The effects of eccentrically-biased versus conventional resistance training in older adults

I. Selva Raj

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I. Selva Raj
B.HM (Hons)

School of Medical Sciences
Science, Engineering and Health Portfolio
RMIT University
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DECLARATION

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Isaac Selva Raj

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1RM: one repetition maximum

f-v: force-velocity

ADLs: activities of daily living

% of young adult strength: percentage of strength remaining in the older group

compared with the younger group

Ecc: eccentric

Iso: isometric

M: male

F: female

V_{max}: maximum contraction velocity

VI_{max}: index of maximal shortening velocity

V_0: maximum unloaded shortening velocity

P_{max}: maximum power

F_{opt}: force at maximum power

V_{opt}: contraction velocity at maximum power

L_f: muscle fascicle length

θ: muscle fascicle pennation angle

OA: old adults

YA: young adults

P_{max}': old adults' maximal power

V_{max}': old adults' maximal contraction velocity

F_{max}': old adults' peak isometric torque

SPPB: short physical performance battery

TRT: traditional resistance training

PT: power training

ERT: eccentric resistance training

KE: knee extensors

PF: plantar flexors

EF: elbow flexors

5RM: five repetition maximum

eV_{max}: estimated maximum contraction velocity

V: contraction velocity

RFD: contractile rate of force development

ADP: adenosine disphosphate

B-TG: beta-thromboglobulin

CV: coefficient of variation

6mFWT: 6 metre fast walk test

TUG: timed up and go test

LOAs: limits of agreement

F1: first familiarisation session

F2: second familiarisation session

T1: first test session

T2: second test session

ANOVA: analysis of variance

ICC: intraclass correlation coefficient

% Diff: percent mean difference

VJ: vertical jump

VL: vastus lateralis

GM: gastrocnemius medialis

EB: eccentrically-biased resistance training

CONV: conventional resistance training

PWV: pulse wave velocity

Vm: mean velocity of the centre of pressure

MVC: maximum voluntary isometric contraction

ΔD: distance in metre

ΔT: time interval in seconds

EDTA: tri-potassium ethylene-diamine-tetra acetic acid

G: gravitational constant

PRP: platelet rich plasma

PPP: platelet poor plasma

COP: centre of pressure

Vd: displacement velocity of each coordinate pair of the centre of pressure

NMAE: normalised mean absolute error

NSAE: normalised standard deviation of absolute error

NPAE: normalised peak absolute error

SD: standard deviation

A.U.: arbitrary units

AA: arachidonic acid

Post 0: immediately post training

Post 120: 2 hours post training

RPE: rating of perceived exertion

Abstract of Thesis

The major objectives of this thesis were: (i) to compare the acute effects of eccentrically-biased and conventional resistance training on arterial stiffness, platelet reactivity, activation and count, postural stability and isometric force steadiness in older men and women; and (ii) to compare the effects 16-weeks of eccentrically-biased versus conventional resistance training on muscle architecture, 1 repetition maximum, isometric strength, isokinetic force-velocity characteristics, functional capacity and pulse wave velocity in older men and women. The results of this research show that both eccentrically-biased and conventional resistance training are effective at increasing strength and improving function in older adults. The improvements in strength during quick isokinetic contractions of the knee extensors after eccentrically-biased resistance training may have implications for functional movements that require rapid movements of the limb, such as recovering from a stumble. However, more research is needed to evaluate the effectiveness of this type of training in this area. The small acute increase in platelet count and postural instability after eccentrically-biased resistance training mean that older adults should exercise caution immediately post-training and appropriate management will decrease these risks.

CHAPTER 1: Introduction

Muscular strength, defined as the maximum force generation capacity of a muscle, and power, defined as being a function of muscular force and velocity of contraction, decline with age after the third decade of life. The proposed major reasons for this being changes to the neuromuscular system and muscle architecture, and skeletal muscle atrophy (31, 98). The decline in power rather than the concurrent loss of strength per se, appears to have the most profound impact on functional capacity in older adults (134) as it is associated with a slowing of walking speeds and increased risk of falling (40, 120). As a means of combating these declines, training interventions using conventional high intensity resistance training, which involves both concentric and eccentric muscle actions performed against a constant external load, have been utilised and demonstrated to have significant positive effects on several aspects of performance and health (74). However, while typically very effective at increasing muscle mass and strength, this traditional mode of resistance training appears to be less effective at increasing muscle power generation during high-speed contractions (109, 135), which are critical for the older adult. Therefore, the effectiveness of alternative strength and power training regimens require investigation.

One of these alternative modalities is eccentric resistance training, which has been reported to increase muscle fascicle lengths in elderly resistance trainers (140). This adaptation should also favourably alter the muscle's force-velocity characteristics by increasing the maximum torque and power generation at higher contraction speeds since longer muscle fascicles have a greater number of sarcomeres in series (166). Additionally, there is evidence that eccentric resistance training provides a more effective stimulus for muscle growth than concentric

training (147). So, given these proposed advantages, eccentric resistance training may be of particular value to older adults with regards to increasing walking speed, lowering the risk of falling and improving functional capacity.

Another aspect favouring eccentric resistance training is that it allows participants to perform the same amount of work at a lower rating of perceived exertion than traditional concentric training (102, 118, 123), a factor that may make it more attractive to those who have been sedentary for many years. From a cardiovascular perspective, there is reason to believe that eccentric training may have more favourable effects on arterial stiffness, at least in young people, than concentric training (119): thereby providing further advantages for its utilisation in a population group already prone to cardiovascular disease. The favourable effect of eccentric contractions may be mediated by lesser blood pressure responses than are seen in the concentric phase of conventional lifting (99). So underloading the concentric phase of resistance training, as occurs in many reported studies, may therefore have beneficial effects on cardiac afterload (102).

The eccentric resistance training typically employed in human studies involves loads being raised by research assistants or machines and then lowered (eccentrically) by the participants (140). Whilst this form of training can be undertaken in research contexts, it is impractical in fitness centres where the general population typically exercise. Therefore a more practical way of obtaining overload during the eccentric portion of exercises needs to be utilised. One of these is 'eccentrically-biased' resistance training, during which the loads are lifted (concentrically) with two limbs and then lowered (eccentrically) with one. This form of training is therefore eccentrically-biased, as it involves a relatively underloaded concentric phase and an overloaded eccentric phase. An example would involve

lifting 50% of the bilateral one repetition maximum (1RM) and then lowering it unilaterally, which in doing so would equate to about 100% of the unilateral 1RM (see page 135 for a discussion on the impact of the bilateral deficit on this example). To date, however, there are no studies comparing the effectiveness of eccentrically-biased training to conventional resistance training in older adults.

