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EFFECTS OF AGING AND STRENGTH TRAINING ON
SHORTENING AND LENGTHENING MUSCLE ACTIONS

IN WOMEN

by

MICHELLE M. PORTER

Faculty of Kinesiology

Submitted in partial fulfilment
of the requirements for the degree of
Doctor of Philosophy

Faculty of Graduate Studies
The University of Western Ontario
London, Ontario
December 1995

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ABSTRACT

There has been much research on strength changes with aging and the consequent effects of resistance training, however, relatively little is known about lengthening (eccentric; ECC) muscle actions. The purposes of these studies were to develop a method of testing and training plantar (PF) and dorsiflexion (DF) of the ankle in a standing position in order to investigate age-related and training effects on shortening (concentric; CONC) and ECC peak torque (PT) in women.

All subjects were healthy and physically active, and performed all testing and training on an isokinetic dynamometer. Strength testing was performed in both standing and supine positions at 30 degrees per second (°/s), between 20° PF to 10° DF. Testing on two occasions, one week apart, had acceptable reproducibility for PT (ICC_{2,1} & r = 0.60 to 0.90, p < 0.05). Standing and supine PT were highly related (r = 0.80 to 0.95, p < 0.05), but standing torques were greater than supine DF torques (p < 0.01).

Passive resistive torque (PRT) of the plantar flexors was tested on two occasions, at 6 °/s from 10° PF to 10° DF while subjects relaxed. The two occasions were found to be reliable (r & ICC_{2,1} > 0.84, p < 0.001), and the two positions (standing and supine) were highly related (r = 0.91, p < 0.01).

The older women (OW; n = 16, age = 67 ± 4 years) had CONC PT, for DF and PF respectively, which averaged 74% and 89% of the younger women (YW; n = 16, age = 27 ± 4), while ECC PT averaged 97% and 100% of YW. PRT was greater in the OW but rate of torque development (RTD) was greater in the YW. Relationships between variables indicated that the maintenance of ECC PT was not due to increases in PRT.

Training of CONC PF and ECC DF was performed twice per week for eight weeks by 15 OW (age = 68 ± 5) in the standing position at > 85% of PT. Significant increases occurred in standing CONC (28%) and ECC (17%) DF PT and
PF RTD, but no significant changes were found for PF PT, or for supine PT, PRT or DF RTD.

These findings suggest that: 1) a standing position can be used to test strength and PRT, 2) PF and DF ECC strength is preserved with age, and 3) ECC DF training can improve both CONC and ECC DF strength.
ACKNOWLEDGEMENTS

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Glossary of Terms

The following words or terms have been defined in order to clarify them for the reader. Although other definitions may be given for these terms these are the operational definitions for use within the context of this thesis.

Aging
The process of senescence from adulthood to death.

Agonist
This is a muscle or muscle group which is the prime mover in a muscle action.

Antagonist
On the opposing side of a joint this muscle or muscle group would be acting in the opposite direction to the action of the agonist or direction of movement.

Coactivation
This is the neural activation of the antagonist.

Concentric (CONC)
A muscle action in which the muscle is shortening.

Cross bridge
The tension producing unit of muscle fibres which is an interaction of a myosin molecule with an actin molecule.

Dorsiflexion (DF)
This muscle action moves the foot towards the shin.

Dorsiflexors
These muscles are located on the lateral aspect of the front of the lower portion of the leg. The specific muscles are anterior tibialis, extensor digitorum longus, extensor hallucis longus, peronius tertius and extensor digitorum brevis.

Eccentric (ECC)
A muscle action in which the muscle is lengthening.

Force
Tension produced by muscles measured in Newtons (N).

Isokinetic
A type of dynamometer or action whereby the movement of the apparatus is controlled to produce a constant velocity.

Isometric
A muscle action in which there is no movement around the joint.

Isotonic
A mode of testing or training strength whereby the load (eg. weight) remains constant, but velocity of movement is variable.

Kinetic Communicator (KIN-COM)
An isokinetic dynamometer which is commercially available (Chattecx, Chattanooga, Tennessee).
Maximal voluntary contraction (MVC)

The maximal torque produced in an isometric muscle action in which a subject uses voluntary activation.

Passive resistive torque (PRT)

The tension produced by moving a joint through a range of motion, while the muscle remains relaxed.

Peak torque (PT)

The maximum amount of torque produced over a range of motion, with torque being the force times the moment arm of the joint of interest.

Plantar flexion (PF)

A muscle action in which the heels are lifted.

Plantar flexors

The muscles on the back of the lower leg. These include the soleus, medial and lateral gastrocnemius, peroneus longus, plantaris, flexor hallucis longus and flexor digitorum longus. The first three can be referred to as the triceps surae.

Rate of torque development (RTD)

The velocity at which torque is produced.

Strength

The maximum voluntary torque which can be produced.

Strength training

A regimen of training where heavy resistance (weight or load) and few repetitions are used to attempt to improve strength. High intensity strength training refers to using a resistance which is \( \geq 70 \% \) of maximum voluntary strength.

Supine

A position of lying on their back.

Synergist

A muscle or muscle group which assists another muscle group in performing a movement.
CHAPTER ONE
INTRODUCTION AND BACKGROUND

1.1 Brief review and background information

Aging is typically characterized by a progressive muscular weakness (see Appendix I for a review of studies on changes in strength with age). However, eccentric (ECC) strength has been shown to be relatively preserved with increasing age compared to other muscle contraction types (Vandervoort et al., 1990b; Poulain et al., 1992; Phillips et al., 1993b; Porter et al., 1995a), and specific training programs have demonstrated significant improvements in the strength of even frail older nursing home residents (see Appendix II for a review of strength training studies). What is not known is why a maintenance of ECC strength occurs, what is the response to ECC strength training, what happens to ECC strength in response to CONC strength training in older individuals, and how well laboratory measured increments in strength can be transferred to the daily lives of older individuals.

1.1.1 Position of strength testing and training. Most strength training regimes utilize commercially available equipment and positions that certainly have the potential to increase strength and muscle size. Yet, compared to strength, improvements in daily tasks like walking speed have been substantially lower, especially in groups who could benefit most (i.e. nursing home residents). In younger (Sale et al., 1992) and older subjects (Frontera et al., 1988; Brown et al., 1990) specificity of training has been demonstrated when training and testing were done using different equipment or modes (eg. isotonic training and isometric testing). It is also conceivable that the position of training would be a factor for the specificity of training. For instance, most training of the legs is done in a seated or supine position using bilateral movements. However, for improving gait it would seem reasonable to utilize a position which reflects the position of the body during gait, and also utilizes
unilateral movement patterns. Differences have been found in neural responses when supine and standing conditions have been compared and are probably due to cutaneous and mechanical effects (Aniss et al., 1992). Therefore a standing position of testing may better reflect the torque generating capabilities of the muscles of the lower leg involved in gait. This position may also be more suitable for training these muscle groups if future gains in functional tasks are desired.

1.1.2 Potential mechanisms of ECC strength preservation. In several muscle groups, including the knee flexors (Vandervoort et al., 1990b; Poulin et al., 1992), knee extensors (Vandervoort et al., 1990b; Poulin et al. 1992; Porter et al., 1995a), and adductor pollicus (Phillips et al., 1993b), there has been relatively less ECC strength loss than CONC or isometric, when older and younger groups of men (Poulin et al., 1992; Porter et al., 1995a) and women (Vandervoort et al., 1990b; Porter et al., 1995a) have been compared. This has also been demonstrated in older versus younger mice (Phillips et al., 1991; Brooks and Faulkner, 1994). However, mechanisms for these observations have not been determined.

In order to determine potential causes of a preservation of ECC strength, basic principles of muscle mechanics need to be examined. Schematic diagrams of force-velocity and force-length diagrams are shown in Figures 1.1 and 1.2. These characteristics of muscle have been determined using isolated animal muscle preparations.

The basic premise of the force-velocity curve is that when muscle is shortening and producing tension there is less force produced than when the muscle length remains constant (i.e. isometric and zero velocity) and even less than when the muscle is actively lengthening. In order for these force levels to be achieved the external perturbation is less than the force capabilities when the muscle is shortening, equal when static, and greater than the intrinsic capabilities when the muscle length is increasing. Velocity has different effects on these muscle actions. When velocity of
movement increases for a shortening action (i.e. CONC) there is a drop in the force producing ability, although little occurs when velocity increases for lengthening actions (i.e. becomes more negative). Cross bridge mechanics have predominantly been used to explain these findings.

However, the other major principle of muscle also needs to enter into this discussion. The force-length curve separates the total force, measured when muscle is active isometrically at different lengths, into active and passive forces. As the muscle is lengthened to a great extent then passive contributions of structural proteins and connective tissue become more important than the active force produced by the muscle. In fact, at great lengths passive properties are solely expressed for measured force.

The increase in force produced under lengthening conditions appears to be affected by active muscle (i.e. cross bridge) mechanics and passive characteristics. It is believed that the cross bridge kinetics are altered such that each cross bridge produces more force and not because more cross bridges are attached (Phillips et al., 1993b).

Another theory to explain the mechanics of lengthening actions describes the "popping" of sarcomeres due to unequal strength characteristics of various sarcomeres (Morgan, 1990). When the cross bridge is stretched beyond its limits and no longer exerts tension, then the connective tissue of the muscle tissue takes up the slack. However, this occurs at the descending arm of the force-length curve where muscle length is stretched to an extreme. It is unknown where the muscles are on the force-length curve when humans perform ECC actions because tendons can also change length to maintain a more suitable overlap distance for the cross bridges (Rack et al., 1983).

Another uncertainty of voluntary ECC actions in humans is neural activation. It has been demonstrated that torque values are much lower during ECC actions than
would be expected based on the force-velocity predictions. In fact, studies using electrical stimulation have observed larger values for torque when artificially stimulated actions are compared to voluntary ones (Westing et al., 1991; Dudley et al., 1990).

In older adults neural activation during ECC actions has not been addressed. The force-length relationship seems to be preserved for the dorsiflexors (van Schaik et al., 1994), but passive resistive torque of the plantar flexors increases with increasing age (Vandervoort et al., 1992). Another age-related change that occurs is a slowing of contractile properties (see Appendix I for a review of studies). This slowing reflects changes in the kinetics of the cross bridges and may affect active torque characteristics during both CONC and ECC actions. In one study where both CONC and ECC actions were performed at different velocities in older and younger men, there was a velocity effect on both actions (Poulin et al., 1992). The CONC actions were more impaired at fast velocities in the older subjects but for the ECC actions both age groups were equivalent (Poulin et al., 1992). Therefore, slowed contractile properties which can be explained by a preferential loss of type II muscle fibres (see Appendix I for references) could potentially explain the relative preservation of ECC strength with age.

1.1.3 CONC versus ECC strength training. As mentioned above several studies have recently demonstrated that high intensity strength training can result in large increases in muscular strength in older adults (see Appendix II for further information). Muscle groups trained have been from both the upper and lower body. The potential mechanisms of adaptation include muscle hypertrophy (Frontera et al., 1988; Fiatarone et al., 1990; Brown et al., 1990; Lexell et al., 1995), alterations in the intrinsic properties of muscles (Blimkie, 1992), decreased stiffness of the antagonistic muscle groups, and neural changes (Sale, 1988). More research is needed to elucidate the mechanisms of adaptation in order to determine what is
important for transferring improvements from the laboratory to the daily lives of older adults.

ECC actions are usually part of isotonic training programs (e.g. using equipment like dumbbells or Universal type machines), however the training intensity and measures are geared to the CONC action. No studies have been done to specifically investigate the effects of ECC training on either CONC or ECC strength in older adults.

Factors that affect torque production are shown in Table 1.1. Potentially many of these factors can be altered by a strength training program, and obviously it would be difficult to try to measure changes in all of these. However, in the initial stages of a training program neural adaptations are thought to be predominant (Sale, 1988). Little is known about changes in passive stiffness, which could have an impact on the rate of torque development (RTD) and antagonist muscle torque and flexibility.
Table 1.1 Factors that affect torque generating capability (peak torque, rate of torque development) of an agonist muscle group.

1. **Muscle morphology**
   - mass
   - adipose and connective tissue content (quantity and quality)
   - fibre type

2. **Muscle mechanics**
   - cross bridges
   - type of muscle action
   - velocity of contraction

3. **Muscle / joint geometry**
   - pennation angle
   - moment arm

4. **Neural activation**
   - motor unit recruitment
   - motor unit rate coding

5. **Antagonist**
   - passive stiffness
   - coactivation
   - muscle mass

6. **Activation history**
   - fatigue
   - potentiation
   - stretch - shortening
Figure 1.1  A schematic of a force-velocity diagram (adapted from Hill, 1951).
Figure 1.2 A schematic of a force-length diagram (adapted from Lieber, 1992).
1.2 Outline of the thesis

The overall purpose of this thesis was to investigate the effects of age and high intensity strength training on concentric and eccentric muscle actions in women. The plantar and dorsiflexors were tested because: 1) of their importance in functional daily activities; 2) they weaken with age in concentric and isometric actions; 3) the plantar flexors have increased passive stiffness which could impact on dorsiflexion range of motion; and 4) of their differing contractile and morphological characteristics.

A standing position was developed to test and also train these muscle groups using an isokinetic dynamometer which reflects the position of the body during gait and stance when these muscle groups are typically utilized. Although reliability has been established for testing concentric DF and PF, no studies have examined the reliability of ECC testing of these muscle groups. In Chapter 2, the standing position equipment and protocol of testing strength are described. Two groups of subjects were tested, one for reliability over two occasions, and another group was tested in both the standing position and a supine position to compare peak torques (PT).

Chapter 3 describes a method of testing passive resistive torque (PRT) of the plantar flexors in the same standing position using an isokinetic dynamometer. No studies have addressed the reliability of an isokinetic dynamometer for measuring PRT, or in a weight-bearing position.

In Chapter 4 the developed method of testing in a standing position is utilized to investigate the potential age-related differences in concentric and eccentric peak torque of the plantar and dorsiflexors. Relationships with PRT and RTD are examined as possible contributors.

A strength training study of the plantar and dorsiflexors is reported in Chapter 5. Both concentric and eccentric actions are trained and tested. PRT and RTD are compared pre- and post-training.
Chapter 6 summarizes all findings and provides suggestions for future research on this topic.

1.3 Hypotheses

1) The standing position would be reliable for testing isokinetic peak torques of the plantar and dorsiflexors.

2) The standing and supine PT would be related, but not identical.

3) The standing position would be reliable for testing PRT.

4) Standing and supine PRT would be related, but not identical.

5) The older women would have greater ECC PT relative to CONC PT compared to the younger women.

6) PRT and RTD would be different between the younger and older women, and they would both contribute to the potential preservation of ECC PT.

7) The strength training study would result in increases in PT, specific to the mode of training, and perhaps also to the CONC action of the muscle group trained eccentrically (e.g. dorsiflexors).

8) Changes may occur in PRT and RTD following training.
CHAPTER 2
A METHOD OF MEASURING STANDING ISOKINETIC PLANTAR AND DORSIFLEXION PEAK TORQUES

2.1 INTRODUCTION

Isokinetic testing and training are used in both clinical and laboratory settings. Reliability assessments have been done with several muscle groups, and different isokinetic dynamometers (Perrin, 1993). However, only three known studies investigated the reliability of testing isokinetic ankle DF and PF strength (Karnofel et al., 1989; Wennerberg, 1991; Morris-Chatta et al., 1994). None of these addressed ECC actions of DF and PF, even though ECC muscle actions are performed in most daily and sporting activities, including gait and balance.

Because PF and DF are done in a weight-bearing and knee extended position in most daily activities, e.g. standing or walking, an upright weight-bearing position was developed to test these muscle groups. Typical isokinetic protocols for testing or training DF and PF involve knee-flexed seated positions (Karnofel et al., 1989; Wennerberg, 1991; Judge et al., 1994), however, testing and training in the knee extended position may be more clinically meaningful (Judge et al., 1994), because the gastrocnemius muscles become more involved in the muscle actions (Sale et al., 1982). As well, even though a supine position could test with an extended knee, this position does not reflect the actual position of the body during movement, and the mechanical and neural effects of weight-bearing (Aniss et al., 1992).

The purpose of this study was to determine the reliability of testing CONC and ECC DF and PF in a standing position. It was hypothesized that this type of testing would result in a sufficiently reliable method for comparing age groups and for an evaluation of a strength training intervention. As well, the standing protocol was compared to a more conventional supine protocol to assess the relationship and
potential differences between the test positions.

2.2 METHODS

2.2.1 Equipment

A KIN-COM 500H isokinetic dynamometer with version 3.21 software (Kinetic Communicator, Chattecx, Chattanooga, Tenn.) was utilized for the isokinetic testing. The standard KIN-COM ankle unit attachment for the 500H was used.

In order to test DF and PF in a standing position, a platform was developed to position the subject beside the dynamometer head (see Figure 2.1). A stand was constructed to meet the following criteria: 1) subject stability and safety, 2) appropriate positioning, 3) adjustment to the size and shape of subjects and, 4) portability within the laboratory.

The stand had a platform height of 0.69 m off the ground, in order to accommodate the lowest setting of the dynamometer head, and a total height of 2.44 m including the back rest. The platform of the stand had a width of 0.45 m and a length of 0.61 m. Features of the stand included removable stairs, a central arm rest, and storage space beneath. Standard velcro straps were attached to the stand at various locations to prevent excessive upper body and knee movement. These straps were also essential for subject safety because, for instance, subjects prone to postural hypotension could faint during testing. Although screening was performed to avoid potential problems, a plinth was positioned beside the platform to allow for transferring a subject to a supine position without descending the stairs.

A weight scale (Pro Shape, Counselor, Rockford, IL.) was mounted onto the platform with a belt, in order to monitor weight shifting during testing. The scale had a large dial which was easily read for peak changes in weight. The scale also had a large platform for extra foot space.
2.2.2 Reliability of the standing method

2.2.2.1 Subjects. Nineteen women participated in this aspect of the study (15 older women, age = 67.0 ± 4.6 years; 4 younger women, age = 25.3 ± 2.2 years). All subjects were free from orthopaedic problems to the tested leg, or any condition which might impair their ability to maximally contract the muscles of their leg. Because the subjects were required to stand for up to twenty minutes, subjects were screened for postural hypotension, proneness to dizziness or lightheadedness. Although the subjects were habitually physically active (mostly involving walking or low impact aerobics) they were not highly trained. All subjects provided written informed consent prior to participating in the study.

2.2.2.2 Subject positioning. Subjects were positioned on the stand with the left ankle attached to the ankle unit of the KIN-COM, and the right foot on the weight scale on the platform (Figure 2.1). The head of the dynamometer was moved so that both of the subject’s feet were the same distance from the ground. The subject’s left ankle was strapped to the KIN-COM ankle unit in a double cross-over fashion. All subjects were tested in stocking feet, and padding was added to the arch area for those subjects requiring it due to discomfort. The ankle axis of rotation was aligned with the axis of rotation of the KIN-COM (Perrin, 1993). Both legs were straight, not hyperextended, and the feet were approximately 20 to 25 cm apart. The hips were square (i.e. both feet had the same front/back orientation). Different sized pillows were placed behind the subjects’ trunk to maintain an upright standing position. This was important for ensuring appropriate angles at the ankle. Weight was evenly distributed between the right and left legs at rest. All testing was done with the arms at the side and the subject looking straight ahead, with safety straps securing the subject’s back to the stand.

2.2.2.3 Testing protocol. Following five minutes of stationary cycling at a low resistance (not to increase heart or respiration rate), subjects performed separate
CONC and ECC muscle actions for PF and DF at 30 °/s. The CONC and ECC actions were performed separately in order to maximize reliability and to avoid potentiated CONC torques (Bosco et al., 1982). The range of motion was standardized for all subjects to be 10° DF to 20° PF. This was according to the position of the ankle unit, with 0° being parallel to the ground and the tibia being perpendicular relative to the sole of the foot. Following a minimum of three familiarization / warm up trials, and an assurance by the subject that she was performing maximum efforts, one minute of rest was given. Three maximal trials for each movement (CONC and ECC) were then performed with about five seconds rest between CONC and ECC actions, and 30 seconds between a pair of CONC and ECC actions. Subjects were instructed to contract as hard and as fast as possible, but were not verbally encouraged during the trial. A period of one week was allowed between test occasions, with DF and PF tested alternately, at the same time of day.

2.2.2.4 Data analyses. The KIN-COM software collected angular velocity, force and angle data at 100 Hz. For all repetitions the raw data file was converted to an ASCII file and imported into a data management / analysis program (SigmaStat, Jandel Scientific, San Rafael, Ca.). To avoid acceleration and deceleration zones which occurred at the start and end of each repetition only torques which were associated with velocities of 30 ± 1 °/s were analyzed. At this velocity only a small number (eg. 3 to 5) of data points are removed from the start and end of the repetition. The force data were then converted to torque using a lever arm length of 0.20 m for all subjects, based on the distance of the load cell from the axis of rotation on the dynamometer head.

For each subject the two highest peak torques (PT) for the CONC and ECC trials for both muscle actions were selected and then averaged to produce one score for each occasion. This averaged PT was then used to calculate ECC:CONC ratios for DF and PF, for each occasion.
The PT values were not gravity corrected (although the gravity correction procedure was done for each subject at an angle of 5° of PF, to ensure similar positioning between occasions). Because subjects shifted their weight during testing, the standard gravity correction procedure would have given spurious results. Therefore the weight shifting aspect was part of the measured value of PT. In the case of PF the subjects tended to shift their weight onto the tested leg, while in DF they shifted onto the support leg (for either ECC or CONC actions). During each repetition the peak change in weight on the support leg was recorded. The weight on the support leg for all muscle actions reached a steady peak, so that reading of the dial for peak weight changes was possible. For each trial the % of body weight on the scale was calculated.

2.2.2.5 Statistical analyses. Pearson Product Moment correlation coefficients, intraclass correlation coefficients (ICC_{2,1}), standard error of the measurement (Fleiss, 1986), method error statistics and paired t tests were used to determine the reliability of the testing procedure. Coefficients of 0.75 or greater were considered to indicate excellent reliability (Fleiss, 1986). The method error (ME) and coefficient of variation (CV) have been used to examine the reliability of variables when the spread in the data is limited (Portney and Watkins, 1993, pg. 525). The ME can also be used to determine sample sizes and effect sizes which can be used for group comparisons and intervention techniques (Chiliback et al., 1994). The ME represents the discrepancy between two sets of repeated scores and when expressed as a percentage of the mean value it is termed CV. In terms of study design, the greater the ME or CV, the greater the measurement error and hence the greater the sample size or effect size required for determining differences between groups or over time. Correlation coefficients (r) were also calculated to determine the relationship between weight shifting and peak torque. All analyses were done using SigmaStat.
2.2.3 Supine versus standing peak torques

2.2.3.1 Subjects. Another group of 15 subjects with similar characteristics as listed for the reliability assessment was tested on one occasion in both the standing and supine positions (8 older women, age = 69.6 ± 4.8 years; 7 younger women, age = 26.1 ± 1.9 years).

