DETERMINATION OF STRUCTURAL AND FUNCTIONAL
THIGH MUSCLE PROPERTIES
IN A HEALTHY OLDER POPULATION
USING MRI AND ISOKINETIC DYNAMOMETRY

by

KAREN PAMELA RUTH VETTER

B. Sc (Biochemistry) The University of British Columbia, 1997
B. Sc (PT) The University of British Columbia, 2000

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Background: No consistent findings have been reported regarding the relationship between aging muscle size and strength. This may be due to the use of an inaccurate method of muscle quantification, anatomical cross-sectional area, and a limited study of muscle group and contraction type. There is little normative data on thigh muscle size and strength, or the nature of relationships among muscle groups of the thigh in a healthy older population.

Purpose: 1) To determine the relationship between muscle volume (MV) of the knee flexors, knee extensors, and hip abductors, and their associated muscle strength and fatigue. 2) To investigate the reliability and validity of stereology to determine MV, and to establish the reliability of a protocol to measure hamstring muscle fatigue. 3) To investigate thigh circumference, and determine whether or not it is representative of MV and/or strength. 4) To establish normative strength ratios for this population.

Subjects: Healthy older males and females, 51-80 years old.

Methods: MV was calculated from MRI's of the subject's legs, using stereology. Isokinetic and isometric strength was measured on the Kin-Com Dynamometer, and muscle fatigue was measured using EMG during an 80% maximum voluntary contraction (MVC). Thigh circumference was determined using a Lufkin steel tape measure.

Results: Average MV was \(1529.57 \pm 500.54\) \(\text{cm}^3\) for the quadriceps, \(776.46 \pm 231.65\) \(\text{cm}^3\) for the adductors, and \(613.59 \pm 159.73\) \(\text{cm}^3\) for the hamstrings. All three muscle groups showed a good to excellent relationship between MV and strength \((r=0.76-0.91)\). Thigh circumference measures at 10 cm had a strong relationship with size \((r=0.55-\)
0.72) and strength (r=0.93) of all muscle groups. Isometric strength ratios were 0.41 for hamstring : quadriceps, and 0.37 for adductor : hamstrings, where MV ratios were 0.51 and 1.03 respectively. The hamstring : quadriceps endurance time ratio was 1.74.

**Conclusions:** The reliability of using stereology to measure MV of the thigh muscles was established, showing strong relationships between thigh muscle size and strength. Muscle strength ratios, and the evidence supporting thigh circumference measures at proximal sites on the thigh to represent functional muscle groups, will assist therapists in the treatment of healthy older adults.
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INTRODUCTION

The profession of physiotherapy relies on visible macroscopic, functional muscle properties, (i.e. muscle strength, range of motion, thigh circumference measurements), in order to make inferences regarding the state of the physiology of the muscle (64). However, the assumptions currently being made regarding the functional properties of the muscle and how they relate to the structural properties of the muscle may not be correct. The size of the muscle may not be directly related to its strength or endurance, and the increase in thigh circumference measured during a rehabilitation program may not be indicative of corresponding gains in strength or function (41). One of the ways in which evidence-based practice in the profession of physiotherapy can be strengthened is if a better understanding of the relationship between functional muscle properties and muscle physiology is established.

One of the primary goals of physiotherapy is to increase an individual’s level of function in order to maintain or increase their independence, thereby improving their quality of life (47). A goal that is achieved through specific exercises or activities aimed at increasing muscular strength and/or endurance. However, without a good understanding of what is occurring within the muscle, physiotherapy assessment and treatment cannot be effective. It has been shown that the strength loss that occurs throughout the aging process is strongly associated with functional losses in the elderly, with a decline in health (16, 18, 25, 42). This implies that if therapists are able to at least maintain, or increase the strength, of older individuals, that this would translate into functional gains, and the independence of these individuals would be preserved (16, 51, 52). Understanding the mechanisms behind the loss of strength that occurs during the aging process is the precursor to designing effective rehabilitation programs for the elderly.
Closely linked with the development of rehabilitation programs is the assessment of the strength of individuals. Establishing a data base of normative strength values, muscle volumes, and strength ratios, (hamstring : quadriceps, adductor : hamstrings), among major muscle groups of the thigh, (knee flexors, knee extensors, hip adductors) would be a valuable reference for future research as well as for physiotherapists involved in designing rehabilitation programs for older individuals (5). Establishing expected normative strength ratios would also assist in injury prevention (9, 93). Understanding the balance of muscle strength across the hip and knee joint in an older population would assist therapists and therefore patients in preserving this dynamic stability and therefore preserving overall function (93). Relating strength measurements and muscle volume to a commonly used clinical measure would further enable therapists to make accurate assumptions as to the meaning of functional muscle properties.

Despite the general understanding that as we age strength decreases and function declines, increasing one's independence on others and likely decreasing one's quality of life, there is little consensus on the consequences of aging on muscle structure and function, and a limited amount of normative data on muscle size, strength, and ratios of key thigh muscle groups (5). Only one study was found that investigated the normal hamstring : quadriceps ratio in healthy older adults (73), and only one group of researchers has begun to investigate an adductor : hamstring ratio, providing levels which may indicate different stages of medial compartment knee osteoarthritis (OA) (105). No studies were found that had investigated thigh circumference, a commonly used clinical measure, on an older population. Finally, the numerous studies that do report on the correlation between size and strength of aging muscle, quantify the contractile tissue using anatomical cross-sectional area (ACSA), a method that has found to be misrepresentative of the contractile tissue size in muscles with any degree of fiber pennation (32, 75, 77). A greater amount of research in the area of aging muscle needs to be done, with careful attention being paid to the method of muscle quantification, and the range of
muscles that are being studied. Physiotherapists need more information on aging muscle to more effectively treat older individuals.

LITERATURE REVIEW

1. Aging Muscle

a. Relationship between structural and functional properties of aging muscle

It has been well established that the amount of force a muscle can generate is related to its size, yet the exact nature of this relationship, and how this relationship changes as we age remains unclear (56). In younger individuals, the majority of studies found seem to support a strong, positive correlation between muscle size and strength (7, 14, 37, 66). In 1997, Arangio and colleagues found a positive correlation between Magnetic Resonance Imaging (MRI) cross-sectional area (CSA) and quadriceps and hamstring peak torque in both involved and uninvolved extremities in individuals after ACL reconstruction (7). Harridge et al in 1999 found that maximum voluntary force was closely related to quadriceps lean CSA – (an attempt to remove non-contractile tissue) (37). Masuda et al in 2003 found a significant relationship between CSA of knee flexors, extensors, hip extensors and flexors and their associated isokinetic strength in well trained soccer players (66).

The discrepancy in the literature becomes more apparent as we look at aging muscle (62). In general, it is well documented that a loss of muscle strength occurs as human’s age (5, 10, 11, 37, 53, 70), yet the mechanisms contributing to the loss of force remain unclear. While some studies support the hypothesis that a loss in muscle size, or CSA, is primarily responsible for the loss in muscle strength (5, 16, 30, 84, 98, 106), other researchers have found that the loss in muscle tissue can not fully account for the strength losses that they have observed (14, 36, 37, 43, 46, 53, 70, 81).

Metter et al, looked at creatine excretion levels and fat free mass and found that muscle mass alone does not explain the age effect on muscle strength (70). Hakkinen and colleagues
argued that despite correlations between decreases in isometric leg strength, and decreases in CSA, there are aspects of muscle function, such as explosiveness, that decline with aging, and the reasons for this decline are multifactorial and cannot be completely explained by changes in cross-sectional area (36, 70). Overend et al in 1992, while studying 13 young (19-34 yrs), and 12 elderly (65-77 yrs) men, determined that there was a loss of strength that was greater then could be accounted for by the decrease in CSA (81). The decrease in isometric strength could be accounted for by the loss of muscle mass, however the decrease in concentric strength was greater then the decrease in muscle CSA (81). Researchers speculate that the strength loss may also be due to additional factors such as; the ability to recruit motor units, increased presence of non-contractile tissue, increase in co-activation of antagonist muscles (62), and perhaps a change in the intrinsic properties of the muscle such as fiber type and pennation angle (49, 75).

Specific tension or strength (amount of force or torque per unit of muscle mass) has also been investigated, and used, as possibly a more appropriate alternative for the description of muscle (16, 36, 46). However the debate continues and conflicting findings are present in the literature. Some studies show that as we age, there is a decrease in specific strength (5, 21, 43, 84, 107) while others report no change, or that an increase in specific strength was observed (16, 21, 36, 46).

Therefore, despite evidence of a loss of muscle mass (atrophy) and muscle strength in older individuals (84, 89, 97), we still do not have a clear understanding of the mechanisms behind the strength loss, and therefore are not closer to being able to design and implement more effective rehabilitation program for this age group.
b. Factors leading to inconsistencies in literature surrounding aging muscle

A few researchers have commented on the possible reasons for the variability of findings noted above, suggesting that no consensus can be reached as there are too many variables that are not standardized among research groups (16, 37). Individuals are studying different muscles, different contraction types, using different units for force, and are looking at subjects with different age groups, and different activity levels (37). Some researchers have begun to distinguish between muscle groups and muscle actions, noting that a general trend is not evident, and that losses in strength vary depending on the muscle action studies (58, 61, 81). Other researchers have noted the importance of investigating all muscles that contribute to a particular action at a joint, and not only focusing on the relationship between strength and volume of the prime mover (81, 84). However the most important factor that may be at the core of the controversies of the relationship between size and strength of aging muscle is the method used to quantify muscle tissue (33, 58, 70, 83).

Numerous methods have been employed over the years to quantify muscle tissue. These methods have ranged from more systematic/global methods of determining fat free mass (FFM), such as dual-energy x-ray absorptiometry (DEXA), 24hr creatine excretion, hydrostatic weighing, and bioelectrical impedance, to more specific imaging techniques such as MRI, computed tomography (CT) scan, and Ultrasound, that allow quantification of a particular muscle's size, by determining either ACSA, PCSA, or MV from the images obtained (30, 36, 58, 61, 70, 81, 84, 96, 97, 107). Despite the precise imaging methods being used to assess muscle quantity, particularly MRI, the controversies regarding the relationship of muscle size to strength remain (62). Perhaps, as some researchers have identified (58, 70), it is not the imaging techniques, but the way in which the muscle is being measured from the image that is the problem. Anatomical cross-sectional area (ACSA), which is currently being used throughout the literature as a means of muscle quantification, does not accurately reflect the amount of force
producing tissue available, particularly in pennate muscles, where the fibers run at an angle to
the line of force of the muscle (30, 32, 67, 75, 77). Therefore, in order to detect subtle changes
in the intrinsic properties of aged muscle, something other then ACSA needs to be used to
quantify muscle (75).

There needs to be a more accurate measure of regional muscle mass implemented in
the research (84). Not only does ACSA not fully account for the contractile area (size) of the
muscle, but it is being used frequently in research as the primary means of describing muscle
quantity without any standardized protocol in place. Some researchers have used one site on
the thigh to estimate CSA of the quadriceps (5, 36, 107), while others will take several sites
along the thigh and take an average (37, 97), or have chosen the slice with the largest value of
CSA (8, 46). In addition, not all research groups are removing non-contractile tissue, such as fat
and connective tissue, from these measurements, and when they are, the methods themselves
are controversial (60). Removal of these non-contractile components is particularly important in
aging muscle, as they have been shown to increase as human’s age (46, 62). It is evident that
defining the relationship between muscle strength and size of the aging muscle is largely
dependent on the method of muscle size determination used (8). A unit of size that takes into
account the complete area of all of the muscle fibers should be employed.
2. Quantification of Muscle Tissue

a. Definition of Terms

Accurately quantifying the amount of force-producing tissue present in a muscle is the first step in being able to identify and define the relationship between muscle size and the macroscopic, or functional, properties of the muscle. When quantifying muscle, or contractile tissue, three key terms are used in the literature; anatomical cross-sectional area (ACSA), or simply CSA, physiological cross-sectional area (PCSA), and muscle volume (MV), each representing the architectural properties of muscle in a slightly different manner (8, 57). ACSA is defined as the area of muscle cross-section at right angle to the long axis of the limb, (i.e. in the transverse plane), represented in cm$^2$ (37, 62, 96). It is the most commonly used method of defining muscle size, as it is the quickest and easiest measure, and is often used in combination with MRI (5, 43, 46). ACSA does not account for muscle length, muscle fiber length, or pennation angle (fiber angle relative to the force generating axis) (57), and comes closer to, (i.e. corresponds to PCSA), representing all muscle fibers if those fibers are oriented longitudinally, (Figure 1.1A), and are equal in length (31). Fibers that do not run the length of the muscle, (due to length, or angle of pennation) can be missed, (Figure 1.1B), since ACSA only accounts for fibers present in one slice (32, 62). Therefore, muscles whose volume varies down the length of the limb will be misrepresented, resulting in a large error in determining muscle size (30, 32, 96). In addition, often only a few images or slices through the muscle of interest are used, or the largest, or average value of ACSA, is taken as being representative of the size of that particular muscle (37, 82).

PCSA, also expressed in cm$^2$, represents the sum of each of the cross-sectional areas of all of the muscle fibers within the muscle (56, p. 31); therefore it is not represented by one single ACSA. PCSA can be defined as 'the magnitude of muscle fiber area perpendicular to the long axis of the individual muscle fibers multiplied by the cosine of the angle of pennation (26,
101). As it accounts for both the fiber length and pennation angle, or obliquity of muscle fibers, (38), PCSA is directly proportional to the maximum force generating capacity that can be generated by a particular muscle (1, 57).

Finally, MV is a three-dimensional measure of the muscle represented in cm³; hence it represents the muscle in its entirety (8). It is a sum of all of the cross-sectional areas (at each slice of the muscle) multiplied by slice thickness of each slice, and in this manner accounts for all of the tissue in both width and length (96). MV, similar to ACSA, does not reflect pennation angle or fiber length, yet it differs from ACSA as it represents the length of the muscle, giving a more complete picture of the entire muscle mass, rather than looking at one single slice of the muscle (8, 72). It has been noted that given its properties, muscle volume can be considered a way of approximating PCSA (72, 96).

After a comparison of the three means of quantifying muscle, PCSA is the most accurate measure, as it is a direct representation of all of the contractile tissue in a muscle (1, 67). Therefore, PCSA may be the only variable that is able to pick up subtle changes in the intrinsic properties of the muscle, under conditions of exercise or aging (1, 32, 75, 77).

b. Current Research

The most accurate reflection of muscle architecture (arrangement of muscle fibers relative to the axis of force generation), and therefore of quantifying muscle, is PCSA (1, 75, 77). Determining the PCSA of a muscle has historically been achieved through cadaver studies, and microscopic dissection of whole muscles (34), thus not lending it to ease of measurement in clinical trials with healthy participants (101). MV seems to have been passed over as the next best option, as it has historically been seen as being more time consuming (96). As a result, researchers have chosen to quantify muscle by means of ACSA, as it is the quickest and easiest to determine, despite its inability to correctly account for all muscle fiber area (67). It is
understandable that there is a need for a time-efficient method with which to quantify muscle size, however basing the choice solely on this fact is problematic. ACSA is a unit of muscle quantification that cannot properly account for all of the contractile area of the muscle tissue, and therefore should not be used (56, 62).

If strength is to be properly related to muscle size, then the cross-section should be taken at right angles to the muscle fiber, rather than the muscle itself (67). Fukunaga et al in 1992 looked at 12 healthy individuals and showed that the PCSA ranged from two to eight times larger than the maximal ACSA across all muscles (32). They also demonstrated that the ACSA of each muscle of the lower limb differed with respect to a given location along the leg (32). This demonstrates the non-inclusive nature of ACSA, as well as the error in using a single slice, or the largest slice, to estimate ACSA. Given their findings, Fukunaga et al felt that functional properties of muscle can not be predicted from ACSA measurements (32). Willan et al in 2002 also identified that there is a clear difference in ACSA of muscle when taken at different points on the thigh (102). ACSA of the upper levels were found to be 12-20% greater than those at the lower levels, which again highlights the issue that one single slice at right angles to the muscle can not possibly be representative of that muscle's size at it is location dependent (102).

Given the inclusive nature of MV versus the single slice used in the determination of muscle ACSA, one would hypothesize that MV would be the more accurate measure, and some studies have used this to quantify muscle (2, 4, 91, 97). Gadeberg et al 1999 did in fact find a stronger relationship between MV and power than ACSA and power in the leg muscles of healthy adults (33). Tracy et al assumed that few researchers were using MV, (or averaging ACSA over many slices), due to investigator time required to digitize many muscle cross-sections on a large number of subjects, therefore they attempted to solve the problem (96). Tracy et al, being strong supporters of using MV due to its ability to more closely approximate PCSA as opposed to ACSA, determined the maximum tolerable distance between axial slices, while maintaining a reasonable error when measuring MV from MRI (96). They determined that
investigators did not need to analyze each slice from the MRI, that as long as the maximum distance between axial slices was 3.1mm, the error was acceptable (96). In this present study, a more accurate and even less time-consuming method of muscle volume determination is proposed as an alternative to that established by Tracy et al. The method of stereology and how it can be applied to MRI images in an efficient, valid, and reliable manner as a means of muscle volume determination will be discussed in later sections (65, 87, 100).

Using MV to calculate PCSA would be the next most logical step, as PCSA remains the most appropriate means with which to quantify muscle (67). A formula engineered by Edgerton and colleagues, shows the relationship between muscle volume and the architecture of the muscle fibers as (26): \( \text{PCSA} = \frac{\text{volume} \times \cos(\text{pennation angle})}{\text{fiber length}} \). This formula states that the PCSA of a muscle is proportional to its volume multiplied by the ratio of its fiber pennation angle to its fiber length (26). Since it is stated by Lieber that 'the architecture of a given muscle is extremely consistent between individuals of the same species' (56, p. 1647-1648, 57), using predetermined fiber lengths and pennation angles in combination with muscle volume in the above mentioned formula, would allow for an estimate of PCSA. As highlighted by Lieber 2000, this equation is important to understand normal muscle, and to make valid estimates of PCSA in human studies in which the attempt is to evaluate performance in a physiological context (56, p. 31, 57). This equation was used in a study by Bamman et al in their investigation to determine PCSA (8), and by Akima and colleagues in 2003 in their investigation of the effects of resistance training during un-weighting and whether it maintained muscle size and function (4). The idea proposed was that combining a measure of MV with the nature of fiber orientation, and fiber length, from standardized tables, would result in the most accurate estimation of the size of the muscle, as it would reflect all of the structural properties of muscle (26, 90). It is the measure of PCSA which tells the most about muscle structure that should be correlated with functional properties (1, 32, 75).
However, despite statements from Lieber that the architectural properties of muscle are valid and are consistent between individuals, researchers now propose that these normative measurements of muscle architecture, determined by cadaveric study, are limited due to errors caused by morphological changes with fixation and other treatment artifacts during investigation, (such as shrinking of muscle fibers) (56, 101). In addition, researchers were unable to study muscles at anything other then resting length (29, 32, 38). Studies have shown that the normative data on fiber pennation angle and fiber length may not be consistent between individuals or exercise conditions (44, 49, 63, 76). Kubo et al and Narici et al in 2003 found a change in the architectural properties of the gastrocnemius muscle with age (49, 75). Other studies have reported that other variables related to exercise, such as contraction type and joint position, can have an effect on pennation angle as well, see Figure 1.2 (44, 63, 76). Therefore when investigating aging muscle, it is apparent that the most accurate determination of muscle quality is to calculate PCSA, using the angle of pennation and fiber length determined specifically for each subject, under each specific exercise condition, combined with measurements of muscle volume (67). However, before this can be achieved, a more efficient and accurate method of determining muscle volume is required.
c. Improving the Accuracy of Muscle Volume Determination

**MRI**

MRI, CT scan, and ultrasound are the imaging techniques commonly used in the quantification of muscle tissue (5, 28, 36, 60, 81, 94, 96, 97). Although CT scan is used more frequently as it is the cheaper option, MRI has several advantages over the other two methods. With MRI the researcher can consistently identify the profile of individual thigh muscles, since the technique allows for detailed imaging of soft tissue structures, as well as superior differentiation (resolution) between bone, connective tissue, and muscle (28). This allows for clear identification of muscles within groups, and of nerves and blood vessels that need to be excluded from the measurement (100). Slice thickness, as well as orientation, can be easily controlled, for example, there is the potential for direct multiplanar imaging with out repositioning the subject (28, 94). MRI has also been found to be very accurate, whereas CT scan has been found to overestimate muscle area by 10-20% (28, 94). Some researchers have even measured fiber pennation angle of the quadriceps femoris from coronal slices, obtained with MRI (77). Finally, MRI is the safer option for subjects, as it offers limited to no exposure to significant amounts of ionizing radiation (28, 60, 94). MRI measures of muscle CSA and subcutaneous and intramuscular adipose tissue have been validated against human cadavers (12, 28, 71).

The limitations of MRI are that it can be expensive, and time consuming for the subjects if images with high resolution are obtained (100). In addition, it requires the researcher analyzing the images to have a definitive knowledge of the CSA anatomy of the thigh (28, 87, 100). At high field strengths, chemical shift artifacts can cause image degradation at the interface of muscle and subcutaneous fat, resulting in misrepresentation of muscle boundaries (86). For the identification of non-contractile tissue, the signal intensity of a given tissue is not absolute, but dependent on pulse sequence characteristics, instrumentation, and object properties (60). Therefore, researchers have to be careful when labeling non-contractile tissue...
based on low pixel intensity alone, since intensity can change depending on the position on the thigh and on the image itself (60).

**Stereology**

Stereology can be defined as the study of estimating geometrical quantities, the most common estimates being quantities in 3-dimensional material (85, 88), and has been used for years as a method to determine precise, unbiased estimates of geometric quantities such as volume and surface area of unknown shape (85). This is of particular importance with skeletal muscle in the extremities, as they are often of irregular, unknown shape (100). These methods are non-empirical, and are design rather than model-based – inherent in their design is an absence of any assumption about the shape of the structure being investigated (35, 85, 88). The formula is designed such that the variables of interest used, the sum of all areas on a particular transect through the object, multiplied by distance between transects, arrive at the true, or real volume of the object. There are no assumptions regarding the shape within the formula (35). For example, when Tracy et al calculated MV, they used a truncated cone formula to arrive at the total volume for each muscle, regardless of shape difference (96). This is assuming that each muscle is shaped like a cone, and is therefore not allowing the true volume of the muscle to be calculated.

The stereological method for estimating the volume of an object is named after Bonaventura Cavalieri who was the first to consider measurement of volume via the analyses of parallel sections through three-dimensional solid objects (65, 85,100). The Cavalieri principle refers to the integration of the measured CSA’s (using stereological methods) of any tissue of interest in the serial slices throughout an object (62). A random systematic sub sample of the whole set of sections is removed, as systematic random sampling yields a lower coefficient of error (COE) than does random sampling for the same amount of effort and is therefore
considered more efficient (33). As described by Walton et al in 1997 and Roberts et al in 2000, the point counting method involves overlying the images entirely with a systematic array of test points, which is laid over the images at consistent intervals (85, 100). The number of occasions on which a point lies with the transect through the structure of interest are counted. The total number of test points counted in all images is then multiplied by the area associated with each point, (correcting for magnification where necessary), and further multiplication by the slice interval gives an unbiased estimate of the muscle volume (85). The calculation looks like this:

$$\text{est}_2V = T(a/p)M^2 (P_1 + P_2 + P_3 \ldots \ldots \ldots \ldots P_m)$$

Where est$_2$V is the unbiased estimate of volume (cm$^3$), T is the distance between sections through the muscle of interest, (a/p) is the test area per test point (cm$^2$), M is the linear magnification in the image, and $P_1 + P_2 + P_3 \ldots \ldots \ldots \ldots P_m$ are the number of occasions on which a test point falls within the defined muscle boundary of the muscle in 1$^{st}$, 2$^{nd}$, 3$^{rd}$, and $m^{th}$ sections, see Figure 1.3 (100). The test system (or grid), must be laid on the images at a uniform random position, see Figure 1.4, as this ensures that the estimator is unbiased (33), and there must be precise rules as to defining whether or not a test point is within a transect, through the structure on the images. By employing a systematic sampling strategy, this method is free from systematic errors (bias) and is extremely efficient (33, 65).