This thesis will begin by reviewing the literature examining the changes in muscular function with age, the functional implications of these changes and the resistance training modalities that aim to reverse these changes. Two studies exploring the reliability of a range of strength, functional and muscle architecture measures will then be presented. These will be followed by a study comparing the acute effects of a conventional versus an eccentrically-biased resistance training session in older adults, with the aim of gaining an understanding of the safety issues surrounding these two training modalities as there is some evidence to suggest that older adults may be at an increased risk of experiencing an adverse event immediately after a training session. Finally, an intervention study comparing the chronic effects of conventional and eccentrically-biased resistance training will be presented.

CHAPTER 2: Literature Review

An earlier version of this chapter has been published:

Raj IS, Bird SR, Shield AJ. Aging and the force-velocity relationship of muscles.

Exp Gerontol. 2010;45(2):81-90.

ABSTRACT

Aging in humans is associated with a loss in neuromuscular function and performance. This is related, in part, to the reduction in muscular strength and power caused by a loss of skeletal muscle mass (sarcopenia) and changes in muscle architecture. Due to these changes, the force-velocity (f-v) relationship of human muscles alters with age. This change has functional implications such as slower walking speeds. Different methods to reverse these changes have been investigated, including traditional resistance training, power training and eccentric (or eccentrically-biased) resistance training. This review will summarise the changes of the f-v relationship with age, the functional implications of these changes and the various methods to reverse or at least partly ameliorate these changes.

INTRODUCTION

Aging in humans is associated with a loss in neuromuscular function and performance (27, 40, 73). This is, in part, related to the reduction in strength and power (98) caused by a loss of skeletal muscle mass (sarcopenia) (73, 113) and changes in muscle architecture. Sarcopenia is attributed to a number of factors, which include: preferential type II myofibre atrophy as a result of motor neuron death (73), decreased physical activity (40, 98), altered hormonal status, decreased caloric and protein intake, inflammatory mediators, and altered protein synthesis (40). Along with reduced muscle mass there are concomitant changes in muscle architecture which include alterations in fascicle length and pennation angle, both of which are reduced with age (113).

As a consequence of these physiological and structural changes, the force-velocity relationship of human muscles alters with aging, and muscular strength and power are reduced across all contraction speeds (52, 58, 85, 94, 117, 124, 166, 167, 170, 172, 176). This decline in muscular strength and power, along with other factors such as the aging of the somatosensory and motor nervous systems (42, 75, 154), has functional implications such as slower walking speeds (22, 40), an increased risk of falling (120, 157), and a reduced capacity to undertake activities of daily living (ADLs), all of which contribute to a loss of independence and reduction in the quality of life (40). This is of major concern at both the individual and societal level, as increasing demands on the healthcare system may compromise its capacity to cope in the future. Consequently, interventions that can prevent or ameliorate these declines in function are likely to have significant benefit, and it is therefore important to understand their underlying impact and identify those that are the most efficacious.

This review will focus on the force-velocity (f-v) relationship of human muscles from the context of changes with age, the functional significance of these changes and interventions designed to slow down, stop or reverse these changes.

CHANGES IN THE FORCE-VELOCITY RELATIONSHIP OF MUSCLES WITH AGE

Cross-Sectional Studies

Aging typically results in reductions of force generating capacity right across the f-v spectrum but the decline appears greatest for concentric actions (71, 131). Table 1 summarises the findings of selected cross-sectional studies that have investigated the effect of aging in healthy adults on the f-v relationship using isokinetic strength tests.

The relative preservation of eccentric strength has been noted by a number of authors (71, 78, 94, 95, 115, 128, 130, 131, 179). With the discovery of the relative preservation of eccentric strength with age first in women (179) and then in men (130), Hortobagyi et al. (71) made the initial effort to explain its cause. They tested sedentary but healthy men (age range 18 to 80 years, $n = 60$) and women (age range 20 to 74 years, $n = 30$) for eccentric, isometric and concentric knee extensor strength on an isokinetic dynamometer, and related the results to fat-free mass and muscle fibre characteristics. This study also found that eccentric strength was relatively preserved in older men, with older women actually being about 5% stronger in eccentric contractions than young women. However, the preservation of eccentric strength with age was found to be independent of muscle mass, muscle fibre type, or size.

Table 1

Age-related changes in isokinetic strength

Muscle tested	Gender	*n,* elderly	*n,* young	Elderly age, decade	% of Young Adult strength					Reference
					Ecc	Iso	60º/s	120º/s	180º/s	
Plantar flexors	M	16	14	8th	-	66[a]	61[a]	55[a]	-	Narici, et al. (2005)
Plantar flexors	F	33	24	8th	-	-	63**	59**	62**	Gajdosik, et al. (1999)
Plantar flexors	F	24	24	6th	-	-	87*	80*	84*	Gajdosik, et al. (1999)
Knee extensors	M	17	20	7th	80	63*	57*	58*	58*	Hortobagyi, et al. (1995)
Knee extensors	M	23	20	5th	98	88*	83*	88*	78*	Hortobagyi, et al. (1995)
Knee extensors	F	6	12	7th	105	76*	63*	67*	86*	Hortobagyi, et al. (1995)
Knee extensors	F	12	12	5th	105	76*	70*	71*	76*	Hortobagyi, et al. (1995)
Elbow flexors	M	4	6	8th	54**	54**	43**	36**	22**	Pousson, et al. (2001)
Elbow flexors	F	6	6	7th	74	54*	44*	41*	33*	Pousson, et al. (2001)

n = number of participants; % of young adult strength = percentage of strength remaining in the older group compared with the younger group; Ecc = eccentric; Iso = isometric; M = male; F = female; Dashes indicate data was not provided; Asterisks indicate significant differences between the elderly and young groups (* $P \leq 0.05$; ** $P \leq 0.01$); a = *P* value not given.

Despite being unable to find a reason for eccentric force preservation with age, Hortobagyi and colleagues (71) suggested possible explanations for this. Firstly, they suggested that the greater amount of intramuscular connective tissue observed in older adults may provide increased passive resistance during muscle lengthening while not affecting concentric or isometric force production. They also suggested that older adults might have less sarcomere instability due to the elimination of weak sarcomeres, adding that the increase in force production with increasing eccentric contraction velocity observed in the elderly but not in the young may support this idea. The third possible explanation they provided is that cross-bridge cycling during eccentric contractions may be somehow modified with age, thus allowing more force to be generated during muscle lengthening.