2.2.3.2 Testing protocol. The same protocol of testing was used as for the standing position. The supine position replicated the same body position as for the standing testing, and used the same test protocol. The leg was extended and stabilized at the shin (and thigh if necessary). A strap was secured around the waist to prevent hip movement and displacement on the testing bed. Additional stabilization was placed on the shoulders to prevent movement, when necessary. The subjects had pillows under the head, and flexed the right knee to provide comfort for the back. The testing order was alternated between standing and supine to avoid order effects.

2.2.3.3 Data analyses. The same procedures for standing were followed for the supine position. Gravity correction was not performed for the supine position because of the small effect of the weight of the foot on torque values. Angle of peak torque was also analyzed on the highest two peak torques for the standing and supine positions in order to assess the torque patterns over the range of motion.

2.2.3.4 Statistical analyses. Paired t tests and Pearson Product Moment correlation coefficients were calculated to determine the potential differences and relationships between the testing positions. Because of the large number of comparisons made, the p value for significance was set at p < 0.01.

2.3 RESULTS

Typical torque - angle curves showing both DF and PF for the standing and supine positions are shown in Figure 2.2. The angle of peak torque was similar between positions, except for ECC DF where the angle of peak torque occurred in a
slightly more plantar flexed position for supine than standing (Figure 2.3). Not all subjects were able to move the ankle unit and/or generate measurable torque for CONC DF through the full range, for either position.

2.3.1 Reliability of the testing position

No significant differences were found between occasion 1 and 2 for PT (p < 0.01; Table 2.1). Correlation coefficients showed excellent reliability for all muscle actions, except for ECC DF which had moderate reliability (Fleiss, 1986; Table 2.1 and Figure 2.4, 2.5, 2.6 and 2.7). The coefficients of variation ranged from 7% to 17% (Table 2.1).

Although ECC DF had only moderate reliability coefficients, two individuals were detected as having undue influence when a linear regression was performed (i.e. large standardized residuals). When the analysis of correlation coefficients was repeated with these two individuals removed as outliers, the coefficients were similar to the other muscle actions (Table 2.1). No measurement errors or other confounding effects (i.e. fatigue) were suspected to have occurred for these subjects. And even though these subjects varied by 54% and 33% for ECC DF they varied by 1% to 5% on the other muscle actions. Because the outlying results for these two individuals cannot be explained, ECC DF has been reported with them included and excluded for the reliability coefficients, included for the method error statistics, and included for the rest of the muscle actions. The outliers were only removed to assist in explaining why the reliability coefficients were much lower than the other muscle actions, but the error introduced into the method has not been eliminated.

For the ratio data the correlation coefficients were lower, and in the case of DF ECC:CONC the CV and ME were high (Table 2.1). Again, however, there were no significant differences between occasion means (Table 2.1).

Weight shifting patterns are shown in Table 2.2, and reveal high correlations between occasions, with the exception of ECC PF, but no significant differences in
the means at the p < 0.01 level. ECC PF was also the only action for which the weight shifting pattern tended to change between occasions (p = 0.04, all others p > 0.1), although this would only amount to a change of approximately less than 6% of body weight. It should also be pointed out that ECC PF PT had the highest reliability coefficients so weight shifting patterns did not appear to have a large influence on the reliability of ECC PF. Also, there were no significant correlations between changes in weight shifting and changes in PT between occasions for any of the muscle actions (r = 0.040 to -0.36; p > 0.1). For DF and PF the percent of weight shifted did not differ between CONC and ECC actions.

2.3.2 Supine versus standing positions

Standing and supine PT, and ratios were highly correlated (Table 2.3, Figure 2.8). The standing position had significantly greater PT for CONC and ECC DF (Table 2.3). No other significant differences were found between the positions.

2.4 DISCUSSION

These findings suggest that testing of DF and PF isokinetic peak torques in a standing position is reliable and presents a viable alternative to the supine testing position. The correlation coefficients between occasions show moderate to excellent reliability, the torque - angle relationships are similar to reported values for DF (Marsh et al., 1981) and PF (Sale et al., 1982), and there is a strong relationship between the more conventional supine position and the standing position.

Many reliability studies have been done for isokinetic testing, especially of knee extension and flexion (Perrin, 1993; Nitschke, 1992). Reliability coefficients have ranged from 0.47 to 0.99 (Perrin, 1993) depending on the subjects, muscle action, velocity of movement, and test position. The only three reliability investigations of isokinetic DF and PF testing have reported inter-occasion Pearson Product Moment correlations of 0.86 to 0.94 (Karnofel et al., 1989), 0.67 to 0.79
(Wennerberg, 1991) and 0.67 to 0.92 (Morris-Chatta et al., 1994), which are comparable to this study. It should be noted that these studies only measured CONC actions, used Cybex (Karnofel et al., 1989; Wennerberg, 1991) and Biodex (Morris-Chatta et al., 1994) dynamometers, and subjects were seated or supine with knees flexed.

At 30 °/s, the Pearson r correlation coefficients were similar to (Morris-Chatta et al., 1994) or greater than (Wennerberg, 1991) previous reports. At higher velocities (eg. 60, 120, 180 °/s) correlation coefficients for DF and PF were affected differently depending on the muscle action and the study. The angular velocity of the present study was chosen for safety reasons because no previous studies have examined ECC actions of the DF and PF in older adults, and it was felt that fast velocities would pose a greater risk of injury for the older subjects because torque levels remain high with an increase in velocity for ECC actions (Perrin, 1993). Also, this velocity has been the most commonly used in other studies (Perrin, 1993), thereby providing the greatest number of studies for comparison. This same velocity was going to be used for a training study, and at fast velocities the number of data points would be small with the sampling frequency of the KIN-COM (i.e. 100 Hz). It was recognized that this angular velocity does not reflect the normal velocity of movement in gait; however, it provided a starting point to assess the reliability of this mode of testing.

No known studies have assessed the reliability of testing ECC actions of the DF and PF. Even though it has been stated for other lower extremity tests that ECC actions tend to be less reliable than CONC actions (Perrin, 1993), acceptable reliability coefficients for both CONC and ECC actions were found (Table 2.1). The DF ratio had poor reliability coefficients, and the CV was high. This is comparable to another study examining ECC:CONC ratios in knee extension and flexion, where the absolute PT were reliable (Kramer et al., 1994). Therefore, although ratios could
potentially provide useful information by normalizing torque production (Kramer et al., 1994), they should be used cautiously, and the method error should be taken into consideration when comparing groups or individuals over time. If ratios are the outcome variable of interest then a larger sample size will be required for DF because of the high method error.

The fact that other dynamometers have been utilized for determining reliability of a testing protocol is only critical in making comparisons between actual torque values rather than their reliability since KIN-COM (Tredinnick and Duncan, 1988; Mayhew et al., 1994), Cybex and Biodex (Timm et al., 1992) dynamometers have been found to have good mechanical and physiological reliability. Also, the fact that the other studies assessing DF and PF reliability testing used flexed knee positions makes it difficult to compare peak torque values because the straight knee position is known to result in greater PF PT (Fugl-Meyer et al., 1980; Sale et al., 1982). It is not known how the knee position would affect reliability, but in this study reliability of DF and PF PT in standing with the knee straight resulted in comparable correlation coefficients (CC) for the same velocity as reported by Morris-Chatta et al. (1994).

While reliability testing of a new method is imperative, it is also worthwhile to compare values to others reported in the literature and testing procedures traditionally used. Even though it is difficult to compare PT between studies because of differences in subjects, testing positions, dynamometers, velocities of movement and subjects, it does give a gauge of how a method compares to others. Appendix III lists various studies of DF and PF at the same angular velocity. It should be noted that the type of muscle action will have a great influence on the PT, with CONC being less than ECC (Perrin, 1993). Generally the PT values of this study are comparable to the others, and differences can be explained by the factors listed above.

The supine PT measured in this study were highly related to the standing PT, but the standing DF values were greater than the supine values. It would be expected
that with a large range in values of peak torque there would be a relationship between the torque generating capabilities of the two positions. Factors like body weight and size would have a large effect on torque in both positions.

Although it was not the purpose of this study to determine the differences between torque generating capabilities of DF and PF in weight-bearing compared to supine, a few explanations can be offered. First, greater torques in standing can be partially explained by the weight of the subject exerting torque in the standing position and therefore influencing the baseline torque level (see Figure 2.2). Second, the fact that subjects were able to shift their weight during testing also contributed. Third, the fact that subjects were in a standing position may have had a mechanical effect due to changes in the joint itself when weight-bearing. As well, mechanoreceptors and reflex responses have been shown to be different in upright weight-bearing positions compared to supine (Aniss et al., 1992).

As for the torque - angle relationship, only isometric studies are available for comparison (Marsh et al., 1981; Sale et al., 1982; van Schaik et al., 1994). The ECC torque curves are very similar to the reported isometric curves (Marsh et al., 1981; Sale et al., 1982; van Schaik et al., 1994), with PT occurring in a lengthened position for both muscle groups. The CONC torque curves, allowing for time to reach PT during the manoeuvre, also concur. As well, no differences in the length tension relationship have been found between young and older subjects for DF (van Schaik et al., 1994), with both groups having low torques when the ankle was in a dorsiflexed position. This may explain the observation that some individuals could not move through the full range of motion for CONC DF, even though their passive range of motion allowed for it. However, DF PT should not have been compromised because it occurs in a plantar flexed position (Marsh et al., 1981; van Schaik et al., 1994).
Therefore, it can be concluded that CONC and ECC DF and PF can be reliably established when subjects are tested in a standing position. This method could be used in comparing groups (e.g. effects of age and gender). It may also prove useful as an outcome measure for a strength training intervention, given the stability in values observed between two test occasions. The advantage of this testing position is that it is weight-bearing, and there may be greater transference of strength gains between training and other functional tasks done in weight-bearing. Future research using this standing protocol could examine the reliability of faster angular velocities, isotonic loading, stretch-shortening cycles, and the relationship of peak torque to functional measures like gait velocity.
Table 2.1  Means for absolute peak torque (N·m) and ratios for concentric (CONC) and eccentric (ECC) plantar flexion (PF) and dorsiflexion (DF) for occasions 1 and 2. Pearson r correlation coefficients, intraclass correlation coefficients (ICCs), the method error (ME), coefficients of variations (CV) and standard error of the measurement (SEM) were also determined for the repeat testing (n = 19).

<table>
<thead>
<tr>
<th></th>
<th>Mean 1 ± SD</th>
<th>Mean 2 ± SD</th>
<th>Pearson r</th>
<th>ICC(_{2,1})</th>
<th>ME (N·m)</th>
<th>SEM (N·m)</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONC DF</td>
<td>15.7 ± 7.0</td>
<td>16.5 ± 5.1</td>
<td>0.84</td>
<td>0.79</td>
<td>2.8</td>
<td>3.2</td>
<td>17.1</td>
</tr>
<tr>
<td>ECC DF</td>
<td>27.9 ± 6.4</td>
<td>29.0 ± 5.8</td>
<td>0.60</td>
<td>0.60</td>
<td>3.9</td>
<td>4.1</td>
<td>13.5</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0.86*</td>
<td>0.85*</td>
<td></td>
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</tr>
<tr>
<td>CONC PF</td>
<td>66.2 ± 17.2</td>
<td>71.1 ± 15.9*</td>
<td>0.84</td>
<td>0.81</td>
<td>6.7</td>
<td>7.5</td>
<td>9.7</td>
</tr>
<tr>
<td>ECC PF</td>
<td>104.6 ± 22.7</td>
<td>104.5 ± 23.7</td>
<td>0.90</td>
<td>0.90</td>
<td>7.4</td>
<td>7.2</td>
<td>7.1</td>
</tr>
<tr>
<td>DF ECC:CONC</td>
<td>2.1 ± 0.9</td>
<td>1.9 ± 0.5</td>
<td>0.33</td>
<td>0.28</td>
<td>0.6</td>
<td>0.76</td>
<td>31.0</td>
</tr>
<tr>
<td>PF ECC:CONC</td>
<td>1.6 ± 0.4</td>
<td>1.5 ± 0.2</td>
<td>0.54</td>
<td>0.39</td>
<td>0.2</td>
<td>0.24</td>
<td>14.6</td>
</tr>
</tbody>
</table>

* Two outliers removed from the data set for correlation coefficients. * Significant differences between the means (p < 0.05).
Table 2.2  Weight shifting patterns (% body weight on support leg) for the two occasions for each muscle action.

<table>
<thead>
<tr>
<th></th>
<th>Mean 1 ± SD</th>
<th>Mean 2 ± SD</th>
<th>Pearson r (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONC DF</td>
<td>86.8 ± 17.4</td>
<td>82.1 ± 18.9</td>
<td>0.81</td>
</tr>
<tr>
<td>ECC DF</td>
<td>87.6 ± 19.2</td>
<td>85.6 ± 15.3</td>
<td>0.76</td>
</tr>
<tr>
<td>CONC PF</td>
<td>19.3 ± 12.7</td>
<td>16.5 ± 9.9</td>
<td>0.79</td>
</tr>
<tr>
<td>ECC PF</td>
<td>20.0 ± 12.5</td>
<td>14.5 ± 5.9</td>
<td>0.41 *</td>
</tr>
</tbody>
</table>

**Note:** CONC = Concentric; ECC = Eccentric; DF = Dorsiflexion; PF = Plantar flexion. * significant difference $p < 0.05$. * $p = 0.09$. 
Table 2.3  Comparison of supine versus standing concentric (CONC) and eccentric (ECC) dorsiflexion (DF) and plantar flexion (PF) peak torques (Nm), and ECC:CONC ratios.

<table>
<thead>
<tr>
<th></th>
<th>Standing (mean±SD)</th>
<th>Supine (mean±SD)</th>
<th>Pearson r (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONC DF</td>
<td>18.9 ± 6.1</td>
<td>14.2 ± 5.2**</td>
<td>0.82 (p &lt; 0.001)</td>
</tr>
<tr>
<td>ECC DF</td>
<td>30.1 ± 6.6</td>
<td>28.3 ± 6.9*</td>
<td>0.95 (p &lt; 0.0001)</td>
</tr>
<tr>
<td>CONC PF</td>
<td>77.3 ± 16.1</td>
<td>70.2 ± 22.8</td>
<td>0.82 (p &lt; 0.001)</td>
</tr>
<tr>
<td>ECC PF</td>
<td>101.1 ± 23.8</td>
<td>100.6 ± 27.5</td>
<td>0.80 (p &lt; 0.001)</td>
</tr>
<tr>
<td>DF ECC:CONC</td>
<td>1.7 ± 0.4</td>
<td>2.1 ± 0.6*</td>
<td>0.64 (p &lt; 0.05)</td>
</tr>
<tr>
<td>PF ECC:CONC</td>
<td>1.3 ± 0.2</td>
<td>1.5 ± 0.3*</td>
<td>0.70 (p &lt; 0.01)</td>
</tr>
</tbody>
</table>

Note: Significant differences between positions indicated (* p < 0.01; ** p < 0.001).
Figure 2.1 A subject is shown in the standing position with all the appropriate stabilizing straps.
Figure 2.2  Torque-angle curves for an individual in both a supine and standing position for concentric and eccentric plantar (B) and dorsiflexion (A). Note: ▲ = concentric supine; ○ = concentric standing; ▼ = eccentric supine; □ = eccentric standing; DF = dorsiflexion and PF = plantar flexion.
Figure 2.3  Angle of peak torques for the concentric (CONC) and eccentric (ECC) muscle actions in the standing and supine positions.
Figure 2.4 Reproducibility of peak torque (PT) for concentric (Conc) dorsiflexion showing individual values (●), means for occasion one and two (□), and the regression line (dashed line).
Figure 2.5  Reproducibility of peak torque (PT) for eccentric (Ecc) dorsiflexion showing individual values (●), means for occasion one and two (□), and the regression line (dashed line).
Figure 2.6  Reproducibility of peak torque (PT) for concentric (Conc) plantar flexion showing individual values (●), means for occasion one and two (□), and the regression line (dashed line).
Figure 2.7 Reproducibility of peak torque (PT) for eccentric (Ecc) plantar flexion showing individual values (○), means for occasion one and two (□), and the regression line (dashed line).
Figure 2.8  Standing and supine peak torque values for concentric dorsiflexion (○), eccentric dorsiflexion (●), concentric plantar flexion (□) and eccentric plantar flexion (■). The solid line shows the line of identity (i.e. \( r = 1.0 \)), and the dashed line is the regression line for all points (\( r = 0.96, p < 0.0001 \))
CHAPTER 3
CONCURRENT VALIDITY AND RELIABILITY
OF MEASURING STANDING PASSIVE RESISTIVE TORQUE

3.1 INTRODUCTION

Flexibility measurements are made in many settings. Tests of range of motion (ROM) or passive stiffness are used: 1) to assess the efficacy of training or therapeutic programs (Misner et al., 1992; Hubley-Kozey et al., 1995; Toft et al., 1989), 2) to examine the acute effects of exercise on muscle due to damage (Howell et al., 1993), 3) to compare different groups based on age (Nigg et al., 1992; Chesworth and Vandervoort, 1989; James and Parker, 1989; Vandervoort et al., 1992; Vandervoort et al., 1990a), gender (Vandervoort et al., 1992) or pathology (Hufschmidt and Mauritz, 1985; Halar et al., 1978; Watts et al., 1986; Thilmann et al., 1991; Sinkjær and Magnussen, 1994), 4) to determine changes due to immobilization (Heerkens et al., 1986), and 5) to investigate the contribution of passive torque to active muscle-joint complex mechanics (Blanpied and Smidt, 1993; Wilson et al., 1994). These tests are completed using standard goniometers (Wright, 1973; Elveru et al., 1986) or flexometers (Hubley-Kozey et al., 1995), manual movements (Chesworth et al., 1991), custom built mechanical devices (Chesworth and Vandervoort, 1988; Wright, 1973; Moseley and Adams, 1991; Wiegner and Watts, 1986) or commercially available isokinetic dynamometers (Broberg and Grimby, 1983; Gravel et al., 1986; Blanpied and Smidt, 1993) which move a joint through a ROM.

Goniometer or flexometer techniques have the advantage of being economical, portable and easy to perform, however, there are disadvantages. If these techniques are applied using active ROM then muscle strength can be a factor affecting ROM (Vandervoort et al., 1992). If applied passively, then determining the end of range
can vary between testers (Chesworth et al., 1991). As well, for these techniques, the mechanical properties of the muscle-joint system cannot be assessed over the entire ROM evaluated (Chesworth and Vandervoort, 1988).

Although custom devices alleviate the problems listed above, accessibility is a major drawback. With the refinement of isokinetic dynamometers to employ computer controlled robotics, passive resistive torque (PRT) can now be measured utilizing commercial equipment which is available to many clinicians, kinesiologists and researchers. To our knowledge, no known studies have assessed the reliability of using a commercially available isokinetic dynamometer to measure PRT.

The purposes of this study were as follows: 1) to determine the reliability of testing passive resistive torque of the ankle plantar flexors in a standing position on a commercially available isokinetic dynamometer in healthy women, and 2) to compare the values of the standing position to a supine position in order to assess the validity of the standing position.

Ankle plantar flexor PRT was chosen as the main outcome of this study because the ankle and the muscles surrounding it are important in gait (Winter, 1991) and balance (Whipple et al., 1987). As well, changes in plantar flexor PRT have been found with age (Vandervoort et al., 1992). Thus, in order to also assess the validity of the testing method, older and younger women were tested, and a comparison was made between the groups to examine the effects of age on PRT.

Because the amount of muscle mass has been found to be associated with passive torque (Wiegner and Watts, 1986; Hufschmidt and Mauritz, 1985; Such et al., 1975), and muscle mass decreases with age (Borkan et al., 1983; Vandervoort and McComas, 1986; Rice et al., 1989; Sipila and Suominen, 1993), the relationship between body weight and PRT needs to be investigated.

Although most tests have been confined to supine / kneeling, a standing position was developed because there may be differences in PRT due to the joint
being in a weight-bearing state. It is important to know these stiffness characteristics in weight-bearing when you are examining active mechanical properties of the ankle-muscle joint complex (Porter et al., 1994).
3.2 METHODS

3.2.1 Reliability of the standing test position

3.2.1.1 Subjects. Recreationally active women between the ages of 20 to 35 (younger) and 60 to 76 years (older) were tested on two occasions, within two weeks (Table 3.1). Both groups of women had similar physical activity patterns. All subjects were free from orthopaedic problems to the tested leg, and reported no tendency to postural hypotension.

3.2.1.2 Testing equipment and position. The same equipment, warm up and testing position as described in Chapter 2 were utilized.

3.2.1.3 Testing protocol. The "Passive" mode on the KIN-COM was selected. The foot was passively moved from a position of 10° PF to 10° DF and back to 10° PF, through six cycles, at 6 °/s angular velocity, with the subject relaxed. The angle was determined according to the position of the ankle unit, with the neutral position (0°) being parallel to the ground, and the tibia perpendicular to the sole of the foot. Electrodes on the lateral gastrocnemius and soleus were used to monitor muscle activity via a biofeedback unit. Some individuals required practice trials to learn to relax muscles and permit passive movement of the ankle.

3.2.1.4 Data analyses. Passive resistive torque (PRT) at 10° DF was the outcome variable of interest. The KIN-COM raw data file, which provided force data, was converted to an ASCII file for analysis using a data management / analysis program (SigmaStat, Jandel Scientific, San Rafael, CA). The first cycle was not used for analysis to allow for subject accommodation. To avoid transition acceleration and deceleration the torque at 10° DF was filtered for velocities of 6 ± 1 °/s. To account for the additional forces attributable to body weight and the ankle unit, the averaged force at 10° PF was subtracted from the averaged force at 10° DF for the five cycles, since the resistive force at 10° PF has been found to be negligible. From this force data, torque was calculated using a common lever arm length for all
individuals, based on the distance of the load cell from the axis of rotation (0.20 m) on the KIN-COM.

3.2.1.5 Statistical analyses. Pearson Product Moment correlation coefficients, intraclass correlation coefficients (ICC$_{2,1}$ (Shrout and Fleiss, 1979)), method error statistics (Portney and Watkins, 1993) and a paired t-test were used to examine the reliability of the testing procedure. ICCs of $\geq 0.75$ were considered to indicate excellent reliability (Fleiss, 1986). All analyses were done using SigmaStat.

3.2.2 Standing versus supine test positions

3.2.2.1 Subjects. Other groups of 14 older and 10 younger women, with similar characteristics as described for the reliability of the standing test were studied, on one occasion, during randomly assigned standing and supine positions (Table 3.1).

3.2.2.2 Testing protocol. The same basic testing protocol was used for the standing and supine positions, including the same body position. The left leg was extended and stabilized at the shin (and thigh if necessary). In this case the ankle angle was determined with the long axis of the ankle unit perpendicular to the ground. A strap was secured around the waist to prevent hip movement and displacement of the subject along the testing bed. Pillows under the head, and flexion of the right knee were used for subject comfort.