This method has been used to determine the volume of other human tissue, such as the liver, bone, and fat (86, 87, 91), yet given the support for its application, few researchers have used it to determine muscle volume. Roberts et al in 1993 had used the method of stereology with MRI to estimate human body composition (87). Closely to follow was Conley et al in 1995 that used stereology in a more global sense to 'non-invasively characterize the structural and energetic properties of muscle in vivo' (18). In 1997 Walton et al reappeared with Roberts, and were one of the first groups to use stereology to determine the size of an individual muscle, the quadriceps femoris muscle (100). In 1999, Gadeberg et al used stereology to quantify the ankle dorsiflexors and plantar flexors, and was the first to use stereological methods to quantify
muscles for the purpose of investigating the relationship of muscle size to power (33). In 2002, Macaluso et al measured the contractile volume of the knee flexors and extensors of 10 young and 10 older healthy women, using stereological methods (62). Relatively few researchers have utilized this method that is proposed to be a more accurate and more efficient method of muscle volume determination (33, 100). Given the limited use of this method in the quantification of contractile muscle tissue, the reliability and validity of the protocol to be used in this study will be established.

d. Future Research – Combining MV with pennation angle and fiber length to calculate PCSA

Measurement of muscle fiber pennation angle from cadaveric dissection is now being replaced with real-time ultrasound, in order to arrive at a measure of PCSA that accurately reflects the architecture of the muscle and the force generating capacity (1, 38, 63, 75, 76). Real-time ultrasound makes it possible to perform in vivo recordings of fiber pennation angle at specific joint angles (muscle lengths) and at specific levels of muscle tension, see Figure 1.2 (1, 38, 63, 75, 76). Aagaard et al in 2001 proved the importance of this by showing that it was the change, ‘the increase in fiber pennation angle that allowed PCSA and therefore the maximum force generating capacity to increase, and the increase was significantly more than that seen with ACSA and/or muscle volume’ (1). Aagaard et al used ultrasound to measure pennation angle, and quadriceps volume was determined by summing CSA’s and multiplying by the interslice distance (1). It was felt that the increase in PCSA (due to a change in pennation angle), was more closely related to the increase in force of the muscle than a change in any of the other variables (ACSA or MV). Narici et al in 2003 clearly demonstrated the importance of measuring muscle quantity with PCSA as opposed to ACSA, by measuring fiber length and pennation angle of the subject group of interest (75). They observed that the architecture of the
gastrocnemius muscle was significantly altered by aging, showing a difference in fiber length and pennation angle between the young and old group (75). Narici et al proposed that PCSA was able to reflect the architectural changes that occurred with aging whereas ACSA was not (75). These architectural changes may play a significant role in the loss of muscle function in old age (75). PCSA is the variable that needs to be used when establishing normative values of muscle size (1, 75). Now, it is only the method of how to determine MV that needs to be improved. In order to achieve this, an accurate measurement of the quantity of muscle needs to be obtained (32) and the method proposed is that of using stereological methods coupled with MRI to determine muscle volume (33).
3. Functional Muscle Properties

a. Muscle Strength

Muscle strength can be defined as the force (N) or torque (Nm) generated by a particular muscle under a given set of conditions (74, 92). Common ways to measure muscle strength include; one-repetition maximum, isometric, and isokinetic testing. Isokinetic concentric and eccentric strength, as well as isometric strength, have been chosen as the strength measures, and thus functional properties of muscle that will be investigated in this study. It is clear from evidence in the literature that the nature of the muscle contraction (concentric versus eccentric) may alter the relationship observed between the force and the amount of muscle present (58, 61). Therefore it is important to obtain all of the different information given by the muscle under different contraction conditions.

In isometric testing, maximal force is generated at one particular joint angle, i.e. at one specific point in the range of motion of the muscle (40). Inner and outer range are thought to be weaker points of the muscle, as a result of the increased and decreased amount of overlap, which affect the amount of force that the muscle can produce (56, pg 184-185, 55). There is a point in the muscle length (at a particular joint angle in the range of motion), where the peak force (N) or torque (Nm) can be developed by the muscle, (as determined by extrapolations from torque-angle curves) (56). Typically, this angle of peak torque is usually somewhere in mid-range, but will vary slightly for each muscle (56). Since isometric strength is only one characteristic of the muscle, and often deemed less functional, a different type of test, such as isokinetic, can help to give a more complete picture of the muscle properties. In an isokinetic test, the movement is dynamic, with the speed of the contraction being kept constant through the range, with the use of a dynamometer (95). This allows for a maximum overload over the entire range of the muscle (80). In this situation, gravitational corrections must be made to ensure that the muscle strength is not incorrectly represented (103). Looking at concentric and
eccentric muscle activity in an isokinetic manner will show how much torque the muscle can produce while shortening and when lengthening, as opposed to isometric activity that will show how much torque the muscle can produce at one particular muscle length with no change in joint position (55).

b. Muscle Fatigue

The functional muscle property most commonly investigated is muscle strength. In this study, muscle fatigue was also investigated in order to add another dimension of muscle function in order to increase the understanding of aging muscle. Muscle fatigue can be defined as the inability to maintain the required or expected force (27). It can give insight into how a muscle may function over long periods of time, and therefore is necessary to consider when investigating how an individual copes with functional tasks, such as activities of daily living. Therefore, clinical rehabilitation programs must focus on increasing muscle strength as well as muscle endurance. Since one of the primary goals of rehabilitation of older adults is to maintain function and independence to preserve quality of life, muscle endurance, or how quickly the muscle fatigues, is very useful information to physiotherapists (47). Finally, muscle fatigue has also been identified as a possible risk factor in hamstring injuries, and therefore is an important functional aspect of muscle to consider with respect to injury prevention (22, 104).

A study by Lindstrom et al in 1997 concluded that ‘thigh muscles of older individuals are weaker than those of younger individuals, but relative to their strength, older individuals have similar properties as younger individuals with respect to muscle fatigue and endurance’ (59, pg B59). Lindstrom demonstrated that ‘increasing age does not markedly affect the ability of the quadriceps muscle to maintain force throughout repeated dynamic contractions’ (59, pg B65). This finding by Lindstrom indicates that despite the decline in muscle strength as we age, older individuals may not decline in all aspects of muscle function, and therefore all aspects need to
4. **Key Muscle Groups of the Thigh**

a. **Anatomy and Functional Grouping**

In determining the relationship between muscle size/structure and functional properties of an older healthy population, it is important that attention not be focused solely on one muscle group. Numerous studies have been done involving the quadriceps or gastrocnemius muscles, fewer involving the hamstrings, and even fewer involving the hip adductors. There is evidence from a single subject case report that investigation of these other muscle groups could provide some relevant information regarding overall muscle function. In the single subject design, an individual with a history of a 15-year old tibial plateau fracture demonstrated a significant loss of quadriceps volume (25%) on the injured limb, yet also demonstrated a simultaneous maintenance of hip adductor volume and a slight increase in volume of two out of the three hamstring muscles (99). This is sufficient evidence to suggest that the relationship among thigh muscle groups may not be straightforward and that investigation of these other muscle groups with respect to muscle volume and strength is warranted. Despite the numerous studies on aging muscle, there is relatively little information on the relationship between key muscle groups of the thigh and the roles that they may play in lower extremity biomechanics in a healthy older population. Little to no normative values of muscle size and strength for this age group and population exist for the hip adductors and hamstring muscle group.

Rather than looking at the relationships between quadriceps muscle volume and knee extensor strength, and hamstring muscle volume and knee flexor strength, the volume of all of the muscles participating in a particular joint action will be summed and then compared to the
torque produced (78, 81). It would be incorrect to compare only the volume of the primary muscle group for that joint action with the torque produced given that there is contribution from other muscle groups. This is a factor that one group of researchers believes may have led to some of the inconsistencies seen in the reported relationships of muscle size to strength in the elderly (70, 84). Therefore, in this study, when comparing muscle volume to strength for the knee flexors, the volume of the hamstrings, sartorius, and gracilis muscles will be summed as they all play a role in flexion of the knee (24). When looking at knee extension, the volume of the quadriceps, and the sartorius muscle, will be summed and compared to the knee extension torque, as they both contribute to knee extension (24). Finally, for hip adduction, the volume of all of the muscles that act to adduct the thigh at the hip joint, pectineus, adductors, gracilis, will be summed and compared to the hip adduction torque (24). In this way, each muscle that contributes to each particular action will be included. See Figures 1.5, 1.6, 1.7 for an anatomical description of each muscle that will be investigated in this study.

b. Ratios of Muscle Strength

By establishing normative muscle strength ratios between key muscle groups of the thigh, physiotherapists can ensure proper muscle balance across joints as a means to injury prevention (9, 45, 93). It is believed that co-activation of the antagonist is necessary to aid the ligaments in maintaining joint stability, helping to provide normal joint mechanics (9). This expected, normative hamstring to quadriceps strength ratio has been well established in a population of young, healthy individuals (9, 17, 39, 45), yet the same ratios have not been established in an older one. A study by Murray et al 1980 did look at the ratios of flexion and extension torque values in young and old men, (50-65, 70-86 years), however they only provided the strength of the old men as a percentage of the young men (73). They did not provide normative data of the two muscle groups. One study in the literature points to a
normative adductor to hamstring ratio in healthy older women, suggesting that this ratio increases in individuals with hip osteoarthritis (105). It is imperative that this data base of normative values is expanded upon on for the healthy elderly, not only to drive future research, but also to assist therapists in establishing effective and appropriate rehabilitation programs for this population.

5. Clinical Measure of Thigh Circumference

a. Findings in literature

Measurements of thigh circumference are one of the most commonly used clinical methods of assessing thigh muscle bulk (23), and are based on the assumption that changes in thigh circumference measurements reflect changes in muscle bulk, (79), which translate into changes in muscle power and strength (19). Despite the frequent use of this clinical measure, there continues to be some questions in the literature regarding how representative it is of muscle size and function, and the appropriate level of the thigh at which the measurements should be taken (19). At this time, no standard protocol is being used in the studies reported.

In 2002, Willan et al, using 41 cadaveric thighs revealed a significant correlation between thigh circumference and muscle cross-sectional area (r=0.94), stating that the quadriceps muscle CSA could accurately be predicted by the regression equation in their results (102). Arangio et al in 1997 found that in individuals with an ACL repaired limb, a positive correlation was found between thigh circumference, and quadriceps and hamstring peak torque in the uninvolved extremity, yet not in the operated extremity (7). Allison et al in 1993 found a positive correlation in their study, with results indicating that girth asymmetry was highly correlated with extension and flexion peak torque asymmetry when measurements were taken more proximal on the thigh (3). Finally, Doxey et al in 1987 agreed that girth measurements may
be a useful method of estimating muscle bulk (23). The majority of the subjects in these studies were less than 35 years old.

Despite the findings above, many researchers have observed opposite results, particularly when looking at thigh circumference measures and their ability to predict change (6, 13, 48, 108). Biette et al in 2004, Koutedakis et al 2004, and Young in 1983 all found that in young healthy individuals, changes in strength observed after an exercise program were not accompanied by changes in thigh circumference measures (13, 48, 108). Andrade et al in 2002 in their investigation of knee performance after ACL reconstruction found a very weak correlation \((r=0.22-0.43)\) between thigh circumference and muscle performance and cautioned that thigh circumference should not be used as a measure to predict muscle performance (6). This was echoed by Maylia et al in 1999 with individuals with unilateral meniscus injuries, who also stated that thigh girth measurements are not reproducible, and vary widely between observers (up to 8.3%, or 4cm) (68, 69). Cooper et al in 1981 also had similar findings, but did note that despite no correlation being found between torque and thigh circumference, serial measures at 5 and 10 cm levels may be an index of quadriceps power (19).

b. Importance/Clinical Relevance

The inconsistencies of findings surrounding the use of thigh circumference measurements pertain primarily to a young, healthy population, or a young population who have sustained common athletic injuries. Only one reference was found that investigated this measure in a healthy older population. Horvat et al 1991 looked at 13 women with a mean age of 69.3 ± 5.1 yrs and found that although significant strength gains were noted in the hamstrings and quadriceps muscle 5 weeks into a resisted exercise program, no significant differences were noted in mid thigh circumference measures (41). Given the fact that this tool continues to be used clinically in all populations, assuming that an increase in thigh circumference is
representative of an increase in strength, it is important that research is inclusive of all age groups. It is important to first establish whether or not there is a correlation between the clinical measure of thigh circumference and either muscle volume or strength in an elderly population. Then, studies can investigate whether or not this measure is able to detect change in muscle strength, power, or volume after an intervention.
SUMMARY

As our population ages, there is a greater chance of these individuals coming into contact with physiotherapists due to increased risk of falls (15), general deterioration of health, and the well documented loss of muscle strength (5, 16, 25, 30, 58). What remains unclear is how much of that loss in muscle strength is attributable to muscle atrophy (decreases in muscle size), versus neurological or structural changes in the muscle fiber (5, 16, 36, 37, 43, 75, 81, 84). If physiotherapists are to assist older adults in maintaining their independence through injury prevention and overall physical conditioning, then the mechanism behind the decrease in strength, and change in contractile properties of aged muscle, needs to be more completely understood. In order to increase the understanding of the relationship between muscle size and function, it is imperative that the method with which muscle is being quantified is accurate (33, 70, 83).

ACSA, the most common method of muscle quantification, is not an accurate reflection of the amount of contractile tissue present in a muscle, and should not be used to define and quantify muscle size (32, 75). Multi-pennated muscles whose muscle fibers do not lie parallel to the line of force generation, such as the quadriceps and hip adductors, will be under-estimated in quantity, as the area of all of the muscle fibers will not be accounted for in a single ACSA measurement, see Figure 1.1 (62, 75). This will result in erroneous deductions being made as to the relationship between muscle size and function. This is of great concern, particularly in an older population, where subtle changes may be occurring in the intrinsic properties of the muscle, which may be overlooked if ACSA remains the manner in which muscle size is quantified (49, 75).

PCSA, since it is the most accurate means of defining the amount of contractile area present within a muscle, should be the way in which muscle quantity is defined (1, 56, 57). Yet in order to arrive at this measure, all of the variables (fiber length, pennation angle, and muscle
volume), in the formula by Edgerton et al that show the relationship between PCSA and the muscle architecture need to be accurately measured (26, 90). Since the method of real-time ultrasound exists, and has been shown to be a reliable and valid method of measuring the angle of fiber pennation, and the length of the fiber, all that remains is to identify an efficient and valid method of measuring MV (1, 75). Stereology applied to MRI (shown to be the most accurate and safe imaging technique), allows for non-invasive, unbiased, and time-efficient in vivo measurements of the amount of non-contractile tissue present in the form of MV (62, 65, 87, 100). Therefore, in this study, it is proposed that stereological methods in combination with images obtained from MRI will be the efficient and valid method needed for MV determination. This will allow future studies to use this method in combination with real-time ultrasound to arrive at a quick and accurate determination of PCSA.

Most often it is the quadriceps muscle that is the focus of strength and or fatigue studies. Given the prevalence of hamstring injuries, (and the citing of hamstring fatigue as a possible risk factor), and the importance of this muscle in the biomechanics of the lower extremity, it is important that we establish measures to test the properties of the hamstrings (20, 104). Protocols exist that utilize hand-held dynamometry, measurement of hamstring muscle reflex time, or manual testing (number of repetitions to lift a percentage of one-repetition maximum) in order to determine the fatigue of the hamstrings, (50, 54), however no protocol has been found that utilizes EMG coupled with isokinetic dynamometry to measure hamstring muscle fatigue. This will assist future studies in establishing the role of hamstring fatigue in lower extremity pathologies.

This study aims to improve the research currently being done with older individuals by; 1) investigating the relationships between muscle size and strength (isokinetic, isometric, and fatigue) using a more accurate method of MV determination, 2) providing normative data for a healthy older population in the form of muscle volume for all of the major muscles of the thigh, and muscle torque for the three primary actions of the lower limb, (knee flexion, knee extension,
and hip adduction), 3) providing normative hamstring : quadriceps and adductor : hamstrings strength ratios, 4) investigating the relationship between muscle size and strength and the measure of thigh circumference, and 5) investigating the reliability of a protocol to measure hamstring fatigue.

Establishing normative data in the form of muscle volumes, torques, and ratios of antagonist to agonist strength, and developing a protocol to test hamstring fatigue will assist physiotherapists and future researchers in distinguishing those individuals at risk of injury, or in progressive stages of joint pathology. Relating these basic muscle properties to a common clinical measure of thigh circumference will help to ensure that physiotherapists are making the correct assumptions during assessment and treatment. This will in turn create more specific research questions and exercise/treatment programs aimed at improving the quality of life of older adults.
PURPOSE OF THE STUDY

The overall purpose of this study is to establish normative strength and volume data while determining the relationships between muscle volume of the muscles contributing to the three main actions of the thigh (knee flexion, extension, and hip adduction), and their associated functional muscle properties; muscle strength - isometric, concentric and eccentric, and muscle fatigue, in the dominant leg of an older population, age 51-80. Secondly, the reliability and validity of a stereological technique to more precisely and efficiently determine muscle volume will be investigated, (using pilot data from a previous single subject design), as well as the reliability of a protocol to measure hamstring muscle fatigue, (using a small group as a pilot test). Thirdly, thigh circumference, a clinical measure commonly used by therapists as a means of extrapolating information about muscle function will be investigated to determine whether or not it is representative of the muscle strength or volume of any of the thigh muscles. Finally, a hamstring : quadriceps, and an adductor : hamstrings ratio will be described for this population.

Aims of the study:

a. To determine the relationship between;
   - Knee extensor (quadriceps, sartorius) strength and MV
   - Knee extensor endurance time (fatigue) and MV
   - Knee flexor (hamstrings, sartorius, gracilis) strength and MV
   - Knee flexor endurance (fatigue) and MV
   - Adduction (adductors, pectineus, gracilis) strength and MV
   - Knee extensor, flexor, and hip adductor strength and MV of the thigh
   - Thigh circumference and muscle MV and strength for each action

b. To evaluate the reliability and validity of a stereological method to determine muscle volume
c. To determine the reliability of a hamstrings (knee flexion) fatigue protocol
d. To define a hamstring to quadriceps, and adductor to hamstrings ratio for this population

Hypotheses

1. There will only be a moderate relationship \((r=0.50-0.75)\), between the MV of the muscles contributing to the three main actions of the thigh (knee flexion, knee extension, hip adduction), and their associated muscle strength, with a lower relationship \((r<0.50)\), for muscle fatigue.

2. The stereological method to determine MV and the method to measure hamstring fatigue will be found to be reliable.

3. The measure of thigh circumference will have a moderate relationship \((r=0.50-0.75)\), to the MV of each of the muscle groups of the thigh, with a lower relationship \((r<0.50)\), expected for muscle strength.

4. The hamstring to quadriceps ratio and the adductor to hamstrings ratio will be similar to that cited in the literature for a young and older population respectively.
**Figure 1.1: Architectural Properties of Muscle**

*Figure 1.1A* shows a muscle displaying *longitudinal architecture*, where the fibers run parallel to the muscle's force generating axis. The angle of pennation is zero, and the length of the muscle fiber ($L_f$) = the length of the muscle ($L_m$). *Figure 1.1B* shows a muscle with *unipennate architecture*, where the muscle fibers run at an angle relative to the muscle's force generating axis, the angle of pennation. In this situation the $L_f$ is not equal to the $L_m$. *Figure 1.1C* shows a muscle *multipennate* in nature, where the muscle fibers run at several angles relative to the muscle's force generating axis.

Figure 1B and 1C are examples of situations where a single slice through the muscle perpendicular to the force generating axis of the muscles would not represent the entire contractile area of the muscle fibers. (Lieber et al 2000).
**Figure 1.2:** Changes in Muscle Fiber Pennation Angle

Ultrasound images of the medial gastrocnemius muscle in the sagital plane. **Figure 1.2A** shows the muscle at rest, with a pennation angle of 20 degrees, while **Figure 1.2B** shows the same muscle, whose pennation angle increased to 45 degrees once it became active. (Lieber et al 2000 reporting pictures from Fukunaga et al 1997).
**Figure 1.3:** Cavalieri’s Principle of Volume Determination

Figure 1.3a depicts how the object of interest is serially cut with uniform thickness \( t \). The distance between slices analyzed \( T \) becomes the number of slices skipped multiplied by \( t \). For example, one every 5 sections is \( T=5t \). The point area is the square of the distance between points \( d \), therefore the area of that slice \( A_i \) is the test point area \( d^2 \), multiplied by the number of occasions on which a test point falls within the region of interest \( P \). To obtain the volume of the object the area of each slice is multiplied by the distance between analyzed slices. It is a two-step process of sectioning and point counting. (Mandarim-de-Lacerda 2003).
Figure 1.4: Use of Grid on MRI

A.

Figure 1.4a shows the type of grid that is used to count the number of points that land on the muscle of interest. Figure 1.4b shows the grid in use as it is placed over an MRI image in the Analyze program. (A. Walton et al 1997, B. Analyze Software Program 5.0).
Figure 1.5 shows the proximal attachment of the hamstring group to the ischial tuberosity, and the distal attachment of the semitendinosus and semimembranosus to the medial aspect of the proximal tibia, and the biceps femoris (short and long heads merge) to the lateral aspect of the proximal tibia. The short head of the biceps femoris, although it is not shown, has its proximal attachment to the posterior aspect of the femur. (Drake et al: Grays Anatomy for Students 2005).
Figure 1.6 shows the anatomical orientation of the quadriceps muscle group, as well as the relationship of each of the muscles within the group in a coronal section through the midthigh. The vasti medialis, lateralis, and intermedius all have proximal attachments on the anterior aspect of the femur, while the rectus femoris arises from the anterior inferior iliac spine and the superior aspect of the acetabulum. The 4 muscles merge in the distal portion of the thigh to form the quadriceps tendon and patellar ligament, forming the distal attachment on the tibial tuberosity. (Drake et al: Grays Anatomy for Students 2005)
Figure 1.7: Medial Thigh – Adductor Muscle Group

Figure 1.7 shows the anatomical orientation of the hip adductors, as well as the relationship of each of the muscles in a horizontal section through the upper thigh. The hip adductors, as well as the gracilis and pectineus arise from the ischium and have distal attachments along the medial and slightly posterior aspect of the length of the femur. The gracilis muscle crosses the knee joint to attach to the medial aspect of the tibia near the attachment site of the sartorius and semitendinosus muscles. (Drake et al: Grays Anatomy for Students 2005).
REFERENCES


It has been thoroughly documented in the literature that a loss of muscle strength occurs as human's age (2, 7, 8, 41, 53). More importantly however, this loss of strength has been associated with decreased health and functional deficits, such as impaired ambulation, in the elderly (14, 19, 30, 39, 40). The effects of decreased strength and loss of function are numerous, affecting both the individual in terms of independence and quality of life, but also the community and society in terms of increasing health care costs associated with increased hospital and rehabilitation center stays (30, 40). It is critical that the reasons for this loss of strength that accompanies aging be understood in order to help prevent parallel losses of function through the prescription of appropriate and effective rehabilitation programs.

Despite overwhelming evidence supporting a decrease in strength in the elderly, no consensus has been reached on whether or not the decrease in strength observed is a result of muscle atrophy (sarcopenia – loss of muscle mass), or other factors, such as changes in the contractile properties of the muscle fiber, or a decreased ability to recruit the muscle (2, 14, 35, 53, 59). Variables such as; inconsistent age groups, activity levels, muscle group and/or muscle action studied, and methods used to quantify muscle tissue have been cited as possible reasons for the discrepancies seen in the literature investigating these strength deficits (44, 45, 53, 59). Specific tension, or muscle efficiency (in this study represented as Nm/cm³), has also been investigated and proposed as possibly a more appropriate alternative to describing muscle, however the debate and conflicting results in the literature continue (2, 14, 17, 26, 33, 35, 62, 76). Some studies show that as we age there is a decrease in specific tension, (2, 33,
62, 76), while others report that there is no change, or that an increase was observed (14, 17, 26, 35).

It appears as though the most logical approach in addressing these discrepancies is to review the method with which muscle is quantified, as it seems that the method that is most commonly used is not the most appropriate. Anatomical cross-sectional area (ACSA) is the most frequently used method of quantifying muscle tissue (2, 27, 35). It is quick to determine, as often only one slice, is taken at right angles to the line of the muscle, therefore requiring few calculations or interpretations of muscle borders, or overall shape (33, 46, 67). Since ACSA takes into account the area located in one slice of a particular muscle, and is two-dimensional in nature, it does not account for the overall mass of the muscle, nor does it take into account the architectural properties of the individual muscle (23, 24). With muscles that are highly pennated, the overall contractile area is greatly underestimated (23). In addition, not only does ACSA measure only one aspect of the muscle, the technique is not standardized among researchers, leading to a variety of ways of arriving at the outcome. Sometimes the slice at the mid-thigh is taken as representative of the CSA, (26), sometimes the largest slice is used, (35), and at other times several slices are averaged in order to arrive at a value (2, 27, 59).

Since fiber angle, or pennation of the muscle fibers, has a direct impact on the amount of force the muscle can generate, this needs to be taken into account when quantifying muscle (42). Physiological cross-sectional area (PCSA) is the most inclusive method by which to estimate the amount of contractile tissue present, however it requires knowing both the overall volume of the muscle in question, as well as the pennation angle and fiber length of the muscle (64). Given that pennation angle and fiber length have been observed to change under such conditions as aging (38, 56), joint angle, and muscle contraction type, (57, 34), it is important that these latter two variables be measured specifically for the subject groups of interest using real-time ultrasound (56). Since, at this time, no accurate and efficient method has been located to determine the overall volume of a muscle, this is the next step that will be addressed in this
study. A technique to measure muscle volume (MV) should then be combined with real-time ultrasound in future research, using the formula postulated by Edgerton et al in order to establish the most accurate determination of muscle size (64).