In a later experiment, Porter et al. (128) made an attempt to test two of the explanations proposed by Hortobagyi et al. (71). They tested the eccentric and concentric strength of the plantar flexors and dorsiflexors in 16 older women (mean age 67 ± 4 years) and 16 young women (mean age 27 ± 4 years). Passive resistive torque of the plantar flexors and average rate of torque development of the plantar flexors and dorsiflexors were also measured. In agreement with previous studies, they found that eccentric strength was relatively preserved in the plantar and dorsiflexors with ageing when compared with concentric strength. Although passive resistive torque of the plantar flexors was significantly higher in the older women, it was determined that this factor did not have a role to play in the preservation of eccentric torque. With regards to rate of torque development, it was found that older women had significantly lower values than young women in both plantar and dorsiflexors. The investigators attributed this finding to the greater loss of type II muscle fibres, as well as a slowing of cross-bridge cycling with age. They argue that

while slower cross-bridge cycling may be detrimental to concentric contractions at high velocities, they may be advantageous in eccentric contractions. Thus, Porter et al. (128) put forward the finding of a slower rate of torque development with age as an indirect explanation of the relative preservation of eccentric force with age.

Most recently, Ochala et al. (115) attempted to explain this phenomenon by studying the behaviour of single vastus lateralis muscle fibres from 6 young men (mean age 31.6 years) and 6 older men (mean age 66.1 years). They applied a quick stretch to the fibres while they were maximally activated. This caused an immediate rise in tension (phase 1) followed by a reduction (phase 2) and then a secondary delayed and transient rise in tension in the fibres (phase 3). Finally the tension in the fibres reached a constant value (phase 4), which was lower than phase 3 but higher than the initial tension in the maximally activated fibre. Ochala et al. (115) discovered that despite fibres from older men having a lower absolute maximal isometric force, the increases in tension in phases 3 and 4 were preserved in the older men. The investigators thus suggest that this discovery could be another possible explanation for the relative preservation of eccentric strength in the elderly.

Despite the important findings of the studies mentioned above, the mechanism for the smaller decrease in eccentric strength compared to concentric and isometric strength in the elderly is still not fully understood. The large decline in concentric force suggests that significant efforts should be made to improve this capacity although, for reasons discussed later in this review, the potential of eccentric training for older adults should be explored further in future research.

Longitudinal Studies

Longitudinal studies investigating the loss of strength with age generally agree with cross-sectional studies, finding losses in strength in the ankle plantar flexors, dorsiflexors, knee extensors and flexors, and elbow extensors and flexors at all contraction velocities tested (6, 51, 55, 183). Aniansson and colleagues (6) re-measured the knee extensor strength of 23 healthy males, 73 to 83 years old, between 30°/s and 300°/s 7 years after an initial strength measurement. They found losses of strength between 10 and 22% ($P < 0.05$) at all contraction velocities between the two examinations, and a decrease in the mean vastus lateralis fibre area of 11% ($P < 0.05$). Eleven years after the initial measurement, Grimby (55) reported losses of 25 to 35% in knee extensor strength in a sub-group of 9 men from the original Aniansson et al. (1986) study. However, only strength at 30°/s declined to a significant ($P < 0.05$) extent between the second and third measurements. A possible reason for this is that these 9 men were reported to participate in moderate level physical activity for at least 4 hours per week, and all except two of the subjects reported unchanged levels of physical activity between the second and third measurements. This observation provides a good illustration of the importance of maintaining physical activity in old age for muscular strength.

Similarly, Frontera et al. (51) carried out a longitudinal study of knee and elbow extensors and flexors in 9 healthy men (mean initial age 65.4 ± 4.2 years) and found losses in strength of between 20 and 30% ($P < 0.05$) after 12 years. The velocities at which the muscles were tested were 60 and 240°/s for the knee extensors and flexors and 60 and 180°/s for the elbow extensors and flexors. Computerised tomography scans of the thighs of 7 of the 9 men showed a reduction of 14.7% ($P < 0.05$) in the cross-sectional area of the thigh muscles over the 12 years. A more

detailed look at these results reveals that knee extensor and flexor strength dropped by between 23.7 and 29.8% at both angular velocities tested (Frontera et al., 2000). However, elbow extensors and flexors showed losses of 19.4 and 16.4% respectively at 60º/s, while at 180º/s, only elbow flexors showed a significant loss in strength of 26.5% (Frontera et al., 2000).

With regards to isometric strength, Winegard et al. (183) examined isometric dorsiflexor and plantar flexor strength in 11 men (mean initial age 73.5 ± 7.5 years) and 11 women (mean initial age 69.5 ± 6.4 years) and re-examined them 12 years later. All participants were generally in good health, and none were taking medication that would affect muscle contractile properties. They found losses of 25.2 and 30% ($P < 0.01$) in plantar flexor strength in females and males respectively (118). Highlighting the different effects of reduced physical activity levels on postural and non-postural muscles were the observations that dorsiflexor strength declined significantly less (3.6 and 9.6% [$P < 0.05$] in males and females respectively) than plantar-flexor strength. In contrast to the longitudinal studies mentioned above, the study by Greig, Botella and Young (53) found no significant loss of isometric quadriceps strength in 4 elderly men (age range 79 to 84 years) and 10 elderly women (age range 79 to 89 years) after 8 years. The authors report that all except one of the participants maintained or increased their physical activity levels over the 8 years and this could account for the preservation of isometric strength among the participants. This finding again underscores the importance of physical activity in preserving strength in the elderly, and indicates that interventions may assist with the maintenance of strength.

Maximum Shortening Velocity of Muscles

In-vivo studies have consistently found that the estimated maximum contraction velocity (V_{max}) of muscles is lower in healthy older adults compared to their younger counterparts (83, 112, 166, 167, 176) (see Table 2). Ochala and colleagues (117) did not estimate or directly measure V_{max}, but reported an index of maximal shortening velocity (VI_{max}). This index was taken as the speed of contraction of the plantar flexors under a load of 10% of each subject's maximal voluntary isometric torque. The group of 11 older men (mean age 67.9 ± 3.6 years) had a mean VI_{max} that was 83% ($P < 0.05$) of the mean VI_{max} of the young group ($n = 12$, mean age 21.7 ± 1.5 years).

The majority of in-vitro experiments comparing single muscle fibres of young versus older adults have found that the maximum unloaded shortening velocity (V_0) of single fibres is lower in older adults (81, 82, 86, 116, 186). For example, Larsson, Li, and Frontera (86) compared single fibres from the vastus lateralis muscles of 4 young (age range 25 to 31 years) and 4 older men (age range 73 to 81 years). They found that the V_0 values of type I and IIa muscle fibres from the older men were significantly ($P < 0.001$) lower than those from the young men (about 57% of young men for type I fibres and about 72% of young men for type IIa fibres). In contrast, despite examining fibres from the same muscle (vastus lateralis), Trappe et al. (172) found no differences in the V_0 of muscle fibres of 6 young men (mean age 25 ± 1 years) and 6 young women (mean age 25 ± 1 years) as compared to 6 older men (mean age 80 ± 4 years) and 6 older women (mean age 78 ± 2 years). It should be noted, however, that differences in the methods used to analyse the muscle fibres compared to the other studies could explain this discrepancy, as the V_0's

reported by Trappe and colleagues in their study were two to four times higher than the V_0's reported by others.