3.2.2.3 Data and statistical analyses. Analyses were identical to that for the reliability of the standing phase. Student's t-tests (unpaired) were performed to compare PRT between the age groups in both positions. In addition, Pearson Product Moment correlation coefficients were used to examine the relationship between age and weight on PRT for both positions.
3.3 RESULTS

Figure 3.1 is a typical torque curve over the 6 cycles in the standing position.

3.3.1 Reliability of the standing test position

There was no significant difference between PRT on the two test occasions (occasion 1 = 12.3 ± 3.3 N·m vs occasion 2 = 12.3 ± 3.7 N·m, p > 0.05; Figure 3.2). The two occasions were significantly related and showed excellent test-retest reliability (r = 0.85, p < 0.001; ICC\textsubscript{2,1} = 0.86; ICC\textsubscript{2,2} = 0.92). The method error was 1.36 N·m, and the corresponding coefficient of variation was 11.0%.

3.3.2 Standing versus supine test positions

The standing test position produced values approximately 8% lower than PRT in the supine position (standing = 10.8 ± 3.9 N·m vs supine = 11.8 ± 4.0 N·m, p < 0.05; Figure 3.3). The PRT determined in the two positions were significantly related (r = 0.91, p < 0.01).

PRT was greater in the older women than the younger women, this difference reached significance in the supine position (13.3 ± 3.1 vs 9.6 ± 4.2 N·m; p < 0.05), but did not for the standing position (11.8 ± 3.7 vs 9.4 ± 4.0; p = 0.15).

Body weight was significantly related to PRT in both positions, with r = 0.58 (p < 0.01) for the standing position, and r = 0.50 (p < 0.05) for the supine position.
3.4 DISCUSSION

The main finding of this study was that the method of testing PRT of the plantar flexors in a standing position was reliable and showed a strong relationship with PRT tested in a supine position. The reliability coefficient and coefficient of variation are comparable to values reported for a similar protocol performed with a custom designed torque motor system (Chesworth and Vandersloot, 1988), and an adapted isokinetic dynamometer moved manually (Otis et al., 1983).

Although the standing position PRT had significantly lower values than the supine position, there was a very strong relationship between the two positions. The difference in PRT between the two positions may be explained by slight differences in ankle angle which may have occurred between standing and supine positions. As well, we cannot rule out a slight dorsiflexor moment occurring in standing, since these muscles were not monitored with EMG. However, subjects were instructed to avoid assisting the movement into DF and had already gained familiarity with relaxing muscles via practice and monitoring the plantar flexors.

The age comparison revealed differences between groups, with the older women demonstrating greater PRT than the younger women. The supine position seemed to be more sensitive than the standing position in determining this difference.

Even though body weight alone was used to give a crude indication of the amount of muscle mass of an individual, there were significant correlations between PRT and weight for both positions, with a slightly higher correlation coefficient for the standing position. Obviously body weight is a function of the combined weights of body fat, muscle, bone and other components. A more specific method of determining muscle mass changes with age would have been to use computed tomography (Borkan et al., 1983; Sipila and Suominen, 1993), magnetic resonance imaging (Baumgartner et al., 1992), or ultrasound (Vandervoort and McComas, 1986; Sipila and Suominen, 1993). These techniques were not available, and anthropometry
was not done because other methods of estimating muscle mass with anthropometric techniques have shown large errors attributed to the infiltration of muscle with adipose and connective tissue with increasing age (Rice et al., 1989; Baumgartner et al., 1992). The method of assessing muscle mass could explain why there was lower explanatory power of body weight to the passive stiffness characteristics of the ankle, than was found for the volume of the upper arm to passive stiffness of the elbow (Wiegner and Watts, 1986). However, Huwschmidt and Mauritz (1985) reported a similar correlation between calf cross sectional area (as approximated from calf circumference) and passive torque, as in the present study.

The other factors which contribute to passive stiffness of a joint-muscle complex are muscle spasticity, fibrous replacement of muscle fibres within muscle, tendons, skin, subcutaneous tissue, the joint capsule, and the bony articulation (Wright, 1973). The contributions of each of these depends on the angle of measurement, and conditions which alter stiffness may be expected to influence these factors dissimilarly (Wright, 1973). With aging there is a known increase in subcutaneous adipose tissue, along with an increase in intramuscular fat and connective tissue in the plantar flexors (Rice et al., 1989). This change in non-muscle tissue probably contributes to the age-related increase in passive stiffness (Alnagheeb et al., 1984), even when muscle tissue itself is decreasing (Vandervoort et al., 1992). When changes in muscle versus non-muscle tissue occur in the opposite direction it is difficult to determine age-related changes in passive resistance (Wright, 1973) and this may explain why published results have been equivocal showing increases (Vandervoort et al., 1992), no change (Chesworth and Vandervoort, 1989) and even decrements (Vandervoort et al., 1990a; Oatis, 1993) in passive characteristics of the ankle and knee (Oatis, 1993) joint complex with increased age.

The effects of tendon should be important in this movement pattern since tendons are known to contribute more to passive resistance as the joint is moved to
the extreme ends of ROM (Wright, 1973). No known studies have examined the changes in stiffness of the human Achilles tendon with age, although age-related anatomical changes have been reported for rabbit Achilles tendon (Nakagawa et al., 1994).

As well, it is not known how changes in skin, the joint capsule or bony articulations with age may affect passive stiffness. However, these factors have been shown to contribute minimally to stiffness in the cat (Johns and Wright, 1962), and would presumably play a minor role in any alteration with age.

In summary, PRT of the plantar flexors can be determined reliably in a standing position on a commercially available isokinetic dynamometer. Passive resistive torques for the standing position were lower than those in the supine position but torques in both positions were highly related ($r = 0.91$). Both positions revealed an age effect on PRT, although this reached significance only in the supine position.
Table 3.1 Characteristics of the subjects.

Standing reliability.

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>age (years)</th>
<th>height (cm)</th>
<th>weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Older Women</td>
<td>13</td>
<td>65.8 ± 3.5</td>
<td>162.5 ± 4.8</td>
<td>68.4 ± 8.3</td>
</tr>
<tr>
<td>Younger Women</td>
<td>4</td>
<td>25.2 ± 2.2</td>
<td>160.8 ± 9.8</td>
<td>55.2 ± 4.6*</td>
</tr>
</tbody>
</table>

Supine versus standing tests.

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>age (years)</th>
<th>height (cm)</th>
<th>weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Older Women</td>
<td>14</td>
<td>67.9 ± 4.9</td>
<td>159.7 ± 5.3</td>
<td>62.1 ± 10.6</td>
</tr>
<tr>
<td>Younger Women</td>
<td>10</td>
<td>26.2 ± 3.3</td>
<td>165.4 ± 4.4*</td>
<td>63.8 ± 10.6</td>
</tr>
</tbody>
</table>

* significant difference, p < 0.01.
Figure 3.1  A typical standing passive resistive torque curve.
Figure 3.2 Reproducibility of passive resistive torque showing individual values (■), means for occasion one and two (○), the regression line (dashed line), and the line of identity (i.e. r = 1.0).
Figure 3.3  Standing and supine passive resistive torque showing individual values for both positions (●), the mean value for each position (□), the regression line (dashed line; r = 0.91, p < 0.01), and the line of identity (i.e. r = 1.0).
CHAPTER 4
ECCENTRIC PEAK TORQUE OF THE PLANTAR AND DORSIFLEXORS IS MAINTAINED IN OLDER WOMEN

4.1 INTRODUCTION

The loss of muscle strength is considered to be an inevitable consequence of the aging process. However, ECC strength seems to be relatively preserved compared to CONC (Vandervoort et al., 1990b; Poulin et al., 1992; Porter et al., 1995a) and isometric (Phillips et al., 1993b; Brooks and Faulkner, 1994; Phillips et al., 1991) strength, in both mice (Brooks and Faulkner, 1994; Phillips et al., 1991) and humans (Vandervoort et al., 1990b; Poulin et al., 1992; Phillips et al., 1993b; Porter et al., 1995a).

To date, mechanisms have not been elucidated which might determine this relative maintenance of strength during ECC muscle actions. Some proposed explanations include changes with age: 1) passive parallel elasticity, 2) cross bridge kinetics and mechanics, or 3) neural activation when voluntary contractions are performed. It has also been speculated that declines in estrogen in women and/or changes in a substance in the cytosol in muscle fibres with increasing age could have an influence on the force of cross bridges during shortening, but not lengthening, muscle actions (Phillips et al., 1993b).

The main objective of this study was to investigate CONC and ECC peak torque during PF and DF, in healthy older (OW) and younger (YW) women. In addition, PRT of the plantar flexors, and rate of torque development (RTD) during both DF and PF were measured to examine their possible relationship to torque generating capabilities. These muscle groups were selected because of reported changes in passive stiffness (Vandervoort et al., 1992), contractile properties (Vandervoort and McComas, 1986), and morphological characteristics (Jakobsson et
al., 1990; Coggan et al., 1992) with age. It was hypothesized that OW would have
greater ECC relative to CONC peak torque, and that differences in PRT and RTD
between OW and YW would be contributing factors.
4.2 METHODS

4.2.1 Subjects

Healthy and independently living women ranging in age from 21 to 33 years (YW) and 60 to 74 years (OW) volunteered. Subject characteristics are shown in Table 4.1. None of the subjects had experienced orthopaedic problems (eg. ankle sprains) of the tested leg within the past year, and subjects were not limited in walking or other daily activities by any other condition. Subjects were habitually involved in recreational activities, but these did not include strength training of the plantar and dorsiflexors or running and jumping sports within the past several months. Thorough screening was done to ensure similar activity patterns in both subject groups.

Subjects did not have conditions or take medications which have known major effects on neuromuscular function. However, nine OW were taking estrogen and two OW were being treated for hypothyroidism.

All subjects were informed of the procedures and provided written consent as approved by the Review Board for Health Sciences Research Involving Human Subjects.

4.2.2 Testing positions and procedures

The standing position and procedures described in Chapters 2 and 3 were used for this study. After the warm up (see Chapter 2), the order of testing was first passive stiffness, and secondly testing of the DF and PF muscle actions were alternated.

4.2.3 Data analyses

The same outcome variables were determined as outlined in Chapters 2 and 3
(i.e. DF and PF CONC and ECC PT. and PRT). Peak torque was also calculated relative to body weight.

In addition to the comparison of PT, the torque-angle relationships were examined for the ECC actions. If neural or passive factors were the predominant cause of a maintenance of ECC peak torque, a different torque-angle relationship could exist between YW and OW. Polynomial regression procedures were performed and the subsequent coefficients were compared to determine an age effect.

The angle of CONC PT was used to calculate the average rate of torque development (RTD) for both PF and DF. The KIN-COM raw data output provides force, angle and velocity at 100 Hz. From the angle of PT, the time to reach peak torque could be calculated based on the angular velocity (30 °/s). The average RTD (i.e. PT (N\(\cdot\)m) / time (sec)) was then calculated using the PT and time to reach this angle.

4.2.3 Statistical analyses

Two separate two way analyses of variance (ANOVA) tests were conducted for PF and DF, with age and action (CONC or ECC) as factors. It was decided a priori to test for differences between groups (using the Student-Newman Keuls test), based on previous differential changes in PT between the muscle actions and age groups. T-tests were performed to compare PRT, RTD, coefficients of the regression equations of the torque-angle relationships, and ECC:CONC ratios between YW and OW. Pearson Product Moment correlation coefficients were used to relate PRT, RTD and CONC and ECC PT. In the OW, t-tests were used to compare the effects of estrogen replacement on torque production. All analyses were done using SigmaStat (Jandel Scientific, San Rafael, Ca.).
4.3 RESULTS

Average CONC PT for the OW were 74% and 89% of the YW, while ECC PT were 97% and 100% of YW for DF and PF respectively (see Figures 4.1 and 4.2 for absolute peak torque values).

4.3.1 Dorsiflexion. On the ANOVA, significant main effects for age (p=0.05) and action (p<0.001) were found, but the interaction (age x action) did not reach significance (p=0.16). However, CONC DF PT was significantly lower in the OW, but ECC DF was not significantly different between the two age groups (Figure 4.1). For PT expressed in ECC:CONC ratios OW had significantly greater values than YW (p<0.01; Figure 4.3).

4.3.2 Plantar flexion. The main effect for action alone was significant (p<0.001; Figure 4.2). However, OW had greater ECC:CONC ratios for PF (p=0.05; Figure 4.3).

4.3.3 Peak torques relative to body weight. These ratios were calculated because most of these muscle actions are performed to either accelerate or decelerate the body during gait. The OW had significantly smaller ratios (PT / body weight) for CONC DF (OW = 0.24 ± 0.02, YW = 0.37 ± 0.03; p < 0.001) and CONC PF (OW = 1.11 ± 0.04, YW = 1.36 ± 0.07; p < 0.01). There were no significant differences for ECC PT / body weight ratios.

4.3.4 Torque-angle relationship for ECC actions. Age-group curves are shown in Figures 4.4 and 4.5. For ECC PF a second order polynomial regression was utilized to represent the curve (the average R² was 0.99 for both groups), and there were no differences between the two groups for any of the coefficients (p > 0.1). For ECC DF a third order polynomial regression was performed (mean R² for
both groups = 0.99). Again there were no differences between the age groups for any coefficient.

4.3.5 Passive resistive torque. Examples of PRT curves are shown in Figure 4.6. PRT of the plantar flexors was 26.4% greater in OW than YW (Figure 4.7, p < 0.01). When PRT was expressed as a percentage of ECC PF PT there was a difference between the groups (OW = 11.9 ± 1.8% vs YW = 9.0 ± 3.6%, p < 0.01). However, when ECC PF PT was corrected for PRT, there was no significant difference between OW and YW (OW = 95.8 ± 16.2 N·m, YW = 99.4 ± 23.3 N·m; p > 0.1). The correlations between PRT, PT and RTD are shown in Tables 4.2, 4.3, 4.4. When a significant correlation was found and it was expected that another variable could be acting as a confounder, a multiple regression was performed. For CONC PF PT and PRT there was a positive correlation. However it is known that muscle mass can affect both variables. When a multiple regression was performed with both PRT and body weight as variables, only body weight exerted a significant effect (p < 0.05) and had an $R^2$ of 0.43. No additional portion of the variance could be explained by PRT.

To examine the potential effect of PRT of the plantar flexors on the antagonist CONC action (i.e. CONC DF), PRT was expressed as a percentage of CONC DF PT. The OW had values approximately twice those of the YW (OW = 18.6 ± 6.7%; YW = 9.5 ± 5.3%).

4.3.6 Rate of torque development. Both PF and DF RTD were significantly greater in the YW than the OW (Figure 4.8, p < 0.05). The relationships between RTD, PT and PRT are shown in Tables 4.3 and 4.4.
4.3.7 Effects of estrogen replacement. The characteristics of the estrogen-replaced women (ER, n = 9) and non-estrogen-replaced women (NER, n = 7) were similar for weight (ER = 64.6 vs NER = 67.0 kg; p > 0.1), height (ER = 162.1 vs NER = 162.2 cm; p > 0.1) and age (ER = 66.2 vs NER = 67.7; p > 0.01). The NER group had 35% greater CONC DF PT (p < 0.05) and a lower DF ECC:CONC PT ratio (p < 0.05) than the ER group. All other comparisons showed no significant differences between groups.
4.4 DISCUSSION

For both DF and PF there were greater age-related losses in CONC than ECC peak torque, and the resulting ECC:CONC ratios were greater in OW for both muscle actions. Even though this finding of preserved torque production during active lengthening has been demonstrated in the knee extensors (Vandervoort et al., 1990b; Poulin et al., 1992; Porter et al., 1995a) and the elbow flexors (Poulin et al., 1992), this is the first report on the plantar and dorsiflexor muscle groups in humans.

In aged mice, specific force during rapid lengthening has been shown to be maintained (Phillips et al., 1991) or even enhanced, for the soleus (Phillips et al., 1991) and the extensor digitorum longus (EDL; Brooks and Faulkner, 1994). This also resulted in larger lengthening to isometric force for the older animals (Phillips et al., 1991). Actual mechanisms for this differential change in strength between shortening and lengthening muscle actions are undetermined; however, in the isolated (Phillips et al., 1991) and single fibre mouse muscle preparations (Brooks and Faulkner, 1994) the effect of a cytosolic substance on the cross bridge has been proposed. This effect was hypothesized to be independent of changes in myosin isoforms (Phillips et al., 1993d). Passive stiffness was dismissed as a potential cause because it represented a small percentage (2%) of the lengthening force, and there were no differences between the young and old animals (Brooks and Faulkner, 1994). In the other study passive force was removed experimentally from contributing to active lengthening force (Phillips et al., 1991). However, in our human model where significant age group differences exist for PRT, stiffness needs to be considered.

4.4.1 Passive resistive torque. As has been previously reported (Vandervoort et al., 1992) OW have greater PRT; in this study the difference was 26%. When
PRT was expressed relative to ECC PF PT, there was also a difference between the groups (OW = 11%; YW = 9%), and both values were much larger than that for the single fibres from EDL of the mouse (2%; Brooks and Faulkner, 1994). However, there were no differences in the active ECC PF torque between the age groups. It also appears from the torque-angle curve that the similarity of torque curves is not dependent upon passive stiffness of the muscle-joint complex because even in a plantar flexed position, where stiffness is low, the two groups exhibit identical torques.

Other evidence suggests that passive stiffness is not the major factor in explaining the maintenance of ECC torque with age because ECC DF PT is also preserved. PT for ECC DF is reached in a plantar flexed position where there is little measurable passive resistance attributed to the muscle-joint complex. However, CONC DF may be adversely affected by PRT.

Passive stiffness of the plantar flexors may affect the measured torque of the antagonist muscle group, the dorsiflexors, when they are active. The dorsiflexors must produce force to move the foot, and also work against the stiffness of the plantar flexors in order to produce movement over the entire range of motion. However, because PRT represents a much larger percentage of CONC DF for the OW, they will have more difficulties in producing movement later in the range, with the force that the dorsiflexors are capable of producing. In fact, only 2 OW were able to produce measurable torque over the entire range, as compared to 10 YW. This inability to dorsiflex the foot because of a loss of muscle strength and an increased intrinsic passive resistance could predispose an older individual to fall (Vandervoort et al., 1992).
Examining the effects of passive stiffness of a muscle-joint complex on the active torques of the agonists and antagonists around that particular joint is complicated. It has been reported in younger subjects that torque producing capabilities can be positively affected by a "stiffer musculotendinous unit" (Wilson et al., 1994). These authors (Wilson et al., 1994) found positive correlations between musculotendinous stiffness and CONC and isometric variables of force, as well as rate of force development. However, there were no such relationships for the ECC variables. In the OW of the present study there was a trend for a positive correlation between PRT and CONC PF PT, but no relationship for the YW. When a multiple regression analysis was done, it was found that body weight was the most important variable in explaining CONC PF PT, and PRT was not included in the model. For PF RTD there was a significant correlation with PRT for the OW again, but not for the YW. Therefore it appears that in the OW, CONC PF RTD abilities are enhanced by a stiffer plantar flexor muscle group, whereas DF may be impaired, and the effects of PRT on CONC and ECC PF PT seem unimportant.

4.4.2 Rate of torque development. The angle of peak torque could be used to determine the average rate of torque development because the plantar (Sale et al., 1982) and dorsiflexors (Marsh et al., 1981) reach maximal torque in a lengthened position, and each CONC action was started in a lengthened position. Also, no difference has been found in the DF isometric length-tension curve between old and young age groups (van Schaik et al., 1994), and reaction time was not a factor in this protocol because recording only began when torque production had started. Therefore the ability to reach peak torque early in the range of motion should be determined to a great extent by the contractile properties of the muscles involved. The slowing of
RTD for the OW compared to YW is similar (≈ 30%) in the plantar and dorsiflexors, and concurs with other studies of the same muscle groups (Thelen et al., 1995b; van Schaik et al., 1994; Vandervoort and McComas, 1986).

The slowing of contraction has been attributed to changes in motivation, muscle recruitment, activation, or muscle mechanics with age (Thelen et al., 1995b). The older subjects in this study were all healthy, active and very motivated to perform maximally, so that does not seem to be a factor. Muscle recruitment or activation has also been dismissed as a contributor in determining rate of torque development in isometric actions (Thelen et al., 1995a). Thus, it appears that changes in the muscle itself with age are the major factor. Losses of both Type I and II muscles fibres (Lexell, 1993) occur with age along with the atrophy of predominantly Type II muscle fibres (Lexell, 1993; Jakobsson et al., 1990; Coggan et al., 1992), resulting in a greater loss of Type II muscle tissue with increased age (Lexell, 1993). In addition, within each fibre type there are also changes in processes related to calcium release, uptake and sensitivity (Brooks and Faulkner, 1994; Larsson and Ansved, 1995) which play a role in reducing contraction and relaxation velocities (Danieli-Betto et al., 1995).

This slowing of contraction, specifically of the individual cross bridges, has been used to explain the greater loss of strength with age during high speed CONC actions (Porter et al., 1995b). Due to the difference in mechanics between shortening and lengthening muscle actions (Lombardi and Piazzesi, 1990), slower cross bridge cycling could be an advantage in ECC actions. In a typical force-velocity curve of isolated animal muscle, active lengthening produces forces greater than shortening, with increased velocity having little effect on lengthening force, but is detrimental
when muscle shortens (Brooks and Faulkner, 1994). The greater force during
lengthening has been attributed to: 1) passive stiffness, 2) an increased number of
attached cross bridges, 3) an increased force per cross bridge, or 4) a combination of
all of these (Phillips et al., 1991). It has been proposed that lengthening of an active
muscle leads to a greater extension of a cross bridge, then forced cross bridge
detachment (non-energy consuming), and finally a reattachment which is 200 times
faster than attachment of cross bridges which have completed a full cycle during
shortening (Lombardi and Piazzesi, 1990). With aging in humans there is a loss of
muscle mass (Lexell, 1993), which would presumably result in a lower number of
cross bridges available during a muscle action. Therefore, it can be surmised that
since passive stiffness does not appear to have an integral role in ECC PT, an
alteration of cross bridge kinetics would have to occur to preserve ECC strength; if
the assumption is made that neural activation does not change with aging.

4.4.3 Neural activation. It is not known however, what differences there may
be in neural activation during ECC actions between older and younger individuals. It
has been demonstrated in younger subjects that electrical stimulation during ECC
actions leads to significantly greater torques than during maximal voluntary
contractions (Westing et al., 1990). In addition, the torques produced during
maximal voluntary lengthening conditions are much lower than those predicted from
animal force-velocity models (Westing et al., 1990). This apparent inhibition has
been attributed to the high tension capability available during ECC actions, and thus
would act as a protective mechanism (Westing et al., 1990). Even though it does not
appear that there are any age-related differences in activation during isometric
(Vandervoort and McComas, 1986) or CONC actions (Harridge and White, 1993), it
is possible that older subjects actually have greater activation during ECC actions, because of the lower potential tensions produced. It is also possible that the increased passive stiffness seen in the older subjects may have an influence on muscle afferent activity which in turn increases motoneuron excitability. Indeed, there was a significant correlation between ECC PF PT and PRT for the older women. However, the torque curves are similar throughout the range and not just where stiffness begins to increase (i.e. as the foot dorsiflexes).