Measurements of MV are three-dimensional and therefore account for the entire mass of the muscle. The only challenge when measuring MV is to apply a method that does not predetermine, or make any assumptions as to the shape of a particular muscle (63, 70). Tracy et al refined a method already in use in an attempt to increase its efficiency (67). However, their technique of MV determination employed the use of a truncated cone formula, which makes the assumption that the muscle is conical in shape, which may not be correct (63, 67). Therefore in this study, the Cavalieri method of stereology will be used in order to alleviate this error of bias (63, 70). Not only does stereology not make assumptions as to the size or shape of the muscle, decisions regarding muscle boundaries are made more easily, and pixels containing non-contractile tissue can easily be excluded, which is extremely important when quantifying the tissue of an aged population (23, 70).

In order to completely understand the changes that occur in muscles as we age, various muscles with different characteristics (i.e. different pennation angles and fiber lengths, and volumes), and different contractions types, need to be investigated. Muscles also need to be studied in the functional groups within which they operate, rather than independently. When investigating the relationships between muscle quantity and the torque produced, another source of error may be introduced if all the muscles involved in generating that particular action are not included (62). For example, if pectineus and gracilis are contributing to hip adduction, then their volumes need to be included when looking at relationships between hip adductor size and strength. In addition, normative values for strength and MV of key muscles of the lower extremity, such as hamstrings, adductors, quadriceps, sartorius, gracilis, need to be established, especially in an elderly population. Diseases such as osteoarthritis, common in older individuals, have been noted to alter the strength of these muscle groups, thereby causing
pain and decreased function (5, 75). Despite the importance of accurate information about muscle size and strength, and the beneficial impact that it would have for therapists and their treatment of these individuals, a limited amount of data is available (2, 23).

To assist physiotherapists in their assessment and treatment of older individuals, information regarding muscle size and strength would become more useful if it were related to a frequently used clinical measure. Thigh circumference is often used to assess a client's 'improvement' in a rehabilitation program. It is assumed that the difference in size between the injured thigh, as compared to the uninjured leg, or the change in thigh size before and after a rehabilitation program, is paralleled by an associated difference or increase in muscle strength (18). The literature surrounding the use of thigh circumference measures, and the strength of their relationship to muscle size and/or strength is variable and incomplete. Some studies report no change in measures of thigh circumference, despite increases in strength after an exercise program (9, 29, 36, 77), and no relation between thigh circumference and muscle mass (4, 6), while other researchers report thigh circumference to be a good predictor of muscle CSA (72), and of strength (1, 4, 19), in an uninjured limb. Not only is there little consensus on the clinical usefulness of this measure, but the populations studied to date have consisted of young adults with various clinical pathologies, commonly seen in an athletic population (3, 9, 36). Only one study was found that investigated the relationship between thigh circumference and thigh muscle size and/or strength in a healthy older population (29). Horvat et al looked at a small number of healthy women (N=13), and found that significant strength gains were found in the quadriceps and hamstrings after 5 weeks of resistance training, with no significant differences in mid-thigh circumference measures (29). In order to determine if this measurement can be used as a tool to indicate change, it must first be determined whether or not a relationship exists between thigh girth measurements and variables such as MV and various strength measures.

Therefore, the purpose of this study was to establish and use, an efficient, reliable, and accurate technique to determine the MV of the thigh muscles (adductors, hamstrings,
quadriceps, sartorius, gracilis) in a healthy older population, establish normative values of the sizes and strengths of the muscles investigated, correlate muscle size with different measures of muscle strength, and relate the findings to a commonly used measure of thigh circumference.
METHODS

Subjects

Ten subjects ($n = 6$ healthy females and $n = 4$ healthy males) were tested twice, one visit was approximately one hour in length and was located at the UBC hospital MRI department, and the other was approximately 2 hours in length for strength testing of the thigh muscles, held at the GF Strong Rehabilitation Research Lab. Subjects were between the ages of 51 and 81 years of age ($64.6 \pm 8.9$ years (mean $\pm$ standard deviation), moderately active, with no history of knee or hip pathology, cardiopulmonary, or neuromuscular conditions, and were recruited from the Greater Vancouver region through posters placed in community centers, pharmacies, and seniors groups. Subjects were asked to avoid participating in physical activity on the day prior to, as well as the day of, testing to avoid any fatiguing effects on the thigh muscles that may have interfered with the tests. All subjects signed an informed consent form. Ethical approval for this study was granted by the University Clinical Ethics Research Board (University of British Columbia). These subjects were recruited from a study conducted by Sunita Mathur PhD on 'Skeletal Muscle Dysfunction in People with COPD and Recipients of Lung Transplants', as part of a healthy control group.

Muscle Volume

MRI analysis was chosen as the imaging technique from which muscle volumes would be determined, as it allows for clear distinction between muscle, bone, and adipose tissue, while exposing subjects to minimal amounts of ionizing radiation (24). It has been previously determined to be a valid and reliable means of analyzing and quantifying muscle tissue (21, 54, 67). For each subject, T1-weighted MR images (TE = 8 ms/TR = 650 ms) were obtained from the anterior superior iliac spine to the tibial plateau. The images were 5 mm thick, contiguous, axial slices obtained in a 40cm² field of view, 512 x 384 pixel matrix (in-plane resolution = 0.78 x 1.04 mm). Once the images were collected, see Figure 1.1, they were analyzed for individual
muscle volumes. Images from efilm were loaded into an Analyze Software Program 5.0, as dicom files, and the two separate upper and lower series were merged into one continuous series of the entire thigh.

The measurement tool of stereology, part of the Analyze Software package, was used to determine muscle volume of each muscle from the MRI images. The reliability and validity of the protocol was established prior to implementing it in the study, (refer to Appendix A for details). The stereological method of point counting was used to determine the volume of each of the following muscles; quadriceps (rectus femoris and vasti), hamstrings (semimembranosus (SM), semitendinosus (ST), biceps femoris long (BF) and short head (BF_s)), adductors (adductor brevis (AB), adductor longus (AL), adductor magnus (AM), and pectineus), gracilis, and sartorius, see Figure 2.2. The start point chosen for each subject was in the region of the superior aspect (base) of the patella, (defined by the last bit of bone seen when scrolling up the thigh), and analysis continued for each muscle until no further evidence of muscle tissue was seen in the MRI image. In this way, a random start point for grid placement was ensured for each muscle investigated as the first and last grid usually fell outside the structure of interest (25). A 10X10 grid was randomly laid over each slice to be analyzed, (see Figure 1.4) beginning at the defined start point and continuing at an interval of every 3 slices for the larger muscles, and every 2 slices for the smaller ones (sartorius and gracilis). Only points landing on the muscle tissue of interest were identified on each slice, and from that, the total volume was calculated by the Analyze Software Program. Pixels that were observed to be white in nature were labeled fat or ‘non-contractile tissue’ and were not included in the total volume calculation (15). In addition, fascia, tendons, and blood vessels within and between the muscle compartments were excluded, see Figure 2.2. Percent non-contractile tissue was determined by first taking the non-contractile volume and dividing it by the total volume (all pixels present), within the boundaries of a particular muscle.
The Analyze Software Program calculated the volume of each muscle using the Cavalieri method, which is based on the following formula:

\[ \text{est}_2V = T(a/p)M^2 (P_1 + P_2 + P_3 \ldots \ldots \ldots \ldots P_m) \]

Where \( \text{est}_2V \) is the unbiased estimate of volume (cm\(^3\)), \( T \) is the distance between sections through the muscle of interest, \( a/p \) is the test area per test point (cm\(^2\)), \( M \) is the linear magnification in the image, and \( P_1 + P_2 + P_3 \ldots \ldots \ldots \ldots P_m \) are the number of occasions on which a test point falls within the defined muscle boundary of the muscle in 1\(^{st}\), 2\(^{nd}\), 3\(^{rd}\), and \( m^{th} \) sections, see Figure 1.3 (48, 70).

The validity of this method has been previously established with other human tissue (63, 65), and once with the quadriceps muscle (70). For this study, the validity of this method was established using a phantom volume of known size, in combination with manual segmentation. In addition, comparisons to muscle volume data collected by the circling method using Image J, whose reliability and validity had been previously established (67) were also made. (See Appendix A for details on establishing the reliability and validity of the stereology method used in this study.)

In order to correctly determine the borders of each of the muscle previously listed, the following sources were utilized; Grants Atlas of Anatomy, an MRI Atlas, inspection of human cadavers, and the study by Willan and colleagues in 2002 that investigated the possible variations in the anatomy of the human quadriceps muscle (72).

**Muscle Strength**

**Instrumentation**

All torque measurements were made with a KinCom isokinetic dynamometer (version 5.30, Chattanooga Group Inc., Hixson TN), which has been established as a valid and reliable method of measuring torque generated by a muscle (22, 28, 50). The protocol utilized was that
described by Mathur et al, in that static gravity correction was performed on the Kin-Corn Isokinetic Dynamometer for quadriceps, hamstrings, and hip adductors for each subject in order to minimize error in the peak torque measurements (49, 73).

Isokinetic Testing

Isokinetic (30 degrees/second) strength, (concentric and eccentric) for the knee extensors, and knee flexors, was collected from the dominant leg (as defined by the lower extremity with which the subject would kick a ball) (49, 60). If they were unable to use their dominant leg due to previous injury and/or discomfort, then the alternate limb was used and noted. However previous studies have shown no significant difference between the dominant and non-dominant limb (23).

Maximal Voluntary Contractions

Given the anatomy of the hamstrings, and its role as a biarticular muscle, muscle strength could be determined by testing hip extension or knee flexion. For this study, knee flexion at 60° was chosen to estimate the strength of this muscle group as it has been previously reported as the angle at which the hamstrings generate their peak torque, which was also confirmed during pilot testing (11, 12, 74). It is also a stable and comfortable position for this age group. A position of 90 degrees of knee flexion was chosen to estimate the isometric strength of the quadriceps (49). Subjects were instructed to pull as hard as they could.

For the hip adductors, 20 degrees of abduction was chosen as the angle at which to determine the maximum voluntary isometric contraction, which differs from the 25 degrees that has previously been determined as the position at which the adductors are able to generate the greatest amount of strength (13, 55). This was done as it was found that 25 degrees pushed most subjects in this age group to their end range, which was not a comfortable testing position,
nor was it preferable to test the muscle at its end range. Subjects were instructed to 'pull their leg in as hard as they could'.

Force values obtained from the Kincom in N (Newtons) were converted to Nm (Newton-meters) to account for the length of the lever arm, thereby providing a more accurate estimate of muscle strength for each muscle group.

General Protocol

The subjects were familiarized with the equipment and given control of a manual stop button that could be used during testing if they felt it was necessary. The knee extensor isokinetic and isometric strength measurements were done on a separate day, but followed the same protocol for the knee flexors, as outlined below. The testing order was isokinetic, and then isometric, with the exception of the adductors, where isokinetic strength was not tested.

The subject was seated carefully on the KinCom seat, with the axis of rotation of the dynamometer aligned to the knee joint line. The backrest and seat angles were adjusted so that the hip was at approximately 80° of flexion. One strap was placed across the subject's pelvis, and two more were placed across the chest to minimize hip and trunk movement during the tests. A padded metal bar was placed on top of the thigh of the leg being tested to ensure that no compensatory strategies were used during testing. The cuff (load cell) of the KinCom was placed at a distance of 75% of the lower leg length (measured from the top of the fibular head to the distal point of the lateral malleolus) (37). During isokinetic testing, the subjects completed 2 sets of four repetitions (concentric followed by eccentric muscle action with a 5 second rest in between) through the range of 30° to 90° of knee flexion. The first set of four was considered a warm-up, and was followed by a one-minute rest before the second set began. In the first set, the first three repetitions were at 50% of maximal effort, and the last at maximal effort. The second set consisted of 4 repetitions at maximal effort, with a 30 second rest in-between.
the maximal effort, the subjects were asked to keep their hands free in their lap, and were asked to pull as hard as they could throughout the range of motion. Visual feedback of the produced force was provided. The three trials whose peak isokinetic force fell within 5% of one another were kept, and an average was calculated.

Once the isokinetic testing was completed, the knee angle was adjusted to 60 degrees of knee flexion for isometric testing of the knee flexors. Four to five repetitions were completed, the first of which was 50% of maximum, followed by a 30 second rest, and then 3-4 trials of a 3 second maximal effort with a one-minute rest in between. The subject was asked to think about the muscles on the back of their leg, and to pull as hard as they could to achieve their maximum. Visual feedback was given on the screen, and the subjects were encouraged verbally to 'pull, pull, pull'.

Once the testing was completed in a seated position, hip adduction was then tested in standing, as it is a functional position for this muscle group (74). Techniques were used to ensure stability of the contralateral hip, and to prevent and/or minimize compensatory strategies (lateral lean of trunk, forward flexion of trunk, hip flexion). The position has been previously used by Calahan et al in 1989, with the hip tested at 20 degrees of abduction, with the exception that this group of researchers used a standing frame, while we did not (13). Subjects were positioned such that the axis of rotation of the dynamometer was in line with the axis of rotation of their hip (central buttock, 1 cm above the level of the greater trochanter) (10, 47), confirmed by asking the subject to move the hip to be tested through range of motion. The contralateral hip was stabilized against the Kin-Corn chair, and the subject was given two locations with which they were able to stabilize themselves. A mirror was placed in front of the subject to allow visual feedback on the positioning of their hips. Subjects were instructed to stand tall, to keep their hips level, to think of the muscles on the inside of their legs, and to pull in as hard as they could. Cues were given regularly to prevent and correct for hip and trunk flexion during hip adduction.
testing. Once set up, the testing leg rested on an elevated platform until the testing began, and during rest periods.

Subjects performed a warm-up of 50% of maximal effort, and then proceeded to do 4-6 maximal isometric contractions with a 45 second rest in between. The three trials within 5% of one another were used to calculate the average isometric force of the hip adductors, which, during this study, were often found to occur during the last three trials. Subjects were asked to hold the contraction for three seconds, and were given verbal feedback of 'pull, pull, pull'.

**Thigh Circumference**

Measurements of thigh circumference were taken on the dominant leg with a tape measure (Lufkin steel tape measure) at points 5cm and 10cm above the superior aspect (base) of the patella. Previous studies have measured thigh circumference at a variety of distances above the superior aspect of the patella, and since little consistency has been found in the literature, the method used in this study was identical to what continues to be used clinically as an indirect measure of gains in muscle strength. A mark was placed at each distance, and the tape measure was placed with the lower border level with the mark. Three recordings at each distance were taken, removing the tape measure each time, and an average was calculated. The subject was lying on a bed, with the knee of the leg of interest in slight flexion, supported by a rolled towel. The tape measure was pulled taut so that no buckles occurred, however not tight enough that it caused an indent in the skin.
Statistical Analysis

Descriptive statistics were used to describe muscle characteristics, and to determine the mean and standard deviation of all strength, volume, and circumference measures. Scatter plots of the data were reviewed to detect the presence of outliers in the data set. The Pearson Product-Moment Correlation Coefficient was calculated to determine the degree of relationship between muscle size and strength of the different muscle groups and contraction types investigated.

Specific strength of the muscle is typically expressed as strength per unit of muscle mass, with units of N/cm² (2, 14). In this study, since strength was expressed as torque, and muscle size was expressed as volume, the term muscle efficiency will be used, and will be expressed as torque per unit of muscle volume, with units of Nm/cm³.

Criteria used for evaluating the Pearson-product moment correlation coefficient for this study will be as follows: 0.00-0.25 little or no relationship, 0.25-0.50 fair degree of relationship, 0.50-0.75 moderate to good relationship, 0.75-1.00 good to excellent relationship (61, pg 494).
RESULTS

I. Properties of Thigh Muscles

a. Size

With respect to muscle volume, the largest muscle group was found to be the quadriceps (vasti + rectus femoris) at $1529.57 \pm 500.54$ cm$^3$. The second and third largest muscle groups were the adductors at $776.46 \pm 231.65$ cm$^3$ and the hamstrings $613.59 \pm 159.73$ cm$^3$ respectively. Since each of the individual components of the hamstring muscle groups were measured, it can be noted that the largest member of the hamstrings group was biceps femoris (both long and short head measured together) at $262.57 \pm 79.62$ cm$^3$. The longest muscle was sartorius, and the shortest muscle was semimembranosus. The muscle with the largest percentage of non-contractile tissue was the vasti (measured as a group) at $2.22 \pm 0.86\%$, closely followed by the rectus femoris at $2.14 \pm 1.04\%$. The muscle with the least amount of non-contractile tissue was the gracilis muscle at $0.44 \pm 0.64\%$. The normative muscle volumes for all of the thigh muscles measured are listed in Table 2.1 and are presented according to gender in Figure 2.3 and 2.4.

b. Strength

The isometric strength of the knee flexors, knee extensors, and hip adductors was measured, with the strongest muscle group being the knee extensors at $137.2 \pm 48.6$ Nm, followed by the knee flexors at $55.6 \pm 21.6$ Nm and the adductors at $19.8 \pm 5.4$ Nm. The values for all of the subjects, in addition to the values of knee flexor and extensor concentric and eccentric strength, are presented in Table 2.2a and 2.2b, and are displayed in graphical format in Figure 2.5.
II. Relationship between Muscle Size and Strength

The relationship between muscle size and strength of the knee flexors, knee extensors, and hip adductors is shown in Figure 2.6.

a. Knee Flexors

When the muscle volume of the knee flexors (hamstrings, sartorius, gracilis) was compared to three different measures of strength, the following was observed; a very strong positive correlation was found with isometric strength \( r = 0.88 \), shown in Figure 2.7, and a very weak and negative correlation was found with both concentric \( r = -0.01 \), and eccentric strength \( r = -0.11 \). Looking solely at the volume of the hamstrings as the primary knee flexor, the following relationships were observed; a very strong positive correlation was found with the isometric strength \( r = 0.90 \), and a very weak and negative correlation was found with both concentric \( r = -0.03 \), and eccentric strength \( r = -0.11 \). Muscle efficiency \( 2, 14 \) was calculated as the torque (Nm) per unit of muscle volume \( (\text{cm}^3) \) and is reported in Table 2.3.

b. Knee Extensors

When the muscle volume of the knee extensors (quadriceps, sartorius) was compared to three different measures of strength, the following was observed; a very strong positive correlation was found with isometric strength \( r = 0.91 \), shown in Figure 2.8, and a moderate correlation was found for both concentric \( r = 0.53 \) and eccentric \( r = 0.64 \) strength. When the muscle volume of the quadriceps alone was compared to the same strength measures, the following was found; a very strong correlation was found with the isometric strength \( r = 0.90 \), and a moderate correlation was found for both concentric \( r = 0.54 \) and eccentric \( r = 0.64 \) muscle strength. Muscle efficiency of the knee extensors as a group is reported in Table 2.3.
c. **Adductors**

When the total muscle volume of the muscles responsible for hip adduction (adductors, pectineus, gracilis) was compared to isometric muscle strength, a very strong correlation was found ($r = 0.77$), shown in Figure 2.9. When the volume of gracilis was removed, and only the muscle volume of the adductors was compared to isometric strength, a similar strong correlation was found ($r = 0.76$). Muscle efficiency of the adductors as a group is reported in Table 2.3.

### III. Relationship between Muscle Groups

a. **Size**

Very strong relationships between muscle sizes were seen between the three muscle groups of the thigh. The total volume of the knee flexors compared to that of the knee extensors, yielded a relationship of $r = 0.94$. When the volume of the knee flexors were compared to the volume of the adductors a similar relationship resulted, $r = 0.93$. The total volume of the adductors compared to the volume of the knee extensors, showed a relationship of $r = 0.97$. An example of the type of relationship observed is shown in Figure 2.10.

When the muscle volumes of the primary muscle group responsible for each action identified were compared with each other, similar relationships were found; hamstrings compared with quadriceps, $r = 0.93$, hamstrings compared with adductors, $r = 0.92$, and adductors compared with quadriceps, $r = 0.96$.

b. **Strength**

Slightly lower, but strong relationships were found between the isometric strength measured for each of the three main actions of the thigh. When knee flexion was compared with knee extension, $r = 0.89$, and when compared with hip adduction, $r = 0.87$. When knee extension was compared with hip adduction, $r = 0.71$. An example of the type of relationship seen is shown in Figure 2.11. When the concentric and eccentric muscle strength for both knee
IV. Relationship between Thigh Circumference and Muscle Size

Overall, for all three muscle groups investigated, a moderate to good correlation was found between the muscle volume of each muscle group responsible for a particular action, and the thigh circumference measures at 10 cm superior to the base of the patella, ($r=0.55-0.72$). A slightly lower, but still moderate to good correlation was observed between the same variables at 5 cm superior to the base of the patella. When only the muscle volume of the prime mover of that group was compared to the thigh circumference measures, similar patterns of correlations were observed. The average thigh circumference measure at 5cm was $40.66 \pm 2.94$ cm and at 10cm was $44.06 \pm 2.76$ cm. Refer to Table 2.4 for Pearson Product-Moment Correlation Values.

Total Muscle Size

When the muscle volume of all of the muscles measured (hamstrings, quadriceps, adductors, sartorius, gracilis) were added up and compared to the thigh circumference measures at 5 and 10 cm, the following correlations were found; $r = 0.53$, and $r = 0.59$ respectively.

V. Relationship between Thigh Circumference and Muscle Strength

A very strong correlation was found between the isometric strength of each of the three actions of the thigh and the measurement of thigh circumference at 10cm superior to the base of the patella. All demonstrated an $r = 0.93$. The relationship between isometric strength and thigh circumference at 5 cm was moderate with all groups. An example of the nature of the relationship seen is shown in Figure 2.12. With respect to the relationship to concentric and
eccentric muscle strength, a moderate relationship was found with knee extension; however no relationship was seen with the knee flexors. Refer to Table 2.5 for all Pearson Product-Moment Correlation Coefficient values.
Figure 2.1: Examples of MRI Images Analyzed for Thigh Muscle Volume

Figure 2.1A is a sagittal image taken through the pelvis of a female subject. Figure 2.1B is through the mid-thigh of the same female subject, and Figure 2.1C is closer to the knee in a different female subject.
Figure 2.2: Cross-sectional Anatomy of the Thigh

Figure 2.2 identifies the structures of interest in a cross-section of the thigh. Similar anatomical diagrams were used in the identification of muscles, nerves, arteries, and veins during determination of thigh muscle volume using the stereological method. (Eycleshymer and Schoemaker).
### Table 2.1: Muscle Volume & % Non-Contractile Tissue

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Volume cm$^3$ Men</th>
<th>Volume cm$^3$ Women</th>
<th>Volume cm$^3$</th>
<th>% Non-Contractile Tissue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectus Femoris</td>
<td>204.07 ± 74.26</td>
<td>274.89 ± 53.06</td>
<td>156.86 ± 39.38</td>
<td>2.14 ± 1.04%</td>
</tr>
<tr>
<td>Vasti</td>
<td>1325.50 ± 429.98</td>
<td>1766.97 ± 239.89</td>
<td>1031.19 ± 195.97</td>
<td>2.22 ± 0.86%</td>
</tr>
<tr>
<td><strong>Quadriceps</strong></td>
<td><strong>1529.57 ± 500.54</strong></td>
<td><strong>2041.85 ± 286.69</strong></td>
<td><strong>1188.05 ± 227.48</strong></td>
<td><strong>4.36 ± 1.90%</strong></td>
</tr>
<tr>
<td>Sartorius</td>
<td>137.82 ± 48.83</td>
<td>189.06 ± 6.71</td>
<td>103.66 ± 27.64</td>
<td>1.05 ± 0.76%</td>
</tr>
<tr>
<td>Gracilis</td>
<td>82.52 ± 25.24</td>
<td>107.12 ± 6.33</td>
<td>66.12 ± 17.78</td>
<td>0.44 ± 0.64%</td>
</tr>
<tr>
<td><strong>Adductors</strong></td>
<td><strong>776.46 ± 231.65</strong></td>
<td><strong>1010.28 ± 168.61</strong></td>
<td><strong>620.57 ± 81.44</strong></td>
<td><strong>1.14 ± 0.51%</strong></td>
</tr>
<tr>
<td>Semimembranosus</td>
<td>214.05 ± 58.20</td>
<td>266.19 ± 34.22</td>
<td>179.29 ± 42.07</td>
<td>1.01 ± 0.71%</td>
</tr>
<tr>
<td>Semitendinosus</td>
<td>136.96 ± 45.85</td>
<td>174.18 ± 51.04</td>
<td>112.15 ± 19.33</td>
<td>1.51 ± 1.85%</td>
</tr>
<tr>
<td>Biceps Femoris</td>
<td>262.57 ± 79.62</td>
<td>336.46 ± 39.33</td>
<td>213.32 ± 56.61</td>
<td>1.40 ± 1.49%</td>
</tr>
<tr>
<td><strong>Hamstrings</strong></td>
<td><strong>613.59 ± 159.73</strong></td>
<td><strong>776.82 ± 39.06</strong></td>
<td><strong>504.76 ± 97.37</strong></td>
<td><strong>3.92 ± 4.05%</strong></td>
</tr>
</tbody>
</table>

Avg Total Volume | 3139.95 ± 945.37 | 4125.14 ± 470.09 | 2483.16 ± 426.59 |

Men: N=4, Women: N=6. Adductors include: pectineus, AL, AB, AM.