Power-Velocity Relationship

The power-velocity (p-v) relationship of human muscles shows age-related reductions in maximum power (P_{max}), force at maximum power (F_{opt}) and contraction velocity at maximum power (V_{opt}) (see Table 2). The decline in P_{max} is markedly greater than the decline in isometric and dynamic strength and has been shown in a number of recent aging studies that have used derivatives of Hill's (1938) equation to calculate power from the f-v relationship (112, 166, 167, 170, 176). This reduction in the P_{max} (and thus F_{opt}) with age is much more marked in the study by Thom et al. (166), where it is only 20% of that of young adults. This discrepancy is hard to explain, but a comparison of the absolute plantar flexor torques produced by the older men in the studies by Narici et al. (2005), Thom et al. (2005) and Thom et al. (2007) reveals that the older men in the Thom et al. (2007) study produced less torque than the older men in the other two studies. Thus, there is a possibility that the older men in the Thom et al. (2007) study were more frail than the older men in the other two studies.

Table 2

Age-related changes in V_{max}, P_{max}, F_{opt}, and V_{opt}

Muscle tested	Gender	*n,* elderly	*n,* young	Elderly age, decade	\% of Young Adults				Reference
					V_{max}	P_{max}	F_{opt}	V_{opt}	
Plantar flexors	M	16	14	8th	84 [a]	52 [a]	65 [a]	82 [a]	Narici, et al. (2005)
Plantar flexors	M	9	15	8th	62 [**]	20 [**]	22 [a]	52 [**]	Thom, et al. (2007)
Plantar flexors	M	18	12	8th	86 [a]	46 [**]	50 [*]	88	Thom, et al. (2005)
Elbow flexors	M	19	19	7th	83 [*]	70 [*]	80 [*]	87 [*]	Toji & Kaneko (2007)
Elbow flexors	M	7	11	7th	83	63 [*]	79 [*]	78 [*]	Valour, et al. (2003)
Elbow flexors	F	9	6	7th	60 [*]	59 [*]	85	71 [*]	Valour, et al. (2003)
Elbow flexors	M	23	18	7th	85 [*]	-	-	-	Labarque, et al. (2002)

\% of young adults = percentage of each characteristic in older adults compared to their young counterparts; M = male; F = female; Dashes indicate data was not provided; Asterisks indicate significant differences between the elderly and young groups ([*] $P \leq 0.05$; [**] $P \leq 0.01$); a = P value not given.

Physiological Basis of Changes to the Force-Velocity Relationship

The reasons for the reductions in muscular strength with age have been extensively reviewed elsewhere (39, 40, 98, 178). Briefly, the main cause of the age-related loss of isometric and concentric muscle strength is the loss of muscle mass. However, although skeletal muscle mass declines significantly with age, there is evidence that declines in the force-producing capacity of muscles occurs earlier and at a faster rate than the reduction in muscle mass (e.g. Macaluso & De Vito, 2004). Also, studies that have investigated changes in the f-v relationship of muscles with age and looked at the contribution of changes in muscle cross-sectional area or

volume to these changes have found that normalisation of torque to cross-sectional area or volume significantly reduced, but did not eliminate age-related differences in torque (166, 167, 170). This implies that the loss of muscle mass alone cannot account for the reduction in the isometric and concentric strength of muscles. Other factors include lower single fibre specific force (or force per unit cross-sectional area), changes in muscle architecture and the infiltration of skeletal muscle by fat and connective tissue (79).

With regards to reductions in V_{max} with age, Thom and colleagues (166) found that the V_{max} of gastrocnemius medialis (GM) muscles in 9 older men (mean age 74.7 ± 4.0 years was 38.2% ($P < 0.001$) lower than the GM V_{max} of 15 young men (mean age 25.3 ± 4.5 years). When velocity was normalised to muscle fascicle length (L_f), which decreases with age, the difference in V_{max} between older men and young men was reduced to 15.9%. Thus, L_f is a significant determinant of V_{max}. Even so, normalisation of velocity to L_f did not eliminate the difference in V_{max} between older and young men, which means that there are other factors that contribute to the lower V_{max} observed in older adults.

One of these factors could be the selective atrophy of type II muscle fibres, which are associated with higher contraction velocities than type I fibres, with age (5, 91). However, according to D'Antona et al. (35), this is caused by the decrease in physical activity that occurs with ageing, rather than ageing per se. Nevertheless, this could partly explain the lower V_{max} of the muscles of older adults. Importantly, D'Antona et al. (35) also found that the V_{max} of type IIa fibres of the vastus lateralis muscles is lower in older adults than in young individuals, regardless of their physical activity levels. In addition to the above findings, Höök, Sriramoju, and Larsson (68) have observed that the actin sliding speed on myosin in type I fibres

from the vastus lateralis muscle is lower with age. Thus, there seems to be a decline in the intrinsic speed of the myosin molecule with age, possibly due to changes in the function of the actin binding and catalytic sites located in the myosin heavy chain head domain (68).

The Role of Muscle Architecture

Muscle fascicle length and pennation angle are routinely reported to be lower in elderly subjects than young adults (107, 113, 166). The decline in pennation angle is secondary to muscle fibre atrophy which, of course, is not advantageous even though a higher percentage of muscle fascicle forces is transferred to tendons (16). With regards to L_f, the shorter fascicles (now with fewer sarcomeres arranged in series) will generate force over a smaller range of motion and exhibit reduced maximum shortening speeds (19). Shorter fascicles will also generate less force at any given rate of shortening than longer fascicles because their sarcomere shortening rates are higher (19).

A number of relatively recent studies have investigated the changes in L_f and θ with age (107, 113, 166). Narici et al. (113) used ultrasonography to evaluate the muscle architecture of the gastrocnemius medialis (GM) muscles in 14 young (age range 27 to 42 years) and 16 older (age range 70 to 81 years) males. All participants were healthy and were matched for physical activity, height and body mass. L_f and θ were found to be smaller in older males by 10.2% ($P < 0.01$) and 13.2% ($P < 0.01$) respectively.