4.4.4 Effects of estrogen. When involuntary stretches were applied to maximal voluntary isometric actions of the adductor pollicis in postmenopausal women, lengthening ' isometric force ratios were greater in the older as compared to younger subjects (Phillips et al., 1993b). These authors believe that their results are analogous to their previous work on isolated mouse muscle (Phillips et al., 1991; Phillips et al., 1993b) and postmenopausal women (Phillips et al., 1993a). They have proposed that the differential loss of strength during lengthening compared to non-lengthening actions can be explained by estrogen deficiency and its possible effects on inorganic phosphate (P_i) (Phillips et al., 1991). It has been reported that increased P_i, normally associated with fatigue, leads to results which are similar to aging, such that force during shortening actions is reduced but there is no effect on lengthening actions (Phillips et al., 1993c). The increased P_i is thought to shift the equilibrium of the cross bridges to the low force state which in turn decreases strength during shortening but has no effect during lengthening because a very fast stretch would drive all cross bridges into the high force state mechanically (Phillips et al., 1991). However, a follow up study did not find any differences in I'; between muscles of old and young mice (Phillips et al., 1993d). Also, a recent study has found that at temperatures
closer to physiological (30° versus 20° C) there is only a minor effect of decreased pH on muscle force production (Pate et al., 1995).

In the present study, although the numbers were small, we did not find that estrogen-replaced women had greater peak torques. In fact, the only significant difference was a greater CONC DF PT for the non-estrogen replaced older women. Therefore, if estrogen does play a role in maintaining strength with age, it seems that its effect must be small and the mechanisms are unknown.

4.4.5 Differential strength loss. There was a differential effect of age on the strength of the two muscle groups for CONC but not ECC actions. The discrepancy between the OW and YW was 25% for DF and 11% for PF, even though losses in both DF and PF RTD were 30%. These results are comparable to another report of testing done at the same isokinetic velocity, although greater strength losses occurred for both muscle groups (Thelen et al., 1995b). Other studies which have investigated strength losses of these two muscle groups, tested isometrically in a flexed knee position, have found greater attrition of PF than DF (Fugl-Meyer et al., 1980; Vandervoort and McComas, 1986).

Strength decrements with age in isometric and CONC actions could potentially be attributed to changes in muscle morphology (Porter et al., 1995b) and/or specific tension (Phillips et al., 1993a), neural activation (Grabiner and Enoka, 1995), physical activity patterns (Porter et al., 1995b), or some combination of these factors. The attrition of muscle tissue of the plantar flexors has been demonstrated using imaging techniques (Rice et al., 1989; Vandervoort and McComas, 1986). Both the lateral gastrocnemius (Coggan et al., 1992) and anterior tibialis (Jakobsson et al., 1990) have shown preferential type II atrophy at the microscopic level. No known
studies however have compared fibre atrophy or fibre number changes in both the plantar and dorsiflexors so it is unclear how morphological changes in the muscles may differentially affect strength loss. Specific tension reductions have been ascribed to decrements in calcium transport and activity, and not to decreases in force produced by individual cross bridges (Brooks and Faulkner, 1994). It is expected that the plantar and dorsiflexors would be affected similarly. During isometric (Vandervoort and McComas, 1986) and dynamic actions (Harridge and White, 1993) older adults have demonstrated an ability to activate the plantar (Vandervoort and McComas, 1986; Harridge and White, 1993) and dorsiflexors (Vandervoort and McComas, 1986). In the isometric actions, if anything, the problem in activation was with the plantar flexors (Vandervoort and McComas, 1986), although this did not have a substantial effect on peak torques (Vandervoort and McComas, 1986).

It seems then, that different losses in strength of the two muscle groups may be explained by the loading which occurs in physical activities like walking. During gait the plantar flexors are the main source of propulsion during the push-off (Winter, 1991). Also, in physically active older women walking speed and the amount of walking done habitually have been positively related to the strength of the triceps surae (Bassey et al., 1988). Most of the older women in the present study were involved in exercise programs which encouraged fast walking that would require greater plantar flexor force than normal walking. Moreover, when CONC PF PT was expressed relative to body weight, there were significant age-group differences (greater than the absolute peak torque differences), so that the older women needed to use a larger portion of their PF strength to move their body weight. This kind of habitual loading may have helped to preserve PF PT. However, even though the
CONC DF PT / body weight ratio was also different between the groups. CONC DF is performed in a non-weight-bearing state during the swing phase, and would not receive this extra loading effect of body weight (Winter, 1991).
Table 4.1  Subject characteristics (mean ± SD).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Older women (n = 16)</th>
<th>Younger women (n = 16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>67 ± 4</td>
<td>27 ± 4</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>162.1 ± 5.2</td>
<td>163.9 ± 6.1</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>65.6 ± 9.0</td>
<td>60.5 ± 10.1</td>
</tr>
</tbody>
</table>
Table 4.2 Correlations (r, significant p value in brackets) between passive resistive torque (PRT), and peak torques (PT).

<table>
<thead>
<tr>
<th></th>
<th>All subjects (n=32)</th>
<th>Younger Women (n=16)</th>
<th>Older Women (n=16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF CONC PT</td>
<td>-0.21</td>
<td>-0.24</td>
<td>0.27</td>
</tr>
<tr>
<td>DF ECC PT</td>
<td>0.26</td>
<td>0.30</td>
<td>0.41</td>
</tr>
<tr>
<td>PF CONC PT</td>
<td>0.05</td>
<td>0.03</td>
<td>0.47 (p = 0.06)</td>
</tr>
<tr>
<td>PF ECC PT</td>
<td>0.38 (p &lt; 0.05)</td>
<td>0.22</td>
<td>0.76 (p &lt; 0.001)</td>
</tr>
</tbody>
</table>

Note: DF = dorsiflexion; CONC = concentric; ECC = eccentric; PF = plantar flexion.
Table 4.3 Correlations (r, significant p value in brackets) between dorsiflexion (DF) rate of torque development and passive resistive torque (PRT) and DF eccentric (ECC) peak torques (PT).

<table>
<thead>
<tr>
<th></th>
<th>All Subjects (n=32)</th>
<th>Younger Women (n=16)</th>
<th>Older Women (n=16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF ECC PT</td>
<td>0.23</td>
<td>0.53 (p &lt; 0.05)</td>
<td>-0.07</td>
</tr>
<tr>
<td>PRT</td>
<td>-0.43 (p &lt; 0.05)</td>
<td>-0.07</td>
<td>-0.49 (p = 0.06)</td>
</tr>
</tbody>
</table>
Table 4.4 Correlations (r, significant p value in brackets) between plantar flexion (PF) rate of torque development and passive resistive torque (PRT). PF eccentric (ECC) peak torques (PT).

<table>
<thead>
<tr>
<th></th>
<th>All Subjects (n=32)</th>
<th>Younger Women (n=16)</th>
<th>Older women (n=16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF ECC PT</td>
<td>0.37 (p &lt; 0.05)</td>
<td>0.32</td>
<td>0.59 (p &lt; 0.05)</td>
</tr>
<tr>
<td>PRT</td>
<td>0.01</td>
<td>0.13</td>
<td>0.56 (p &lt; 0.05)</td>
</tr>
</tbody>
</table>
Figure 4.1  Concentric (CONC) and eccentric (ECC) dorsiflexion peak torque for the older (OW) and younger (YW) women (mean ± SE; * significant difference between the groups, p < 0.05).
Figure 4.2  Concentric (CONC) and eccentric (ECC) plantar flexion peak torque for the older (OW) and younger (YW) women (mean ± SE).
Figure 4.3  Eccentric (ECC) to concentric (CONC) peak torque ratios (mean ± SE) for the older (OW) and younger (YW) women for dorsiflexion (DF) and plantar flexion (PF; significant differences between the groups: ** p < 0.01, * p = 0.05).
Figure 4.4  Eccentric dorsiflexion torque-angle curves for the older and younger women.
Figure 4.5  Eccentric plantar flexion torque-angle curves for the older and younger women.
Figure 4.6 Passive resistive torque for one older (OW) and one younger (YW) woman over the range of motion.
Figure 4.7  Passive resistive torque (PRT) for the older (OW) and younger (YW) women (mean ± SE; * p < 0.05).
Figure 4.8  Rate of torque development (RTD) for the older (OW) and younger (YW) women for plantar (PF) and dorsiflexion (DF; mean ± SE, * p < 0.05).
CHAPTER FIVE
EFFECTS OF CONCENTRIC AND ECCENTRIC STRENGTH TRAINING
ON THE PLANTAR AND DORSIFLEXORS IN OLDER WOMEN

5.1 INTRODUCTION

The plantar and dorsiﬂexors of the ankle, which are functionally important in gait (Winter, 1991), balance and falls (Wolfson et al., 1993), show losses in CONC (Thelen et al., 1995b; Cunningham et al., 1987) and isometric strength (Vandervoort and McComas, 1986; Fugl-Meyer et al., 1980) and ﬂexibility with age (Vandervoort et al., 1992). Few studies have examined strength training of these muscle groups in older adults (Perkins and Kaiser, 1961; Blanpied and Smidt, 1993; Hicks et al., 1991; Judge et al., 1994) and even less research has been done on ECC actions which are performed in most daily physical activities, and strength training protocols.

In younger subjects, controversy exists over using CONC versus ECC actions in a strength training program. Some investigators believe that ECC actions are required to promote hypertrophy (Hather et al., 1991; Dudley et al., 1991) and sizeable gains in muscle strength (Lacerte et al., 1992; Colliander and Tesch, 1990). Others have found no difference in strength increments between training protocols that either include or exclude ECC actions (Hortobagyi and Katch, 1990; Johnson, 1972; Johnson et al., 1976; O’Hagan et al., 1995; Pavone and Moffat, 1985; Jones and Rutherford, 1987; Mannheimer, 1969). Muscle hypertrophy has also occurred without ECC actions (Housh et al., 1992; O’Hagan et al., 1995). It is difﬁcult to come to a conclusion based on this range of results due to the variety of training and testing protocols utilized (see Appendix IV for details of these studies).

ECC actions are always part of the training regimen when isotonic modes are used, however ECC strength is usually not measured, and the intensity of training is relative to the CONC component. ECC training should be examined in older subjects.
because of the differential loss of CONC versus ECC strength with increasing age (Phillips et al., 1993b; Vandervoort et al., 1990b; Poulin et al., 1992), and also because ECC actions are so important in daily movements. One study has investigated ECC training and changes in ECC peak torque in older men (Grimby et al., 1992). However, in this complex training routine other actions (i.e. isometric and CONC) were also performed by the knee extensor muscle groups (Grimby et al., 1992). In another study, CONC and ECC training with elastic tubing (emphasizing ECC actions) led to about 10% increases in ECC strength of the knee extensors and flexors (Mikesky et al., 1994), but a non-significant CONC increase. In many other studies, as mentioned, ECC actions are performed but it is unknown what role those actions played in strength increases, as measured concentrically or isometrically. It would be especially meaningful to learn the importance of ECC actions in strength gains and hypertrophy because these muscle actions are thought to cause more muscle damage than CONC or isometric actions (Faulkner et al., 1993). If they are unessential in training then perhaps they can be avoided to lessen the damage and potential sequelae.

The purpose of this study was to investigate the effects of CONC or ECC training on CONC and ECC PT of the plantar and dorsiflexors. Although both CONC and ECC actions were performed, it was not the specific purpose of this study to compare the efficacy of CONC versus ECC strength training. Therefore, the plantar flexors were trained using CONC actions, and the dorsiflexors performed ECC actions. These actions were chosen for safety reasons (i.e. to avoid continuous high tension ECC PF actions) and because these muscle actions are crucial for gait (Winter, 1991). The subjects trained in the standing position, but were tested in both the standing and supine positions. It was hypothesized that if the effect of training was specific to the muscle tissue itself, then strength increases would be apparent in both positions. However, if the training only led to increases in the standing position,
this would indicate that the improvements could be attributed to neural effects or some systematic effect of the standing position itself.

Other variables investigated pre- and post-training were PRT, RTD, average torque and angle specific torque. Changes in PRT could have contributed to changes in PT. RTD was investigated because the results to date on contractile property changes following resistance training have been inconclusive (Brown et al., 1990; Rice et al., 1993). Average torque and angle specific torque have not been investigated for ECC DF and PF, or with a strength training program in older adults. It was speculated that subjects would not only increase peak torque but would increase their torque production over the whole range, and perhaps even more in the weaker portions of the range. These variables were also examined because differential changes in average versus peak torque could reveal potential mechanisms for changes in torque development.

5.2 METHODS

5.2.1 Subjects

Fifteen healthy older women participated in this strength training study (see Table 5.1 for subject characteristics). All subjects were involved in regular physical activity, but not specific training programs for strength or for an athletic event.

5.2.2 Testing procedures

Subjects were tested: 1) one or two weeks prior to training, in both the standing and supine positions; 2) at the mid-point, in the standing position only; and 3) after training, in both positions. The order of testing pre- and post-training was alternated between positions. Testing was conducted as outlined in Chapters 2 and 3. Passive resistive torque was tested first, and then the strength testing was alternated between pre- and post-testing for muscle action (i.e. DF or PF) and position (i.e. supine or standing).
5.2.3 Training protocol

Training was conducted on the KIN-COM at 30 °/s, in the standing position only. The actions performed were ECC DF and CONC PF. The KIN-COM passively moved the subject’s foot through the opposite direction (see Figure 5.1). Three sets of eight repetitions for each action were done in separate sets. Target bars were set at 80% to 100% of the subjects’ initial PT for ECC DF and CONC PF. Subjects were instructed to reach their individual target bar. The target bar levels were adjusted based on the mid-point testing. Subjects trained twice per week for eight weeks, except for two subjects who completed the eight weeks of training over 9 weeks due to personal reasons. All subjects completed 100% of the training sessions (i.e. 16). The two training sessions a week were at least two days apart.

5.2.4 Data analyses

Torque data for the training sessions was analyzed to determine the intensity at which the subjects actually trained, since the feedback given was only a visual target. Sessions 2, 4, 6, 8, 10, 12, 14, and 16 were evaluated. Peak torques for each repetition of the second set were determined using the KIN-COM software. The mean of all eight repetitions of a particular set was calculated for an individual. The mean for these sessions was then used to calculate the intensity of training as a percent of the initial and mid-point peak torques, for the first four weeks and last four weeks respectively.

Testing data is as described in Chapters 2 and 3. For isokinetic strength testing, filtering was done, then peak torque, average torque and angle specific torques were determined. Average torque was calculated by averaging all data points over the range (SigmaStat). The angles for determining angle specific torques were 5° PF for the DF values, and 15° PF for PF torques. These angles were chosen because they occurred at a low torque area of the torque-angle curve. In the case of DF, an angle was chosen at which all subjects could produce measurable torque. The
highest angle was also taken at which CONC DF torque could be measured (i.e. the highest possible angle was 10 degrees of DF).

5.2.5 Statistical analyses

One way repeated measures analysis of variance was used to determine if differences over time existed for the mean peak torque of the training sessions. A paired t-test was done to compare the intensity of training (% PT) in the first four weeks and the last four weeks, relative to initial and mid-point testing, respectively.

Two way repeated measures analysis of variance tests were used to contrast pre- and post-training changes in peak torque between the standing and supine positions for each muscle action. The factors were time (pre/post) and position (standing/supine). When a significant effect was found, pairwise multiple comparisons were performed using the Student-Newman-Keuls method.

Paired t-tests were used for all other pre/post comparisons (e.g. average and angle specific torques). Because several comparisons were made the p value for significance was set as < 0.01. To determine the relationships between various changes Pearson Product Moment correlations were utilized. All statistical tests were done with SigmaStat (Jandel Scientific, San Rafael, Calif.).

5.3 RESULTS

All 15 subjects tolerated the training well, with no substantial muscle soreness or training-related injuries.

5.3.1 Training intensity

Figures 5.2, 5.3 and 5.4 show the absolute and relative peak torques of the training sessions. For both DF and PF there was an increase in the absolute torque values, which reached significance for PF (p < 0.05), but not DF (p = 0.051). There was a tendency for the first four weeks to have a greater percent intensity than the last four weeks (relative to mid-point testing; p = 0.055 n = 11 due to missing
data from training sessions).

5.3.2 Passive resistive torque

Although there was a significant difference between the standing and supine positions as previously reported in Chapter 2, there was no significant change from pre- to post-training (Table 5.2 and Figure 5.5).

5.3.3 Peak torque

Mean percent changes in peak torque ranged from 1.4% for ECC PF to 29.8% for CONC DF in standing, and -4.5% ECC PF to 9.6% CONC PF in the supine position. For CONC and ECC DF there were significant main effects for time and position, and a significant interaction between them (Table 5.2 and Figures 5.6 & 5.7). Post hoc analysis revealed for both DF muscle actions that the standing values increased with training, but there was no change in supine peak torque. The main effect of position was significant for both PF actions (standing > supine), but time was not (Table 5.2., Figures 5.8 and 5.9).

5.3.4 Average and angle specific torques

Figures 5.10, 5.11, 5.12 and 5.13 show torque-angle curves for all the muscle actions, pre- and post-training. All time (pre/post) effects were quite similar to peak torques with DF actions showing significant increases and PF actions demonstrating no change (Tables 5.3 & 5.4). The highest angle achieved in CONC DF also increased with training (pre = 3.9 ± 3.1, post = 5.6 ± 2.9; p < 0.05). Only standing values were compared, because of the lack of change in supine peak torque values, and also because there were very high correlations between peak torque and both angle specific and average torques for a given muscle action in the standing position (Table 5.5). This has also been found for CONC actions of these same muscle groups in younger subjects in another study (Woodson et al., 1995).

5.3.5 Angle of peak torque and rate of torque development

There were no significant changes in angle of peak torque for CONC DF and
PF (Table 5.6; see Figure 5.10 & 5.12). RTD did not change for CONC DF, but there was for an increase in CONC PF RTD (p = 0.014; Figure 5.14).

5.3.6 Body weight and weight shifting patterns

As seen in Table 5.1, there was no change in body weight. Weight shifting patterns, as reflected by body weight on the scale, during testing of the muscle actions were unchanged for CONC and ECC PF (Table 5.6). However, weight on the scale did increase significantly for ECC DF, and the same tendency existed for CONC DF (Table 5.7).

5.3.7 Interrelationships between variables

Even though weight shifting increased for DF, there was no significant correlation between % change in weight on the scale and % change in PT (p > 0.1). As well, there were no relationships between % change PT and % change in PRT, or training intensity. A negative relationship existed between the initial standing CONC DF PT and the change in CONC DF PT (r = -0.69; p < 0.01), but this was not the case for PT of any of the other muscle actions or for the supine position. This was also true for pre-training CONC DF RTD versus percent change in this variable (r = -0.79; p < 0.001).

5.4 DISCUSSION

The main finding of this study was that standing CONC and ECC DF torque significantly increased following high intensity resistance training. This was not the case for standing PF or any action in the supine position. The relative increase was approximately 30% for CONC DF and 15% for ECC DF. These changes are comparable to previous reports on changes in ECC PT with strength training in older adults (Grimby et al., 1992; Mikesky et al., 1994). However, increases in CONC DF PT were greater than CONC changes in either of the two mentioned studies. It is difficult to compare results between studies because different muscle groups were
trained and the training modes were also different.

In the present study only ECC actions were performed by the dorsiflexors. The training intensity was approximately 90% of ECC DF PT. This was equivalent to about 190% and 150% of CONC DF PT in the first and last four weeks respectively. Typically in an isotonic training session where both CONC and ECC actions are performed, the training intensity would be relative to the CONC action and be approximately 80% of the maximum load. Therefore the relative tensions achieved in the ECC DF protocol were much greater than for most strength training studies. This may explain why relative increases were approximately twice as great in CONC DF as ECC DF, but the absolute torque changes were almost equal.

The two major categories of adaptation to resistance training are muscular and neural (Sale, 1988). Potential muscular transformations include: 1) hypertrophy of individual muscle fibres and therefore whole muscles (Frontera et al., 1988); 2) myosin isozyme shifts (Adams et al., 1993); and 3) muscle membrane excitability (Hicks et al., 1992). Neural adaptations could possibly include (Sale, 1988): 1) full activation of the prime movers; 2) changes in antagonist activation; and 3) alterations in rate of force development. In the present study, changes in strength seemed to be specific to the position of testing. At first glance, it would appear that neural adaptations were prominent and muscle alterations were minor or non-existent. However, hypertrophy has also been reported in the absence of strength change, when testing and training modes were different (Sale et al., 1992; Frontera et al., 1988; Brown et al., 1990). It has been speculated that early increases in muscle mass may not be contributing to the gains in voluntary strength seen in the training mode (Sale et al., 1992). A compensatory hypertrophy model in rats found that initial hypertrophy was accompanied by a reduction of specific force of the soleus (Kandarian and White, 1989). In the human model, though, increases in co-contraction and alterations in pennation angle of the muscle fibres cannot be
discounted in also contributing to this differential change in muscle size and strength (Sale et al., 1992).

The present subjects were tested in the same mode, but in a different position. Therefore, adaptations specific to the weight-bearing position may have occurred that did not affect strength in the supine position. Many subjects seemed to have an increased usage of plantar flexor activity in the support leg, as reflected in the increased weight on the scales during DF. This contralateral influence could have acted to increase strength specifically in this position.

Other studies of the DF have found 48% (Hicks et al., 1991) and 25% (Judge et al., 1994) increases in strength. Plantar flexor changes were 13% (Judge et al., 1994), 57% (Perkins and Kaiser, 1961) and 37% (Blanpied and Smidt, 1993). The studies with lower changes utilized isokinetic testing (Judge et al., 1994) compared with MVC (Blanpied and Smidt, 1993) or 1RM (Perkins and Kaiser, 1961; Hicks et al., 1991) tests. Potential explanations for the lack of response of the plantar flexors in the present study include: 1) a lower intensity of training (compared to DF) since it was relative to the CONC actions; 2) the absence of ECC actions; 3) the concurrent strength and endurance training patterns of the subjects; 4) their initial strength and 5) a lower potential for adaptation in the plantar flexors.

Correlations have been found in previous studies between amount of walking done habitually and/or speed of walking and plantar flexor strength in older women (Bassey et al., 1988). Most of the women in the present study were involved in exercise programs involving fast walking, so their initial strength level could have been elevated already. In fact, older women in the cross-sectional study were only 11% (non-significant) less than the younger women in CONC PF, as compared to 25% less for CONC DF. This apparent preservation of PF could have had an influence on their ability to adapt further to training stimuli. For standing DF there was a significant negative relationship between subjects' initial strength and
improvement in strength, such that weaker individuals improved more.

The fact that many subjects were simultaneously performing endurance and strength training might have also been detrimental to strength improvement (Hickson, 1980; Kraemer et al., 1995), although this has not always been the case (Sale et al., 1990; Dudley and Djamil, 1985), apparently because of variations in training volume (Sale et al., 1990). It would be expected in the present study that BCC DF would be affected similarly by the combined training.