---

**Figure 2.3: Thigh Muscle Volumes for Each Gender**

- RF = rectus femoris, Quadriceps = RF + Vasti, SM = Semimembranosus, ST = Semitendinosus, BF = Biceps Femoris (long and short head), Hamstrings = SM + ST + BF, Adductors = Hip adductors + Pectineus.
Figure 2.4: Total Muscle Volume per Group for Each Gender

Knee Flexors = Hamstrings + Sartorius + Gracilis, Knee Extensors = Quadriceps + Sartorius, Hip Adductors = Adductors + Pectineus.

Table 2.2a: Muscle Strength of Knee Flexors, Knee Extensors, & Hip Adductors

<table>
<thead>
<tr>
<th>Subject</th>
<th>Knee Flexors</th>
<th>Knee Extensors</th>
<th>Adductors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Isometric</td>
<td>Concentric</td>
<td>Eccentric</td>
</tr>
<tr>
<td>1</td>
<td>37</td>
<td>70</td>
<td>91</td>
</tr>
<tr>
<td>2</td>
<td>51</td>
<td>16</td>
<td>31</td>
</tr>
<tr>
<td>3</td>
<td>78</td>
<td>84</td>
<td>101</td>
</tr>
<tr>
<td>4</td>
<td>48</td>
<td>84</td>
<td>113</td>
</tr>
<tr>
<td>5</td>
<td>97</td>
<td>48</td>
<td>76</td>
</tr>
<tr>
<td>6</td>
<td>63</td>
<td>43</td>
<td>70</td>
</tr>
<tr>
<td>7</td>
<td>34</td>
<td>55</td>
<td>84</td>
</tr>
<tr>
<td>8</td>
<td>70</td>
<td>57</td>
<td>84</td>
</tr>
<tr>
<td>9</td>
<td>49</td>
<td>29</td>
<td>47</td>
</tr>
<tr>
<td>10</td>
<td>28</td>
<td>47</td>
<td>74</td>
</tr>
</tbody>
</table>

Strength is measured in Nm, and at 90 deg for isometric knee extension, 60 deg for isometric knee flexion, and 20 deg for isometric hip adduction. Isokinetic strength (concentric and eccentric) measured at 30 deg/sec.
Table 2.2b: Muscle Strength – Group & Male/Female Averages

<table>
<thead>
<tr>
<th>Group</th>
<th>Knee Flexors</th>
<th>Knee Extensors</th>
<th>Adductors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Isometric</td>
<td>Concentric</td>
<td>Eccentric</td>
</tr>
<tr>
<td></td>
<td>St Dev</td>
<td>St Dev</td>
<td>St Dev</td>
</tr>
<tr>
<td>Average</td>
<td>56</td>
<td>53</td>
<td>79</td>
</tr>
<tr>
<td>St Dev</td>
<td>22</td>
<td>22</td>
<td>28</td>
</tr>
<tr>
<td>MEN</td>
<td>Average</td>
<td>77</td>
<td>58</td>
</tr>
<tr>
<td>St Dev</td>
<td>15</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td>WOMEN</td>
<td>Average</td>
<td>41</td>
<td>50</td>
</tr>
<tr>
<td>St Dev</td>
<td>9</td>
<td>25</td>
<td>35</td>
</tr>
</tbody>
</table>

Strength is measured in Nm, and at 90 deg for isometric knee extension, 60 deg for isometric knee flexion, and 20 deg for isometric hip adduction. Isokinetic strength (concentric and eccentric) measured at 30 deg/sec.

Figure 2.5: Isometric Muscle Strength per Group for Each Gender

Knee Flexors = Hamstrings + Sartorius + Gracilis, Knee Extensors = Quadriceps + Sartorius, Hip Adductors = Adductors + Pectineus.
Figure 2.6: Relationship between Muscle Size and Strength

Knee Flexors = Hamstrings + Sartorius + Gracilis, Knee Extensors = Quadriceps + Sartorius, Hip Adductors = Adductors + Pectineus.

Figure 2.7: Muscle Volume vs Isometric Strength of the Knee Flexors

Isometric strength measured at 60 degrees knee flexion, and MV includes volume of all flexors of the knee; hamstrings, sartorius, and gracilis.
Table 2.3: Muscle Efficiency

<table>
<thead>
<tr>
<th>Muscle Group</th>
<th>Isometric</th>
<th>Concentric</th>
<th>Eccentric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Flexors</td>
<td>6.57 ±1.21</td>
<td>6.92 ± 3.65</td>
<td>10.34 ± 5.35</td>
</tr>
<tr>
<td>Knee Extensors</td>
<td>8.25 ± 1.16</td>
<td>4.97 ± 1.74</td>
<td>8.19 ± 2.53</td>
</tr>
<tr>
<td>Hip Adductors</td>
<td>2.35 ± 0.55</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Average muscle efficiency expressed as Nm/cm$^2$, multiplied by 100 to express as %.

Figure 2.8: Muscle Volume vs Isometric Strength of the Knee Extensors

Isometric strength measured at 90 degrees knee flexion, and MV includes volume of all extensors of the knee; quadriceps and sartorius.
Figure 2.9: Muscle Volume vs Isometric Strength of the Hip Adductors

Isometric strength measured at 20 degrees hip abduction, and MV includes volume of all hip adductors; (AL, AM, AB), and pectineus.

Figure 2.10: Total Muscle Volume of Knee Extensors vs Knee Flexors

Figure 2.11: Isometric Muscle Strength of Knee Extensors vs Knee Flexors

Isometric strength measured at 60 degrees knee flexion for knee flexors and 90 degrees knee flexion for knee extensors.

Table 2.4: Pearson-Product Moment Correlation Coefficient Values for Thigh Circumference and Muscle Volume

<table>
<thead>
<tr>
<th>Muscle Volume</th>
<th>5 cm</th>
<th>10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Flexors</td>
<td>0.61</td>
<td>0.67</td>
</tr>
<tr>
<td>Hamstrings</td>
<td>0.62</td>
<td>0.66</td>
</tr>
<tr>
<td>Knee Extensors</td>
<td>0.49</td>
<td>0.68</td>
</tr>
<tr>
<td>Quadriceps</td>
<td>0.47</td>
<td>0.56</td>
</tr>
<tr>
<td>Hip Adductors</td>
<td>0.53</td>
<td>0.72</td>
</tr>
<tr>
<td>Adductors</td>
<td>0.52</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Knee flexors = hamstrings + sartorius + gracilis, Knee extensors = quadriceps + sartorius, Hip adductors = adductors + pectineus + gracilis. Thigh circumference was measured at a distance of 5 and 10 cm superior to the base of the patella.
Figure 2.12: Adductor Strength vs Thigh Circumference Measures

Table 2.5: Pearson-Product Moment Correlation Coefficient Values for Thigh Circumference and Muscle Strength

<table>
<thead>
<tr>
<th>Muscle Strength</th>
<th>Thigh Circumference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 cm</td>
</tr>
<tr>
<td><strong>Knee Flexion</strong></td>
<td></td>
</tr>
<tr>
<td>Isometric</td>
<td>0.70</td>
</tr>
<tr>
<td>Concentric</td>
<td>-0.21</td>
</tr>
<tr>
<td>Eccentric</td>
<td>-0.31</td>
</tr>
<tr>
<td><strong>Knee Extension</strong></td>
<td></td>
</tr>
<tr>
<td>Isometric</td>
<td>0.52</td>
</tr>
<tr>
<td>Concentric</td>
<td>0.56</td>
</tr>
<tr>
<td>Eccentric</td>
<td>0.61</td>
</tr>
<tr>
<td><strong>Hip Adduction</strong></td>
<td></td>
</tr>
<tr>
<td>Isometric</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Strength measured in Nm. Isometric strength measured at 90° knee flexion for knee extensors, 60° knee flexion for knee flexors, and 20° hip abduction for hip adductors. Isokinetic strength was measured at 30 deg/sec, and thigh circumference was measured at a distance of 5 and 10 cm superior to the base of the patella.
DISCUSSION

I. Properties of Thigh Muscles

a. Size

In this study, it was observed that the largest muscle of the thigh was the quadriceps, and the second largest was the adductors, both as a group average, and for the men and the women separately. Biceps femoris (long and short head) was the largest muscle in the hamstring muscle group for both men and women. It was difficult to make comparisons to muscle volumes found in the literature, since normative values were only present for one out of the three major muscle groups of the thigh, the quadriceps. No normative values of muscle volume were located for the hamstrings, or the adductors. In addition, normative values were not always reported, and age groups of the subjects often differed between studies. The average quadriceps femoris volume measured in this study was 1529.57 ± 500.54 cm³, with men at 2041.85 ± 286.69 cm³ (mean age = 65.5 ± 6.7 yrs), and the women at 1188.05 ± 227.48 cm³ (mean age = 64 ± 10.8 yrs). This was close to values reported by Tracy et al 2003 of 1741 ± 150 cm³ for older men (mean age = 69 ± 3 yrs) and 1095 ± 177 cm³ for older women (mean age = 68 ± 3 yrs), and Ivey et al 2000 who reported volumes of 1753 ± 44 cm³ for older men (65-75 yrs) and 1125 ± 53 cm³ for older women (65-75 yrs) (67, 31). The quadriceps femoris muscle volumes obtained in this study are in contrast to those reported by Trappe et al in 2001 (68). They reported muscle volumes of 721.4 ± 57.7 cm³ for older men (73-93 yrs), and 511.9 ± 37.9 cm³ for older women (72-86) (68). However, their subjects were considerably older than those in this study, and they were also sedentary (68). Both factors could account for a large difference in muscle volume. The oldest subject in this study was 80 yrs old and she had the third smallest quadriceps volume and the smallest total muscle volume, suggesting that age did have an impact on muscle size.
It is interesting to note that the adductors (pectineus, adductor longus (AL) adductor magnus (AM), and adductor brevis (AB)) were found to be the second largest muscle group for both sexes, and yet there are few studies reporting normative values for their size and strength, and the muscles possible connection to lower extremity pathologies (5, 13, 32, 58). It seems intuitive that the adductors are larger than the hamstrings given their gross anatomy, filling in the medial aspect of the thigh, as well as their overall function. The adductors as a group, operate over one joint and are involved at multiple actions at the hip, (adduction, flexion, extension), they are a stabilizer of the pelvis, and they are important for frontal plane balance control and fall prevention (32, 69). The closed kinetic chain theory also suggests that hip strength is needed for control of distal segments to prevent injury (58). Given the size of the adductors found in this study and the findings of other researchers (5, 58, 75), there is sufficient evidence to warrant further investigation into the size and strength of the adductors in a healthy population and their functional role in maintaining healthy joint mechanics.

There is no question that the adductors are a large and important muscle group that has been overlooked. However, a decision as to which muscle group is larger, the adductors or the hamstrings, can only be made once a measure of PCSA is used, as it more accurately reflects the quantity of contractile tissue. When comparing the difference in anatomy and architecture between these two groups of muscle, one finds that AM (13.1 cm), AL (10.8 cm), AB (11.5 cm), and pectineus (10.2 cm) have longer muscle fibers then SM (7.0 cm) and BF (8.3 cm) (40, 41), however BF (14.5 cm) and ST (16.0 cm) of the hamstring group have the longest of all (40, 41). With respect to pennation angle, SM and BF are highly pennated at 10-20 degrees and 20-25 degrees respectively, while AL only shows a pennation angle of 5-8 degrees (42, 43). Given the equation with which to calculate PCSA from MV and these architectural properties, it is unclear as to which muscle groups have the largest volume of contractile tissue. MV is a closer estimate and truer measure than CSA, however PCSA needs to be used to truly compare the two muscle groups.
b. **Strength**

Isometric strength values were compared to those found in the literature for the three main actions tested, knee flexion, knee extension, and hip adduction. In this study, the findings of strength were consistent with what is known of the anatomy and functional roles of the thigh muscles. Isometric and isokinetic knee extension generated the largest muscle force for both the men and women, which can be explained by the highly pennated architecture, and large volume of the quadriceps, and their overall role as a power muscle (71). The hamstrings have to operate over two joints and therefore and typically have longer fibers and are quicker, but don't generate as much force (42). Finally the weakest muscle, the adductors, operates in a very small range and is primarily a hip and pelvis stabilizer assisting with postural control (32). Only isometric strength values were compared to those in the literature, as speed and range of motion for isokinetic testing for the knee flexors and extensors differed across studies, the age of subjects differed, and often studies were found looking at the muscle of interest, however results were only presented in graphical format, or in different units of muscle strength. With respect to isokinetic testing, in this study it was found that women showed less of a difference between their eccentric and concentric strength measurements for both knee flexion and knee extension, supporting recent findings that eccentric strength is preserved in older women (8).

In this study, the overall average isometric knee flexion torque measured was 55 ± 22 Nm. This was quite different to the value of 109 ± 7 Nm that Overend et al reported in 1992 in elderly men aged 65-77 yrs (59). However, when the subjects were divided into genders, the torque of the 4 men in this study showed an average value of 77 ± 15 Nm, which is a little closer to Overend et al (59). Both studies measured knee flexion at 60 degrees, however Overend had an N=12, therefore the differences in sample size may account for the difference in strength measurements observed (59). The 6 women in the present study had an average torque of 41 ± 9 Nm, which is close to that reported by Macaluso et al in 2002 of 34.6 ± 8.9 Nm for women in a
similar age group, mean age = 69.5 ± 2.4 yrs (46). However Macaluso measured knee flexion at 90 degrees therefore I would expect their values to be slightly lower, as this is not the angle of peak torque for the hamstrings (11, 46). The angle of peak torque for the hamstrings has been reported as 59 degrees of knee flexion by Brockett et al in 2001 and therefore 60 degrees was used in this present study at the angle at which to measure knee flexor MVC (11).

The knee extensors had an overall average torque of 137 ± 49 Nm, 183 ± 39 for men, and 106 ± 23 for women. These values are close to those obtained by Bazzucchi et al in 2004 who found the MVC of knee extensors to be 97.1 ± 19.4 Nm in women aged 70.6 ± 2.6 yrs, and Overend et al in 1992 reported the isometric knee extension of elderly men, 65-77 yrs to be 199 ± 10 Nm (7, 59). Macaluso et al in 2002 identified a strength of 78.7 ± 13.6 Nm in women mean age = 69.5 ± 2.4 yrs (46). These values do differ from those reported by Harridge et al in 1999, who reported maximum voluntary torque of the knee extensors to be 61.0 ± 21.6 Nm before a strength training program in individuals aged 85-97 yrs (27). This could partially be due to the fact that they were looking at a much older age group.

The hip adductors demonstrated an overall average isometric torque of 20 ± 5 Nm, with the men at 24 ± 3 Nm, and the women at 17 ± 5 Nm. These values differed from those found in the literature. Johnson et al in 2004 reported an average torque of 58.8 ± 17.2 Nm in older individuals (mean age = 74 ± 6.8 yrs), and Arokoski et al in 2002 reported an average torque of 157 ± 35 Nm for controls and 118 ± 29 Nm in individuals with hip osteoarthritis (mean age 56.2 yrs) (5, 32). Calahan et al in 1988 reported average torques at 10 degrees of hip abduction for isometric adduction of 104 ± 29 Nm for older men (mean = 54 yrs), and 59 ± 17 Nm for older women (mean age = 53 yrs) (13). However, a wide variety of hip adductor muscle strengths have been reported in the literature, both within control groups (5) and throughout studies, and have been attributed to differences in testing positions (standing versus supine), and study design (5). Both Johnson and Calahan tested the adductors in a standing position (as done in this study), as compared to Arokoski who tested the muscle group in supine (5, 13, 32). Yet
II. Relationship between Muscle Size and Strength

Overall, for all of the muscle groups investigated, no studies were found that investigated the relationship of muscle volume to strength. Macaluso et al was the only group that used muscle volume instead of CSA, and isometric strength of the knee flexors and extensors in their study; however they did not report what the correlations were between the knee flexors and knee extensors size and strength.

a. Knee Flexors

In this study, an excellent correlation ($r=0.88$) was observed between the knee flexor (hamstring group, sartorius, gracilis) muscle volume and the isometric MVC. The volume of the hamstring group alone also showed an excellent correlation with the MVC ($r=0.90$). The only study found in the literature that investigated the relationship between hamstring muscle size and strength was Overend et al in 1991 who reported a correlation of $r=0.73$ between the CSA of the hamstrings and the maximum isometric torque at 60 degrees flexion in elderly men aged 65-77 yrs (59). Since the $r$ value obtained in this study was higher than that of Overend et al, this suggests that when a more accurate measure of muscle size is obtained, such as muscle volume, a stronger relationship is observed (59).
Little or no relationship was found between the muscle volume of the knee flexors and the concentric and eccentric knee flexion torque. This was an interesting finding given what we know about muscle. It was felt that a lower correlation would be found between the hamstring size and strength as compared to the quadriceps size and strength given their difference in function and fiber type; however this finding of little to no relationship was unexpected. It may have been due to the position of testing, in that the hamstring were placed in a shortened length and therefore (according to the length-tension curve), were unable to reach their peak torque (42). In sitting, the subjects were also compressing the hamstring muscle belly, which may have decreased blood flow and altered force production. Lastly, it was felt that subjects had a more difficult time with the testing of the knee flexors as compared to the knee extensors. It appeared as though they had more control of their knee extensors, as a greater amount of practice was necessary for the hamstring testing as compared to all others. Of these factors, it is felt that the hamstrings acting in a shortened position is the most likely reason for the altered force and therefore unexpected relationship observed between muscle volume and isokinetic knee flexor strength.

b. Knee Extensors

The correlation between the knee extensor (quadriceps, sartorius), muscle volume and the MVC was excellent, (r=0.91), as well as for the quadriceps alone (r=0.90). This was slightly better than the relationship observed between the knee flexor volume and isometric strength. These findings are similar to other results reported in the literature. Akima et al in 2001 found a strong relationship between the CSA of quadriceps femoris and the maximum knee extensor torque in men, r=0.827, and women r=0.657, aged 20-84 yrs (2). Harridge et al in 1999 found a correlation of r=0.84 between the lean CSA and strength prior to an exercise program in individuals aged 85-97 yrs (27). Overend et al in 1991 found a slightly lower correlation of
r=0.67 between the CSA of the quadriceps and maximum isometric strength in men aged 65-77 yrs (59). Hakkinen et al in 1991 found an overall correlation of 0.82 between the CSA of the quadriceps and the maximum voluntary force, which was only an r=0.67 in the women aged 66-75 yrs, similar to the relationship between quadriceps CSA and isometric strength found by Young et al in 1984 of r=0.66 (26, 76). However despite some findings of consistency in the literature in terms of r values, (generally a strong relationship found), there is still quite a range in those values describing the relationship of knee extensor muscle volume and strength, from moderate to excellent.

It is hypothesized that this variability was observed because not one study reviewed measured CSA or isometric knee extension in the same manner. Akima et al measured knee extension at 80 degrees of flexion and averaged CSA over two slices (2). Harridge et al measured knee extension at 90 degrees knee flexion and averaged CSA over three slices (27). Overend et al measured knee extension at 30 degrees knee flexion and averaged CSA over 5 slices (59). Hakkinen measured knee extension at 107 degrees flexion and took one slice as representative of CSA (26). Not only were the strength and size protocols different between the studies, but the age ranges of the subjects were as well, making comparison difficult.

A moderate correlation was found between the size of the knee extensors and the isokinetic strength, r=0.53 concentric and r=0.64 for eccentric. All of the literature found compared isometric strength to muscle size, not isokinetic strength; therefore no comparisons are made here. The relationship obtained in this study was reasonable given the size, function, and anatomy of the quadriceps. The relationship between muscle strength and muscle volume was expected to be higher for the isometric contraction as compared to the isokinetic, as there are fewer variables that can affect the torque produced during an isometric contraction. An isometric contraction occurs at one muscle length, at one particular joint angle (42). The angle of peak torque is what is used when one wishes to elicit the maximum strength of a particular muscle (11, 42). However isokinetic strength, since it occurs throughout a joint range of motion
and goes through a variety of muscle lengths, can be affected by the speed of contraction, the range of motion, and the type of contraction (concentric or eccentric) (42). This makes it more difficult to elicit a consistent level of maximum torque production from the muscle, and to compare results between studies. These variables affect the strength produced during an isokinetic contraction and therefore will affect the type of relationship observed between muscle size and strength.

c. Adductors

In this study, the relationship between the hip adductor (pectineus, AL, AB, AM, gracilis), muscle volume and the isometric MVC was excellent ($r=0.77$) as well as for the adductors alone ($r=0.76$). The only study found in the literature that looked at the relationship between hip adductor size and strength was Arokoski et al in 2002 who found an $r=0.064$ between adductor CSA and isometric strength. This is very different than the relationship observed in this study. However, Arokoski et al measured the CSA as only an average of two slices, and measured the strength of the hip adductors in a neutral position in supine (5). Therefore I would expect Arokoski’s group to present a different strength measure, possibly higher, as compared to this study (5). Their subjects did not have to stabilize with their core muscles as the ones in this study would have done during the standing test of hip adductor strength, which would likely have affected the torque of the adductors and therefore the relationship observed with muscle volume. With respect to the technique used to measure ACSA, there is one large source of error present here. The adductors are a triangular shaped muscle, whose contractile volume would certainly not be well represented by an average of only two slices over its entire mass, the relationship obtained would vary depending on where the ACSA was measured.
III. Relationship between Muscle Groups – Size and Strength

There was a strong correlation between the muscle volumes (r=0.92-0.97) as well as the isometric strength (r=0.71-0.89) of all of the three major muscle groups studied. No studies were found that investigated the inter-relationship of thigh muscle size or strength, however despite this, this finding is very important and very relevant to therapists. This finding indicates that in healthy older adults, there exists a strong relationship among the major muscle groups of the thigh (knee flexors, knee extensors, hip adductors) with respect to both the size and strength of the muscles. This suggests that in this population, there is an expected relationship between the muscle groups. When treating older healthy individuals, therapists must be aware that although there are differences in muscle strength between these three groups, there should be a balanced inter-relationship among them.

When the concentric strength was compared to the eccentric strength for both the knee flexors and knee extensors, good to excellent correlations were observed in this healthy older population, (r=0.96 and r=0.75 respectively). The relationship found for the quadriceps is similar to that reported by Tourny-Chollet et al in 2002 for soccer players with a mean age of 22.0 ± 3.0 yrs, who found that relationships between the 2 modes of contraction for hamstrings was r=0.76, and for quadriceps, r=0.71 (64). Sedentary subjects with a mean age of 22.9 ± 2.1 yrs showed a significant correlation of r=0.78 for hamstrings, but none for quadriceps (66). This suggests that in older individuals, there is a relationship between the two modes of contraction for both the knee flexors and knee extensors. One would expect that if the individual was able to produce a certain force eccentrically with one muscle group, then there is a certain level of concentric force that would be expected. For the hamstrings, when the concentric force was divided by the eccentric force, the average for the group was 0.66, when this was repeated for the quadriceps, the average for the group was 0.62. This indicates that when treating individuals, the concentric strength of the knee flexors is approximately 66% of the eccentric
torque, and the concentric strength of the knee extensors is approximately 62% of the eccentric torque. This validates the torque-velocity curve as it demonstrates the ability of an eccentric action to produce a greater amount of force (46).

Muscle efficiency, or the muscle strength (Nm) per unit muscle size (cm$^3$) (14, 26, 35), was calculated for each muscle strength measured. The eccentric contraction of the knee flexors was found to be the most efficient muscle activity, as it produced the largest amount of force per cm$^3$ of muscle tissue. The least efficient muscle action was found to be the hip adductors with their isometric muscle strength. This could be explained by the small range of motion within which the muscle has to work, allowing a shorter fulcrum, therefore decreasing the muscle strength that it can produce. (43, 71) There was a large difference in isometric muscle force between the knee flexors and knee extensors, (81.6 Nm) that almost disappeared when the muscle efficiency was calculated, as only a difference of 1.68 Nm/cm$^3$ was found. Narici et al in 1988 also found this to be the case, suggesting that both aspects of the muscle function should be explored (56). By looking at the muscle in terms of overall torque versus the amount of torque it produces per unit of size, allows for a broader understanding of the muscle and how its structure relates to its function.

IV. Relationship between Thigh Circumference and Muscle Size

Stronger correlations between muscle volume and thigh circumference were observed with measurements of thigh circumference taken 10cm superior to the base of the patella, as opposed to 5 cm, for all muscle groups, therefore strengthening the finding. This indicated that if these measurements are to be used clinically to represent muscle size, then the 10 cm mark should be chosen instead of the 5 cm distance. In addition, stronger relationships were observed when the total volume of muscles responsible for a particular action was correlated to the thigh circumference measures as opposed to the volume of only the prime mover (most
Relationships of Muscle Volume, Strength, and Thigh Circumference in a Healthy Older Population
Chapter 2 - Discussion

notable change in r value was found with the adductors). This tells therapists who use these measures, that a measure of thigh circumference is more reflective of the size of the group of muscles responsible for a particular action, rather than the one main contributing muscle.

With respect to relationships between muscle size and thigh circumference, mixed results were found in the literature. Willan et al in 2002 reported a very strong relationship between the CSA of the quadriceps and thigh circumference taken at 15cm superior to the base of the patella with cadavers, and yet Arangio et al in 1997 found no correlation between thigh circumference and CSA at any point measured on the thigh (4, 72). It is felt that the large discrepancies seen in the literature are arising due to inconsistent and incorrect use of CSA as a measurement tool of muscle size (51, 52).