Similarly, Thom et al. (166) found that GM L_f was 19.3% ($P < 0.05$) smaller in a group of 9 healthy older men (age range 69 to 82 years) when compared to 15 young men (age range 19 to 35 years). Morse et al. (107) also found GM L_f to be

16% ($P < 0.01$) smaller in 12 healthy elderly men (age range 70 to 82 years) than in 15 young men (age range 19 to 35 years). In addition, they found that values of θ for all triceps surae muscles were 15 to 18% ($P < 0.05$) smaller in the elderly group.

As can be seen from the studies above, there is clear evidence that L_f and θ are reduced with age. Although a smaller θ is an advantage in terms of fibre force transmission to tendons, the combined effect of these changes to muscle architecture is a reduction in the force-producing capacity of older muscles. As stated earlier, shorter muscle fascicles also mean that the shortening speed of muscles is reduced, partly explaining the lower values of estimated V_{max} and power at high shortening velocities seen in older individuals. Thom et al. (166) showed that about 22% of the age-related decline in V_{max} was due to shorter fascicle lengths.

Exercise interventions that aim to reverse or at least reduce the effects of aging should address not only muscle atrophy but also the reductions in fascicle length that also occur, as muscle architecture may be as important, if not more important, to muscle function than other factors such as fibre type (16, 24).

Summary

In summary, aging is associated with a downward and leftward shift of the f-v curve (as indicated by arrow 1 in Figure 1) due to the lower force-producing capacity of muscles across all contraction speeds. This loss of strength is in the order of about 20 to 40% by the 7th and 8th decades. There is, however, a relative preservation of eccentric strength compared to concentric strength, with losses in eccentric strength 10 to 30% less than losses in concentric strength. In addition, there is a reduction in V_{max} of about 20 to 40% in adults in their 7th and 8th decades compared to young adults. With regards to the p-v relationship, a downward and

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leftward shift of the curve (as indicated by arrow 2 in Figure 1) is observed with

aging. Thus, P_{max}, F_{opt}, and V_{opt} are lower, with losses in P_{max} of around 30 to 80% by

the 7th and 8th decades.
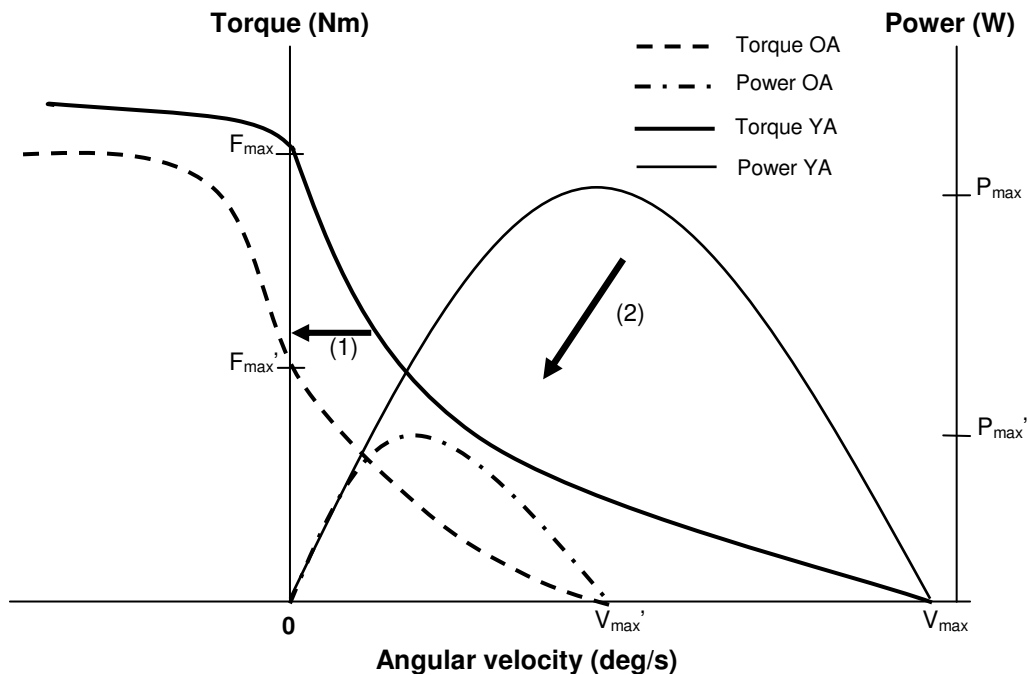
Figure 1. A summary of the changes to the f-v and p-v relationship with age based on

data from the studies referenced in this review. OA = old adults; YA = young adults;

P_{max}' = old adults' maximal power; V_{max}' = old adults' maximum contraction

velocity; F_{max} = young adults' peak isometric torque; F_{max}' = old adults' peak

isometric torque.

FUNCTIONAL IMPLICATIONS

Logically, the changes in the f-v relationship (and therefore p-v relationship)

that have been discussed will affect the daily function of the elderly in terms of the

amount of force applied in movements and the speed of movement. This section will

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discuss selected studies that have made the link between these changes and the impairments in daily function that are observed in the elderly.

Impact of Loss of Strength and Power

When reviewing the evidence from many of these studies it is important to recognise that correlations, no matter how strong, have their limitations, as they do not prove causation. The majority of studies investigating this area have assessed the relationship between lower limb muscle strength or power (or both) and function in tasks such as stair-climbing, rising from a chair, or walking (10, 11, 13, 20, 23, 34, 122, 125, 134, 138, 148, 162, 181).

Two studies have also looked at upper limb strength and power in relation to functional capacity (65, 156), while only one study investigated the relationship between V_{opt} and physical functional performance in elderly women (32). There is a general consensus that there is a correlation between muscular strength (13, 122) and power (10, 138) and performance in functional tasks, with the relationship between power and function stronger than the relationship between strength and function (11, 34, 134, 162).

For example, in an early study, Bendall et al. (13) ascertained that walking speed was positively associated with isometric calf strength in a group of 67 women (mean age 72 ± 4 years; $r = 0.36$; $P \leq 0.01$) and 58 men (mean age 71 ± 4 years; $r = 0.41$; $P \leq 0.01$). In a more recent large study, Ostchega et al. (122) (758 men and 741 women aged 50 years and older) supported these earlier findings when they found that isokinetic knee extensor strength was associated with walking speed after adjusting for age, ethnicity, weight, and height ($P < 0.01$).