The final factor, the trainability of the plantar flexors, has been questioned in younger subjects (Tanner, 1952). However, there is little evidence for a lack of hypertrophy or potential for strength gain in the muscles of the calf following short term training (Weiss et al., 1988; Ishida et al., 1990; Alway et al., 1989). In this study, an improvement in strength was the factor of interest, and not hypertrophy. It was expected that hypertrophy would have a minor role in increasing strength with only 8 weeks of training, but neural changes would occur (Sale, 1988).

Therefore, it is unclear how to explain the finding of no increase in the strength of the plantar flexors. However, a combination of no eccentric actions, a lower training stimulus (based on absolute tension) in active subjects, and concurrent strength and endurance training may explain this. If untrained subjects were studied it would be expected that larger changes would be found. It would also seem unadvisable to have older adults perform strength training alone, and miss the potential benefits of a cardiovascular program involving walking.

Angle of peak torque did not change with training for either muscle group. However, RTD for CONC DF (↑ 15.8%) and PF (↑ 10.5%) tended to be greater post-training. This appears to be due to the increases in PT, because the angle of peak torques did not change. However, what this means functionally is that a given level of torque was reached quicker, which could have implications for preventing falls or improving movements that depend on speed. Past studies have reached
inconclusive findings on physiological measures of RTD, with no change (Brown et al., 1990; Hicks et al., 1991), a decrease (Rice et al., 1993), and an increase (Hakkinen and Hakkinen, 1992). Differences between studies can probably be explained by the muscle groups studied, the type of training done and the different measurement techniques.

The absence of a change in PRT was not unexpected based on the fitness level of the subjects. Although a similar group of older women did demonstrate greater PRT relative to a younger group of equally physically active younger women (Chapter 3), the changes were probably age-related and not amenable to alterations in the short-term caused by this type of training.

Flexibility though, appears to have been affected by training. Active DF flexibility is not solely dependent on passive stiffness but also the strength of the dorsiflexors to overcome the stiffness of the opposing plantar flexors. In this isokinetic testing the weight of the ankle unit along with the passive resistive torque of the plantar flexors has to be countered by active force production of the dorsiflexors. Even though these women could actively move their ankle through the ascribed range (i.e. 20° PF to 10° DF), the additional weight of the KIN-COM ankle unit prevented them from producing measurable torque throughout the range during CONC DF testing. Following training though, they did improve their ability to produce measurable torque further into DF. This could have implications for gait, especially in untrained individuals who have both weak dorsiflexors and stiff plantar flexors.

An advantage of the ECC training done in this study was that training could be done in the weaker portions of the range. In a typical isotonic training program the weakest part of the range limits the amount of weight that can be lifted. Also, depending on the equipment, the range of weight to be used cannot accommodate particularly weak actions. In isokinetic training where the resistance of the machine accommodates to the resistance produced by the subject, the whole range of
movement can be trained. In the case of ECC DF this would be at tension levels
much greater than during CONC DF. However, there is a controversy surrounding
the efficacy of isokinetic training for muscle hypertrophy or strength enhancement. In
most studies where isotonic training and testing are done, the percent changes are
much larger than those in isokinetic studies. This could be attributed to the type of
training itself, the amount of skill (i.e. balance) required for the movement, and also
the fact that unless strict biomechanical controls are in place, movements done in
testing pre- and post-training may not be identical (Grimby et al., 1992).

Another plausible advantage of this strength training protocol was the standing
position. Although no measurements were made in this particular investigation to
determine the transferability of gains in strength to functional tasks like walking speed
or balance, it could be proposed that this position would more likely lead to
improvements than seated or lying positions. More research is needed in this area of
specificity of strength training for older adults. To date, even when large increases in
strength (> 100%) are reported in frail older adults following training using
traditional exercises, much smaller increases are reported for tasks like gait velocity
(11.8%; Fiatarone et al., 1994).
Table 5.1 Subject characteristics (n = 15; mean ± SD).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>68 ± 5</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>159.5 ± 5.4</td>
</tr>
<tr>
<td>Weight (kg) - Pre</td>
<td>64.4 ± 11.8</td>
</tr>
<tr>
<td>Weight (kg) - Post</td>
<td>64.1 ± 11.2</td>
</tr>
</tbody>
</table>
Table 5.2 Results of the two way repeated measures analysis of variance test for passive resistive torque (PRT), concentric (CONC) and eccentric (ECC) plantar (PF) and dorsiflexion (DF) peak torques. P values are shown for the main factors of TIME (pre- vs. post-training) and POSITION (standing vs. supine), and the interaction between TIME and POSITION.

<table>
<thead>
<tr>
<th>Variable</th>
<th>TIME</th>
<th>POSITION</th>
<th>TIME X POSITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRT</td>
<td>0.066</td>
<td>&lt; 0.0001</td>
<td>0.24</td>
</tr>
<tr>
<td>CONC DF</td>
<td>&lt; 0.01</td>
<td>&lt; 0.0001</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>ECC DF</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>CONC PF</td>
<td>0.17</td>
<td>&lt; 0.0001</td>
<td>0.94</td>
</tr>
<tr>
<td>ECC PF</td>
<td>0.58</td>
<td>&lt; 0.05</td>
<td>0.21</td>
</tr>
</tbody>
</table>
Table 5.3 Angle specific torque values for pre- and post-training (mean ± SD).
Dorsiflexion (DF) values were taken at 5° of plantar flexion (PF) for both concentric (CONC) and eccentric (ECC) actions, and PF values at 15° PF.

<table>
<thead>
<tr>
<th>Action</th>
<th>Pre-training (N·m)</th>
<th>Post-training (N·m)</th>
<th>% change</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONC DF</td>
<td>11.3 ± 3.8</td>
<td>14.5 ± 4.3</td>
<td>28.3</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>ECC DF</td>
<td>26.0 ± 4.0</td>
<td>30.0 ± 5.4</td>
<td>16.5</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>CONC PF</td>
<td>52.2 ± 12.3</td>
<td>55.3 ± 13.5</td>
<td>5.9</td>
<td>&gt; 0.1</td>
</tr>
<tr>
<td>ECC PF</td>
<td>50.5 ± 11.4</td>
<td>51.9 ± 12.6</td>
<td>2.8</td>
<td>&gt; 0.1</td>
</tr>
</tbody>
</table>
Table 5.4 Average torque values for pre- and post-training (mean ± SD).

<table>
<thead>
<tr>
<th>Action</th>
<th>Pre-training (N·m)</th>
<th>Post-training (N·m)</th>
<th>% change</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONC DF</td>
<td>10.1 ± 2.9</td>
<td>12.4 ± 3.1</td>
<td>22.8</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>ECC DF</td>
<td>22.1 ± 3.4</td>
<td>26.2 ± 4.7</td>
<td>18.6</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>CONC PF</td>
<td>60.4 ± 13.1</td>
<td>64.0 ± 12.9</td>
<td>6.0</td>
<td>&gt; 0.1</td>
</tr>
<tr>
<td>ECC PF</td>
<td>76.7 ± 17.3</td>
<td>78.4 ± 19.0</td>
<td>2.2</td>
<td>&gt; 0.1</td>
</tr>
</tbody>
</table>
Table 5.5 Relationships between pre-training levels of peak torque (PT), average torque and angle specific torque in the standing position for concentric (CONC) and eccentric (ECC) plantar (PF) and dorsiflexion (DF) muscle actions (Note: " p < 0.01, """ p < 0.001).

<table>
<thead>
<tr>
<th>Action</th>
<th>Average torque (N m)</th>
<th>Angle specific torque (N m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONC DF PT (N m)</td>
<td>0.99 ***</td>
<td>0.86 ***</td>
</tr>
<tr>
<td>ECC DF PT (N m)</td>
<td>0.76 ***</td>
<td>0.82 ***</td>
</tr>
<tr>
<td>CONC PF PT (N m)</td>
<td>0.99 ***</td>
<td>0.94 ***</td>
</tr>
<tr>
<td>ECC PF PT (N m)</td>
<td>0.96 ***</td>
<td>0.65 **</td>
</tr>
</tbody>
</table>
Table 5.6  Weight shifting patterns for pre- and post-training (mean ± SD). Actual amount of weight on scales.

<table>
<thead>
<tr>
<th>Action</th>
<th>Pre-training (kg)</th>
<th>Post-training (kg)</th>
<th>% change</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONC DF</td>
<td>50 ± 10</td>
<td>55 ± 14</td>
<td>9.9</td>
<td>0.06</td>
</tr>
<tr>
<td>ECC DF</td>
<td>51 ± 11</td>
<td>57 ± 13</td>
<td>12.4</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>CONC PF</td>
<td>11 ± 5</td>
<td>11 ± 6</td>
<td>0</td>
<td>&gt; 0.1</td>
</tr>
<tr>
<td>ECC PF</td>
<td>14 ± 6</td>
<td>15 ± 6</td>
<td>7.1</td>
<td>&gt; 0.1</td>
</tr>
</tbody>
</table>
Table 5.7  Angle of peak torque changes for pre- and post-training (mean ± SD).

<table>
<thead>
<tr>
<th>Action</th>
<th>Pre-training (°)</th>
<th>Post-training (°)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONC DF</td>
<td>-12.7 ± 2.1</td>
<td>-12.8 ± 1.5</td>
<td>&gt; 0.1</td>
</tr>
<tr>
<td>CONC PF</td>
<td>0.4 ± 2.2</td>
<td>-0.2 ± 0.5</td>
<td>&gt; 0.1</td>
</tr>
</tbody>
</table>
A typical eccentric dorsiflexion training set for one individual (torque = solid line; angle = dashed line).

Figure 5.1
Dorsiflexion torque over the training sessions (mean ± SE).

Figure 5.2
Figure 5.3  Plantar flexion torque over the training sessions (mean ± SE).
Figure 5.4  Intensity of training (% of peak torque) over the training sessions (mean ± SE). For sessions 2 to 8, training peak torques are relative to pre-testing. For sessions 10 to 16, peak torques are relative to mid-point testing.
Figure 5.5  Passive resistive torque of the plantar flexors in the standing and supine positions from pre- to post-training (mean ± SE).
Figure 5.6  Concentric (CONC) dorsiflexion peak torque in the standing and supine positions from pre- to post-training (mean ± SE; * p < 0.05).
Figure 5.7  Eccentric (ECC) dorsiflexion peak torque in the standing and supine positions from pre- to post-training (mean ± SE; * p < 0.05).
Figure 5.8  Concentric (CONC) plantar flexion peak torque in the standing and supine positions from pre- to post-training (mean ± SE).
Figure 5.9  Eccentric (ECC) plantar flexion peak torque in the standing and supine positions from pre- to post-training (mean ± SE).
Figure 5.10  Torque-angle curves for concentric dorsiflexion pre- and post-training. All 15 subjects were overlayed using a 4th order polynomial regression for each occasion. The dotted line represents the 95% confidence interval.
Figure 5.11  Torque-angle curves for eccentric dorsiflexion pre- and post-training.

All 15 subjects were overlayed using a 3rd order polynomial regression for each occasion. The dotted line represents the 95% confidence interval.
Figure 5.12  Torque-angle curves for concentric plantar flexion pre- and post-training. All 15 subjects were overlaid using a 4th order polynomial regression for each occasion. The dotted line represents the 95% confidence interval.
Figure 5.13  Torque-angle curves for eccentric plantar flexion pre- and post-training. All 15 subjects were overlayed using a 2nd order polynomial regression for each occasion. The dotted line represents the 95% confidence interval.
Figure 5.14  Rate of torque development for pre- and post-training for plantar (PF) and dorsiflexion (DF; mean ± SE).
CHAPTER SIX
OVERALL SUMMARY AND CONCLUSIONS

6.1 Summary

6.1.1 New testing methods.

The first two chapters of this thesis outlined new methods developed to test strength and passive stiffness using an isokinetic dynamometer, namely the KINCOM. Reliability coefficients and method errors for DF and PF PT, and PRT were acceptable. However, the method errors associated with calculating DF and PF ECC:CONC ratios were high, so caution should be used in interpreting results based on ratios unless the sample size is large or the effect size is great.

In an attempt to assess the validity of these methods, results were compared to those from the literature for other test positions, and also to measured values of a supine position. The peak torque values were comparable to reported values, when the subjects, mode of testing, and muscle actions were taken into account. Also, the torque-angle curves were similar.

Passive resistive torque values were higher than a similar protocol using a torque-motor system (Chesworth and Vandervoort, 1989), however the torque-angle curve was analogous. Differences in PRT can be explained by factors like body size, muscle mass, the actual ankle angles tested, and also the activity patterns of the subjects because long term endurance activity may increase collagen and PRT as aging occurs (Kovanen, 1989). Standing values of PRT were also different from the supine test position. Some of the factors listed above, except differences in subjects, may be responsible for this difference between positions.
More in depth biomechanical measures and electromyographic equipment would be needed to examine the differences between positions. Tests could also be done to investigate the possible relationships between the standing or supine tests and functional outcomes such as gait and balance.

6.1.2 Age-related changes in CONC and ECC strength.

The present study supports the observations that ECC strength is maintained with age despite losses in CONC strength. Even though muscle mass was presumably decreased and RTD was reduced, mechanisms which may exert a negative influence on CONC and isometric actions could have a positive effect on ECC actions. Passive stiffness was ruled out as being a major contributor to ECC torque capabilities. However, increased stiffness of the plantar flexors along with losses in CONC force production of the dorsiflexors that occur with increasing age, would make CONC DF difficult over a large range of motion. Based on animal work it seems that a change with age in a cytosolic substance, perhaps calcium, alters cross bridge kinetics or force (Brooks and Faulkner, 1994; Phillips et al., 1991). This happens in addition to changes which may be occurring in myosin isoforms with age in the human. Activation may also be different between older and younger subjects performing ECC actions, and contribute to the differential loss of CONC and ECC strength.

Along with determining the mechanisms for the preservation of ECC torque capabilities with age, the functional implications remain to be elucidated. The plantar and dorsiflexors have important roles in gait and balance (Winter, 1991). Therefore, discovering mechanisms behind these adaptations in stiffness, contractile properties and torque development will be instrumental in preventing mobility impairment.

6.1.3 Effects of CONC and ECC strength training

Both CONC and ECC DF tested in a standing position increased following
ECC DF training in the same position. Neither standing PF action was improved by standing CONC PF training. All actions tested in the supine position remained unchanged.

The increases in DF could not be explained by a reduction in passive stiffness of the plantar flexors because PRT was not altered by the training. Therefore, either neural activation or intrinsic characteristics in the dorsiflexor muscle group must have changed. It is difficult to determine what combination may have occurred with the testing that was done. No improvements were seen in the untrained supine position. However, it cannot be assumed that muscle was not a location of adaptation because the training in standing may not have specifically stressed parts of the muscles that were tested in the supine position. However, it does appear that most of the change probably occurred as a result of neural adaptation, because even those studies which have found increases in muscle cross-sectional area have found greater increases in strength (Frontera et al., 1988; Fiarone et al., 1990; Fiarone et al., 1994; Roman et al., 1993; Brown et al., 1990; Lexell et al., 1995).

Neural adaptations which are believed to occur following high intensity resistance training (Sale, 1988) are: 1) decreases in coactivation of antagonist muscle groups; 2) synchronization of agonist activation; 3) reflex potentiation; 4) increased coordination of synergists; and 5) task-specific activation of motor units.

Because the standing position also required the person to use other muscle groups to steady themselves, it is possible that changes may have occurred in the muscles of the tested leg in order to stabilize other joints. As well, the support leg may have undergone changes which assisted in producing DF moments. The standing position itself would have provided different sensory inputs (e.g. cutaneous or vestibular) to the subjects. In addition, because the training was done in the standing position alone, there may have been adaptations which were set-related. Clearly, the
differences in neural inputs and set of the subject in the two positions could have had a major impact on the strength changes which were seen in dorsiflexion.

The fact that increases in CONC DF actions were twice as great as ECC on a relative scale but were equal on an absolute scale suggests that the absolute tension levels required were a major contributor to change. Even though the plantar flexors were trained at the same relative intensity (to CONC PF), the tension levels were greater for DF. Both CONC PF and ECC DF were not substantially different from values measured in younger subjects. Therefore, in those subjects who were already fairly fit, greater intensities of training may be required, and can only be achieved if ECC actions are performed.

6.2 Recommendations for future research

Isokinetic testing

1) The standing position can be tested for reliability using other velocities, isotonic actions and stretch-shortening actions.

2) Differences between the standing and supine position can be evaluated from biomechanical and neurological perspectives.

3) Comparisons of torque measured in both positions could be related to functional activities like balance or gait velocity, in various populations of subjects.

Passive resistive torque testing

4) Other assessments of the passive resistive torque curve could be examined to calculate stiffness and hysteresis.
Age-related changes in CONC and ECC strength

5) It needs to be determined whether activation patterns are different between older and younger subjects during ECC actions.

6) Stretch-shortening cycles could also be examined. It is possible that passive stiffness may be more of an influence with this type of action.

7) More sophisticated tests could be done to assess calcium metabolism within muscle fibres, and its influence on the preservation of ECC strength.

8) The effects of a preservation of ECC strength in these individuals should be related to functional outcome variables.

9) Do the results of fit older individuals resemble those of untrained older individuals?

10) What would the results be for male subjects?

Strength training in older adults

11) Untrained subjects could train using this protocol, and then could be tested for changes in gait velocity or balance.

12) A comparison of supine and standing training could be done to assess whether one position is more beneficial than the other in terms of transferring strength gains to daily activities.

13) Do alterations occur in the support leg, and how do these potential changes contribute to the changes of the trained leg.

14) Compare actual CONC and ECC training for one muscle group.

15) Other velocities of movement could be used.
Aging of human muscle: structure, function and adaptability


With increasing age, human skeletal muscles gradually decrease in volume, mainly due to a reduced number of motor units and muscle fibers, and a reduced size of type 2 fibers. As a result, progressive weakening and impaired mobility occur. High-resistance strength training is beneficial, even in the very old, and could possibly reverse some of the detrimental effects of age-related weakness. The importance of exercise for older people affords an excellent opportunity for the medicine community as a major source of information and promotion of physical activity for this rapidly growing segment of the population. In this review, we summarize the current knowledge of the effects of aging on the human neuromuscular system, describe some of the major underlying mechanisms of the aging atrophy and focus on the importance of strength training to improve muscle function in older people.

Key words: aging, muscle, muscular atrophy, physical fitness, physiological adaptation

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Accepted for publication November 18, 1994

With increasing age, skeletal muscle mass is lost, and this aging atrophy is accompanied by a reduction in muscle strength. As a result, many older individuals have impaired mobility, and increased risk of falls and hip fractures, and a considerable number require assistance with everyday activities. In all developed countries throughout the world, the number of older individuals is increasing, and the effects on the health care system may be substantial (1). At the same time, health in general among old people is gradually improving and the rate of disability is beginning to decline (2). Many old men and women are both able and motivated to continue to keep fit and mobile. Physical activity and exercise play a key role, in treatment and rehabilitation, and could possibly be of importance in the prevention of frailty among elderly people. Furthermore, the number of older men and women participating in various sporting activities and competitions has increased during recent years. Whether it is treatment, prevention or competitive sports, knowledge of the neuromuscular system and its response to training in older groups is necessary to enable physicians, physiotherapists and fitness instructors to give the best possible advice and to plan optimal exercise programs for this rapidly growing segment of the population.

During the last decade, attention to the effects of aging on the human locomotor system, the underlying pathophysiological mechanisms of aging atrophy and the importance of physical activity and exercise, in particular strength training, to improve muscle function in older individuals has markedly increased. The number of studies focusing on the aging human muscle, its structure, function and adaptability is steadily growing, particularly in the sports medicine community. Our purposes here are to review these studies, to describe some unsolved problems and to indicate some likely lines of development.

Loss of voluntary muscle strength

One of the most noticeable effects of increasing age is the reduction in muscle strength. A variety of limb muscles have been compared between groups of young, middle-aged and older adults, showing that decreases in voluntary strength do not become apparent until after the age of 60 years (3). When muscles in the upper and lower limb, including proximal and distal locations, have been examined, the size of the age effect revealed only small variations from muscle to muscle. For both men and women the reduction in strength across the adult age range tends to be curvilinear, with some suggestion that the relative effect of aging on isokinetic strength is more pronounced in women.

Particular attention has been paid to the strength...
of the quadriceps femoris muscle group, which has been measured extensively in test conditions involving all 3 actions of muscles: isometric, concentric and eccentric (Table 1). Healthy people in the seventh and eighth decades score on average 20 to 40% less during isometric and concentric strength tests than young adults, and the very old show even greater (50% or more) reduction.

Only longitudinal studies of the knee muscles are available, and it is of interest to compare these results with data from cross-sectional studies. Amannson et al. (14) and Grieg et al. (15) found less decline than expected in their 7-year and 8-year follow-up studies of subjects living into the ninth decade. This result may reflect the biological superiority of those who live longer than average or may reflect their adaptive lifestyle. Kallman et al. (16), on the other hand, reported that age versus grip strength was quite comparable between two types of analysis: a cross-sectional survey of subjects of different ages and a semi-longitudinal follow-up of subjects in the Baltimore Longitudinal Study of Aging.

It was recently found that the differences between young and older groups of men and women were consistently less for the eccentric type of muscle action (lengthening) than during either isometric or concentric contractions (9, 11, 13, 17), but the mechanism for this relative advantage of aged muscle to lengthen against resistance remains undetermined. It has been suggested that hormonal factors may affect crossbridges during shortening or isometric actions but not during lengthening actions (17, 18). In fact, these authors found that postmenopausal women who had been receiving estrogen replacement therapy had greater specific muscle force than non-replaced postmenopausal women, and the decline in specific force in men seemed to follow the more gradual decline in testosterone with age (18). What is important from a functional perspective is that, for a given absolute load, the intensity of muscular effort would be less for an eccentric condition than concentric, thereby suggesting that the aged might find some relative advantage in using muscles under lengthening situations.

Muscle groups at the ankle show comparable declines in strength to the knee extensors when young adults are compared with older adults. Davies et al. (19) examined the triceps surae muscle in elderly men and women (mean age 70 years) and reported 38% and 28% differences, respectively, in ankle plantar flexion strength from young male and female adults. Vandervoort & McComas (20) observed that healthy young and middle-aged men and women had similar isometric strength of ankle plantarflexors and dorsiflexors; values then decreased approximately 15% per decade. Testing of concentric strength of ankle plantar flexors in men also demonstrated a significant age-related decrement (21).

To what extent do these age differences reflect a failure of descending drive from the motor cortex? Vandervoort & McComas (20) assessed descending motor drive using the twitch interpolation technique. A brief percutaneous electrical shock was applied to the motor nerve during a maximal voluntary contraction (22). Most of the healthy older subjects, ranging in age from 60 to 100 years, were able to activate their ankle muscles maximally, because a superimposed twitch stimulus added little to their volitional force. Thus, the age-related declines in strength in these healthy older people must have been due predominantly to a decreased excitable muscle mass. It should be remembered that this was an isometric, single joint task, and central nervous system coordination could still be an important factor in dynamic strength maneuvers involving many muscle groups (23).