V. Relationship between Thigh Circumference and Muscle Strength

At 10 cm superior to the base of the patella, there was an excellent correlation with the thigh circumference measurement and muscle strength for all three muscle groups, (r=0.93), again strengthening the finding as it was consistent between all three groups. These findings are much higher than any results found in the literature. Arangio et al in 1997 found a positive correlation between the quadriceps femoris and hamstring strength and thigh circumference in healthy limbs of individuals (mean age= 32.3 yrs), but did not report an r value (4). Cooper et al in 1981 found that serial measures at 5 and 10 cm (using both measures as opposed to only one), may be an index of quadriceps power, r=0.54 and r=0.70 respectively (78). Andrade et al in 2002 found a weak correlation between thigh circumference and muscle performance in individuals (mean age 32 ± 18 yrs) post ACL reconstruction, r=0.22-0.43 (3). Maylia et al in 1999 found no correlation between muscle power and thigh circumference in individuals with a mean age= 34.3 yrs (51, 52), and a few studies have shown no change in thigh circumference
measures with training (9, 36, 29). No studies have investigated an older population and therefore it is not appropriate to make direct comparisons with their findings.

The findings in this study indicate to therapists that the isometric strength of healthy, older individuals’ knee flexors, knee extensors, or hip adductors is strongly correlated with the measurement of thigh circumference taken at 10 cm superior to the base of the patella. This does not mean that changes in strength are reflected by changes in thigh circumference measure, only that the strength itself is related to the distance around the thigh. Further studies are needed to investigate whether or not measurements of thigh circumference can reflect a change in muscle strength during treatment, or after a training program in the thigh muscles of a healthy older population.

LIMITATIONS

The main limitation of this study was the small sample size, especially once the group was divided into genders. The next is what has been previously discussed, is that the use of MV gets closer to more accurately representing the contractile tissue present in a muscle, however it is still not as good as PCSA. Therefore the stereological method used in this study to measure MV needs to be used in combination with real-time ultrasound to accurately calculate the amount of contractile tissue present in each muscle. As discussed in the section on the relationship between muscle size and strength, the position of testing for the knee flexors may have limited the torque that was produced, as the hamstring muscles were in a shortened range. Finally, the method of calculating muscle volume would have been even less time-consuming if the Analyze Software Program would have allowed the calculation of several muscle volumes to be done at the same time, as opposed to only one.
CONCLUSION

It is important that rehabilitation programs, particularly those involving older individuals who may be at increased risk of falls, and hip and knee joint OA, incorporate the strengthening of all muscle groups that may play a role in decreasing these risk factors. In this study it was shown that for this group of healthy older individuals, the three primary muscle groups of the thigh (knee flexion, knee extension, and hip adduction), showed a strong correlation with one another in both size and strength. The three groups of muscles also showed an excellent correlation between isometric strength and muscle size, and were best represented by measures of thigh circumference at 10 cm superior to the base of the patella. The hip adductors, despite being the second largest muscle group of the thigh, were the weakest muscle, demonstrating the lowest muscle efficiency, as they did not produce much torque per unit volume.

Using stereology in combination with MRI as a reliable and valid measure of muscle volume, it was shown that in healthy older adults, there continues to be a strong relationship between the volume of the muscle and the force or torque that it can generate. Future studies need to combine this method with measurements of fiber pennation angle and length using real-time ultrasound to arrive at an even more accurate representative measure of muscle size, PCSA. Future research also needs to be done to determine whether differences in thigh circumference measurements taken at 10 cm superior to the base of the patella are indicative of change in muscle size and/or strength. Finally, more studies need to investigate the second largest thigh muscles, the hip adductors. The role of the hip adductors in lower extremity biomechanics should be investigated in order to assist individuals in preventing injury and maintaining function through effective rehabilitation programs.
REFERENCES


Ratios of Muscle Size, Strength, and Fatigue in a Healthy Older Population

INTRODUCTION

It is well understood, and has been well established in several subject groups, that imbalances in muscle strength and flexibility are associated with various athletic injuries (17, 28). In fact, the best predictor of a muscle strain injury is the strength ratio of the agonist to antagonist muscle groups (32). There is little doubt that the proper balance of strength in the muscles surrounding a joint assist in injury prevention by providing the necessary dynamic stability needed to assist the more static stabilizers within the joint itself, (i.e. ligaments) (4, 16, 29). The quadriceps and hamstrings have been the primary muscle groups investigated, with little focus on the relationships among other key muscles of the thigh. The main subjects studied have been healthy, young, athletic individuals, as opposed to older individuals. When we begin to look at aging muscle, we realize that this notion of there being a proper balance of muscle strength across joints, that can protect young healthy athletes from sustaining injuries, may also be important to individuals as they age, particularly with conditions such as osteoarthritis, or weakness post hip and knee surgery.

As noted above, the hamstrings to quadriceps ratio has been well investigated in a young healthy population, under a variety of contraction conditions (16). It has been shown that the strength of the hamstrings plays an important role as an antagonistic muscle against the quadriceps for stability of the knee, as well as protecting against excessive stress (4, 29). Normative data for this ratio has been established in young adults, and several studies have used this to investigate whether or not deviations from the norm result in certain injuries (4, 16, 25, 29). Common injuries, such as ACL reconstruction, have been thoroughly investigated, looking at the change that the reconstruction causes to this hamstring to quadriceps strength ratio, and how this may be corrected for, and/or avoided (29). Few studies were found in the
literature regarding normative strength ratios for older adults, and whether or not muscle imbalance around the knee joint puts these individuals at risk of injury.

Some studies have investigated the strength of the hamstrings and quadriceps in various knee pathologies and as such, treatment has focused on increasing the strength and decreasing the pain of these muscles, primarily the quadriceps (24, 36). However, clinical evidence of tenderness around the adductor tubercle of individuals with medial compartment knee osteoarthritis (30) led to an investigation into the role of the adductors in knee stability (36). In fact Yamada found no difference in the hamstring to quadriceps ratio between a control and an osteoarthritis group, yet found a significant difference in the adductor to hamstring ratio between the two groups (36). This suggests that the change in joint mechanics, caused by the location of the pathology, affected the strength of the hamstrings and/or adductors, rather than the quadriceps (36).

It is surprising that few studies have looked at hip weakness with various types of lower extremity pathology, since proximal core hip strength is needed for control of distal segments to prevent injury (27). Adequate strength of all hip muscles helps to balance important biomechanical forces in the body, for example, the adductors are important for limb position during pivoting and deceleration activities, as they stabilize and help to decelerate the limb (11, 27, 32). Even in running, the proximal risk factors have not been investigated (26). Some researchers have begun looking at hip abduction, but even fewer have investigated the role of the adductors of the hip, especially in an older population (14, 36).

Adductor weakness has been implicated in such conditions as post-ACL reconstruction, overuse injuries in runners, and adductor strains in hockey players (11, 27, 32), again this is in reference to a younger population. However, Yamada et al in 2001 did investigate an older population (mean age = 62.3 years in osteoarthritis (OA) group, and 60.5 years in control group), and found that the strength of the adductors in individuals with medial compartment knee OA changed as the severity of the disease progressed (36). This research group looked at
a ratio of adductor to hamstring strength and found that this ratio increased as individuals progressed through the different stages of knee OA. Another group looked at men with hip osteoarthritis (mean age = 56.2 ± 4.9 years), and found that hip isometric adductor strength was 25% lower in subjects with osteoarthritis than in controls, and the CSA of the pelvic and thigh muscles was 6-13% lower on the more severely affected hip (3). Therefore it is clear that further information regarding the level of adductor and hamstring strength expected in a healthy older population would provide useful information when treating individuals at risk of, or with, these types of pathologies.

Another component of rehabilitation programs, in addition to muscle strength, is muscle endurance. As we age, it is critical that we maintain the strength necessary to accomplish a task, as well as the muscle endurance required to complete an entire activity, allowing an individual to function over the course of an entire day. Therefore in the investigation of the ratio of hamstring : quadriceps, and adductor : hamstrings isometric muscle strength, the ratio of endurance time in a fatiguing task for hamstrings : quadriceps was also investigated. It is important to determine whether or not similar relationships exist between the antagonist and agonist muscle groups in a different type of functional muscle activity. Physiotherapists involved in the treatment of older adults would benefit from understanding the strength relationships that exist between the major muscle groups of the thigh as well as how the muscles relate in a more functional aspect. A ratio of hamstring to quadriceps endurance time would help to achieve this.

The purpose of this study was to establish normative strength and volume measurements for the adductors, hamstrings, and quadriceps muscles in a healthy older population, and to investigate the relationship between these muscle groups through the use of two ratios; hamstring to quadriceps, and adductor to hamstrings. In addition, a more functional ratio, the dynamic control ratio (31) will be calculated for this population, to investigate the eccentric strength of the hamstrings as compared to the concentric strength of the quadriceps (31). Further expanding on the functional comparisons between these two major muscles...
groups, a hamstring to quadriceps ratio of endurance time will be calculated. Having a clear understanding of these normative values will assist physiotherapists in the treatment of individuals, both helping to maintain and prevent deterioration of function as they age, as well as helping to identify those at risk of injury or progressing disease.
METHODS

Subjects

The description of the subjects who participated in this study has been reported in Chapter 2.

Muscle Volume

Stereological methods were used in combination with MRI to obtain measurements of MV for all thigh muscles in the described subject group. Details on the method used can be found in Chapter 2.

Muscle Strength

Instrumentation and methods of strength testing used in this study can be found in Chapter 2.

Muscle Fatigue

Details of the method used to measure hamstring fatigue using EMG and Kin-Com dynamometry, as well as the reliability, can be found in Chapter 4.
RESULTS

I. Muscle Size & Muscle Strength

Please see Table 2.1 and Table 2.2a and 2.2b in Chapter 2 for the muscle volume and muscle strength data, including group and gender averages.

a. Ratios of Muscle Volume

Muscle Volume ratios for all subjects are listed in Table 3.1a, with group and gender averages listed in Table 3.1b.

i. Hamstring : Quadriceps Ratio

The average ratio of total knee flexor muscle volume (hamstrings, sartorius, gracilis) to total knee extensor muscle volume (quadriceps, sartorius) was found to be 0.509 ± 0.059, and the average ratio of hamstring muscle volume to quadriceps muscle volume was determined to be 0.410 ± 0.054.

ii. Adductor : Hamstrings Ratio

The average ratio of total hip adductor muscle volume (adductors, pectineus, gracilis) to total knee flexor muscle volume (hamstrings, sartorius, gracilis) was found to be 1.034 ± 0.105, and the average ratio of adductor muscle volume (adductors, pectineus) to hamstrings muscle volume was determined to be 1.266 ± 0.139.

b. Ratios of Muscle Strength

Muscle strength ratios for all subjects are listed in Table 3.2a, with group and gender averages listed in Table 3.2b.
Chapter 3 - Results

i. Isometric

The average knee flexor to knee extensor strength ratio for an isometric contraction was
0.410 ± 0.091. The average hip adductor to knee flexor strength ratio for an isometric
contraction was 0.373 ± 0.075.

ii. Concentric

The average knee flexor to knee extensor strength ratio for a concentric contraction
measured at 30 deg/sec was 0.769 ± 0.404.

iii. Eccentric

The average knee flexor to knee extensor strength ratio for an eccentric contraction
measured at 30 deg/sec was 0.691 ± 0.372.

iv. Eccentric/Concentric – Dynamic Control Ratio (DCR)

The eccentric torque of the hamstrings was divided by the concentric torque of the
hamstrings in order to arrive at a DCR for this healthy older population (31). The Hamstring_{eccen}:
Quadriceps_{conce} for the group was 1.16 ± 0.627. For ratios for each subject, as well as gender
averages, please see Table 3.2a and 3.2b.
II. Muscle Endurance

a. *Ratios of Endurance Time*

When looking at the ratios of endurance time for the 80% MVC contraction for the knee flexors : knee extensors, a ratio of 1.74 ± 1.51 was found. Please refer to Table 3.3a and 3.3b for all data and group and gender averages. One subject had a ratio of 5.82, defined as an outlier, and when this one data point was removed, the standard deviation was not as high, and the ratio was determined to be 1.28 ± 0.51.

The men had a lower endurance time than the women for the knee flexors, whereas the women had a lower endurance time than the men for the knee extensors. The ratio of endurance times was very close when the outlier was removed from the calculations, as the women's ratio changed from 2.2 ± 1.8 to 1.2 ± 0.4.

Initially there was little to no relationship found between the endurance time of the knee flexors and the knee extensors, r=-0.013, see Figure 3.1. However an outlier was present, and when this was removed, the new relationship was found to be moderate to good, see Figure 3.2.

b. *Relationships between Muscle Strength, Size & Endurance Time*

i. Volume & Fatigue

For the knee flexors, little to no correlation was found between the endurance time (sec) and both the total knee flexor, and hamstring muscle volume. The r values were -0.212 and -0.248 respectively, see Figure 3.3.

However for the knee extensors, a fair degree of correlation was found between the endurance time (sec) and both the total knee extensor, and quadriceps muscle volume. The r values were 0.362 and 0.370 respectively, see Figure 3.4.
ii. Strength & Fatigue

When investigating the possible relationship between isometric strength and endurance time, an opposite relationship was found for the knee flexors and knee extensors. Isometric knee flexor strength was moderately negatively correlated with endurance time, $r=-0.396$, see Figure 3.5, whereas isometric knee extensor strength showed a fair degree of correlation with endurance time, $r=0.429$, see Figure 3.6.
### Table 3.1a: Muscle Volume Ratios

<table>
<thead>
<tr>
<th>Subject</th>
<th>Knee Flexor : Knee Extensor</th>
<th>Hamstring : Quadricep</th>
<th>Hip Adductor : Knee Flexor</th>
<th>Adductor : Hamstring</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.501</td>
<td>0.403</td>
<td>0.932</td>
<td>1.161</td>
</tr>
<tr>
<td>2</td>
<td>0.620</td>
<td>0.511</td>
<td>0.978</td>
<td>1.185</td>
</tr>
<tr>
<td>3</td>
<td>0.452</td>
<td>0.350</td>
<td>1.015</td>
<td>1.280</td>
</tr>
<tr>
<td>4</td>
<td>0.569</td>
<td>0.471</td>
<td>0.996</td>
<td>1.152</td>
</tr>
<tr>
<td>5</td>
<td>0.441</td>
<td>0.353</td>
<td>1.146</td>
<td>1.414</td>
</tr>
<tr>
<td>6</td>
<td>0.488</td>
<td>0.383</td>
<td>1.130</td>
<td>1.436</td>
</tr>
<tr>
<td>7</td>
<td>0.481</td>
<td>0.400</td>
<td>1.180</td>
<td>1.413</td>
</tr>
<tr>
<td>8</td>
<td>0.563</td>
<td>0.455</td>
<td>0.864</td>
<td>1.058</td>
</tr>
<tr>
<td>9</td>
<td>0.521</td>
<td>0.420</td>
<td>0.977</td>
<td>1.163</td>
</tr>
<tr>
<td>10</td>
<td>0.452</td>
<td>0.350</td>
<td>1.123</td>
<td>1.394</td>
</tr>
</tbody>
</table>

Ratios for Knee Flexors, Knee Extensors, and Hip Adductors, include the muscle volume of all muscles contributing to that action.

### Table 3.1b: Muscle Volume Ratios – Group and Gender Averages

<table>
<thead>
<tr>
<th>Group</th>
<th>Knee Flexor : Knee Extensor</th>
<th>Hamstring : Quadricep</th>
<th>Hip Adductor : Knee Flexor</th>
<th>Adductor : Hamstring</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average</strong></td>
<td>0.509</td>
<td>0.410</td>
<td>1.034</td>
<td>1.266</td>
</tr>
<tr>
<td><strong>St Dev</strong></td>
<td>0.059</td>
<td>0.054</td>
<td>0.105</td>
<td>0.139</td>
</tr>
<tr>
<td><strong>Men</strong></td>
<td>0.486</td>
<td>0.385</td>
<td>1.039</td>
<td>1.297</td>
</tr>
<tr>
<td><strong>St Dev</strong></td>
<td>0.055</td>
<td>0.049</td>
<td>0.130</td>
<td>0.174</td>
</tr>
<tr>
<td><strong>Women</strong></td>
<td>0.524</td>
<td>0.427</td>
<td>1.031</td>
<td>1.245</td>
</tr>
<tr>
<td><strong>St Dev</strong></td>
<td>0.061</td>
<td>0.055</td>
<td>0.098</td>
<td>0.124</td>
</tr>
</tbody>
</table>

Ratios for Knee Flexors, Knee Extensors, and Hip Adductors, include the muscle volume of all muscles contributing to that action.
Table 3.2a: Muscle Strength Ratios

<table>
<thead>
<tr>
<th>Subject</th>
<th>Isometric</th>
<th>Ratios</th>
<th>Dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hamstring :</td>
<td>Concentric</td>
<td>Eccentric</td>
</tr>
<tr>
<td></td>
<td>Quadriceps :</td>
<td>Hamstring :</td>
<td>Quadriceps :</td>
</tr>
<tr>
<td></td>
<td>Adductor :</td>
<td>Quadriceps</td>
<td>Hamstring :</td>
</tr>
<tr>
<td></td>
<td>Hamstring :</td>
<td>Quadriceps</td>
<td>Eccentric :</td>
</tr>
<tr>
<td>1</td>
<td>0.338</td>
<td>1.077</td>
<td>1.213</td>
</tr>
<tr>
<td>2</td>
<td>0.469</td>
<td>0.211</td>
<td>0.217</td>
</tr>
<tr>
<td>3</td>
<td>0.457</td>
<td>0.737</td>
<td>0.716</td>
</tr>
<tr>
<td>4</td>
<td>0.581</td>
<td>1.254</td>
<td>1.310</td>
</tr>
<tr>
<td>5</td>
<td>0.408</td>
<td>0.348</td>
<td>0.267</td>
</tr>
<tr>
<td>6</td>
<td>0.429</td>
<td>1.075</td>
<td>0.680</td>
</tr>
<tr>
<td>7</td>
<td>0.433</td>
<td>0.640</td>
<td>0.832</td>
</tr>
<tr>
<td>8</td>
<td>0.398</td>
<td>0.687</td>
<td>0.483</td>
</tr>
<tr>
<td>9</td>
<td>0.346</td>
<td>0.322</td>
<td>0.373</td>
</tr>
<tr>
<td>10</td>
<td>0.241</td>
<td>1.343</td>
<td>0.822</td>
</tr>
</tbody>
</table>

Only isometric strength was tested for the hip adductors. Dynamic refers to the Dynamic Control Ratio (DCR) defined in the results section.

Table 3.2b: Muscle Strength Ratios – Group and Gender Averages

<table>
<thead>
<tr>
<th>Group</th>
<th>Isometric</th>
<th>Ratios</th>
<th>Dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hamstring :</td>
<td>Concentric</td>
<td>Eccentric</td>
</tr>
<tr>
<td></td>
<td>Quadriceps :</td>
<td>Hamstring :</td>
<td>Quadriceps :</td>
</tr>
<tr>
<td></td>
<td>Adductor :</td>
<td>Quadriceps</td>
<td>Hamstring :</td>
</tr>
<tr>
<td></td>
<td>Hamstring :</td>
<td>Quadriceps</td>
<td>Eccentric :</td>
</tr>
<tr>
<td>Average</td>
<td>0.410</td>
<td>0.769</td>
<td>0.691</td>
</tr>
<tr>
<td>St Dev</td>
<td>0.091</td>
<td>0.404</td>
<td>0.372</td>
</tr>
<tr>
<td>Men</td>
<td>0.423</td>
<td>0.712</td>
<td>0.536</td>
</tr>
<tr>
<td>St Dev</td>
<td>0.026</td>
<td>0.298</td>
<td>0.207</td>
</tr>
<tr>
<td>Women</td>
<td>0.401</td>
<td>0.808</td>
<td>0.795</td>
</tr>
<tr>
<td>St Dev</td>
<td>0.119</td>
<td>0.485</td>
<td>0.437</td>
</tr>
</tbody>
</table>

Only isometric strength was tested for the hip adductors. Dynamic refers to the Dynamic Control Ratio (DCR) defined in the results section.
### Table 3.3a: Endurance Time and Ratios

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Endurance Time (sec)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Knee Flexors</td>
<td>Knee Extensors</td>
</tr>
<tr>
<td>1</td>
<td>128</td>
<td>22</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>59</td>
<td>47</td>
</tr>
<tr>
<td>4</td>
<td>43</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>23</td>
<td>42</td>
</tr>
<tr>
<td>6</td>
<td>27</td>
<td>39</td>
</tr>
<tr>
<td>7</td>
<td>51</td>
<td>36</td>
</tr>
<tr>
<td>8</td>
<td>85</td>
<td>46</td>
</tr>
<tr>
<td>9</td>
<td>45</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>72</td>
<td>61</td>
</tr>
</tbody>
</table>

Endurance Time = time subject able to hold isometric contraction at 80% of MVC for that muscle group

### Table 3.3b: Endurance Time and Ratios – Group & Gender Averages

<table>
<thead>
<tr>
<th>Group</th>
<th>Endurance Time (sec)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Knee Flexors</td>
<td>Knee Extensors</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>56.3</td>
<td>38.2</td>
</tr>
<tr>
<td><strong>St Dev</strong></td>
<td>32.0</td>
<td>14.1</td>
</tr>
<tr>
<td><strong>Men</strong></td>
<td>48.5</td>
<td>43.5</td>
</tr>
<tr>
<td><strong>St Dev</strong></td>
<td>29.2</td>
<td>34.7</td>
</tr>
<tr>
<td><strong>Women</strong></td>
<td>61.5</td>
<td>34.7</td>
</tr>
<tr>
<td><strong>St Dev</strong></td>
<td>35.4</td>
<td>17.7</td>
</tr>
</tbody>
</table>

Endurance Time = time subject able to hold isometric contraction at 80% of MVC for that muscle group
Figure 3.1: Relationship between Knee Flexor and Knee Extensor Endurance Times

Endurance time is the length of time that the muscle group held the 80% MVC contraction. Point defined as an outlier was 120, 22.

Figure 3.2: Relationship between Knee Flexor and Knee Extensor Endurance Times, (without outlier)
Figure 3.3: Relationship between Knee Flexor Muscle Volume and Endurance Time

Endurance time is the length of time that the knee flexors held and 80% MVC contraction. Muscle Volume is the volume of the hamstrings, sartorius, and gracilis.

Figure 3.4: Relationship between Knee Extensor Muscle Volume and Endurance Time

Endurance time is the length of time that the knee flexors held and 80% MVC contraction. Muscle Volume is the volume of the quadriceps, and sartorius.
Figure 3.5: Relationship between Knee Flexor Strength and Endurance Time

Endurance time is the length of time that the knee flexors held an 80% MVC contraction. Isometric strength is the MVC measured at 60 degrees of knee flexion.

Figure 3.6: Relationship between Knee Extensor Strength and Endurance Time

Endurance time is the length of time that the knee extensors held an 80% contraction. Isometric strength is the MVC measured at 90 degrees of knee flexion.
DISCUSSION

I. Muscle Size & Muscle Strength

a. Ratios of Muscle Volume & Muscle Strength

i. Hamstring : Quadriceps

The findings in this study indicate, or suggest, that an isometric hamstring : quadriceps ratio of 0.41 is normal in this small, but healthy older population. This ratio indicates that the torque of the hamstring strength was 41% ± 9% of the torque produced by the quadriceps. The ratio of muscle volume between the hamstring and quadriceps was interestingly similar to that of the strength for these muscles (0.51 was the group average), however no studies were found that reported on the ratio between hamstring and quadriceps muscle volume. Only one study was found looking at muscle strength in healthy older individuals and that was by Murray et al in 1980, whose findings were similar to those in this study (26). They looked at 72 healthy men divided into 3 age groups, (20-35, 50-65, 70-86 yrs) and found isometric hamstrings : quadriceps ratios for the older two groups (strength measured at 60 degrees knee flexion and extension), of 0.43 and 0.46 (26).

It was difficult to compare the findings of this study to other findings in the literature, as the other values of hamstring : quadriceps ratio located were for young, athletic individuals, either healthy, or with a common sporting injury (7, 8, 25, 30). Kellis et al in 1995 summarized some of the literature on hamstring : quadriceps ratio and reported generally accepted normative values as 0.60 (possibly as low as 0.51) for an isometric contraction (16). However they stated that there is a great deal of variability in the literature, and that ratios will differ as angular velocity (for isokinetic), position (for isometric), and the patient population changes (16). They also noted the importance of using gravity correction when testing muscle strength as a means to decreasing some of the variability (16).
In this study, the concentric strength ratios for hamstring : quadriceps were 0.81 for women, and 0.71 for men, and the eccentric strength ratios were 0.80 for women, and 0.54 for men for eccentric. The values obtained in this study are different than the isokinetic concentric (30 degrees/second) hamstring : quadriceps ratios reported by Murray et al in 1980 of 0.54 (men age 50-65 yrs) and 0.55 (men aged 70-86 yrs) (26). The values in this present study are more similar to those reported by Colliander et al in 1989, at least for the men (7). However, the age of their subjects was much younger, with a mean of 27 yrs. Colliander et al found at 30 deg/sec, a concentric hamstring : quadriceps ratio of 0.59 for females and 0.58 for males, and an eccentric hamstring : quadriceps ratio of 0.48 for females and 0.51 for males (7), which are comparable to other values cited in the literature, by other researchers, for younger age groups (2, 12, 35). Frontera also reported isokinetic concentric hamstring : quadriceps ratios in an older population, however their measurements were done at 60 degrees/second, giving a ratio of 0.58 for men and 0.53 for women, aged 55-64 (10). These are also different from the ratios observed in this study. Colliander et al found that the isokinetic strength ratio varied depending on the muscle action and speed at which it was studied (7), which has been supported by others (16). However, there is some conflicting evidence on whether increases in velocity cause ratios to increase (35) or decrease (25).