Impact of Loss of Power on Function

With regards to the link between power and function, Bassey et al. (10) found that the leg extensor power of 13 frail elderly men (mean age 88.5 ± 6 years) and 13 frail elderly women (mean age 86.5 ± 6 years) was significantly correlated with the time taken to rise from a chair, climb a flight of stairs, and walk 6.1 meters. Similar results were obtained by Rantanen and Avela (138), who measured leg extension power in healthy elderly adults using a sledge ergometer in a sitting position. Participants were asked to "jump" while attached to an inclined sliding chair that was on rails. Power was measured using a force plate, which was positioned at the feet. Maximal walking speed was also measured over a distance of 10 meters. The investigators discovered that walking speed was correlated with leg extension power in 80-year-old men ($n = 41$; $r = 0.412$; $P = 0.007$), 80-year-old women ($n = 56$; $r = 0.619$; $P < 0.001$), 85-year-old men ($n = 8$; $r = 0.939$; $P = 0.001$), and 85-year-old women ($n = 23$; $r = 0.685$; $P = 0.001$).

Bean et al. (11) found that leg power, as measured during bilateral leg press and unilateral knee extension in 45 mobility-limited older adults (age range 65 to 83 years), was more closely related to functional performance than leg strength. The functional performance tests employed in their study were stair-climb time, tandem gait, habitual gait, maximal gait, and the short physical performance battery (SPPB). The SPPB involved the testing of standing balance, a timed 2.4-meter walk, and a timed test of rising from a chair and sitting down five times. The study by Cuoco et al. (34), which used similar measures in 48 elderly men and women (age range 65 to 91 years), had comparable findings.

Suzuki et al. (162) also confirmed the assertion that peak muscle power is a more important factor in functional performance in older adults than muscle strength.

They used an isokinetic dynamometer to measure dorsiflexor and plantar flexor isokinetic peak torque, peak power and isometric peak torque in 34 older women (mean age 75.4 ± 5.1 years) with self-reported functional limitations. They assessed functional capacity with stair climb time, repeated chair rise time, and maximal and habitual gait velocity. Dorsiflexor peak power was found to be correlated to chair rise time ($r = 0.50$; $P < 0.002$) and stair climb time ($r = 0.49$; $P < 0.003$), and plantar flexor isometric strength was correlated with habitual ($r = 0.53$; $P < 0.001$) and maximal gait velocity ($r = 0.47$; $P < 0.005$).

More recently, the study by Puthoff and Nielsen (134) added to the growing body of evidence that power has greater influence over functional capacity than strength. In their study they assessed lower-extremity strength and power in 25 older women and 5 older men (mean age 77.3 ± 7.0 years) with mild to moderate functional limitations by means of a bilateral leg press machine. Functional capacity was assessed using the SPPB and a six-minute walk test, where participants were asked to cover as much distance as possible within six minutes. Although both strength and power were significantly correlated to the measures of functional capacity, power consistently explained more of the variance in functional ability than strength (134).

With regards to the relationship between function and upper limb strength and power, experiments by Herman et al. (65) showed that triceps strength and power in 37 mobility-limited older adults (age range 65 to 93 years) were significantly correlated with performance in the SPPB, a timed stair climb test and 4-metre walk time. And yet again the correlation was found to be greater for power ($r = 0.88$-0.89; $P < 0.001$) than strength ($r = 0.69$; $P < 0.001$).

The Role of Contraction Speed

Recognising the large amount of evidence suggesting that muscular power rather than strength is the key determinant of physical functioning in daily life, Clémençon et al. (32) investigated the relationships between the determinants of maximal leg power (optimal velocity and optimal torque) and functional performance in 39 healthy elderly women (age range 72 to 96 years). They found that optimal velocity significantly correlated with 6-metre walking speed, chair-stand time ($r = -0.596$; $P < 0.01$) and stair-climb time ($r = -0.522$; $P < 0.001$), however, optimal torque did not correlate with any of the functional performance measures (32). Therefore, it seems that the contraction velocity component of muscular power, rather than torque, is more important with regards to functional capacity. This has significant implications for this thesis as one objective of the eccentrically-biased resistance training utilised in Chapter 6 is to increase torque at fast contraction velocities, or conversely, to increase contraction velocity at a given level of torque. Thus, it would be expected that eccentrically-biased resistance training would lead to greater improvement in functional capacity than traditional, or conventional, resistance training.

Impact of a Reduction in Eccentric Strength and Steadiness

Although eccentric strength is relatively preserved with old age, it has been observed that older adults find tasks involving eccentric contractions, such as stair descent, especially difficult (160). One possible explanation for this is the increased variability, or unsteadiness, of force production in older adults compared to young adults (45). Recently, Carville et al. (27) measured steadiness during isometric, eccentric and concentric contractions in 44 young adults (mean age 29.3 ± 0.6), 34

older adults with a history of falls (mean age 70.6 ± 4.6), and 44 older adults without any history of falling (mean age 75.9 ± 0.6). Steadiness during dynamic (eccentric and concentric) contractions was measured by the standard deviation of acceleration during the contractions. They showed that healthy older people were significantly less steady during dynamic contractions than young adults ($P < 0.002$) (27). In addition, older fallers were significantly less steady during eccentric contractions than older non-fallers ($P < 0.013$) (27). The authors state that eccentric contractions may be intrinsically less stable than other types of contractions, requiring greater neural control (27). If older fallers have impaired neural control compared to older non-fallers, this may partly explain the reduced steadiness during eccentric contractions in older fallers. However, steadiness during dynamic contractions can be improved with resistance training (171), emphasising the importance of training for older adults.

Summary

In summary, the age-related decline in skeletal muscle's force-producing capacity and contraction velocity (and thus, power) is associated with a decline in measures of functional capacity in older adults. The relationship between muscular strength and to a greater extent, power, with functional performance has been demonstrated in numerous studies despite differing methods used to assess strength, power and functional capacity. Therefore, it may be inferred that improving the muscular power of older adults could improve their ability to perform daily tasks such as walking and climbing stairs. Also, recent evidence suggests that the optimal contraction velocity of muscles is correlated with functional capacity, which indicates a need to focus attention on methods for improving contraction velocity

under varying loads as a means of improving functional performance. Finally, reduced steadiness during eccentric contractions with age is a possible explanation for the difficulty experienced by older adults when performing tasks involving eccentric contractions.

METHODS FOR IMPROVING THE FORCE-VELOCITY RELATIONSHIP IN OLD AGE

The changes to the f-v and p-v relationships that occur with age and the functional implications of these changes have led many researchers to investigate different methods of improving these relationships, and thus the functional capacity of older adults. These include traditional resistance training (TRT), power training (PT), and eccentric (or eccentrically biased) resistance training (ERT). Ideally, interventions to improve the f-v relationship would result in an upward and rightward shift in the f-v curve, as well as an increase in V_{opt}. This would mean that muscles could produce more force at all contraction velocities (eccentric and concentric) and the maximum contraction velocity of muscles would be higher. In terms of muscle architecture, the adaptations expected to be associated with these improvements in strength and contraction velocity would be increases in fascicle pennation angle (secondary to fibre hypertrophy) and fascicle length. The practical functional benefits of this may include improvements in functional capacity, and balance recovery following a stumble (126).