<table>
<thead>
<tr>
<th>Reference</th>
<th>Authors</th>
<th>Year</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Test condition</th>
<th>Proportion of young adult value</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Larson et al.</td>
<td>1979</td>
<td>M</td>
<td>60-69</td>
<td>Isometric</td>
<td>75%</td>
</tr>
<tr>
<td>5</td>
<td>Murray et al.</td>
<td>1980</td>
<td>M</td>
<td>70-86</td>
<td>Isometric</td>
<td>55%</td>
</tr>
<tr>
<td>6</td>
<td>Young et al.</td>
<td>1984</td>
<td>F</td>
<td>71-81</td>
<td>Isometric</td>
<td>65%</td>
</tr>
<tr>
<td>7</td>
<td>Murray et al.</td>
<td>1985</td>
<td>F</td>
<td>70-86</td>
<td>Isometric</td>
<td>63%</td>
</tr>
<tr>
<td>8</td>
<td>Young et al.</td>
<td>1985</td>
<td>M</td>
<td>70-79</td>
<td>Isometric</td>
<td>61%</td>
</tr>
<tr>
<td>9</td>
<td>Vandervoort et al.</td>
<td>1990</td>
<td>F</td>
<td>66-69</td>
<td>Concentric 90°/s</td>
<td>47%</td>
</tr>
<tr>
<td>10</td>
<td>Overend et al.</td>
<td>1992</td>
<td>M</td>
<td>65-77</td>
<td>Concentric 120°/s</td>
<td>66%</td>
</tr>
<tr>
<td>11</td>
<td>Poulin et al.</td>
<td>1992</td>
<td>M</td>
<td>60-75</td>
<td>Concentric 180°/s</td>
<td>69%</td>
</tr>
<tr>
<td>12</td>
<td>Stanley &amp; Taylor</td>
<td>1993</td>
<td>F</td>
<td>60-70</td>
<td>Concentric 180°/s</td>
<td>51%</td>
</tr>
<tr>
<td>13</td>
<td>Porter et al.</td>
<td>1994</td>
<td>M</td>
<td>62-88</td>
<td>Concentric 90°/s</td>
<td>58%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eccentric 90°/s</td>
<td>75%</td>
</tr>
</tbody>
</table>
Reduction in muscle volume and cross-sectional area

As older men and women are able to activate their muscles maximally, or near maximum, the main reason for the age-related decline in strength must be a reduction in muscle volume and mass. Muscle cross-sectional area and muscle volume have been estimated indirectly using various radiological imaging techniques. Young et al. (24, 25) used ultrasonography and found 25–35% reductions in the cross-sectional area of the quadriceps muscle in older men and women compared with the young. More recently, computed tomography scanning has been applied and has shown similar age-related reductions in cross-sectional area of the psoas major and sacrospinalis muscles (26), the quadriceps muscle (27, 28), the brachial biceps and triceps muscles (29), and the plantarflexors (29).

Two of these studies have also documented increases in non-muscle tissue, i.e., fat and connective tissue, within the older muscle. Rice et al. (29) found 27%, 45% and 81%, respectively, more non-muscle tissue in the arm flexors, arm extensors, and plantarflexors of older people. Overend et al. (28) found increases in non-muscle tissue of 59% (quadriceps) and 127% (hamstrings). As a result of this age-related infiltration of fat and connective tissue, the reduction in muscle contractile tissue may be greater than the actual reduction in muscle volume and muscle cross-sectional area.

Direct measurements of the muscle cross-sectional area are, on the other hand, very limited, due to the technical and ethical constraints involved in more direct detailed studies of whole human muscles. Only very small parts of muscles have been analyzed, with consequent difficulties in the interpretation of the results. Large cryomicrotomes and modified morphometric procedures now make it possible to prepare and to analyze cross-sections of whole human (autopsied) muscles (30). Lexell et al. analyzed the vastus lateralis of previously healthy men (31) between 15 and 83 years of age and found that the average reduction in muscle area between 20 and 80 years was 40% (Fig. 1); for this muscle, the reduction in area begins as early as 25 years of age, approximately 10% of the muscle area is lost by the age of 50, and thereafter the reduction accelerates. These findings are, of course, limited to one limb muscle. We can, however, conjecture that other human muscles could be affected in a similar way, although the actual values may be different.

Changes in size, numbers and proportions of muscle fiber types

To understand the causes of the aging atrophy, numerous attempts have been made to assess the muscle morphology of aging muscles. In a majority of these studies, the vastus lateralis of the quadriceps muscle has been examined, and the overall conclusion is very consistent: type 2 (fast-twitch) fiber size is reduced with increasing age, while the size of type 1 (slow-twitch) fibers remains much less affected (31–44). Several studies present only qualitative data and make comparisons only with data from other studies, with apparent limitations in the inferences of the results. Table 2 summarizes studies based on quantitative data.

Other limb muscles have been assessed much less. A comparison of young and old tibialis anterior (45) revealed a selective hypotrophy of type 2 fibers of the same magnitude as in the vastus lateralis. When the muscle morphology of the vastus lateralis and the biceps brachii of 78- to 81-year-old men and women was analyzed (38), the mean area of type 2 fibers was significantly smaller in the leg than in the arm, particularly in women. This could indicate differences in the aging process and/or a difference in the activity pattern between arms and leg. Further studies of muscles in the upper and lower extremity in the same individual and comparisons with data from young and old are needed to explain this finding.

In many studies, the reduction in fiber size is moderate in comparison with the reported muscle volume reduction, and in particular, the expected reduction in muscle contractile tissue. It has therefore been questioned whether decreased fiber areas alone can explain the muscle hypotrophy or if a loss of fibers also occurs (46). A reduction in the number of fibers was reported in vocal muscles (47) and in the minor pectoral muscles (48). It was not until techniques allowed analysis of whole large muscles that it became evident that the total number of fibers was sig-
Table 2. Reductions in size of different types of muscle fibers in the vastus lateralis muscle of older individuals

<table>
<thead>
<tr>
<th>Reference</th>
<th>Authors</th>
<th>Year</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Type 1 fibers</th>
<th>Type 2 fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>Tomonaga</td>
<td>1977</td>
<td>M/F</td>
<td>60-90+</td>
<td>7%</td>
<td>52%</td>
</tr>
<tr>
<td>35</td>
<td>Larson et al</td>
<td>1978</td>
<td>M</td>
<td>22-65</td>
<td>1%</td>
<td>25%</td>
</tr>
<tr>
<td>36</td>
<td>Scelsi et al</td>
<td>1980</td>
<td>M/F</td>
<td>65-89</td>
<td>7%</td>
<td>24%</td>
</tr>
<tr>
<td>42</td>
<td>Essen-Gustavsson &amp; Borges</td>
<td>1988</td>
<td>M</td>
<td>20-70</td>
<td>15%</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>F</td>
<td>20-70</td>
<td>25%</td>
<td>45%</td>
</tr>
<tr>
<td>31</td>
<td>Lexell et al</td>
<td>1988</td>
<td>M</td>
<td>15-63</td>
<td>1%</td>
<td>29%</td>
</tr>
<tr>
<td>44</td>
<td>Lexell &amp; Taylor</td>
<td>1991</td>
<td>M</td>
<td>19-86</td>
<td>6%</td>
<td>35%</td>
</tr>
</tbody>
</table>

In an attempt to identify the determinants of the size of human muscles at different ages, the original data have been reanalyzed (50). The cross-sectional area of the vastus lateralis muscle is mainly determined by the total number of fibers, and to a lesser extent by the size and/or the number of type 2 fibers. Thus, the loss of fibers seems to be the main explanation for the reduced area of this muscle with increasing age. However, we should be aware that no other limb muscle has been analyzed with respect to the total number of fibers. It remains therefore to be established whether the same mechanism is responsible for the atrophy of muscles in the arm and other muscles in the leg.

A reduction in the total number of fibers with advancing age could involve a loss of a specific type of fiber. This could alter the fiber type proportion, provided that fibers retain their original histochemical characteristics throughout life. Several studies have attempted to determine the effects of age on the proportion of type 2 fibers using data from single biopsies – again only the vastus lateralis muscle – but the findings are conflicting (36, 40, 41, 51, 52). Data from studies of whole muscle cross-sections (31) show that the average proportion of type 2 fibers in the vastus lateralis is unaffected with increasing age; the mean proportion of type 1 fibers at 20 years of age is 51% and at 80 years of age 55%. All other studies have found similar mean type 1 fiber proportions in old muscles, while the mean proportion for young muscles have varied and in some studies have been reported to be as low as 40% (51). An extensive survey of the literature (53) has persuasively shown that the mean proportion of type 1 fibers is close to 50% in the young human vastus lateralis muscle. In addition, the proportion of fiber types can vary considerably as a function of depth within the vastus lateralis (30, 31). Thus, sampling variability is a likely reason for some of the discrepancies in the literature, and the conclusion is that the overall reduction in fiber number with increasing age – for a whole population – seems to affect type 1 and type 2 fibers to the same extent.

Fig. 2. Relationship between age and mean area of type 1 and type 2 fibers (A) and between age and total numbers of fibers (B). Data reproduced with permission from Lexell et al (31).
However, the relationship between fiber number, fiber size and fiber type proportion is much more complex, and the effects of increasing age on type 1 and type 2 fibers may be somewhat counterbalanced. This would indicate that fiber type properties are not static and that muscle fibers can alter their histochemical profile throughout life. Electrophoretic analysis of single muscle fibers (54) have revealed that elderly subjects have a higher proportion of fibers showing coexpression of myosin heavy chain types 1 and 2A as well as 2A and 2B. These authors suggested that it could reflect an ongoing transition process or a "dynamic equilibrium" between the fiber populations, due to denervation and/or disease.

In the study of the fiber type composition of whole vastus lateralis (31), it was noted that the mean proportion of type 2 fibres varied much more between individuals in the old age-group than in the young. Some old individuals had a high proportion of type 1 fibers, while others had a clear predominance of type 2 fibers; this could be due to a selective loss of one fiber type or an equal loss of type 1 and type 2 fibers with a transformation of fiber types. When the proportion of type 2 fibers and the mean area of type 2 fibers were combined to form the relative type 2 fiber area and regressed against age, the relationship was found to be stronger than the two individual relationships (Fig. 3) (55). This indicates that the proportion of the fiber area in the muscle cross-section occupied by type 2 fibers is significantly reduced with increasing age, and that this reduction is accounted for by a concurrent effect on the fiber number and fiber size. In those muscles where type 2 fibers are lost to a great extent, the size of type 2 fibers seems to be maintained. If there is an equal loss of type 1 and type 2 fibers, or even a greater reduction of type 1 fibers, there is selective type 2 hypertrophy. Thus, for the vastus lateralis muscle, increasing age is accompanied by a greater loss of contractile material of fast-twitch type than of slow-twitch type. This loss is mediated through a reduction in number and/or size of type 2 fibers. Such a process is likely to be a major contributor to the aging atrophy in the vastus lateralis muscle, and the concomitant reduction in muscle strength.

Changes in the nervous system and motor unit properties

There exists clear indirect and direct evidence for quantitative as well as qualitative changes in motor units with increasing age. Studies of the number of motor neurons in the spinal cord (56) and of the numbers and sizes of motor axons in ventral roots (57-59) have shown that with increasing age there is a loss of alpha motor neurons from the spinal cord with a subsequent degeneration of their axons. The number of motor neurons in the lumbosacral cord (56) was reduced above the age of 60 years, with some cases exhibiting counts of only 50% of those in young. This was supported by studies of Kawamura et al. (57, 58) in which a loss of motor neurons in the lumbar spinal cord was accompanied by a reduction in the numbers of large and intermediate ventral root fibers.

Quantitative electromyography (EMG) has shown changes in both duration and amplitude of motor unit action potentials (MUAP) (60, 61). Subsequent analysis of the motor unit size, using macro EMG (62-64), has clearly revealed an increase in motor unit size in several limb muscles above the age of 60 years, i.e., an increased number of muscle fibers per motor unit. Estimates of the number of motor units (65-69) are all in agreement with other neurophysiological studies, and indicate a reduced number of motor units in older individuals.
Extensive neuropathic changes are also common in muscles of old very old individuals (32–34). When the fiber type arrangement in the vastus lateralis muscle at various ages was examined, an increase in fiber type grouping—an indirect evidence of a neuropathological process—was seen in old muscles (70, 71). All these results point in the same direction: increasing age is accompanied by a reduction in the number of functioning motor units with an increase in the size of remaining surviving motor units. This implies that the fiber population with increasing age undergoes several cycles of denervation followed by reinnervation, resulting from death of motor neuron in the spinal cord or from irreparable damage to peripheral nerve axons.

Changes in muscle contractile properties: effects on neuromuscular performance

There is also indirect and direct evidence for age-related changes in intrinsic properties of muscle fibers. With regard to contractile characteristics, the distal muscle groups are more feasible for investigation in humans. Most frequently studied are the components of the triceps surae group at the ankle, as a whole or separate studies of the gastrocnemius and soleus. Davies et al. (19) reported a significant increase in both the time to peak tension and the time to relaxation following evoked twitches of the triceps surae in elderly subjects. Vandervoort & McComas (20) reported the same finding in both the plantar flexor and dorsiflexor muscle groups of the ankle. While similar results have been shown for individual muscles of the lower leg and foot (72, 73), only minor age-related differences have been presented for the elbow flexors (69, 74).

The observed slowing of contraction may stem in part from the reduced proportional contribution of type 2 fibers to the twitch contraction. Vandervoort & McComas (20) found a pronounced effect of age on the gastrocnemius muscle twitch but less on the soleus, the latter having fewer fast-twitch motor units than the gastrocnemius muscle of young adults (75, 76). The effects of age on the proportion of type 2 fibers in the quadriceps muscles (31, 55) can also be observed in the reduced rate of force development and ability to accelerate the limb (4, 12). An interesting observation from the sample of Vandervoort & McComas (20), which covered an age range from 20 to 100 years, was that the twitch times increased in a linear fashion with age, but changes in muscle strength did not become evident until the seventh decade (Fig. 4A–B).

Twitch prolongation with aging could reflect greater efficiency for the contraction of elderly muscles, as lower frequencies of nerve impulses are required to attain a given muscle tension or reach tetanic fusion (19, 77). Further to this effect, does the aged muscle show greater resistance to fatigue? The research in this area has been inconclusive, partly due to the variety of methods used to induce fatigue. For example, Narici et al. (78) used a 30 Hz stimulation protocol and observed a decrease in fatiguability across ages in a study of the adductor pollicis in men, but Lennmarken et al. (79) observed increased fatiguability in a similar study done at 20 Hz. Klein et al. (80) reported no differences between samples of young and older men in fatiguability of the triceps surae muscle, but Davies et al. (19) found increased susceptibility to fatigue in their aged sample. The latter investigators felt that blood flow may have been more occluded in the older subjects, thereby diminishing
the capacity of the predominately aerobic muscle to sustain contraction.

When sustained voluntary contractions have been studied, the results have been more consistent in demonstrating that there is no effect of aging on muscle fatigability (81–83). These investigations all examined leg muscles, but varied in the use of submaximal versus maximal contractions, and sustained versus intermittent efforts. Despite the relatively greater proportion of type I fibers available for force generation, fatigue-resistance of aged muscle is not enhanced. The reason for this is not known, but the capacity of aged muscle may not be optimized due to a lack of training (84, 85). Otherwise, healthy, fit older individuals could potentially experience less metabolic stress during a submaximal exercise bout than sedentary young adults (86).

Another functional implication of the slowing of contraction is that it gives older muscle a reduced capacity for power (87) or rapid production of force in protective reflexes (88), thereby amplifying the impact of muscle weakness on mobility (89, 90). Earlier research has already shown that the peripheral segmental reflex loop has a significant delay in older subjects (91, 92), and Vandervoort & Hayes (88) demonstrated a 45% difference between young and very old women in the rate of torque development of an H-reflex contraction of the ankle plantarflexors. Furthermore, the capacity of a twitch to potentiate due to prior activation is reduced with increased age (20, 72, 93). Hicks et al. (83, 93) have noted that both muscle excitability and twitch potentiation appear to be enhanced following strength training, but it remains to be determined if actual reflex function can be influenced by an exercise program. Contractile changes with aging are also coupled with an increased passive resistance of the connective tissue structures of the antagonistic muscles, a factor that acts against rapid elongation and therefore rotation of aged joints, particularly in older women (94).

Strength training in older adults

Can appropriate exercise programming reduce or prevent the age-related changes in muscle structure and function? The adaptability of aging muscles, in particular the possibility of improving muscle strength and increasing muscle mass in older adults, is receiving more and more interest from researchers, health care workers, and older adults themselves who want to maximize the quality of their retirement. Many studies have related low muscular strength with other conditions such as increased susceptibility to falls and fractures and increasing dependence in older adults (95, 96). Also, as much as half of the loss in aerobic fitness (relative to body weight) seen with aging has been attributed to a loss of muscle mass (97). Thus, many of the physical function problems seen in elderly individuals could be alleviated by improving muscle mass and strength. In this review we focus on the effects of aging on muscle strength and how strength may be improved by training. Thus, high-intensity strength training, involving near maximal lifting, is the type of resistance exercise of primary interest: for general information on the effects of exercise on older individuals, other reviews can be consulted (98–100).

Strength training can be defined as progressively overloading the neuromuscular system using near maximal muscle contractions against high resistance. Its purpose is to increase the ability to perform maximal contractions or increase muscle size. Performing sets of 10 RM loads or less are typically used for strength training, with 1 RM (one repetition maximum) being the maximum weight an individual can lift one time, and 10 RM being the weight an individual can lift exactly 10 times. These values represent 100% and approximately 70% of maximum capability for 1 RM and 10 RM, respectively.

The different methods of training and types of muscle actions used put different physiological demands on the neuromuscular system, so the adaptations would also be expected to be different (101). The different types of muscle actions include concentric (shortening), isometric (static), eccentric (lengthening), isotonic (constant load), and isokinetic (constant velocity). The 1 RM is usually reported as the maximum concentric isotonic capability for a certain movement.

In recent years, interest in the effects of strength training in older men and women has increased dramatically and the number of studies has grown exponentially. Table 3 summarizes controlled and dynamic high-intensity strength training studies. Experimental controls for these studies included nonexercising limbs (102, 103), contralateral limbs (84, 93), sedentary self-selected subjects (107, 109) sedentary randomly selected subjects (84, 86, 105, 106, 108, 111), endurance training subjects (86) and placebo exercise subjects (112). Although the studies in Table 3 have attempted to use controls for learning or placebo effects, it should be noted that strength training studies can seldom be done as rigorously controlled randomized trials, for the following reasons: i) the inability to totally blind the subjects to the treatment; ii) subjects are volunteers from a particular community and may not be representative; and iii) the lack of blinding of the experimenters. Also, there is often a lack of reliability analysis of the testing procedures. With these limitations in mind, the research findings from these studies will be presented.
Table 3: Improvements in muscle strength following high intensity dynamic training in older individuals

<table>
<thead>
<tr>
<th>Reference</th>
<th>Authors</th>
<th>Year</th>
<th>Sex</th>
<th>Age (years)</th>
<th>n</th>
<th>Muscle action</th>
<th>Duration, sets/ reps</th>
<th>Strength gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>102</td>
<td>Frontera et al.</td>
<td>1988</td>
<td>M</td>
<td>60-72</td>
<td>12</td>
<td>Knee flex, Knee ext</td>
<td>12 weeks, 3/8</td>
<td>1 RM 22%</td>
</tr>
<tr>
<td>86</td>
<td>Hagberg et al.</td>
<td>1989</td>
<td>M/F</td>
<td>70-79</td>
<td>23</td>
<td>Chest press, Leg ext</td>
<td>26 weeks, 1/8-12</td>
<td>1 RM 18%</td>
</tr>
<tr>
<td>103</td>
<td>Brown et al.</td>
<td>1990</td>
<td>M</td>
<td>60-70</td>
<td>14</td>
<td>Elbow flex</td>
<td>12 weeks, 4/10</td>
<td>1 RM 48%</td>
</tr>
<tr>
<td>104</td>
<td>Fittarone et al.</td>
<td>1990</td>
<td>M/F</td>
<td>85-96</td>
<td>10</td>
<td>Knee ext</td>
<td>8 weeks, 3/8</td>
<td>1 RM 174%</td>
</tr>
<tr>
<td>105</td>
<td>Charette et al.</td>
<td>1991</td>
<td>F</td>
<td>64-86</td>
<td>13</td>
<td>Knee flex, Leg press, Hip ext</td>
<td>12 weeks, 6/6</td>
<td>1 RM 115%</td>
</tr>
<tr>
<td>93</td>
<td>Hicks et al.</td>
<td>1997</td>
<td>M/F</td>
<td>66-3</td>
<td>11</td>
<td>Dorsiflex</td>
<td>12 weeks, 4/10-15</td>
<td>1 RM 15%</td>
</tr>
<tr>
<td>84</td>
<td>Gurnsey et al.</td>
<td>1992</td>
<td>M</td>
<td>73-84</td>
<td>9</td>
<td>Knee ext, Con/sec</td>
<td>25 sessions, 3/4</td>
<td>1 RM 20%</td>
</tr>
<tr>
<td>106</td>
<td>Judge et al.</td>
<td>1993</td>
<td>M/F</td>
<td>71-97</td>
<td>13</td>
<td>Knee flex</td>
<td>12 weeks, 3/8-10</td>
<td>1 RM 32%</td>
</tr>
<tr>
<td>107</td>
<td>Monkes et al.</td>
<td>1993</td>
<td>M</td>
<td>50-70</td>
<td>11</td>
<td>Upper/lower body</td>
<td>16 weeks, 2/1/15</td>
<td>1 RM 45%</td>
</tr>
<tr>
<td>108</td>
<td>Nichols et al.</td>
<td>1993</td>
<td>F</td>
<td>67-8</td>
<td>18</td>
<td>Upper/lower body</td>
<td>24 weeks, 3/8-10</td>
<td>PT 32-55%</td>
</tr>
<tr>
<td>109</td>
<td>Rice et al.</td>
<td>1993</td>
<td>M</td>
<td>65-78</td>
<td>10</td>
<td>Elbow ext</td>
<td>26 weeks, 4/6-8</td>
<td>1 RM 18-71%</td>
</tr>
<tr>
<td>110</td>
<td>Roman et al.</td>
<td>1993</td>
<td>M</td>
<td>67-7</td>
<td>5</td>
<td>Elbow flex</td>
<td>12 weeks, 13&quot;/8</td>
<td>MVE 23-50%</td>
</tr>
<tr>
<td>111</td>
<td>Pyka et al.</td>
<td>1994</td>
<td>M/F</td>
<td>61-78</td>
<td>36</td>
<td>Upper/lower body</td>
<td>10 weeks, 3/8</td>
<td>1 RM 23-62%</td>
</tr>
<tr>
<td>112</td>
<td>Fittarone et al.</td>
<td>1994</td>
<td>M/F</td>
<td>72-98</td>
<td>100</td>
<td>Hip/knee ext</td>
<td>10 weeks, 3/8</td>
<td>1 RM 30-95%</td>
</tr>
</tbody>
</table>

Flex = flexion, ext = extension; 1 RM = one repetition maximum; MVC = maximal voluntary contraction; PT = isokinetic peak torque; Con = concentric; Ecc = eccentric; * only mean age available; ** 4 sets of isokinetic training and 3 sets of 3 free weight exercises (All strength gains are statistically significant.)