It is felt that the findings in this study may differ from those in the literature given that there is such a small sample size, with a large amount of variability (standard deviation) in the results. However, it is of interest to note that the women maintained a similar level of strength even with an eccentric contraction. For example, the women maintained a ratio of approximately 0.80 for hamstring : quadriceps strength for both concentric and eccentric contractions, while the men dropped to a ratio of 0.54, from the concentric hamstrings : quadriceps ratio of 0.71. This indicates that the women maintained the eccentric strength of their hamstrings better than the men, supporting the hypothesis that women maintain eccentric strength as they age (5, 21, 22).
For this population a dynamic control ratio (DCR) was calculated, dividing the maximal eccentric strength of the hamstrings by the maximum concentric strength of the quadriceps as discussed by Tourny-Chollet et al in 2002 (31). This ratio investigates the ability of the hamstrings to act as a break during a maximal extension of the quadriceps (31), similar to that found during the swing phase of the gait cycle (18). This is important, as the co-activation of the hamstrings is an important factor in maintaining the stability of the knee joint, and reducing tension on the ACL (1, 16). Since knee extension during gait, or during an action such as kicking a soccer ball, is an open-chain activity, there is little to control the powerful action of the quadriceps, other than the eccentric action of the hamstrings (31). The DCR takes the common ratio of hamstring to quadriceps strength and expands on it, looking at a specific activity of the pair of muscles in a more dynamic, and therefore, functional manner.

Tourny-Chollet measured this DCR strength ratio at 60 deg/sec and reported a ratio of 0.80 for soccer players aged 22 ± 2.85 yrs, and 0.93 for sedentary subjects aged 22.9 ± 2.06 yrs (31). Jonhagen et al in 1994 reported a DCR of 0.55 at 30 deg/sec in sprinters, and determined that this ratio increased with increasing angular velocity (15).

A normative DCR seems to depend on the population of interest (31). The ratio obtained will reflect the muscular demands of an individual’s particular lifestyle or sporting interest (31). For example, with soccer players the DCR is lower due to a higher concentric torque of the quadriceps, developed as a result of training involving running and large amounts of kicking activities (31). It has been quoted in the literature that if the ratio is below 0.75, there is a need to strengthen the eccentric action of the hamstrings, as it is weak (6). In this study, the average group DCR was 1.2, with the men at 1.1 and the women at 1.2. This indicates that the subjects in this study were able to produce a larger eccentric torque with their hamstrings than concentric torque with their quadriceps. A DCR for older adults was not found in the literature, however given the changes that occur in the biomechanics of knee joints with certain pathologies
common to older individuals (i.e. OA), it may be of some use to begin calculating a strength ratio that reflects the dynamic roles of the muscles and that provides more functional information.

Normative hamstring : quadriceps ratios that express the strength of the hamstrings to that of the quadriceps exist as a means to maintaining optimal joint alignment and mechanics, therefore preventing soft tissue injuries of the surrounding structures (i.e. ligaments, meniscus etc) (2, 4, 29). This normative ratio exists, (and changes), for different conditions such as joint angle, speed of contraction and contraction type (2, 16, 31). These variables represent different loads through the joint and lower extremity, therefore requiring different amounts of strength from the agonist and antagonist to maintain proper joint alignment (16). It is therefore postulated by the author of this study that since aging is a variable that affects muscle strength (atrophy), and may affect joint alignment and function through conditions such as OA, it is important to establish normative hamstring : quadriceps strength ratios for a healthy older population. Although Highgenboten et al in 1988 reported no effect of age or sex on flexion/extension ratios, the oldest subject that they looked at was 34 years old (12). There may be a significant effect of aging on these flexion/extension ratios and therefore we cannot compare the strength ratios of older individuals to the ratios obtained in young, healthy athletes. If these were established, then therapists would have a better idea as to the muscle balance and strength required in the lower extremities of older individuals to prevent injury and deterioration of function.

\[ ii. \text{Adductor} : \text{Hamstrings} \]

Recent studies have begun looking at other strength relationships in the thigh, such as the relationship between the hamstrings and the adductors (36). Therefore in this study, the adductor : hamstrings ratio was calculated and found to be 0.37 for the group, 0.41 for women, and 0.32 for men. This indicated that for the group, the torque produced by the hip adductors was 37% ± 7.5% of the torque produced by the hamstrings. Yamada et al in 2001 looked at the
hip adductor muscle strength in patients with varus deformity of the knee due to OA (36). They found control subjects (mean = 62.3 years), to have an isometric adductor : hamstrings ratio of 0.59, and that individuals with knee joint OA started at this ratio, which increased as the severity of the knee joint OA increased (36). Arokoski et al found that in 27 men, mean = 56.2 years with hip OA, hip adductors strength decreased by 25-31% in individuals with hip joint OA (3).

Unfortunately an adductor : hamstrings ratio was not calculated as hamstring strength was not tested. The difference in ratios between this study and the findings of Yamada et al may be due to the testing position. Yamada et al tested their subjects in sitting, while in this study the subjects were tested in standing, a more functional position (36). Other researchers have commented on the presence of variability when testing movements of the hip, and have hypothesized that the differences observed are likely due to testing position (3).

A very different ratio was observed when the muscle volume of the hip adductors was divided by the muscle volume of the knee flexors. If the total volumes were used, then an average group ratio of 1.03 was found, however if only the volume of the prime movers was used a ratio of 1.25 was found. Either way, this differed substantially from the strength ratio of 0.37. It is felt that this reflects the contrasting structural skeletal anatomy and intrinsic (architectural) properties of the hip adductors versus the knee flexor muscles. The hamstrings (primary knee flexor) are built for speed and execution over a large joint range (as they cross two joints), and therefore have long muscle fibers and some angle of fiber pennation (19). Yet the adductors, despite crossing only one joint, also have some very long fibers and large pennation angles (19). The difference lies in the length of the lever arm (the distance from the skeletal structure with which the muscles are attached to) (19). The adductors appear to be designed for force production, yet are placed in the lower extremity in such a way that the short moment arm with which they work limits the extent of the force that they can produce (37, pg
In chapter 2, the muscle efficiency of the adductors was calculated to be very low, which is reflected here in the difference of ratios of muscle size and muscle strength.

Clinically, it is important to know the efficiency of a particular muscle group, or the amount of force that it can produce for a given amount of contractile tissue, so that correct assumptions are made regarding the size of the muscle and how that may translate into strength. Recognizing that the adductors have a short lever arm, one would expect a lower force from them, given their overall size (34). Therapists should ensure that strengthening occurs throughout range and is accompanied by frequent stretching to ensure that the range does not become limited, putting the muscle at more of a disadvantage.

Regardless of the increased difficulty and thus variability in testing movements of the hip, a greater amount of focus needs to be placed on researching hip muscle strength in a healthy older population, and establishing strength ratios such as that discussed above, adductor : hamstrings. The adductors are a muscle group that acts at the hip joint, contributing to movements of hip adduction, flexion and extension, (9), that are involved in postural control (14), and that are also involved in pelvic and trunk stability, and in preventing knee and ankle overuse injuries by providing a stable core from which the distal segments can work (27). Therefore, if pathology exists at either the hip, or the knee joint (such as hip or knee OA that often occurs in old age), there is evidence that the adductors will be affected in some way (3, 35).

For example, in hip OA, Arokoski showed that the strength of the hip adductors decreased by 25-31% in individuals affected with this condition (3). The decrease in strength of the hip adductors could be attributed to a neurological feedback mechanism whereby the increased hip pain causes a reflex decrease in neurological input/weakness in muscles around the hip, resulting in selected atrophy of type II fibers, disuse atrophy, and fear of movement (3). A ratio with hamstring strength was not calculated, however one might assume that if adductor
strength decreased and hamstring strength remained the same, then individuals with hip OA would demonstrate a lower adductor:hamstrings ratio.

In the study by Yamada et al, the adductor ratio was found to increase in individuals with knee OA (36). There it was postulated that the knee joint pathology resulted in an increase in adductor strength (in contrast to above), as the adductors were trying to prevent, or correct for, the varus deformity that was occurring as a result of the OA presenting in the medial compartment of the knee joint (36).

Knowledge of a normative strength ratio for adductor:hamstrings in an older population would be helpful to therapists treating individuals in both situations of hip or knee OA. Deviation from the expected normative ratio, in either direction, could be detected and possibly prevented. Investigating the hip adductors further and establishing stronger evidence for the effect of common lower extremity pathologies on this ratio would assist therapists in designing rehabilitation programs aimed at improving function and protecting against further deterioration and injury. Increasing the strength of the hip adductors in an individual with hip OA, and therefore restoring a normal adductor:hamstrings strength ratio may increase function and decreased pain and further changes in the integrity of the hip joint.

II. Muscle Endurance

a. Endurance Time

Knee Flexion:Extension Ratios

Both the group and males and females demonstrated longer endurance times for the knee flexors as compared to the knee extensors. The group was able to hold an 80% MVC contraction with their knee flexors for 56.3 seconds, however were only able to hold an 80% MVC contraction with their knee extensors for 38.2 seconds. Since the contraction was high, 80% of MVC, there was no preferential activation or use of type I versus type II fibers, according
to Lieber (19, pg. 87). Both fiber types are being activated to maintain the contraction, therefore the difference in the ability of the hamstrings and quadriceps to maintain this contraction lies in the length of time it takes the neuromuscular junction to fatigue (19, pg 87). It may also be that that the ATP and/or creatine phosphate levels in the hamstring muscles were greater than that of the quadriceps, allowing the hamstrings to maintain a longer endurance time due to the greater supply of energy (19, pg 102-103). In comparison, the knee extensors had to maintain a higher force than the knee flexors during the endurance task, because the MVC of the knee extensors was greater, they were the stronger muscle group. However this cannot be a reason why the knee extensors did not hold the contraction as long, because the force was relative, each muscle group was attempting to hold 80% of the MVC of that muscle group.

The average group ratio of knee flexion : knee extension endurance time was 1.74, as compared to the isometric strength ratio of 0.41. This clearly indicates that muscle endurance and muscle strength are very different functional properties of the muscle. Therapists can not make assumptions about muscle endurance simply by testing the isometric strength of the muscle. With respect to strength, the individuals in this study demonstrated greater quadriceps as compared to hamstring strength, however with respect to muscle endurance; the hamstrings were able to maintain a contraction longer than the quadriceps. The structure (architectural properties) of the muscle may differ as well as the utilization of energy (ATP).

When the relationship of the endurance time of the knee flexors was compared to that of the knee extensors (see Figure 3.1), and the outlier was removed (see Figure 3.2), moderate to good relationship was observed. Despite each muscle group showing difference endurance times, they are both primary muscles of the lower extremity, and one would expect that with normal activities of daily living, there would be some degree of relationship between the endurance of these two muscles. Functionally, it would not make sense if there wasn’t, as individuals can not use one muscle group without using the other during the course of the day.
b. Relationships between Muscle Strength, Size & Endurance Time

When the relationship of muscle volume, isometric strength and endurance times of the knee flexors and knee extensors was investigated, no relationship was observed for the knee flexors, and only a fair degree of relationship was observed for the knee extensors, for both volume and strength. It may be that the strength values obtained for the knee flexors were not the maximum that could be generated by that muscle, given the position of testing, therefore accounting for the absence of relationship with the knee flexors. This is discussed in chapter 2 in the section on the relationship between muscle size and strength. A strong relationship between muscle size and/or isometric strength and endurance times was not expected, as strength and volume reflect different characteristics of the muscle. The physiology of muscle endurance is discussed below, suggesting possible reasons why there may not be a direct and strong relationship between muscle size and muscle endurance.

The contraction performed was 80% of the muscle groups MVC, therefore the hamstrings were required to hold a lower force than the quadriceps, yet the forces were relative to the overall capabilities of the muscle. The maximum contraction time for the knee flexors was 128 seconds, just over two minutes, whereas for the knee extensors, it was 61 seconds, just over one minute. Both muscles were relying on their anaerobic systems to provide the energy given the intensity of the contraction (23, pg 129). At one minute it is likely that both muscles moved from 90% anaerobic to approximately 70% anaerobic and 30% aerobic, and the hamstrings, at the two-minute mark were likely obtaining 50% of their energy from each system (23, pg 129). The muscles were likely using the ATP stored in the muscle, creatine phosphate present, and they were beginning to use stored muscle glycogen through anaerobic glycolysis to generate ATP (23). This system does not require oxygen and is used in the situation of short-term, high intensity work. In the hamstrings, a greater demand was beginning to be placed in the aerobic system to start to provide ATP (as oxygen levels would have been depleting and
there would have been a build up of lactic acid) (22, pg 196). In both muscles, type I and type II fibers were likely being recruited given the intensity of the contraction (19). Since so much of a muscles ability to maintain a contraction depends on the presence, use, and ability to generate ATP, it was not expected that the muscle size or its isometric strength would be related to the length of time that it could hold a contraction. It seems from the physiology that endurance times should have a stronger relationship to muscle glycogen or muscle ATP levels, as opposed to muscle volume.

The ability of a muscle to voluntarily generate force not only includes the burning of energy and its source, but also CNS processes and the transfer of the action potential along motor neurons and into the neuro-muscular junction (33). The next step in the generation of force production, such as the amount of Ca\(^{2+}\) released into the cytosol and its binding to troponin and subsequent cross-bridge formation, could also be an area of difference between the knee flexors and knee extensors that resulted in a difference of endurance times (33). All of these factors are in addition to the size of the muscle. Therefore, clinically, the difference between muscle size, strength and endurance times needs to be remembered, at the same time understanding some of the architectural basis and physiological processes behind the function of interest. A large isometric contraction of the quadriceps does not imply good endurance, and a ratio of 0.41 for isometric strength of the hamstring : quadriceps does not imply that the same relationship exists with respect to endurance, as evidenced by the results in this study.

LIMITATIONS

The primary limitation in this study is the small sample size, particularly when the sample was divided into genders. With respect to the ratios obtained, more information would have been gathered if the concentric and eccentric strength ratios had been calculated with different speeds of angular velocity. There are discrepancies in the literature as to the effect that
increasing the angular velocity has on the strength ratio, therefore calculating this ratio at
different velocities in this age group may have added to the findings. For other study limitations,
please see limitations in chapter 2.

CONCLUSION

In this group of healthy older adults, a hamstring : quadriceps ratio of 0.41 was observed
for isometric strength and a similar ratio was observed for muscle volume. However despite an
adductor : hamstrings ratio of 0.37, a muscle volume ratio of 1.03 was found. This demonstrates
the low muscular efficiency of the adductors. Despite their architectural properties designed for
force production, their placement in the skeletal system with a short lever arm has limited how
much force they can produce. The ratio of endurance time for an 80% MVC contraction of the
knee flexors to knee extensors was 1.74, highlighting the difference in muscle function when
different functional muscle properties are investigated.

These findings indicate to therapists that there are specific relationships between
different muscle groups of the thigh, as well as between different types of functional muscle
properties. Future studies need to establish normative hamstring : quadriceps and adductor :
hamstrings ratios in a larger subject group of healthy older individuals in order for therapists to
be able to create an effective rehabilitation program of injury prevention and maintenance of
function. Research also needs to look more closely at common lower extremity pathologies in
older individuals and investigate the possibility of deviations of these strength ratios from the
norm.
REFERENCES


Reliability of Surface EMG during a Submaximal Isometric Contraction of the Hamstrings

INTRODUCTION

Muscle fatigue has been defined as 'any reduction in the maximal capacity to generate force or power output' (2, 49). The methods used to quantify muscle fatigue during a muscular contraction vary from recording the endurance time - time taken to the failure of the task (usually holding a specified percentage of a maximum voluntary contraction (MVC)) (32, 33, 42), to counting the number of repetitions an individual is able to repeatedly perform of a single muscle group over time (28, 49, 54). Both methods, some investigators would argue, are performance measures, which are cognitively perceived (25). Therefore, test results could be affected, as these measures are susceptible to voluntary control on behalf of the subject (25). Another method that is widely used to measure muscle fatigue, that allows access to the physiological process occurring in the muscle, thereby bypassing some of the cognitive complications, is surface electromyography (EMG) (25). EMG is a non-invasive method that 'comprises the sum of the electrical contributions made by the active motor units of the muscle' (12), and has been used to investigate the central and peripheral properties of the neuromuscular system using a number of muscles throughout the human body (12), including the lumbar paraspinals (21) as well as muscles of the extremities, such as the quadriceps (42), and hand muscles (41).

The hamstrings are a group of muscles that originate from the ischial tuberosity and lie on the posterior aspect of the leg (58). The semimembranosus and semitendonosus muscles comprise the medial hamstring muscle group as they insert onto the medial aspect of the tibia (58). The biceps femoris muscle, which comprises the lateral hamstring muscle group, is divided into the long and short head, (the latter which arises from the shaft of the femur), which converge to attach over the medial aspect of the tibia (58). The hamstrings as a group are innervated by the tibial portion of the sciatic nerve, with the short head of biceps femoris
receiving innervation from the common peroneal division (58). As a group the hamstrings act at the hip joint to produce hip extension, and at the knee joint to produce knee flexion, as well as a minor role in tibial internal and external rotation. This need of the hamstring muscle to be of sufficient length to cover a large joint range is reflected in the architecture of the muscle. The hamstrings as a group have long fibers, which not only allow for this excursion, but also allow the muscle to act quickly to counteract the power of the quadriceps (59). With regards to muscle size, the hamstrings are approximately 40% of the quadriceps volume (see chapter 2 and 3), making it the third largest muscle group in the thigh (see chapter 2).

The anatomical and functional complexities of the hamstring muscles make it susceptible to hamstring strains or pulls (53). This is a common injury in sports that involve rapid active knee extension, (sprinting, soccer, football, rugby), and/or activities involving positions of maximal muscle lengthening, (martial arts, dance) (7, 16, 17, 23). It is hypothesized that the hamstrings are often injured during eccentric contractions of the muscles, as they are trying to act as a break for the quadriceps, as the greatest amount of force is generated during an eccentric-type contraction (53, 59). Among the risk factors cited, hamstring fatigue has been identified as a predisposing factor for hamstring strains (8, 53). However despite the prevalence of this injury, (Orchard et al in 2001 discovered that in an Australian Football League, 18% of injuries in a 22 match season with 40 players were hamstring strains, with a 34% recurrence rate (38), evidence is lacking regarding the risk factor of primary importance, with hamstring fatigue receiving the least amount of attention (38, 52, 53). The studies that have investigated hamstring fatigue have done so using performance-based measures as discussed above (27, 28). No studies have been found that have combined the use of EMG with a tool that is valid and reliable in measuring muscle strength, such as isokinetic dynamometry (20, 35). Not only has hamstring fatigue been cited as a risk factor for hamstring strains, but it has also been found to affect the dynamic stability of the knee, altering the neuromuscular response to anterior
tibial translation (54). A protocol to accurately and reliably measure hamstring fatigue would be useful in the investigation of more than one type of lower extremity pathology.

In order to fully understand or investigate the hamstrings, both the medial and lateral hamstring muscle groups need to be investigated separately, the assumption that they work equally under various conditions simply cannot be made (13, 14). Just as differences have been found in the muscle activity of vastus medialis and vastus lateralis of the quadriceps, there may also be similar differences in the medial and lateral hamstring components (24, 42). During a fatiguing contraction, the hamstring muscle may alternate activity between components of the same group, therefore it would be incorrect to analyze one muscle of a group and use it to characterize the group as a whole (10, 44). As noted by Fiebert et al (13), cycling experiments have shown that all muscle groups need to be analyzed, as they are not working equally (13). This group of researchers has gone on to shown that the percent contribution to the total integrated EMG of the lateral hamstrings was less during submaximal contractions as compared to maximal contractions (13). Fiebert et al (14) have also demonstrated that the angle of tibial rotation has an effect on the activity of the medial and lateral hamstring muscle group, as the medial hamstring group showed an increase in activity with internal or neutral tibial rotation (14). They also note that as the knee flexion angle increased, the activity of the EMG decreased. Therefore in this study, the EMG signal of both the medial and lateral hamstring muscle groups was analyzed, since there is evidence to suggest that a difference may exist in the rate of fatigue, and relative activation, of the medial and lateral hamstring muscles during submaximal contractions (15).

Surface EMG is influenced by a number of properties, both physiological, such as motor unit discharge rates and muscle fiber membrane properties (conduction velocity), and non-physiological, such as electrode size, shape, location, and conductivity of the surrounding tissue (12). However it has been shown that EMG registrations during static (isometric) contractions are generally considered as reproducible and valid, as the amount of movement during data
collection is reduced (18). Given the number of factors that can affect surface EMG, it is imperative that the reliability of measures obtained from this technique is established. This is of particular importance when comparisons are being made between individuals or within the same individuals over time (33).

The most common measures derived from EMG are amplitude and frequency. It has been observed that 'during sustained static contractions, characteristic changes occur: increases in signal amplitude, and shifts in the EMG spectrum towards lower frequencies (spectral shifts) which is indicative of muscle fatigue (18, 21, 32). These changes in EMG have been demonstrated in a variety of contraction levels ranging from 20% to 100% of MVC (18, 32, 47). Increases in amplitude during sustained, fatiguing contractions have been thought to be due to an increase in neuromuscular activation (increased recruitment of motor units), as the muscle attempts to maintain force output (3, 50). These changes are required physiologically as 'the ability of the muscle to generate force decreases with sustained activity' (34). Shifts to a lower frequency on the power spectrum are thought to be due to peripheral changes such as a slowing of conduction velocity (prolonged muscle fiber action potential), a decrease in motor unit discharge rate, or the build up of metabolites, (such as H+ or lactate), that 'accumulates during fatiguing exercise and is cleared from the muscle rapidly following contraction' (3, 10, 41). In order to express this shift in frequency, changes in mean and median frequency have commonly been used (21, 35). Median frequency (MDF) is defined as the point at which the spectral power is divided into equal low and high frequency halves, and is less susceptible to noise than the mean frequency (1, 23). Previously, the slope of the MDF and amplitude measures have been used to describe the changes in these parameters during a fatiguing contraction; however these methods have been found to have low reliability (34). Therefore, in this study, normalized values or ratios (final value/initial values) for the MDF and amplitude measures will be used to describe the change in these parameters (34). In a previous study by Mathur et al 2004, it was determined that using the normalized values of median frequency and amplitude as opposed to
slope is a more reliable method of quantifying muscle fatigue (33). Another method that will be used to quantify the ability of the hamstring muscles to maintain force will be endurance time (31).

The primary purpose of this study was to examine the test-retest reliability of the measures of normalized frequency and normalized amplitude derived from surface EMG signal as a measurement of the fatigue of the hamstring muscle group. The medial and lateral hamstring muscle groups were investigated during a submaximal contraction of 80% of MVC. In addition, differences in MDF and amplitude between the two muscle groups were examined.
METHODS

Our method to develop a protocol to measure the fatigue of the antagonistic muscle group, the hamstrings, was based on the work done by Mathur et al 2005, in which quadriceps fatigue was measured in a healthy population (33). As these two are the primary muscle groups at the knee, future comparisons of muscle fatigue could be made.

Subjects

Eleven subjects ($n = 8$ healthy females and $n = 3$ healthy males) were tested twice, one week apart. Subjects were between the ages of 51 and 81 years of age ($63.2 \pm 8.2$ years (mean $\pm$ SD)), moderately active, with no history of knee or hip pathology, cardiopulmonary, or neuromuscular conditions. Subjects were asked to avoid participating in physical activity on the day prior to, as well as the day of, testing to avoid any fatiguing effects on the hamstring muscles that may have interfered with the tests. All subjects signed an informed consent form. Ethical approval for this study was granted by the university clinical ethics research board (University of British Columbia).

EMG

Instrumentation

All torque measurements were made with a KinCom isokinetic dynamometer (version 5.30, Chattanooga Group Inc., Hixson TN), which has been established as a valid and reliable method of measuring torque generated by a muscle (11, 20, 36).