Traditional Resistance Training

Most early intervention studies involved TRT, which consists of lifting and lowering heavy loads (2 to 3 sets of 8 to 10 repetitions at more than 65% of the 1-

repetition maximum [1RM] performed 2 to 3 days per week) at a slow speed. This

type of training maximally overloads only the concentric portion of each lift (149).

According to the systematic review of strength training studies involving older adults

by Latham, Bennett, Stretton, and Anderson (88), most progressive TRT studies

continued for a duration of 8 to 12 weeks, but the duration ranged from 2 to 104

weeks. These interventions showed a significant positive effect on strength, but only

modest effects on functional measures such as gait speed and time taken to rise from

a chair.

With regards to how TRT affects the f-v and p-v relationship in healthy older

adults, the general finding of intervention studies is that isometric strength, strength

at slow to medium contraction velocities and P_{max} is increased. In other words, there

is an upward displacement of the f-v curve (see Table 3), which would mean a

reversal of the changes in the f-v curve seen with age (Figure 1). However, there

seems to be little improvement in the ability of older muscles to produce force

eccentrically following TRT (140, 141), which as previously indicated is important

in many activities of daily living and falls prevention (27, 45, 160).

Table 3

A summary of TRT studies involving older adults and observed changes in the f-v and p-v

relationship

Muscle trained	Gender	n	Age, decade	Frequency, days/week	Duration, weeks	Changes observed	Reference
KE	M	16	7th	3	16	↑ 1RM[**], ↑ F_{max}[**], ↑ P_{max}[**], ↔ eV_{max}	Ferri et al. (2003)
PF	M	16	7th	3	16	↑ 1RM[**], ↑ F_{max}[*], ↑ P_{max}[**], ↔ eV_{max}	Ferri et al. (2003)
KE	M/F	10 (4M,6F)	8th	3	12	↑ strength at 60º/s[*] & 180º/s[*]	Suetta et al. (2008)
KE	M	12	7th	3	12	↑ 1RM[**], ↑ F_{max}[*], ↑ strength at 0 - 60º/s[*], ↔ strength at 120, 180, & 300º/s	Frontera et al. (1988)
KE	M/F	18 (10M,8F)	8th	3	14	↑ F_{max}[*], ↑ strength at 50º/s, 100º/s, 150º/s, & 200º/s[**], ↔ ecc strength	Reeves et al. (2005)
EF	M	23	7th	2/3	26	↑ F_{max}[*], ↑ strength at 100 - 500º/s[*], ↔ strength at 600º/s, ↑ $eVmax$[*]	Labarque et al. (2002)
KE	M/F	18 (10M,8F)	8th	3	14	↑ 5RM[**], ↑ F_{max}[*]	Reeves et al. (2004)
PF	M	11	8th	2	52	↑ F_{max}[**]	Morse et al. (2007)
KE	M/F	30 (14M,16 W)	7th	3	16	↑ 1RM[**], ↑ F_{max}[**], ↑ V at 20 - 50% F_{max}[**]	Petrella et al. (2007)

KE = knee extensors; PF = plantar flexors; EF = elbow flexors; M = male; F = female; 1RM = 1 repetition maximum; 5RM = 5 repetition maximum; eV_{max} = estimated maximum contraction velocity; V = contraction velocity; Asterisks indicate significant differences between pre- and post-training ([*] $P \leq 0.05$; [**] $P \leq 0.01$).

Relatively few studies involving older adults have extrapolated the f-v curve to determine if there was any change in estimated V_{max} as a result of TRT (48, 83). Ferri and colleagues (48) found no change in estimated V_{max} while Labarque et al. (83) observed an increase in the estimated V_{max}. One possible reason for this difference in findings could be because the study by Ferri et al. (48) employed a high-intensity training protocol (10 repetitions at 80% of 1RM) while Labarque et al. (83) employed a low- to moderate-intensity training protocol (30 repetitions at 30RM). Also, Labarque et al. (83) tested isokinetic elbow flexor strength between 100 and 600º/s. However, most isokinetic strength tests involving older adults include velocities only up to about 360 to 400º/s. Lanza et al. (85) illustrate this point by reporting that some older subjects in their study were unable to reach angular velocities of more than 270º/s during knee extension and 120º/s during ankle dorsiflexion.

With regards to in-vitro experiments, one study by Trappe et al. (173) looked at changes in single vastus lateralis muscle fibres in 7 older men (mean age 74 ± 2 years) following 12 weeks of TRT performed 3 days per week at 80% of 1RM. They found that the diameter of type I and IIa fibres increased by 20 and 13% ($P < 0.05$) respectively. F_{max}, fibre V_0 and power were 55, 75 and 128% ($P < 0.05$) higher in type I fibres and 25, 45 and 61% ($P < 0.05$) higher in type IIa fibres respectively following TRT. These changes are of a higher magnitude than that observed in in-vivo studies, as single fibre segments are not influenced by neural control or muscle architecture.

As indicated earlier, muscle architecture plays an important biomechanical role in the ability of a muscle to produce force. The effect of TRT on muscle architecture in older adults has been examined in a number of studies (108, 141, 143-

145, 161). The recurrent finding is that there is an increase in muscle fascicle pennation angle following TRT, which means that more sarcomeres are added in parallel, allowing muscles to produce more force across all concentric contraction speeds. In general, there is an increase in fascicle length in older adults with TRT, with only one study showing no change (108) and four finding an increase in fascicle length (141, 143-145). A factor to consider is the role of increased muscle excursion on L_f. Older adults who become more active as a result of participating in resistance training would be expected to respond to the increased muscle excursion by increasing fascicle length. Therefore, resistance training studies that compare the effects of different resistance training modes on L_f are needed to determine the most efficacious mode.

Power Training

Recognition that power declines faster than strength with advancing age and that power is the more important determinant of functional capacity has led researchers to focus on methods for improving muscular power in older adults (22, 28, 36, 50, 62, 63, 120, 149).

The power training (PT) interventions in the available studies typically last between 8 and 16 weeks, and generally require participants to lift loads corresponding to 20 to 80% of their 1RM as quickly as possible during the concentric phase of each exercise. Training frequency is usually 2 to 3 times per week, with each session consisting of 3 to 4 sets of 8 to 14 repetitions for each exercise. All of the above studies reported significant improvements in isometric and concentric strength and power as a result of PT, with some reporting improved functional performance (22, 62, 63), rate of force development, impulse during

isometric contractions (28), and balance (120). However, to date, no power training studies involving older adults have investigated changes in muscle architecture with training.