Important strength training variables

The intensity of training seems to be a critical variable, with higher-intensity training leading to larger increases in strength. Studies involving low-intensity training in older adults report strength increases less than 20% (96). In comparison, high-intensity training (>70% of 1 RM) has resulted in increases of up to 227% in 1 RM (Table 3).

In addition to intensity, variables like the number of sets and repetitions of a given exercise, the frequency and duration of a program, the muscle group(s) exercised, and the type of testing and training, must be considered when strength training programs are analyzed. With all of these variables and different subject groups (i.e., age, gender, initial strength), direct comparison between studies is difficult. Those reported in Table 3 had training frequencies of 2 to 3 times per week, durations of 8 to 52 weeks, with most using 8 weeks or 12 weeks, and 1 to 4 sets per training session. Although Hagberg et al. (86) used one of the longest (26 weeks) programs, the first 13 weeks was a low-intensity adaptation phase, with only 1 set of each exercise done over the whole study, which may explain why the subjects only increased strength by 9 to 18%. As well, the training volume can be an important aspect of optimizing the adaptive response to strength training (113).

The increases in 1 RM strength values are variable, but 12 weeks of high intensity (>70% of 1 RM) resistance training will result in a large improvement in strength, as measured dynamically by 1 RM. However, maximal voluntary isometric contraction (MVC) changes in these same studies ranged from no change (102, 103) to an average increase of 22.6% (114). Studies done with young subjects have also shown increases in 1 RM but not MVC (115). This discrepancy may be attributed to the specificity of neural adaptations (23) or the fact that, unless strict biomechanical restrictions are adhered to, 1 RM testing may not be appropriate for measuring strength
Aging of human muscle

Mechanisms of strength gains in older individuals: adaptability of the muscle and role of the nervous system

Several factors are believed to explain strength gains following high-intensity resistance training. These include changes in muscle morphology and muscle biochemistry, muscle and connective tissue biomechanics, central nervous system activation, motor skill coordination and psychological drive. Only recently have studies attempted to elucidate to what extent morphological, neurophysiological and intrinsic muscle property adaptations contribute to strength gains in old people.

Moritani & deVries (114) studied how muscle hypertrophy and neural factors affected strength changes of the elbow flexors in young and older men. While both groups increased maximal isometric strength and neural activation, only the young group demonstrated significant increases in muscle cross-sectional area. They concluded that neural factors alone might be responsible for the increases in strength seen in older subjects.

In contrast, Frontera et al. (102) reported that 60- to 72-year-old men had gained 107% and 22% in knee extension and knee flexion 1 RM strength, respectively, along with an 11% increase in total muscle area of the thigh, and an increase in protein turnover. They concluded, in contrast to Moritani & deVries (114), that muscles, even of old individuals, have the potential to hypertrophy in response to high-intensity resistance training.

The different conclusions of Moritani & deVries (114) and Frontera et al. (102) may be explained by variations in training intensity, measurement techniques and/or muscle groups trained. First, the intensity of training used by the former was only 66% of 1 RM, whereas the latter used 80% of 1 RM. The measurement techniques for hypertrophy were also quite different. The earlier study (114) used anthropometry to estimate changes in muscle size, whereas the latter used computed tomography (102). More recent studies using CT scans (103) and MRI (110) have shown that high-intensity resistance training does result in muscle hypertrophy, even in nursing home residents up to 98 years of age (104, 112).

Hypertrophy of both type 1 and type 2 fibers have been demonstrated following short-term high-intensity training in older adults (Table 4). There appears to be a tendency for greater hypertrophy of type 2 fibers, although this conclusion remains tentative. When changes were minor and nonsignificant, it was consistent with small strength gains (84).

A recent study reported that the rate of synthesizing proteins is similar in young and older subjects following short-term resistance training (118). This study, and those described above, provide evidence that the aging human muscle is capable of adapting to increased short-term physical demands. However, the hypertrophic changes with long-term (several months/years) training remain to be determined, and, while it is evident that aged muscle can increase in size following strength training, hypertrophy is relatively small compared with the large increases in 1 RM strength reported. Furthermore, the large increases are not fully transferrable to different modes of test-

<table>
<thead>
<tr>
<th>Reference</th>
<th>Authors</th>
<th>Year</th>
<th>Type 1</th>
<th>Type 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>102</td>
<td>Frontera et al.</td>
<td>1988</td>
<td>34%</td>
<td>28%</td>
</tr>
<tr>
<td>103</td>
<td>Brown et al.</td>
<td>1990</td>
<td>16%</td>
<td>30%</td>
</tr>
<tr>
<td>105</td>
<td>Cherelle et al.</td>
<td>1991</td>
<td>7%</td>
<td>20%</td>
</tr>
<tr>
<td>84</td>
<td>Grimby et al.</td>
<td>1992</td>
<td>8%</td>
<td>5%</td>
</tr>
<tr>
<td>110</td>
<td>Romani et al.</td>
<td>1993</td>
<td>24%</td>
<td>37%</td>
</tr>
<tr>
<td>111</td>
<td>Pyka et al.</td>
<td>1994</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) 15 weeks</td>
<td></td>
<td></td>
<td>29%</td>
<td>20%^{ab}</td>
</tr>
<tr>
<td>b) 30 weeks</td>
<td></td>
<td></td>
<td>48%</td>
<td>62%</td>
</tr>
</tbody>
</table>

*^{ab}S represents not significant; all other changes are statistically significant (P<0.05).
Porter et al.

ing (i.e., 1 RM vs MVC or isokinetic). This suggests that a certain amount of skill or motor coordination is required depending on the movement, and that specific neural adaptations are made to activate the prime movers while inhibiting co-contraction of antagonists following training (23).

In older adults, Brown et al. (103) found that complete (98%) motor unit activation was achieved pre- and post-training in the elbow flexors, using the interpolated twitch technique (22). While these results suggest that nervous system activation of muscle is not important, it is certainly possible that during dynamic movements, as opposed to isometric MVC maneuvers, central nervous system coordination or activation is a contributing factor (96).

Intrinsic characteristics of muscle, such as excitation/contraction coupling, muscle fiber packing density and muscle fiber composition can alter force production (101), which, in turn, may be reflected in the evoked contractile properties. Following strength training in older adults, Brown et al. (103) reported increases in rate of force development, but slowing of relaxation. They speculated that this slowing of muscles following training, in addition to the slowing following aging (20), would allow older adults to utilize lower rates of nervous system activation to achieve maximal force production. Rice et al. (109) reported a longer time to peak force but no change in any other contractile variables. They suggested that this was due to training-induced changes in muscle morphology that made the muscle more elastic or compliant. It is evident that results for contractile property changes with training are not clear and other measurements, such as joint stiffness (94, 119), may be of importance.

The ability to transfer strength gains into improved performance of daily activities would be most important for frail individuals. Fiatarone et al. (112) demonstrated increases in gait velocity (11%), stair-climbing power (28%) and spontaneous physical activity (34%) following resistance training in 72- to 98-year-old nursing home residents. Although these increments were statistically significant, the absolute changes in gait velocity were not very large, and all were small compared with the increases in muscle strength. Other variables such as muscle power may be more important in terms of performing functional tasks (87, 120).

Whitlow

Several factors may account for the reduction in muscle volume and concomitant loss of strength with increasing age (Fig. 5). Although knowledge of these factors has increased, more research is needed to understand the detailed mechanisms behind the structural and functional changes in the aging muscle. For example, how is concentric versus eccentric strength affected with increasing age? Are the mechanisms known to be responsible for the atrophy of the thigh muscles, also involved in the atrophy of distal leg muscles and of muscles in the arm? What is the significance of the connective tissue increase? What causes the deterioration in the nervous system and can the loss of motor units be prevented? Which age-related subcellular and molecular changes take place in individual muscle fibers and how is the function of the whole aged muscle affected?

The results of high-resistance strength training clearly indicate that we should never accept aging as an unalterable process of decline and loss. To successfully promote active aging, rehabilitation and physical activity for older people, several issues need to be clarified, at least partially. One of the main areas is the relative importance of muscle hypertrophy and neural adaptation for the improvement in strength, and this requires more controlled studies to decrease learning effects, tester bias and placebo effects. Furthermore, the complexity of the neural adaptation needs to be understood to make inferences about the specificity of training and the transferability of strength from the training mode to other tasks. We must also clarify to what extent functional improvements can be achieved with strength training, and how this improvement in strength can be maintained over a longer period.

Human aging and longevity have replaced birth rate as the most important issue in developed countries (121, 122). Over the next decade, we can envisage increased attention to the aging of human muscle, its structure, function and adaptability, and this affords an excellent opportunity for the medicine community as a major source of information and promotion of physical activity for this rapidly growing segment of the population.

Acknowledgements

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of the Swedish Sports Federation, the Swedish Society of Medicine, the Hans and Loo Osterman Foundation and the County Council of Norrbotten, and in Canada Natural Science and Engineering Research Council (NSERC) and the Canadian Fitness and Lifestyle Research Institute (CFLRI).

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74 McDonagh MJN, White MJ, Davies CTM. Different effects of ageing on the mechanical properties of arm and leg muscles. Gerontology 1984: 30: 49-54.


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121. Olshansky SJ, Carnes BA, Cassel CK. In search of MALTHUSIAN LIMITS TO HUMAN LONGEVITY. Science 1990 250 634–640.

High-intensity strength training for the older adult—A review

Aging is associated with declining muscular strength. However, research demonstrates that older individuals can increase strength by resistance training. Although improvements were initially attributed to neural mechanisms, muscle hypertrophy has now been documented, even in nonagenarians. In terms of performance, reported increases have been as high as 227% for dynamic lifting, with more moderate gains in static strength tests. More research is needed to confirm what functional improvements result from increases in strength and muscle mass. This article examines the extent and mechanisms of strength changes, potential benefits, and programming implications for high-intensity strength training in older adults. Key words: aging, muscle, strength training.

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The possibility of improving muscular strength and muscle mass in older adults is receiving more interest from researchers, health care workers, and older adults themselves who want to maximize the quality of their retirement years. Many studies have related low muscular strength with conditions such as increased susceptibility to falls and fractures, as well as increasing dependence.1 2 Also, as much as half of the aerobic fitness lost with aging has been attributed to a reduction of muscle mass.3 Thus it would appear that many of the physical function problems seen in the older individuals may be alleviated by increasing strength and muscle mass.

The association between aging and declining muscular strength has been demonstrated in numerous studies.2 4 Several mechanisms have been proposed to explain this process: a decreased amount of excitable muscle tissue,5 which may be secondary to a loss of

This study was funded by the National Science and Engineering Research Council of Canada and the Canadian Fitness and Lifestyle Research Institute.
motoneurons and muscle fibers; an increase in adipose or connective tissue in the muscle; changes in muscle contractility; enzyme activity; molecular changes associated with genetic information translation; poor nutrition or illness; hormonal changes; and a decline in physical activity or the appropriate type of activity. Although these age-related changes do occur, it appears that even very old individuals can make adaptations in their neuromuscular system in response to progressive resistance training.

In this study, high-intensity strength training, involving near-maximal lifting, is the type of resistance exercise of primary interest. Consult other reviews for general information on the effects of exercise on older individuals. Lower intensity strength training will be mentioned to provide an historical perspective, because using high-intensity resistance in training older adults is a relatively new intervention.

DEFINITIONS AND PRINCIPLES OF RESISTANCE TRAINING

Muscular strength is the ability to perform a maximal contraction, whereas muscular endurance is the ability to perform a number of contractions at a percentage of maximum or the ability to hold a contraction over a certain period of time. Strength training, therefore, can be defined as progressively overloading the neuromuscular system using high resistance to increase the ability to perform maximal contractions. Performing sets of 10 RM (repetition maximum) or less are usually used for strength training, with 1 RM being the maximum weight an individual can lift just one time and not more than once, and 10 RM being the weight an individual can lift 10 times only. These values represent 100% and about 70% of maximum capability for 1 RM and 10 RM, respectively.

Resistance training using a lower intensity or lower amount of resistance may improve muscular endurance. Training for muscular endurance, as compared to strength, will produce different adaptations in the neuromuscular system, so making improvements in one will not necessarily mean an improvement in the other.

Different methods of training (ie, isometric, isotonic, or isokinetic) and different types of muscle actions can be performed with resistance training (ie, isometric, concentric, or eccentric) (see Table 1). The various methods and types of muscle actions place different physiologic demands on the neuromuscular system, so adaptations would be specific to the joint angle or velocity stressed in training. To train in the ways described above, several types of equipment or exercises can be used (eg, body weight, tubing, elastic bands, weight machines, free weights, or isokinetic machines).

TRAINING STUDIES

Strength changes

The details from studies on strength training and aging are shown in Tables 2-10, 18-39 and 3,4,11,40-49 The male and female subjects ranged in age from 42 to 98 years. The mode of training included isometric (static), calisthenics, body weight, isotonic, and variable resistance. The muscles trained were the large muscles of the upper and lower extremities and individual fingers. Despite differences among studies listed above, most investigators report increases in strength after resistance training in older subjects. The studies that were more controlled and used dynamic high-intensity strength training are
shown in Table 3 and are the major focus of this article. Design controls for these studies included nonexercising limbs,\textsuperscript{40,42} contralateral limbs,\textsuperscript{45,50} sedentary self-selected subjects,\textsuperscript{46,48} sedentary randomly selected subjects,\textsuperscript{13,41,43,47} aerobic training subjects,\textsuperscript{41} recreation-therapy service participants,\textsuperscript{13} and blinding of testers for some procedures.\textsuperscript{11} Although the studies described in Table 3 attempted to use controls for learning or placebo effects, it should be noted that strength training studies can seldom be done as rigorously controlled randomized trials for the following reasons:

- It is not possible to totally blind the subjects to the treatment.
- Subjects are volunteers from a particular community and may not be representative.
- It is not possible to blind the experimenters.
- There is often a lack of reliability analysis of the testing procedures.

With these limitations in mind, an analysis of the research findings from these studies will be presented.

The intensity of training seems to be a critical variable, with higher intensity training leading to larger increases in strength. Studies involving low-intensity training in older adults have reported strength increases of less than 20%.\textsuperscript{28,22,27,29,32} In comparison, high-intensity training (70% to 80% 1 RM) resulted in increases of up to 227% in 1 RM\textsuperscript{40} (see Table 3 for results of other high-intensity training studies).

In addition to intensity, other variables (such as the number of sets and repetitions of a given exercise, the frequency and duration of a program, the muscle group[s] exercised, and the type of training and testing) must be considered when analyzing strength training programs. All of these variables and different subject groups (ie, age, gender, and initial strength) make comparisons between studies difficult. The studies reported in Table 3 had a training frequency of 2\textsuperscript{44} to 3 times per week and a duration of 8 to 52 weeks with most using 8 or 12 weeks, and 1 to 4 sets. Although Hagberg et al\textsuperscript{141} had one of the longest (26 weeks) programs, the first 13 weeks were a low-intensity adaptation phase, with only 1 set done for each exercise. This may explain why the subjects increased strength by only 9% to 18%. Training volume is also important, because excessive amounts of training (ie, sets) can lead to limited increases or even decreases in

<table>
<thead>
<tr>
<th>Type</th>
<th>Action performed</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Isometric</td>
<td>No movement</td>
<td>Making a fist</td>
</tr>
<tr>
<td></td>
<td>Constant resistance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Variable velocity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Concentric (decreased joint angle)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Eccentric (increased joint angle)</td>
<td></td>
</tr>
<tr>
<td>II. Isotonic</td>
<td>Lifting an object</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lowering an object</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kin-Com and Cybex dynamometers</td>
<td></td>
</tr>
<tr>
<td>III. Isokinetic</td>
<td>Variable resistance</td>
<td>Pushing against the machine</td>
</tr>
<tr>
<td></td>
<td>Constant velocity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Concentric</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Eccentric</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Summary details of studies on low-intensity or noncontrolled high-intensity strength training in older adults

<table>
<thead>
<tr>
<th>Author and data</th>
<th>Age of subject, yrs</th>
<th>Sex</th>
<th>N</th>
<th>Type of training</th>
<th>Muscles trained</th>
</tr>
</thead>
<tbody>
<tr>
<td>deVries (1970)</td>
<td>52-87</td>
<td>M</td>
<td>112</td>
<td>Isotonic</td>
<td>Knee/hip extension</td>
</tr>
<tr>
<td>Chapman et al (1972)</td>
<td>63-88</td>
<td>M</td>
<td>20</td>
<td>Isotonic</td>
<td>Whole body</td>
</tr>
<tr>
<td>Liemohn (1975)</td>
<td>42-83</td>
<td>M</td>
<td>52</td>
<td>Isometric</td>
<td>Index finger</td>
</tr>
<tr>
<td>Mortizani and deVries (1980)</td>
<td>67-72</td>
<td>M</td>
<td>5</td>
<td>Isotonic</td>
<td>Knee flexion/extension</td>
</tr>
<tr>
<td>Larsson (1982)</td>
<td>56-65</td>
<td>M</td>
<td>6</td>
<td>Isotonic circuit</td>
<td>Elbow flexion</td>
</tr>
<tr>
<td>Kauffman (1985)</td>
<td>65-73</td>
<td>M</td>
<td>10</td>
<td>Isometric</td>
<td>Knee extensors</td>
</tr>
<tr>
<td>Craig et al (1989)</td>
<td>62.8*</td>
<td>M</td>
<td>9</td>
<td>Variable resistance</td>
<td>Upper/lower extremities</td>
</tr>
<tr>
<td>Kofler et al (1992)</td>
<td>52-60</td>
<td>M</td>
<td>7</td>
<td>Variable resistance</td>
<td>Upper/lower extremities</td>
</tr>
<tr>
<td>Lexell et al (1992)</td>
<td>71-77</td>
<td>F</td>
<td>7</td>
<td>Isotonic</td>
<td>Elbow flexion</td>
</tr>
<tr>
<td>Blanpied and Smith (1993)</td>
<td>57-71</td>
<td>F</td>
<td>14</td>
<td>Isotonic</td>
<td>Plantarflexors</td>
</tr>
<tr>
<td>Roman et al (1993)</td>
<td>67.6*</td>
<td>M</td>
<td>5</td>
<td>Isotonic</td>
<td>Elbow flexion</td>
</tr>
<tr>
<td>Connolly et al (In press)</td>
<td>66-90</td>
<td>F</td>
<td>10</td>
<td>Isokinetic</td>
<td>Knee extension</td>
</tr>
<tr>
<td>Heisler (1994)</td>
<td>50-64</td>
<td>F</td>
<td>22</td>
<td>Elastic straps</td>
<td>Whole body</td>
</tr>
<tr>
<td>Hikkinen and Pakkarinen (1994)</td>
<td>64-73</td>
<td>M/F</td>
<td>10/11</td>
<td>Isotonic</td>
<td>Leg press</td>
</tr>
</tbody>
</table>

All of the cited studies reported gains in strength that seemed to depend on the intensity of training (see text.) *Only mean age was available.

The improvements in 1 RM strength values are variable, but it seems that 12 weeks of high-intensity (> 70% 1 RM) resistance training will result in a large increase in strength, as measured dynamically by 1 RMAs. All but one study from Table 3 have used isometric or concentric strength gains as
outcome measures after training, even though eccentric muscle actions are part of most isotonic strength training exercises and most daily activities and there are differential losses in concentric and eccentric strength with increased age. The one study of eccentric strength showed that gains can be elicited with isokinetic eccentric training and testing. The subjects followed a complicated training routine with a mixture of isometric, concentric, and eccentric isokinetic actions. Increases in eccentric strength were slightly larger than increases in concentric strength but both were much lower than increases reported for 1 RM testing. This may be explained by the high fitness level of the subjects, the mode of testing or training (isokinetic versus isotonic), and the training program itself. More studies that specifically address eccentric

Table 3. Controlled high-intensity (70% to 80% 1 RM) dynamic strength training studies for older adults

<table>
<thead>
<tr>
<th>Study</th>
<th>Age (years), gender</th>
<th>N</th>
<th>Muscle action</th>
<th>Duration, sets/repetitions</th>
<th>Strength gain (1 RM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontera et al16</td>
<td>60–72, M</td>
<td>12</td>
<td>Knee flexion/extension</td>
<td>12 wk, 3/8</td>
<td>↑ 107% to 227%</td>
</tr>
<tr>
<td>Hagberg et al14</td>
<td>70–79, M/F</td>
<td>47</td>
<td>Chest press, leg extension</td>
<td>26 wk, 1/3–12</td>
<td>↑ 9% to 18%</td>
</tr>
<tr>
<td>Brown et al15</td>
<td>60–70, M</td>
<td>14</td>
<td>Elbow flexion</td>
<td>12 wk, 4/10</td>
<td>↑ 48%</td>
</tr>
<tr>
<td>Fisarone et al16</td>
<td>86–96, M/F</td>
<td>4/6</td>
<td>Knee extension</td>
<td>8 wk, 3/8</td>
<td>↑ 174%</td>
</tr>
<tr>
<td>Charette et al16</td>
<td>64–66, F</td>
<td>19</td>
<td>Knee/hip extension, leg press</td>
<td>12 wk, 6/6</td>
<td>↑ 28% to 115%</td>
</tr>
<tr>
<td>Hicks et al16</td>
<td>66.3°, M/F</td>
<td>4/7</td>
<td>Dorsiflexion</td>
<td>12 wk, 4/10–15</td>
<td>↑ 48%</td>
</tr>
<tr>
<td>Grimby et al15</td>
<td>78–84, M</td>
<td>9</td>
<td>Knee extension, concentric, eccentric</td>
<td>25 sessions, complex</td>
<td>Concentric: ↑ 10%/eccentric: ↑ 19%↑</td>
</tr>
<tr>
<td>Meredith et al15</td>
<td>61–72, M</td>
<td>11</td>
<td>Knee flexion/extension</td>
<td>12 wk, 3/8</td>
<td>↑ 104%</td>
</tr>
<tr>
<td>Judge et al16</td>
<td>71–97, M/F</td>
<td>24/13</td>
<td>Knee extension</td>
<td>12 wk, 3/8–10</td>
<td>↑ 32%</td>
</tr>
<tr>
<td>Menkes et al16</td>
<td>50–70, M</td>
<td>11</td>
<td>Upper/lower body</td>
<td>16 wk, 1–2/5</td>
<td>3 RM ↑ 45%</td>
</tr>
<tr>
<td>Nichols et al16</td>
<td>67.8°, F</td>
<td>30</td>
<td>Upper/lower body</td>
<td>24 wk 3/8–10</td>
<td>↑ 18% to 71%</td>
</tr>
<tr>
<td>Rice et al17</td>
<td>65–78, M</td>
<td>18</td>
<td>Elbow extension</td>
<td>24 wk, 4/6–8</td>
<td>↑ 30%</td>
</tr>
<tr>
<td>Pyka et al17</td>
<td>61–78, M/F</td>
<td>8/17</td>
<td>Upper/lower body</td>
<td>30 wk, 3/8</td>
<td>↑ 23% to 62%</td>
</tr>
<tr>
<td>Fisarone et al18</td>
<td>72–90, M/F</td>
<td>37/63</td>
<td>Hip and knee extension</td>
<td>10 wk, 3/8</td>
<td>↑ 24% to 216%</td>
</tr>
</tbody>
</table>

RM = repetition maximum. All increases are statistically significant. Hicks et al16 had a training frequency of two times per week and Grimby et al15, two to three times per week. All other studies had training frequency of three times per week. *Only mean age was available. †Peak torque, not 1 RM. For those studies that utilized control subjects, the a includes the controls.
training and changes in eccentric strength after resistance training are needed in this age group. Even though the previously active men in the study of Grimby and colleagues experienced no muscle or joint problems with this type of training, eccentric actions have been shown to produce muscle damage from which older subjects recover more slowly. Therefore, this type of training must be done cautiously.