Surface electromyography (EMG) was collected from two electrode sites on the hamstrings muscle using pairs of self-adhesive, silver, silver-chloride pellet electrodes (7 mm diameter, fixed interelectrode distance of 30 mm, Kendall Meditrace). The raw signal was passed through a differential amplifier, input impedance of 10 $\Omega$ohm, CMRR of 115dB, and a
gain of 1000 (Bortec Electronics, Calgary, Canada). The analogue signal was digitized at 1024 samples per second (AT-MIO-64E-3, National Instruments), and bandpass filtered (second order Butterworth filter) at 10-400Hz. The first 250 ms segments of each second of EMG were processed on-line using Hamming window processing. The frequency content (ie. power spectrum) was determined for each window using discrete fast fourier transform (FFT) methods, and the statistical definition of ‘median’ was used to calculate the MDF in each window. Custom off-line processing (MatLab, The MathWorks Inc., Natick MA) was used to detect the point of fatigue and to determine the start and end-points of force and EMG. The end-point of the contraction (i.e., the point of fatigue) was defined as the point where the force generated dropped 20% from the target level. Data collected over a five-second window between the start and end points were averaged to obtain a single value for initial and final MDF and amplitude of EMG.

**Electrode Placement**

EMG recordings were taken from two sites on the hamstrings: lateral hamstring group (biceps femoris long and short head), 50% of the distance on a line between the ischial tuberosity and the lateral epicondyle of the tibia, and the medial hamstring group (semitendinosous and semimembranosous), 50% of the distance on a line between the ischial tuberosity and the medial epicondyle of the tibia. Landmarks used for electrode placement were those recommended by the Surface ElectroMyography for the NON-Invasive Assessment of Muscles, (SENIAM) Project, a program in the Biomedical Health and Research Program (BIOMED II) of the European Union (46). The patella was chosen as the site for the ground electrode. Subjects were also asked to contract their hamstrings against resistance in order to determine if electrodes were placed over the muscle belly. Electrodes were placed collar to
collar in the appropriate location parallel to the orientation of the muscle fibers. Skin was cleaned with alcohol prior to placing the electrodes.

To minimize noise due to pressure on the electrodes, a piece of high-density foam (1.5 inches thick) with a channel cut out on the lateral side, was placed underneath the subjects. A channel was not required on the medial side, as there was minimal to no pressure on these electrodes.

**Muscle Strength**

*Maximal Voluntary Contractions*

Given the anatomy of the hamstrings, muscle strength could be determined by using hip extension or knee flexion. For this study, knee flexion at 60° was chosen to estimate the strength of this muscle group as it has been previously reported as the angle at which the hamstrings generate their peak torque (6), as well as being a stable and comfortable position for this age group.

The subject was seated carefully on the KinCom seat, with the axis of rotation of the dynamometer aligned to the knee joint line, and the electrodes within the groove on the foam. The backrest and seat angles were adjusted so that the hip was at approximately 80° of flexion. One strap was placed across the subject's pelvis, and two more were placed across the chest to minimize hip and trunk movement during the tests. A padded metal bar was placed on top of the thigh of the leg being tested to ensure that no compensatory strategies were used during testing. The cuff (load cell) of the KinCom was placed at a distance of 75% of the lower leg length (measured from the top of the fibular head to the distal point of the lateral malleolus) (26). This length, and the seating position, was recorded to ensure the same placement for the second testing session. The subjects completed an isokinetic warm up through the range of 30° to 90° of flexion. During the warm-up, two sets of four repetitions were completed, with a one
minute rest in-between. In the first set, the first three repetitions were at 50% of maximal effort, and the last at maximal effort. The second set consisted of 4 repetitions at maximal effort. After the warm-up, the electrodes were put in place, with the subject in standing, and the subject was repositioned. The subject then performed a submaximal isometric contraction at 60° knee flexion to ensure proper positioning of the electrodes, and functioning of the EMG. Following this, subjects did four isometric MVC’s of the knee flexors. Subjects were instructed to think about the muscles on the back of their leg, keep their hands free in their lap, and asked to pull as hard as they could for three seconds. Visual feedback of the produced force was provided. A one minute break was given between MVC trials. MVC’s were done on both testing days on the dominant leg. The average of the three measures that were within 5% of each other was defined as the MVC of the hamstrings and used to calculate the target force for the endurance task. Leg dominance was determined by asking each subject which leg they had more control over (i.e., which leg they would use to kick a ball).

Force values obtained from the Kincom in N (Newtons) were converted to Nm (Newton-meters) to account for the length of the lever arm thereby providing a better estimate of muscle strength.

**Endurance Task (Fatiguing Contraction)**

Subjects performed a fatiguing contraction at 80% of their MVC, as previous studies have determined that submaximal contractions are more reliable then maximal contractions (25, 56). Visual feedback of the target and produced force was provided, and verbal encouragement was given by the tester to maintain the force at the target level until the target force could no longer be met. The endurance time was determined from the software program and was defined as the point at which the produced force matched the target force to the point at which the produced force dropped 20% from the target level.
The same endurance task was repeated on the second testing day, and the 80% target value was calculated from the MVC produced on that second day. Subjects were not told their results until the testing on the second day was completed.

**Statistical Analysis**

Statistical analysis was done using SPSS version 11.0 (SPSS Inc., Chicago IL). Descriptive statistics were used to describe sample characteristics, and to determine the mean and standard deviation of all MDF and amplitudes on both testing days. Normalized final MDF and amplitude were calculated as a ratio of the final value to the initial value (i.e., final value/initial value). For amplitude, initial and final values were normalized first by dividing by the peak amplitude obtained in the MVC measurements. These values were then used to calculate the normalized amplitude. Scatter plots of the data were reviewed to detect the presence of outliers in the data set. Intraclass correlation coefficients (ICC) were used to express relative reliability of the measures (48). The ICC expresses the ratio of between-subject variance to within-subject variance and is a unit less value (48). Munro’s descriptors for reliability coefficients were used to describe the degree of reliability: 0.00 to 0.25 – little, if any correlation; 0.26 to 0.49 – low correlation; 0.50 to 0.69 – moderate correlation; 0.70 to 0.89 – high correlation and 0.90 to 1.00 – very high correlation (51). Standard error of measurement (SEM) was used to express the absolute reliability of the measure, as it reflects the reliability of the response (43). SEM was calculated from the square root of the error variance (i.e., mean of standard deviations from day 1 and day 2) and has the same unit as the tested variable, also taking into account the reliability coefficient of the measurement. Smaller values of SEM reflected more reliable measures (43). To compare absolute reliability between measurements, the SEM was expressed as a percent of the mean value (SEM/mean x 100%). Differences between medial and lateral hamstring muscle groups were evaluated using initial and final
values for amplitude using t-test. Initial and final amplitudes obtained during the fatiguing
contraction were normalized using peak amplitude from the MVC measurements prior to making
comparisons.
RESULTS

i. Torque Measures & Endurance Time

All 11 subjects completed both testing sessions. Peak torque for the hamstrings was 55 ± 20 Nm on day 1, and 53 ± 17 on day 2, with an ICC = 0.97. The start torque (defined as 80% of MVC) for the fatiguing contraction showed very high reliability: 44 ± 16 Nm on day 1 and 43 ± 14 Nm on day 2, with an ICC = 0.97, and a SEM of 3 Nm. Endurance time also showed high reliability. Mean endurance time was 65.64 ± 41.46 sec on day 1, and 67.36 ± 40.48 sec on day 2, with an ICC = 0.78, and a SEM of 19.22 sec.

ii. Median Frequency (MDF)

Figure 4.1 shows the normalized MDF measures collected on day 1 vs. day 2, for the lateral hamstrings, and demonstrates the high correlation, ICC of 0.88. Mean and standard deviations of the data are displayed in Table 4.1.

Figures 4.2a - 4.2c show the initial, final, and normalized frequency for the medial hamstrings plotted day 1 vs. day 2; means and standard deviations are shown in Table 4.1. ICC values are 0.79, 0.92, 0.46, respectively. Although moderate to high correlation was found between the initial and final frequency on day 1 and day 2, a low correlation was found between day 1 and day 2 values of normalized frequency. For the lateral hamstrings, high correlations were observed for initial and final values on day 1 and day 2 for both MDF and amplitude. For both of these variables of the lateral hamstrings a high correlation was maintained with the normalized values.

iii. Amplitude

Figures 4.3 and 4.4 show the normalized amplitude for the medial and lateral hamstrings plotted day 1 vs. day 2. A high correlation was found for both muscle groups, with ICC = 0.75 for
medial hamstrings and ICC = 0.84 for lateral hamstrings. All data (including initial and final values), with means and standard deviations are displayed in Table 4.2.

Reliability calculations for the MDF and amplitude measures for both muscle groups can be found in Table 4.3

iv. Differences between muscle groups

During the fatiguing contraction, 10 out of the 11 subjects tested showed a drop in MDF from the initial to the final MDF values for both the medial and lateral hamstring muscle groups. This was evidenced by the ratio value normalized MDF being less than 1.0. However, with respect to the measure of amplitude, approximately 50% of the subjects tested showed an increase from initial to final amplitude measures over the course of the fatiguing contraction, while the other 50% showed a drop, or decrease. This was seen consistently in both the medial and lateral hamstring muscle group.

In order to compare the recruitment of the medial hamstring muscle group with that of the lateral hamstring muscle group, the start amplitudes, (expressed as a % of peak amplitude obtained during the MVC measurements) and the end amplitudes (also expressed as a % of peak amplitude) were compared for each day for both muscle groups, see Table 4.4. Using a one-sample t-test, no significant difference was found between the muscle groups using the amplitude measures, p>0.05.
Figure 4.1: Normalized Median Frequency of the Lateral Hamstrings

![Graph showing the normalized median frequency of the lateral hamstrings.](image)

Normalized MDF = final MDF/initial MDF. Values were plotted for each subject on Day 1 vs Day 2.

Table 4.1: EMG Median Frequency Parameters for 80% Contraction of the Hamstrings

<table>
<thead>
<tr>
<th></th>
<th>Medial Hamstrings</th>
<th>Lateral Hamstrings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day 1</td>
<td>Day 2</td>
</tr>
<tr>
<td><strong>Initial (Hz)</strong></td>
<td>108.91 ± 17.55</td>
<td>111.95 ± 22.01</td>
</tr>
<tr>
<td><strong>Final (Hz)</strong></td>
<td>91.06 ± 20.58</td>
<td>94.32 ± 20.57</td>
</tr>
<tr>
<td><strong>Normalized (Hz)</strong></td>
<td>0.83 ± 0.10</td>
<td>0.85 ± 0.13</td>
</tr>
</tbody>
</table>

Normalized frequency = final frequency/initial frequency. Values shown are mean ± standard deviation.
Figure 4.2a: Initial Median Frequency of the Medial Hamstrings

Figure 4.2b: Final Median Frequency of the Medial Hamstrings
Figure 4.2c: Normalized Median Frequency of the Medial Hamstrings

Normalized MDF = final MDF/initial MDF. Values were plotted for each subject on Day 1 vs Day 2.

Figure 4.3: Normalized amplitude for the Medial Hamstrings

Normalized Amplitude = final amplitude/initial amplitude. Values were plotted for each subject on Day 1 vs Day 2.
Figure 4.4: Normalized amplitude for the Lateral Hamstrings

![Graph showing normalized amplitude for the Lateral Hamstrings.](image)

Normalized Amplitude = final amplitude/initial amplitude. Values were plotted for each subject on Day 1 vs Day 2.

Table 4.2: EMG Amplitude Parameters for 80% Contraction of the Hamstrings

<table>
<thead>
<tr>
<th></th>
<th>Medial Hamstrings</th>
<th>Lateral Hamstrings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day 1</td>
<td>Day 2</td>
</tr>
<tr>
<td>Initial (uV)</td>
<td>154.98 ± 131.40</td>
<td>115.68 ± 43.81</td>
</tr>
<tr>
<td>Final (uV)</td>
<td>125.43 ± 72.96</td>
<td>100.75 ± 41.89</td>
</tr>
<tr>
<td>Initial (%MVC)</td>
<td>69.43 ± 9.57%</td>
<td>76.86 ± 17.68%</td>
</tr>
<tr>
<td>Final (%MVC)</td>
<td>63.33 ± 19.90%</td>
<td>68.74 ± 21.20%</td>
</tr>
<tr>
<td>Normalized (uV)</td>
<td>0.91 ± 0.26</td>
<td>0.91 ± 0.24</td>
</tr>
</tbody>
</table>

Initial and final amplitudes are expressed as absolute values (uV), as well as a percentage of amplitude achieved during MVC. Normalized amplitude = final amplitude/initial amplitude. Values shown are mean ± standard deviation.
Table 4.3: Reliability of MDF and Amplitude Measures for 80% Contractions

<table>
<thead>
<tr>
<th></th>
<th>Medial Hamstrings</th>
<th>Lateral Hamstrings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICC</td>
<td>SEM</td>
</tr>
<tr>
<td>Frequency-MDF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial (Hz)</td>
<td>0.79</td>
<td>9.07 (8.21%)</td>
</tr>
<tr>
<td>Final (Hz)</td>
<td>0.91</td>
<td>6.17 (6.66%)</td>
</tr>
<tr>
<td>Normalized (Hz)</td>
<td>0.48</td>
<td>0.08 (9.95%)</td>
</tr>
<tr>
<td>Amplitude</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial (uV)</td>
<td>0.45</td>
<td>64.97 (48.01%)</td>
</tr>
<tr>
<td>Final (uV)</td>
<td>0.63</td>
<td>34.93 (30.85%)</td>
</tr>
<tr>
<td>Initial (%MVC)</td>
<td>0.26</td>
<td>0.12 (16.03%)</td>
</tr>
<tr>
<td>Final (%MVC)</td>
<td>0.90</td>
<td>0.06 (9.84%)</td>
</tr>
<tr>
<td>Normalized (uV)</td>
<td>0.75</td>
<td>0.13 (13.75%)</td>
</tr>
</tbody>
</table>

Initial and final amplitudes are expressed as absolute values (uV), as well as a percentage of amplitude achieved during MVC. Normalized amplitude = final amplitude/initial amplitude. SEM is given in units provided and expressed as a % means of Day 1 and 2.

Table 4.4: Initial and Final % Peak Amplitude for Medial and Lateral Hamstrings

<table>
<thead>
<tr>
<th></th>
<th>Medial Hamstrings</th>
<th>Lateral Hamstrings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day 1</td>
<td>Day 2</td>
</tr>
<tr>
<td></td>
<td>Initial</td>
<td>Final</td>
</tr>
<tr>
<td>Subject</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.646</td>
<td>0.301</td>
</tr>
<tr>
<td>2</td>
<td>0.672</td>
<td>0.572</td>
</tr>
<tr>
<td>3</td>
<td>0.720</td>
<td>0.720</td>
</tr>
<tr>
<td>4</td>
<td>0.682</td>
<td>0.893</td>
</tr>
<tr>
<td>5</td>
<td>0.770</td>
<td>0.995</td>
</tr>
<tr>
<td>8</td>
<td>0.731</td>
<td>0.531</td>
</tr>
<tr>
<td>9</td>
<td>0.910</td>
<td>0.561</td>
</tr>
<tr>
<td>10</td>
<td>0.532</td>
<td>0.449</td>
</tr>
<tr>
<td>R01</td>
<td>0.709</td>
<td>0.774</td>
</tr>
<tr>
<td>R02</td>
<td>0.615</td>
<td>0.622</td>
</tr>
<tr>
<td>R03</td>
<td>0.651</td>
<td>0.550</td>
</tr>
<tr>
<td>Avg</td>
<td>0.694</td>
<td>0.633</td>
</tr>
<tr>
<td>St Dev</td>
<td>0.096</td>
<td>0.199</td>
</tr>
</tbody>
</table>

Initial and final amplitudes are expressed as a % of peak amplitude obtained during MVC measurements of the knee flexors. *indicates missing data.
DISCUSSION

This study determined that the unique measures of normalized frequency and amplitude previously determined by Mathur et al in 2004 (34), are reliable measures of hamstring fatigue for the lateral hamstring muscle group, and both the medial and lateral hamstring muscle groups respectively, in an older population. The start torque for the 80% fatiguing contraction was found to be reliable, as was the endurance time, or time to task failure between day 1 and day 2. Ten out of 11 subjects tested showed a decrease in MDF from initial to final values, yet in the measure of amplitude, 50% of the subjects showed an increase, while 50% showed a decrease from initial to final amplitude. This was consistent for both the medial and lateral hamstring muscle groups on both testing days. Finally, when analyzing the differences in muscle groups using the measure of amplitude expressed as a % of peak amplitude during MVC, no statistically significant difference was found for either muscle group in initial or final amplitude values, on either testing day.

i. Reliability of Normalized Median Frequency of EMG

In our study, high reliability was found for the initial and final MDF for both the medial and lateral hamstring muscle groups across testing days, with the lateral hamstring muscle group showing higher reliability than that of the medial. This is consistent with other studies that have shown reliability of initial MDF with sustained submaximal contractions of the elbow extensors (1) and trunk extensors (39). For the lateral hamstring muscle group, high reliability was found with respect to the normalized MDF measure; however, low reliability was observed with the normalized MDF measure for the medial hamstring muscle group.

The low reliability observed between day 1 and day 2 values of normalized MDF for the medial hamstring muscle group may have been due to a small range in the data. ICC needs to be carefully interpreted, as it is a ratio of different variance components, a ratio composed of the
between-subject variance to the total variance. For the ICC to be meaningful, the between-subject variance needs to be greater than the within-subject variance. If there is not sufficient variability between the various subject scores relative to that within the subject’s scores, the ICC will be artificially low, and the reliability will be underestimated (45). The other factor that may have caused the low ICC value with the medial hamstring group was that previous studies have shown that the position of the knee, both in regards to amount of flexion as well as the position of the tibia (internal, external, or neutral), can affect the muscle recruitment of either the medial or lateral hamstring muscle group (13, 14). In this study, the angle of knee flexion was controlled for, however other than a visual check, the tibial rotation was not measured, and therefore could have varied slightly from day 1 to day 2. This variation in tibial rotation could have altered the extent to which each component of the hamstring muscle group was recruited and could have increased the between-day variance (13, 14, 33).

Kollmitzer et al in 1999 investigated the reliability of using shifts in MDF and root mean square (RMS) EMG data to measure fatigue at 50% of MVC (25). They found differences in individual muscle components of the quadriceps group (25). The MDF shifts in rectus femoris were highly reproducible, however there was poor reliability found for the vastus lateralis and vastus medialis (25). Kollmitzer et al attributed this to subtle rotations that may have occurred in the thigh during sustained knee extension resulting in altered loading of the different quadriceps muscles (25). The low reliability of the root mean square EMG data in these same two muscle components may have been due to positioning bias of the subjects (25). This supports what was observed in this study with the medial and lateral hamstring components.

Ten out of 11 subjects showed a decrease in MDF over the course of the fatiguing contraction. This decrease in frequency has been observed in other studies by Bigland-Ritchie et al (3,4) looking at the adductor pollicus muscle, Masuda et al (32) who investigated a 50% MVC contraction of the vastus lateralis muscle, Ng et al (37) who investigated a maximal contraction of the lumborum and multifidus muscles of the back, and Petrofsky et al (41) who
investigated handgrip muscles in brief 3 second isometric contractions. There is sufficient evidence to support the understanding that during prolonged maximal effort, muscle force decreases, and the shift to lower frequencies is caused by the prolongation of the motor unit action potential, which is thought to be caused by a decrease in the motor unit firing rate (conduction velocity) (57). The decrease in conduction velocity is thought to be due to an increase in metabolic by-products, such as lactate (32). However Masuda et al in 1999 showed that in dynamic contractions, the relationship between the muscle fiber conduction velocity and the motor unit action potential is not necessarily linked (32). In their study, they found that the duration of the motor unit action potential was prolonged and the MDF decreased, however the conduction velocity did not change (32). The velocity was observed to change in the static contraction, which was 50% of MVC in the vastus lateralis of healthy males (32).

ii. Reliability of Normalized Amplitude of EMG

A low correlation was found for the initial amplitude, and a high correlation was found for the final amplitude. However the normalized amplitude measures revealed high test-retest reliability for both the medial and lateral hamstring muscle groups. This finding was similar to that of Mathur et al who determined that this measure of normalized amplitude was highly reliable during the fatiguing contraction of the quadriceps in a healthy younger population (33).

When the initial and final amplitude values were reviewed for each subject, it was observed that on day 1, 45% of the subjects demonstrated an increase in amplitude during the fatiguing contraction for both muscle groups. This was the same for the medial hamstring muscle group on day 2, while 54% on subjects showed an increase in amplitude on day 2 for the lateral hamstring muscle group. During fatigue, it has been hypothesized that an increase in amplitude should be observed as the muscle needs to recruit a greater number of motor units in an attempt to sustain the contraction (3). This has been observed in previous studies of the
adductor pollicus (4), and vastus lateralis muscle (5, 32), shoulder flexors (19) and knee extensors (18). However no change, or a decrease in amplitude has also been observed (4, 40, 55). Wretling et al in 1997 reported no change in amplitude during fatiguing dynamic knee extensions in 9 healthy women age 23± 3 years (55). Bigland-Ritchie saw a decrease in amplitude during a fatiguing MVC of the adductor pollicis muscle (4) and Petrofsky et al in 1979 observed a decrease in amplitude of the quadriceps muscle in three male subjects during bicycle ergometry at 20-100% the VO2 max (40). Vollestad et al in 1997 commented on the variability of the amplitude as a measure from surface EMG, and the findings of this study are certainly consistent with that fact (49). Muscle fatigue may not necessarily be represented by an increase in amplitude obtained from surface EMG.

iii. Differences among Hamstring Muscle Groups

No significant difference was found between the initial and final amplitude values expressed as a % of peak amplitude during the MVC between muscle groups for either day. This suggests that each of these muscles groups were functioning at a similar capacity, but were not necessarily equally recruited. Since amplitude is meant to reflect motor unit recruitment, both groups were at a similar % of peak motor unit recruitment.

Other studies, using integrated EMG and root mean square, have shown a difference in the activity of the medial and lateral hamstring muscle groups (13, 14). It has been hypothesized that this difference in muscle activity has been caused by; a change in the angle of knee flexion, (i.e. in internal/external rotation), and the type of muscle contraction, (i.e. submaximal vs maximal) (13, 14, 15). As integrated EMG was not used in this study, we were unable to compare the muscle activity of each muscle group, however it can be stated that each group was working at similar % of their maximum motor recruitment. Since the level of maximum for
each muscle group may differ, we cannot conclude that they demonstrated equal motor unit activity.

Given the scarcity of literature concerning the electrical activity of the medial and lateral hamstring muscle groups during knee flexion in neutral (14), the above is a useful piece of information. However, since there was such a small N, and given the limitation in the conclusions that can be drawn regarding comparisons of the muscle activity between groups, both components of the hamstrings need to be studied further, potentially using integrated EMG to allow for a better comparison between muscle components. Other studies have investigated muscle with multiple components (triceps surae) and found that at times during a prolonged muscle contraction, the muscle alternated between components (10), or that not all components of the muscle groups demonstrated signs of fatigue (19), indicating that all components of the muscle group should be studied in order to provide a complete picture about what is occurring in that particular muscle. The results of this study do indicate that both groups could be used to provide similar measures of hamstring fatigue, (with the exception of the medial hamstring muscle group, which only showed good reliability with the normalized amplitude measure).

LIMITATIONS

The primary limitation of this study was the small sample size. The other possible source of error was the testing position of the hamstrings. This was previously discussed in chapter 2; however putting the hamstrings in a shortened position may have decreased the torque that they produced. During the fatiguing contraction, the testing position may have caused increased pressure on the hamstrings and the surrounding vessels, therefore decreasing the blood supply and possibly shortening the endurance time. Finally, the pressure on the electrodes, although decreased with the foam, may have caused some small amount of background noise during testing.
CONCLUSION

Directions for further research would include repeating this study with a larger sample size to determine if the low reliability of the MDF measure for the medial hamstring group was due to clustering of data, altered recruitment of the components of the hamstring group on testing days, electrode placement, or possibly due to some other factors. The use of the method of integrated EMG, would assist as a greater number of comparisons could be made between the medial and lateral hamstring components.

The findings of this study have helped to establish a protocol that could be used to test the property of fatigue in hamstrings in various clinical and pathological conditions, i.e. hamstring strain. It would help to clarify of what order of importance hamstring endurance is during treatment or rehabilitation of hamstring strains. It could also be used in studies of hip osteoarthritis to determine if this function of the muscle is impaired. Also in conditions or diseases where patients present with symptoms of weakness and fatigability such as multiple sclerosis or chronic fatigue, a greater understanding of the fatigue and how to treat it can only come after the development of reliable protocols by which to measure fatigue (31). Also, since it has been determined in a number of studies that fatigued muscles are at a higher risk of injury, reliability protocols to test this functional muscle property are necessary (30).
REFERENCES


55. Wretling ML, Larsen KH, Gerde B: Inter-relationship between muscle morphology, mechanical output and electromyographic activity during fatiguing dynamic knee-


DISCUSSION – CONCLUSIONS AND AREAS OF FUTURE RESEARCH

This study established the reliability of three different protocols that will assist researchers in muscle quantification and testing of functional muscle properties. It highlighted the importance of investigating all muscles of the thigh, including muscles such as the hip adductors, and looking at these muscles as a part of the functional group to which they belong. This study also established normative data for muscle size, and strength, as well as for the inter-relationships between functional muscle groups of the thigh in older adults. This study took these findings into the clinical setting, by relating them to a clinical measure of thigh circumference. Each of these areas will be discussed and summarized below, and will include suggestions for future research.

