/Week	Time/Day		Intensity of Activity (1,2, 3, 4)*
					Hours	Minutes	
1.							
2.							

3.							
4.							
5.							
6.							
7.							
8.							

Description of Household Activities	Age Started	Age Ended	No. of Months/Year	No. of Days/Week	Time/Day		Intensity of Activity (1,2, 3, 4)*
					Hours	Minutes	
1.							
2.							
3.							
4.							
5.							

6.							
7.							

*Intensity of activity

1. Activities that are done sitting. Only include activities in this category for the occupational chart.
2. Activities that require minimal effort
3. Activities that are not exhausting, that increase heart rate slightly and may cause some light perspiration.
4. Activities that increase heart rate and cause heavy sweating.