Endurance changes

In addition to increasing strength, high-intensity resistance training in older adults has also improved endurance capacity. In one study the subjects increased their ability to lift their initial maximal weight (1 RM) from 1 repetition to 7–19 repetitions. Functionally, this could mean improved ability in activities that require muscular endurance (e.g., carrying a heavy object) rather than muscular strength (e.g., lifting objects whose weight is at the limit of someone’s ability).

Mechanisms of strength gains

There are several mechanisms that are believed to explain strength gains after high-intensity resistance training. These include changes in muscle biochemistry and morphology, muscle and connective tissue biomechanics, activation by the central nervous system, motor skill coordination, and psychologic drive. Only recently have studies attempted to elucidate to what extent adaptations of morphologic, neurologic, and intrinsic muscle properties contribute to strength gains in older individuals.

Morphologic changes

Moritani and deVries studied how hypertrophy (muscle enlargement) and neural factors affected strength changes in younger and older men. Although both groups increased maximal isometric strength and neural activation, only the younger men demonstrated significant enlargements in muscle cross-sectional area. The researchers concluded that neural factors alone might be responsible for the improvements in strength seen in older subjects. In contrast, Frontera and colleagues reported that 60- to 72-year-old men gained 107% in knee extension and 227% in knee flexion 1 RM strength along with an 11% increase in thigh total muscle area and an increase in protein turnover. These researchers concluded, in contrast to Moritani and deVries, that even the muscles of older individuals have the potential to hypertrophy in response to high-intensity resistance training.

The different conclusions of these two studies may be explained by training intensity or measurement techniques. First, the intensity of training used in one study was only 66% of 1 RM, whereas the intensity of the other was 80% of 1 RM. The measurement techniques for hypertrophy were also quite different. The earlier study measured girth to estimate changes in muscle size, whereas the later study used computerized tomography (CT scans). This has significance because the quality of muscle is known to change with age such that muscle becomes increasingly infiltrated with greater amounts of fat and connective tissue. This process cannot be detected by anthropometric measurements but can be detected noninvasively by CT scans. Other studies using CT scans have shown that high-intensity resistance training does result in hypertrophy, even in 86- to 98-year-olds. More recently magnetic resonance imaging (MRI) was used to measure muscle
hypertrophy that followed high-intensity strength training in older men.37

At the microscopic level, enlargement of both type I (slow) and type II (fast) muscle fiber areas occur after strength training in older adults (Table 4).37,40,42,43,49 When changes were minor and nonsignificant, they were consistent with small strength gains.

A cross-sectional survey study showed that older strength trainers had greater type I and II fiber areas than swimmers, runners, and nonathletes of the same age, and similar areas as young control subjects.5 In addition, the average type IIb (fast glycolytic) fiber area for the older strength-trained group was greater than the average type IIb fiber area for each of the other subject groups, including the young subjects. Finally, a recent study reported that the rate of protein synthesis in response to short-term resistance training is similar in young and older subjects.40 The study indicates that the ability of muscles to hypertrophy is not impaired by aging.40 This study and those described above provide evidence about the adaptive processes of aging muscle, but the hypertrophic changes with long-term training remain to be determined. And, although it is now evident that aged muscle can enlarge, these hypertrophic changes are relatively small compared with the tremendous increases in 1 RM strength reported.

Neurologic changes

A large part of the increase in strength that follows resistance training, especially early gains, has been attributed to neural adaptations.18 Moritani and deVries44 concluded that neural adaptation might be totally responsible for gains in elbow flexion strength made by older adults. Although muscle hypertrophy has now been shown to occur,11,12,37,40,42,43,49 it alone certainly fails short of explaining the majority of the strength gains. Also, the increases are not fully transferrable to different modes of testing (ie, 1 RM versus maximum voluntary isometric contraction [MVC] or isokinetic). This suggests that a certain amount of skill or motor coordination is required depending on the movement and that specific neural adaptations are made to activate the prime movers while inhibiting co-contraction of antagonists after training.18

Brown and colleagues49 found that complete (98%) motor unit activation was achieved pre- and posttraining in the elbow flexors using the interpolated twitch technique44 during an MVC (ie, no further increase in muscle activation occurred when the twitch stimulus was supplied). Although these results suggest that nervous system activation of muscle is not a problem, it is certainly possible that during dynamic movements, as opposed to isometric MVC maneuvers, central nervous system coordination or activation is an important factor.5 More research is definitely needed in this

Table 4. Muscle fiber area changes after high-intensity (70% to 80% 1 RM) resistance training in older adults

<table>
<thead>
<tr>
<th>Study</th>
<th>Type I</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frayn et al40 (1988)</td>
<td>↑ 33%</td>
<td>↑ 28%</td>
</tr>
<tr>
<td>Brown et al40 (1990)</td>
<td>↑ 14%</td>
<td>↑ 30%</td>
</tr>
<tr>
<td>Chatteet al40 (1991)</td>
<td>↑ 7%, NS</td>
<td>↑ 20%</td>
</tr>
<tr>
<td>Grisby et al40 (1992)</td>
<td>↓ 8%, NS</td>
<td>↓ 5%, NS</td>
</tr>
<tr>
<td>Roman et al40 (1993)</td>
<td>↑ 23%, NS</td>
<td>↑ 37%</td>
</tr>
<tr>
<td>Pyka et al40 (1994)</td>
<td>15 wk</td>
<td>↑ 25%, ↑ 20%, NS</td>
</tr>
<tr>
<td></td>
<td>30 wk</td>
<td>↑ 46%</td>
</tr>
</tbody>
</table>

NS = nonsignificant change.
area to elucidate the effects of specificity of training on strength gains.

**Intrinsic muscle property changes**

In addition to changes in neural activation and muscle morphology, muscle characteristics such as excitation and contraction coupling, muscle fiber packing density, and muscle fiber composition can alter force production, which may be reflected in evoked contractile properties. After strength training in older adults, Brown and colleagues reported increases in the rate of force development but slowing of relaxation. They speculated that this even greater posttraining slowing, in addition to aging, would allow these older adults to use lower nervous system activation rates to achieve maximal force production. Rice and colleagues reported a longer time to reach peak force but no change in any other contractile variables. They suggested that this was caused by training-induced changes in muscle morphology that actually made the muscle more elastic or compliant. It is evident that contractile property changes with training are not clear, and other measurements, such as passive joint stiffness, may be of value.

Although Hicks and coworkers found no changes with age in several contractile indexes in the lower leg muscles, they did suggest that there may be possible changes in the excitability of the muscle membrane in two other muscle groups with resistance training in older adults. These results seem to correspond with increased sites for the sodium-potassium (Na⁺-K⁺) transport system found in older trained versus sedentary men. Changes in the Na⁺-K⁺ system or muscle membrane excitability could have implications for contractile properties of muscles and, in turn, the function of older subjects after training. The ability to reach peak tension more rapidly could help to prevent falls and subsequent injuries.

**BENEFITS OF STRENGTH TRAINING**

The ultimate objective of strength training programs for most older adults is to have an improvement in the performance of daily physical activities along with health. However, limited information is available on the transferability of strength gains and muscle mass changes measured in a laboratory to real life.

Schultz has argued that the basic strength requirements for tasks such as maintaining balance and rising from a chair are less than the strength capabilities of even the most frail individuals. He suggests that more biomechanical analyses need to be done to determine the strength requirements of other daily activities and to investigate other potentially more important variables like muscle power.

Fiatarone et al recently reported functional outcomes of a placebo-controlled, high-intensity strength training program for 72- to 98-year-old nursing home residents. In addition to increases in muscle strength and size, positive changes were seen for mobility and spontaneous physical activity. Mobility measures included habitual gait velocity and stair-climbing ability. This study is important because the subjects were included even in the presence of disease and because functional changes that may have the most meaningful influence on quality of life were seen. However, the percentage increases were still much smaller for the functional changes (8% to 51%) than the measures of strength (26% to 215%) after the 10
weeks of training. It may be that the gains in strength, although statistically significant and large on a relative basis, do not have as great a clinical significance.67

The prevention of frailty, and fractures resulting from falls and osteoporosis, is receiving a lot of attention. Smith and Gilligan44 recently reviewed the effects of a variety of exercise programs on bone metabolism. They concluded that exercise, including strength training, can have a positive influence on bone, but the improvements are not that substantial. More recently though, Menkes et al45 found that a slight increase in bone mineral density that followed short-term strength training in older men was accompanied by an elevation of markers of bone formation. Long-term training studies are needed to determine chronic effects of strength training on bone itself, along with the risk of fracturing.

Strength training is also being investigated as a possible intervention for fall prevention because “frequent fallers” have been shown to have lower levels of muscular strength than nonfalling controls.41,48 A prospective prevention study using a low-intensity exercise program called “stand-up/step-up,”79 found that time to first fall was not affected by the training.71 However, the exercise program was not of a high enough intensity to elicit changes in strength either. Higher intensity training may have increased strength and might have also helped to prevent falls. Future trials should give some insights into this research area.72-73

The improvement in muscular endurance with strength training42-45,98 might be of particular significance for the performance of most daily physical tasks because these tasks do not require maximal strength unless an individual is extremely weak. Therefore, if strength can be increased, each task would require less effort and become much less physically stressful.26 Other potential benefits of strength training for older adults include improving gastrointestinal transit time,30 glucose tolerance,28 cardiovascular response to high-intensity lifting,11 and clinical measures of functional mobility11 and flexibility,3 and decreasing joint stiffness.21

Clearly, studies are being done to determine what benefits can be achieved from strength training for older adults. However, most results should be considered tentative until more conclusive research with appropriate controls has been done.

PROGRAMMING IMPLICATIONS

Although there are still a number of unanswered questions about the efficacy of strength training and the mechanisms of adaptation, programs are being initiated in many locations. This section addresses the considerations pertinent to conducting preventive strength training programs. Strength training information for individuals with specific conditions is less available, although Fisher and colleagues77,78 have begun to examine high-intensity strength training for individuals with arthritis.

In exercise programs for older individuals, there is always a fine line between rehabilitation and prevention. Many of the following guidelines and considerations can be applied to most older adults, with obvious precautions and progressions for individuals with specific conditions and rehabilitation needs. It is encouraging that even very old nursing home residents with multiple chronic conditions have been able to safely and successfully complete strength training programs.10-13
To conduct a safe and effective strength training program, several factors must be considered. Most studies have addressed the physiologic outcomes and not the programming aspects of strength training for the older adult; therefore, only limited information can be drawn from the literature.

Screening

To ensure that any exercise program is appropriate for an individual, screening is necessary. In this context screening can be defined as using tools (e.g., questionnaires or physical testing) to determine whether an individual can safely participate in a physical activity program. In an older age group, screening is even more important to avoid exacerbating pre-existing conditions and to individualize the program. The studies discussed in this article have used a variety of exclusion criteria. In general, the following factors, drawn from several studies, can be used to exclude or limit participation in a strength training program:

- unstable cardiovascular disease,
- other unstable chronic conditions (e.g., uncontrolled diabetes),
- a recent bone or joint injury,
- cognitive impairment (if not directly supervised), and
- any condition that prevents strong muscular contractions.

Even in the oldest trained subjects (86 to 98 years old) who had a number of chronic conditions, no cardiovascular or orthopaedic incidents were reported. However, "training was conducted under constant supervision by one of the study investigators." Another study, which did not report such strict supervision, did report musculoskeletal injuries in men and women 70 to 79 years old performing 1 RM tests (11 injuries in the 57 subjects, 19.3%). However, the incidence of injury during the strength training program (2 of 23 subjects were injured) was lower than the 1 RM testing and the high-intensity aerobic training, which consisted of fast walking or jogging (9 of 21 subjects were injured).

Strength testing

The results from Pollock et al suggest that 1 RM testing might increase the risk for injury. Also, because doing a proper weight-lifting exercise is a learned motor skill, the results from 1 RM testing might not be a good measure of strength, especially at the beginning of training when both the tester and participant tend to be cautious. Simply ensuring that participants are actually doing 8 RM sets would satisfy requirements for monitoring intensity and improvements in strength when isotonic machines or free weights are used in a community program setting. This has been the authors' experience with local strength training programs for seniors.

Training intensity and frequency

The results from training studies in older adults indicate that high-intensity resistance is needed to make large gains in strength. Therefore, it is suggested that more than one set of eight repetitions at 70% to 80% of 1 RM (or 8 RM) be done per training session. However, it may take several weeks for some older individuals to reach this target.

As for frequency, most studies have used three times per week; however, Hicks and colleagues did demonstrate comparable increases (48%) in 1 RM with only two times per week. It is important that at least 48 hours be allowed between sessions using a particular muscle group so adaptation can occur.
Duration of the program

The longest of the high-intensity strength training studies reported for older adults is 52 weeks.49 In comparison to the age of the subjects (up to 98 years), most training periods have been very short, especially if several weeks at the beginning of the program are devoted to low-intensity build-up.10 Preliminary results suggest that plateaus in strength increases do not occur.11,38 Little is known about the chronic (ie, years or lifelong) effects of resistance training on muscle strength or function of older adults. And as with younger subjects,57 detraining or a return to a sedentary lifestyle will lead to rapid and significant declines in strength.11 The effects of resuming a previous strength training program also need to be investigated, particularly because many older independently living adults take prolonged breaks from their training regimens for various reasons (eg, traveling or looking after a family member).

FUTURE RESEARCH

Although it is evident that high-intensity resistance training can be done safely and result in large increases in strength, there are a number of issues that should be addressed. More studies have to be conducted to control for tester bias and learning and placebo effects. More information is needed about the mechanisms of adaptation of muscle activation in dynamic tasks, specificity of training, changes in intrinsic muscle characteristics, and neural alterations versus muscle hypertrophy, and their contribution to strength changes. In a more practical sense the following research topics deserve attention:

- What is the transferability of strength improvements or muscle hypertrophy to functional and health-related outcomes?
- What are the long-term effects of strength training, either started later in life or as a lifelong activity?
- How much can eccentric strength be improved, what effect can it have on function, and is eccentric exercise safe?
- Do older men and women respond similarly to strength training?
- What impact can strength training have on the quality of life, cognitive function, and independence of frail older men and women?

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APPENDIX III. A schematic of the starting positions of the foot for testing concentric (CONC) and eccentric (ECC) plantar and dorsiflexion. The bolder arrow represents the direction of ankle unit of the KIN-COM. The other non-bolder arrow shows the direction that subjects tried to move their foot.

CONC DORSIFLEXION  ECC DORSIFLEXION

CONC PLANTAR FLEXION  ECC PLANTAR FLEXION
Appendix IV.  Reported mean peak torques for concentric (C) and eccentric (E) dorsiflexion (DF) and plantar flexion (PF).

<table>
<thead>
<tr>
<th>Study and subjects</th>
<th>Sex</th>
<th>Age (years)</th>
<th>(°/s)</th>
<th>DF (N m)</th>
<th>PF (N m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present study</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>supine</td>
<td>F</td>
<td>20 - 75</td>
<td>30</td>
<td>19C, 30E</td>
<td>77C, 101E</td>
</tr>
<tr>
<td>standing</td>
<td>F</td>
<td>20 - 75</td>
<td>30</td>
<td>14C, 28E</td>
<td>70C, 100E</td>
</tr>
<tr>
<td>Oberg et al. (Oberg et al., 1987)</td>
<td>M</td>
<td>34 ± 9</td>
<td>30</td>
<td>40C</td>
<td>168C</td>
</tr>
<tr>
<td>Cunningham et al. (1987)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>young sedentary</td>
<td>M</td>
<td>21</td>
<td>30</td>
<td>62C</td>
<td></td>
</tr>
<tr>
<td>young active</td>
<td>M</td>
<td>23</td>
<td>30</td>
<td>88C</td>
<td></td>
</tr>
<tr>
<td>old sedentary</td>
<td>M</td>
<td>64</td>
<td>30</td>
<td>57C</td>
<td></td>
</tr>
<tr>
<td>old active</td>
<td>M</td>
<td>63</td>
<td>30</td>
<td>61C</td>
<td></td>
</tr>
<tr>
<td>Alexander et al. (1990)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>elite sprinters</td>
<td>M &amp; F</td>
<td>21</td>
<td>30</td>
<td>31C/40E</td>
<td>96C/104E</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>22</td>
<td>30</td>
<td>34C/44E</td>
<td>103C/109E</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>20</td>
<td>30</td>
<td>25C/32E</td>
<td>85C/ 94E</td>
</tr>
<tr>
<td>Wennerberg et al. (1991)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>intercollegiate athletes</td>
<td>M</td>
<td>18 - 22</td>
<td>30</td>
<td>40C</td>
<td>101C</td>
</tr>
<tr>
<td>Morris-Chatta et al. (1994)</td>
<td>M &amp; F</td>
<td>75.2</td>
<td>30</td>
<td>14C</td>
<td>33C</td>
</tr>
</tbody>
</table>
Appendix V. Studies which have compared eccentric (ECC) strength training to concentric (CONC) or isometric training.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Muscle Group / Exercise</th>
<th>Actions performed in training</th>
<th>Actions tested</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colliander et al. 1990</td>
<td>Quadriceps</td>
<td>Conc or Conc/Ecc</td>
<td>UniConc/Ecc, BilConc/Ecc</td>
<td>Conc/Ecc &gt; Conc, both neural since short-term change in fibre areas were low</td>
</tr>
<tr>
<td>Dudley et al. 1991</td>
<td>Leg press / Leg extension</td>
<td>Conc/Ecc or Conc or 2xConc</td>
<td>3RM</td>
<td>Conc/Ecc &gt; Conc/Conc &gt; Conc</td>
</tr>
<tr>
<td>Duncan et al. 1989</td>
<td>Quadriceps</td>
<td>Conc or Ecc</td>
<td>Conc and Ecc</td>
<td>Specific increases for Ecc but not Conc</td>
</tr>
<tr>
<td>Hather et al. 1991</td>
<td>Leg press / extension</td>
<td>Conc/Ecc or Conc or 2xConc</td>
<td>UniConc/Ecc, BilConc/Ecc</td>
<td>Hypertrophy greater in Conc/Ecc Capillary density increased in Conc2x and Conc</td>
</tr>
<tr>
<td>Hortobagyi et al. 1990</td>
<td>Bench press and squat</td>
<td>Conc or Conc/Ecc</td>
<td>Conc</td>
<td>No difference between groups</td>
</tr>
<tr>
<td>Housh et al. 1992</td>
<td>Arm/leg flex/ext</td>
<td>Conc</td>
<td>Conc</td>
<td>Hypertrophy occurred, strength increased</td>
</tr>
<tr>
<td>Johnson et al. 1972</td>
<td>Bench press, knee flex/ext</td>
<td>Conc or Ecc</td>
<td>1RM</td>
<td>No difference between groups</td>
</tr>
<tr>
<td>Johnson et al. 1976</td>
<td>Elbow/shoulder/knee flex/ext, arm press</td>
<td>Conc on one side Ecc on other side</td>
<td>Conc (1RM)</td>
<td>No difference between groups</td>
</tr>
<tr>
<td>Jones et al. 1987</td>
<td>Quadriceps</td>
<td>Conc on one side Ecc on the other side</td>
<td>Isometric</td>
<td>No difference between Conc and Ecc</td>
</tr>
<tr>
<td>Komi &amp; Buskirk 1972</td>
<td>Forearm flexors</td>
<td>Conc or Ecc</td>
<td>Conc, Ecc, Isometric</td>
<td>Ecc &gt; Conc</td>
</tr>
<tr>
<td>Lacerte et al. 1992</td>
<td>Quadriceps</td>
<td>Conc or Conc/Ecc</td>
<td>Conc/Ecc</td>
<td>Conc/Ecc &gt; Conc</td>
</tr>
<tr>
<td>Mannheimer et al. 1969</td>
<td>Triceps brachii</td>
<td>Conc or Ecc</td>
<td>Conc and Ecc</td>
<td>Early Ecc &gt; Conc, Overall no difference Exercise 5 days consecutively</td>
</tr>
<tr>
<td>Reference</td>
<td>Muscle Group</td>
<td>Description</td>
<td>Test Type</td>
<td>Result</td>
</tr>
<tr>
<td>----------------------</td>
<td>--------------------</td>
<td>------------------------------------</td>
<td>-----------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>O'Hagan et al. 1995</td>
<td>Elbow flexors</td>
<td>Conc on one side, Conc/Ecc on other side</td>
<td>IRM, Conc</td>
<td>No difference in strength, but Conc/ECC &gt; Conc in increasing muscle mass</td>
</tr>
<tr>
<td>Pavone et al. 1985</td>
<td>Quadriceps</td>
<td>Ecc or Conc or isometric</td>
<td>Isometric</td>
<td>No difference between groups</td>
</tr>
<tr>
<td>Petersen 1960</td>
<td>Elbow flexors</td>
<td>Isometric or Ecc</td>
<td>Isometric</td>
<td>Isometric &gt; Ecc</td>
</tr>
<tr>
<td></td>
<td>Knee Extensors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reinking et al. 1991</td>
<td>Tibialis anterior</td>
<td>Conc or Ecc (theraband)</td>
<td>Conc and Ecc</td>
<td>No change in peak torque for either, Ecc increased in Ecc total work</td>
</tr>
<tr>
<td>Singh &amp; Karpovich</td>
<td>Forearm extensors</td>
<td>Ecc</td>
<td>Agonists and antagonists tested Conc, Ecc, isometric</td>
<td>Agonist &gt; Antagonists Conc &amp; Isometric &gt; Ecc</td>
</tr>
<tr>
<td>1967</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tomberlin et al. 1991</td>
<td>Quadriceps</td>
<td>Conc or Ecc</td>
<td>Conc and Ecc</td>
<td>Increases specific to training</td>
</tr>
</tbody>
</table>
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