I. Reliability and Validity of Stereological Method Established

The reliability and validity of a stereological method of muscle volume determination based on the Cavalieri principle was established, and used in this study to determine the muscle volume of the thigh muscles in this healthy older population (20, 23). The resultant muscle volumes were similar to those found in the literature of muscles for which data was available (12, 22). Despite the strong relationships between muscle volume and strength that were observed in this subject group, as well as the normative data obtained, these findings are still not sufficient. A greater amount of research needs to be done to fine tune these relationships. The valid and time-efficient method of muscle volume determination established here needs to be used in combination with real-time ultrasound in order to calculate PCSA. Only in this manner, will relationships and normative data be established that are as reflective as possible of all of the contractile area present in a muscle (1, 16).
II. Normative Data

This study demonstrates that despite some of the findings in the literature indicating the opposite, this group of older adults maintained a strong relationship between the size and strength of the muscles of the thigh (2, 5, 9, 19). Comparisons were difficult to make however, because much of the research that has been done to date has not utilized measurements of MV and still uses the less inclusive method of ACSA (2, 11, 13). Therefore given the rationale behind the method used to quantify muscle in this study, it is felt that these findings are closer to what should be expected for older adults with respect to muscle properties.

A strong relationship was also observed among the three major groups of thigh muscles both in size and in strength. This is a good reminder to therapists that despite an individual’s age, there remains a balance in the strength of the lower extremity that should be preserved in order to maintain function. Gross differences in muscle size and/or strength in the ipsilateral limb of an individual is not to be considered adequate for proper function and may indicate pathology or simply may need treatment focus to regain strength in order to prevent dysfunction.

Through the investigation of the muscle volume and strength of these three groups of thigh muscles, muscle efficiency was discussed (5, 10). With respect to isometric strength, it was observed that the knee extensors were the most efficient muscle, whereas the hip adductors were the least efficient muscle. This highlighted another of the important structural aspects of muscle and it’s relation to function. Despite the architectural properties of the hip adductors which seem to have been designed for large amounts of force production (large pennation angle, and large muscle volume), this muscle group was unable to generate the force that may have been expected of it (16, 24). This discrepancy between architectural properties and actual force production can be explained by their orientation into the skeletal anatomy, as in their placement into the human body, they were left with a short lever arm, therefore decreasing
the amount of force that they are capable of producing (16). Therapists need to understand this concept, and be aware of the misleading muscle volume of the hip adductors.

III. Strength Ratios

An isometric hamstring to quadriceps strength ratio was found to be 0.41 for this sample, which is lower than that for younger individuals, but consistent with that observed by other research groups studying individuals of this age range (15, 18). It is strongly felt that if therapists are able to assist their clients in maintaining a normal strength ratio such as this in these muscle groups, then individuals will be less likely to develop overuse injuries that can result from improper wear on soft tissues due to altered joint mechanics (3, 4, 21). This is of particular importance in an older population where altered joint mechanics is common due to such age-related diseases as knee and/or hip osteoarthritis (26). This leads into the next important strength ratio calculated, the hamstrings to adductor ratio, which was found to be 0.37. This ratio has already been cited in the literature as an important ratio in the detection of degenerating stages of knee OA (26). As the severity of the disease progresses, and the medial compartment of the knee gets worn away, an increase in the ratio is observed as the adductors attempt to compensate for the varus stress on the knee joint (26). The importance of this ratio was recognized, and for that reason, in this study, this ratio was calculated, hoping that this will assist in furthering the research of the relationship between the adductor and hamstring muscles in an older population, both in healthy subjects and in those presenting with common lower extremity pathologies.

IV. Muscle Fatigue

The reliability of a protocol to test hamstring fatigue in older adults using EMG and KinCom Dynamometry was established. Given the prevalence of hamstring strains in sporting
injuries, and the impact of fatigue on both joint mechanics and on an individual’s overall level of function, it is felt that this protocol will be very useful in future research in many different areas (17, 25). In future studies, it would be helpful if the technique of integrated EMG was utilized when analyzing the fatigue of muscle groups with multiple components. It has been indicated several times in the literature that all components of a muscle group may not react in a similar manner to the same fatiguing condition (7, 8, 14). Therefore if integrated EMG was used, a greater number of comparisons could be made between the components of the muscle group, increasing the understanding of the role of each muscle, and possibly identifying weaknesses within the group.

The fatigue protocol was used to test the ability of the knee flexors and the knee extensors to sustain an 80% MVC isometric contraction. It was observed that the knee flexors were able to hold this contraction longer than the knee extensors, with an endurance time ratio of 1.74. This indicates to therapists, when compared to the isometric strength ratio of 0.41, that assumptions of the endurance of a muscle group can not be made from brief measures of isometric strength.

V. A Clinical Measure

Measures of thigh circumference are commonly used in clinical practice as an estimate of the change in muscle size and/or strength (6). However, there is relatively little evidence in the literature to support its use in a younger population, and no studies were found that reported the use of this measure in a healthy older population. In this study it was determined that thigh circumference measures at 10 cm superior to the base of the patella showed a good to excellent relationship to the strength of all three thigh muscle groups. The relationship to muscle volume was slightly lower, but still moderate to good; however it was observed that when the thigh muscles were arranged in functional groups, the relationship strength was increased. This
tells therapists that when making these assumptions, it is critical that they are thinking of the 'knee extensors' as a group, and not relating these measures of thigh circumference specifically to the quadriceps, or prime mover. These findings need to be taken into future research studies that investigate whether or not thigh circumference measures at this level on the thigh can detect changes in muscle size and/or strength after an exercise intervention.

STRENGTHS AND WEAKNESSES

The primary strengths of this study include the use of the stereological method in combination with MRI to determine the muscle volume of all of the muscles of the thigh, the functional grouping of the muscles when investigating relationships, and the consistency of findings amongst the three muscle groups.

The primary weakness of this study is the small sample size (N=10), which is even smaller when the group was divided into males and females for comparison with the literature. The other weakness is that when testing the knee flexors, the subjects were in a seated position, as it was felt that given the age of this population, maximal exertion while in a supine position was not comfortable, nor would it have been easy for the subjects to get in and out of supine. This placed them on top of the electrodes and put the hamstring muscle in a shortened range and therefore may have limited the torque output.

CONCLUSION

As individuals age, independent function and quality of life can only be maintained if there is a clear understanding of the effects of aging on the human body. It is evident that there is a need for more careful research on aging muscle, research that can accurately quantify muscle tissue and that can be inclusive in all of the different types of muscle and modes of contraction that it studies. Physiotherapists are treating older individuals with rehabilitation
techniques and exercises that they feel will benefit this population based on their training and knowledge of disease, tissue healing, and the structure and function of the human body. However, some of the treatments being used may not be effective as they are not targeting the right muscles group, or functional muscle property. Therefore it is imperative, not only that more research be conducted on aging muscle, but that these research findings be summarized in such a way that quickly becomes clinically relevant. These findings need to reach the clinician so that they can be translated into rehabilitation programs that will benefit the very people that the research is about, a healthy older population.
REFERENCES


Reliability and Validity of Stereological Method

The validity of the stereological method used in this study was determined prior to taking measurements of muscle volume. Some information regarding the coefficient of error (COE) to reduce the error in measurement, and appropriate grid size is available; however the volume measurements taken on human tissue have primarily been on the brain, liver, and only a few studies have used stereology on muscle, such as the quadriceps, hamstrings, and gastrocnemius, (1, 2, 5). Roberts et al reported that for a COE of 4-5%, approximately 100 points should be counted over all sections of the structure of interest (5). It is stated in the literature that a COE of 5% is suited to the estimation of human muscle volume (5). However in the lab it was decided that a COE of 3% would be used in order to increase the accuracy of volume measurement. This is also supported by Walton et al who state that a COE of 3% can be used for practical purposes (5). Since this technique has been used relatively infrequently with muscle volume determination, the more conservative approach will be taken. Grid size, as well as slice interval distance was determined and was done using measurement of a phantom volume with manual segmentation. Then, a comparison of rectus femoris and vasti volumes of 5 subjects achieved with stereology was made with volumes obtained from a previously established method of muscle volume determination, manual circling in combination with the truncated cone formula (3, 4).

a. Determination of Phantom Volume

A water bottle filled with a predetermined volume of water, 410 ± 5 ml, was placed in between a subjects legs during their MRI. These images were then loaded into the Analyze Software Program, merging both the separate upper and lower series of images, and saving as one complete, continuous series of images of the entire thigh. The water outline was then
identified, and manually segmented (The border of the water was outlined, creating an object map, which was copied and slightly adjusted for each slice, or image, that the water appeared in.) The volume of this region of interest was then calculated by the software program, using different grid sizes. A grid size was chosen by the analyzer, and the software generated a volume each time. The results are random, given that the application of the grid itself is random each time the volume is calculated. A grid size that generated the closest volume to the actual volume of the water bottle with the smallest standard deviation (variation of results) was chosen. The water bottle was plastic, therefore all that appeared was the grayness of the water itself. Table A.1 shows the three grids that were used and the results that were obtained.

A grid size of 10x10 was chosen, (see Figure 1.4), as it met the criteria noted above, but it was also the grid size used by Walton et al in 1997 to determine the muscle volume of the quadriceps. This technique established that the method of point counting, or stereology, was sufficient to determine the volume of a cylindrical object of even shape, with a grid size of 10x10, however did not speak to the validity of using stereology to determine the volume of an object of unknown shape, such as a muscle. Therefore, the method of stereology using a grid size of 10x10, and an interval that allowed for a coefficient of error of less then 3%, (3 slices), was used to determine muscle volumes of two muscles on 5 subjects. These muscle volumes were then compared to volumes obtained using a method previously established for validity and reliability (4).

b. Muscle Volumes – A comparison between Manual Circling and Point Counting

In order to determine if stereology could be used to calculate muscle volume using MRI Images and the Analyze Software Program, 5 subjects were chosen for a check of the validity of this method. Two muscles were chosen, rectus femoris and the vasti as a group, as their borders were clearly delineated (as opposed to the adductors or the hamstrings), which ensured
that it was the method that was being tested and not the tester and the decision that they had to make regarding muscle boundaries. The muscles were also two muscles that varied in size and in shape. The rectus femoris is typically long and narrow, while the vasti as a group is large and more of a semicircle.

The results are shown for one subject in Table A.2 and Table A.3, and are displayed in graphical format in Figure A.1 and Figure A.2. The overall results are displayed in Table A.4. It was determined that the average percent error for the rectus femoris was 3.73% and for the vasti it was 10.30%. There was a very strong correlation between the two sets of muscle volumes, $r=0.98$ for both the rectus femoris and the vasti group. The values for the stereological method were always larger. It was determined that 3.73% and 10.30% were acceptable levels of error given that there was such a strong correlation for all subjects between the number of points counted and the actual number of pixels circled per slice. For the rectus femoris, the $r$ values ranged from 0.94-0.98, and for the vasti muscle group, the $r$ values ranged from 0.98-0.99. It was expected that the rectus femoris muscle would have a smaller error than the vasti group since it is a smaller muscle.

It is felt that the error, or difference between the two methods, lies in the equation that is being used to calculate the overall volume. The Analyze program is using one that does not make any assumptions as to the overall shape of the muscle, whereas with the manual circling method, a truncated cone formula is being used, and therefore may be overestimating the size of the muscle because it is not conical shaped as it merges into the tendon, rather it comes more to a point. If error lay in the identification of the muscle tissue, then such a strong correlation between the points counted and the pixels circled would not have been observed, nor would there have been such a strong relationship between the number of pixels and the area per slice. Further testing in vitro, using muscles of known weight, would be another way to validate this stereological method for determination of muscle volume.
It is felt that the above findings were enough to satisfy the requirements of validity, and therefore this method was used to determine the muscle volumes of the thigh muscles in this study. It should be noted that when this method was used in the study, the interval distance had to be changed for two of the muscles that were significantly smaller than the others. For the gracilis and sartorius muscles, an interval of 2 slices was used, since an interval size of 3, resulted in a COE that was larger then 3%.

c. *Intra-tester Reliability*

Six muscle groups were measured for one subject on two separate occasions. The grid was randomly generated on both occasions, yet the size (10x10) and the interval distance of 3, remained the same. The average percent error was 1.70% for all muscles measured. Refer to Table A.5 for raw data and percent area for each individual muscle.
### Table A.1: Phantom Muscle Volumes with Varying Grid Sizes

<table>
<thead>
<tr>
<th>Grid Size</th>
<th>9 x 9</th>
<th>10 x 10</th>
<th>12 x 12</th>
<th>20 x 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumes (cm³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 x 9</td>
<td>417.014</td>
<td>404.053</td>
<td>422.314</td>
<td>419.922</td>
</tr>
<tr>
<td>10 x 10</td>
<td>415.778</td>
<td>410.156</td>
<td>408.020</td>
<td>410.156</td>
</tr>
<tr>
<td>12 x 12</td>
<td>413.058</td>
<td>407.410</td>
<td>399.475</td>
<td>412.598</td>
</tr>
<tr>
<td>20 x 20</td>
<td>401.609</td>
<td>416.870</td>
<td>419.678</td>
<td>451.660</td>
</tr>
<tr>
<td>411.328</td>
<td>417.480</td>
<td>408.691</td>
<td>407.715</td>
<td></td>
</tr>
<tr>
<td>416.530</td>
<td>413.818</td>
<td>415.283</td>
<td>382.080</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>412.553</td>
<td>411.631</td>
<td>412.244</td>
<td>414.022</td>
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<tr>
<td>St dev</td>
<td>5.790</td>
<td>5.364</td>
<td>8.478</td>
<td>22.488</td>
</tr>
<tr>
<td>% difference from phantom</td>
<td>+0.623</td>
<td>+0.398</td>
<td>+0.547</td>
<td>+0.981</td>
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</tbody>
</table>

Muscle volumes were automatically generated by Analyze Software program using selected grid size and region of interest identified with manual segmentation.

### Table A.2: Raw Data for Rectus Femoris Muscle of One Subject

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<th>Analyze Slice #</th>
<th>MRI Slice #</th>
<th>Stereology - # points</th>
<th>Circling - # pixels</th>
<th>Area (cm²)</th>
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Pearson (pnts & pixels) 0.98
Pearson (pnts & area) 0.98

161
Figure A.1: Relationship between Points & Pixels for Rectus Femoris
Table A.3: Raw Data for Vasti Muscle Group of One Subject

<table>
<thead>
<tr>
<th>Analyze Slice #</th>
<th>MRI Slice #</th>
<th>Stereology - # points</th>
<th>Circling - # pixels</th>
<th>Area (cm²)</th>
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</thead>
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<tr>
<td>knee - 24</td>
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<td>25.33</td>
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<td>pelvis - 105</td>
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</table>

Pearson (pnts & pixels) 0.99
Pearson (pnts & area) 0.99
Figure A.2: Relationship between Points & Pixels for Vasti

![Graph showing the relationship between No. Points and No. Pixels for Vasti.](image)

Table A.4: % Error of Point Counting vs Circling

<table>
<thead>
<tr>
<th>Subject</th>
<th>Muscle Volume RF (cm³)</th>
<th>Muscle Volume Vasti (cm³)</th>
<th>% Error</th>
<th>Absolute Difference (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Circling</td>
<td>Pnt Cnt</td>
<td>Circling</td>
<td>Pnt Cnt</td>
</tr>
<tr>
<td>1</td>
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</tr>
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</tr>
<tr>
<td>Avg</td>
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<td></td>
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</table>
Table A.5: % Error – Intra-tester Reliability for Stereological Method

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Day 1</th>
<th>Day 2</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectus Femoris</td>
<td>116.06</td>
<td>121.77</td>
<td>-4.80%</td>
</tr>
<tr>
<td>Vasti</td>
<td>997.29</td>
<td>996.09</td>
<td>0.12%</td>
</tr>
<tr>
<td>Hamstrings</td>
<td>390.01</td>
<td>389.40</td>
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<td>Sartorius</td>
<td>72.02</td>
<td>76.90</td>
<td>-6.56%</td>
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<tr>
<td>Gracilis</td>
<td>55.85</td>
<td>54.93</td>
<td>1.65%</td>
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<tr>
<td>Adductors</td>
<td>565.19</td>
<td>569.46</td>
<td>-0.75%</td>
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<tr>
<td><strong>Avg</strong></td>
<td></td>
<td></td>
<td><strong>-1.70%</strong></td>
</tr>
<tr>
<td><strong>St Dev</strong></td>
<td></td>
<td></td>
<td><strong>3.23%</strong></td>
</tr>
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</table>
REFERENCES


Reliability of Testing Protocol for Hip Adductor Strength

The protocol used to test the isometric strength of the hip adductors was as outlined in Chapter 2. Each subject that arrived for testing was asked if they would like to return in one week's time to participate in the reliability segment of the study. Seven out of ten of the subjects returned, and the additional three subjects came from volunteers within the same age group. The subjects that participated in the entire study were tested approximately one week after the first testing day, at which time the entire testing protocol was repeated, not only the adductor testing component. It was felt that if the entire test was not completed, it would not be a valid test of the reliability of the protocol for testing the adductors, as the testing conditions would not be the same.

The three subjects that volunteered to participate in the reliability study came to GF Strong testing laboratory on three separate occasions in order to parallel the experience that the other subjects had encountered. During all three sessions, the same testing protocol was administered; however data was only collected on the later two sessions, allowing the first to serve as an introduction to the Kin-com dynamometer and the EMG testing protocol.

It was determined that the protocol used to test the isometric strength of the hip adductors was reliable under these conditions. Data for each subject on both testing days and for each trial is can be found in Table B.1, along with ICC values and averages of hip adductor strength measurements.
### Table B.1: Isometric Strength Data – Averages and ICC Values

<table>
<thead>
<tr>
<th>Subject</th>
<th>Trial 1 Day 1</th>
<th>Trial 2 Day 1</th>
<th>Trial 3 Day 1</th>
<th>Average Day 1</th>
<th>Average Day 2</th>
</tr>
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<td>221</td>
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<td>238</td>
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<td>210</td>
<td>211</td>
<td>204</td>
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</table>

| ICC     | 0.72          | 0.80          | 0.70          | 0.75          |

Strength measured in Newtons (N), not converted to Nm here to allow ICC's to be calculated on raw data. 'R' designates subjects that participated in the reliability portion of the study only.
# Table 1: Muscle Volume Data per Muscle, per Subject

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>RF</th>
<th>Vasti</th>
<th>Quads</th>
<th>Sartorius</th>
<th>Gracilis</th>
<th>Adds</th>
<th>SM</th>
<th>ST</th>
<th>BF</th>
<th>Hams</th>
<th>Total</th>
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<td>1F</td>
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<td>632.63</td>
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<td>264.59</td>
<td>544.74</td>
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<td>2F</td>
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| Avg    | 64.6 | 204.07 | 1325.50 | 1529.57 | 137.82    | 82.52    | 776.46 | 214.05 | 136.96 | 262.57 | 613.59 | 3139.95 |
| St Dev | 8.9  | 74.26  | 429.98  | 500.54  | 48.83     | 25.24    | 231.65 | 58.20  | 45.85  | 79.62  | 159.73 | 945.37 |

**MEN**

| Avg    | 65.5 | 274.89 | 1766.97 | 2041.85 | 189.06    | 107.12   | 1010.28 | 266.19 | 174.18 | 336.46 | 776.82 | 4125.14 |
| St Dev | 6.7  | 53.06  | 239.89  | 286.69  | 6.71      | 6.33     | 168.61  | 34.22  | 51.04  | 39.33  | 39.06  | 470.09 |

**WOMEN**

| Avg    | 64.0 | 156.86 | 1031.19 | 1188.05 | 103.66    | 66.12    | 620.57  | 179.29 | 112.15 | 213.32 | 504.76 | 2483.16 |
| St Dev | 10.8 | 39.38  | 195.97  | 227.48  | 27.64     | 17.78    | 81.44   | 42.07  | 19.33  | 56.61  | 97.37  | 426.59 |
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### MH_amp_e (%MVC)

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Study Procedures:

You will be required to come on three separate days. The total time required to participate in the study is about 3 hours. On the first day (Visit 1), you will perform a breathing test and an exercise test. For the breathing test, you will be required to take as deep a breath as possible, and then blow forcefully through the mouth into a tube to measure the airflow out of your lungs. For the exercise test, you will be required to pedal on a stationary bike as the resistance is gradually increased for 20 minutes or so, until you can no longer continue exercising at the higher levels of resistance. In order to measure your maximum exercise capacity, you will be encouraged to continue pedaling until shortness of breath or leg fatigue force you to stop pedaling. During the test, you will be required to breathe through a tube attached to a sterile mouthpiece on one end and a gas analyzer on the other. Electrodes will be placed on the skin over your heart to measure your heart rate and rhythm. Visit 1 should take about 80 minutes in total.

On Visit Two, (at least four days after Visit One), the strength of your thigh muscles (quadriceps) will be tested. You will be seated in a chair with a seat belt. A padded lever will be placed against your shin. You will be asked to straighten your knee as strongly as possible against the lever. Following the strength test, you will undergo a MRI (magnetic resonance imaging) exam of your thigh muscles. The MRI uses a magnet to visualize cross-sections of the body. You will be asked to remove any jewelry (rings, watches etc.) and articles of clothing that contain metal (belt buckles, zippers, metal buttons). If you have a pacemaker you will not be imaged, as the pacemaker cannot function in the magnetic field of the imager. You will be asked to lie on a table, which will then be moved automatically through the imager. You will be asked to lie still for a period of five to ten minutes at a time while the images are being taken. Some people may feel “closed in” during the MRI however there is a constant intercom with the technician and you may get out at any time. Visit 2 should take about 80 minutes in total.

On Visit Three, at least ten days after Visit One, a medical doctor will remove a small muscle sample in order to examine it under a microscope for possible causes of atrophy and weakness. A local anaesthetic will be used to numb a small area of skin and muscle on the side of your thigh muscle, midway between your knee and your hip. A tiny incision will be made and a 5mm sterile needle will be inserted to remove a small muscle sample (about 100mg, which is less than 0.01% of the total mass of the thigh muscle). The skin will be closed with Steri-Strips. You can remove the Steri-Strips seven days following the procedure. Your muscle tissue sample will be frozen and used only for the purposes of this study. If you choose to withdraw from the study, your tissue will be destroyed using standard procedures. Visit 3 should take about 20 minutes in total.

On Visit Four, the testing will be similar to Visit Two, the difference being that the strength of your thigh muscles (hamstrings and adductors) will be tested instead. In addition, the endurance of the muscles on the back of your leg will be tested in a similar manner as to those on the front of your leg. The equipment will be the same, you will be seated in a chair with a seat belt. A padded lever will be placed against your shin. You will be asked to bend your knee, and pull your leg in as strongly as possible against the lever. The distance around your leg will also be measured with a tape measure, three times.

The exercise test, spirometry, lung volumes and inspiratory muscle testing, MRI and anthropometry and muscle biopsies will be done at Vancouver Hospital. Quadriceps strength and endurance will be measured at G.F. Strong Research Lab.
Exclusions:
If you do not understand sufficient English to comprehend the informed consent form, you will be excluded from the study.

If you suspect that you may be pregnant, have any injury or disease of the knee or leg which may be worsened by exercise, any diseases of the heart or arteries, or clotting disorder, other lung conditions or previous lung surgeries, cancer, or have used steroids within the past 2 months, then you will be excluded from the study.

Risks:
There are minimal risks associated with testing procedures outlined in the study. During the exercise test on the cycle, there is a remote possibility (less than 1 in 10,000) of experiencing a heart attack or abnormal heart rhythm. During the exercise test, you may feel “closed in”, which could cause some anxiety, or even a panic attack in people who have previously had panic attacks. Following the muscle strength test, you may experience some mild fatigue and soreness in the thigh muscle immediately afterwards but this should not last longer than 1 to 2 hours. Immediately following the muscle biopsy, you may feel some slight local discomfort but should not be incapacitated in any way. There is a slight possibility of infection with the muscle biopsy. There is a risk that you may feel “closed in” during the MRI procedure.

Compensation of Injury
Signing this consent form in no way limits your legal rights against the sponsor, investigators or anyone else.

Benefits:
An honorarium will be paid for your participation in the study. After completion of the study, you will be given access to the information from your tests and the study results if you request.

Alternative Treatments:
There are no alternative treatments to this study protocol. You do not have to participate in this study to receive treatment for your condition. Participation is voluntary.

Confidentiality:
Your confidentiality will be respected. No information that discloses your identity will be released or published without your specific 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 Health Canada and the UBC 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.

Contact:
If you have any questions or desire further information with respect to this study, or if you experience any adverse effects, you should contact the principal investigator or co-investigators at the numbers listed on page 1 of this consent form. If you have any concerns about your treatments or rights as a research subject you may contact the Research Subject Information Line in the UBC Office of Research Services, 604-822-8598.
Patient Consent:

I understand that participation in this study is entirely voluntary and that I may refuse to participate or I may withdraw from the study at any time without any consequences to my continuing medical care.

I have received a copy of this consent form for my own records. I consent to participate in this study.

----------------------------------------
Subject Name (Printed)

----------------------------------------
Subject Signature Date

----------------------------------------
Witness Name (Printed)

----------------------------------------
Witness Signature Date

----------------------------------------
Investigator’s Name (Printed)

----------------------------------------
Investigator’s Signature Date