Although most PT studies involving older adults have not directly investigated the effect of training on the f-v relationship, some conclusions can be drawn from the results of these studies. For example, de Vos et al. (36) randomised 112 healthy older adults into groups to perform explosive resistance training at 20% ($n = 28$, mean age 69.4 ± 5.8 years), 50% ($n = 28$, mean age 68.1 ± 4.5 years), or 80% ($n = 28$, mean age 69.0 ± 6.4 years) of 1RM and a non-training control group ($n = 28$, mean age 67.6 ± 6.0 years). The training was performed over 8 to 12 weeks twice weekly, with each training session consisting of 5 exercises performed for 3 sets of 8 explosive concentric and slow eccentric contractions. The exercises (bilateral horizontal leg press, seated chest press, bilateral knee extension, seated row, and seated bilateral knee flexion) were performed on digital pneumatic resistance machines. The velocity of concentric contractions at peak power did not improve significantly and was similar between all groups, but force at peak power increased significantly (12 to 16%; $P < 0.001$) in all training groups. Thus, it was concluded that older adults are able to produce higher peak power outputs with greater loads without losing movement velocity after 8 to 12 weeks of PT.

In another study involving 20 old (mean age 62.7 ± 2.2 years) and 12 very old (mean age 81.8 ± 2.7 years) adults, 12 weeks of explosive heavy (75 to 80% 1RM) resistance training was performed twice a week (28). Each session consisted of 4 sets of 8 to 10 repetitions of the following exercises: bilateral knee extension; horizontal leg press; hamstring curls; calf raise and inclined leg press performed on isoinertial resistance training equipment. Contractile rate of force development (RFD) was

calculated before and after training during maximal isometric voluntary contractions performed on a leg press device. RFD increased in the old ($\Delta18\%$; P = 0.003) and very old ($\Delta51\%$; P = 0.005) groups as a result of the training protocol.

Some studies that compared TRT and PT have found that they are equally effective at improving muscular strength (22, 50), but that PT is more effective at improving muscular power and functional capacity in older adults than TRT (22, 50). However, a recent study by Henwood et al. (62) observed similar improvements in maximal isometric strength, peak and average muscle power, and functional performance after TRT and PT. Although more research comparing TRT and PT in older adults is needed, it seems at this stage that PT is at least as effective as, if not more effective than TRT in improving functional capacity in older adults.

Eccentric Resistance Training

It should be noted that the various eccentric resistance training methods, such as using an eccentric leg cycle ergometer or using a percentage of concentric 1RM, discussed below may have resulted in different eccentric resistance training intensities. Therefore, the magnitude of changes with eccentric training should be compared between studies with caution. Numerous studies involving young adults have found greater hypertrophy and strength gains after eccentric training when compared to concentric training (69, 70, 114). This was also found in the study by Farthing and Chillibeck (46) who compared isokinetic eccentric and concentric strength training in young males, and found that eccentric training resulted in greater hypertrophy and strength gains (both eccentric and concentric strength) than concentric training. Although there are other studies that have shown almost identical muscle hypertrophy in response to eccentric-only and concentric-only resistance

training (76, 140, 158), the balance of evidence does seem to support the superiority of eccentric training over concentric training with regards to muscle hypertrophy. Even if the benefits of eccentric and concentric training with regards to hypertrophy are similar, there may be other advantages to eccentric training, as discussed below.

Although few studies have compared the effects of exclusively eccentric resistance training (ERT) with those of TRT or PT in older adults, there are some potential advantages to ERT. For example, ERT allows participants to perform the same amount of work at a lower metabolic cost and perceived rate of exertion than concentric training (102, 118, 123). Also in contrast to concentric training, 8 weeks of ERT has not been found to increase arterial stiffness, which has been reported following concentric training (119). Furthermore, there is no reason to believe that the absence of concentric contractions from a resistance training program will reduce its positive effects on muscle mass (67, 89, 94).

Exclusively eccentric resistance training has also been reported to increase vastus lateralis fascicle lengths in the elderly to a greater extent than TRT (140). It should be noted, however, that exclusively eccentric training usually encourages participants to use a greater range of motion than TRT since participants do not have to perform the subsequent and more taxing concentric contraction, and this may have contributed to the greater increase in fascicle length observed after eccentric resistance training than after TRT. This fascicle elongation, which has previously been observed as a consequence of eccentric training in young adults (41, 129) and after decline running in rats (96, 97) counters the reduction which appears to occur in elderly muscle (107, 113, 166). As fascicle shortening and the associated loss of sarcomeres in series is thought to account for a significant portion of the decline in muscle power observed in old age (166) it might be expected that eccentric resistance

training will have positive effects on torque and power generation during high velocity concentric actions. Reeves and colleagues (2009) reported that the effects of their ERT were largest when measured during eccentric isokinetic actions but there was also a significant improvement in the torque generated at the fastest concentric velocity employed (200°/s). Some ERT studies in young people have also shown similar effects on high velocity concentric torques (79, 98). Clearly more research is needed to more fully describe the effects of ERT on changes in fascicle length and the effects of those changes on performance in the elderly.

Valour et al. (177) explored the effect of 7 weeks of elbow flexor ERT performed 3 times a week on elbow flexor characteristics in 8 older female adults (mean age 65 ± 6 years). The training involved 5 sets of 6 unilateral eccentric elbow flexor contractions of the dominant arm at an intensity corresponding to 100% of the 3RM (3 repetition maximum). Free weights were used for the training. The force-velocity and power-velocity relationship of the elbow flexors were determined before and after training. It was found that P_{max}, torque produced at all inertial conditions (2, 10, 20, 30, 40 and 50% of F_{max}) and the index of maximal contraction velocity (VI_{max}) increased significantly ($P < 0.05$). Thus, it can be concluded that the force-velocity relationship was shifted upwards and V_{max} was increased.

With regard to the functional benefits of ERT, LaStayo et al. (87) investigated the effects of 11 weeks of lower extremity training performed 3 times a week on a recumbent high-force eccentric leg cycle ergometer as compared to TRT in 11 male and 10 female frail elderly subjects (age range 70 to 93 years). Participants were randomised to the eccentric training group ($n = 11$) or the TRT group ($n = 10$). Vastus lateralis muscle fibre cross-sectional area increased significantly after training in both groups ($P < 0.05$), and isometric knee extension

strength increased significantly only in the eccentric training group ($P < 0.05$).

Balance and stair descent ability improved only in the eccentric training group ($P < 0.05$) while timed up and go task ability improved ($P < 0.05$) in both groups, however, only the eccentric training group improved timed up and go task performance to a sufficient extent to cross the falls-risk threshold of 14 seconds (87). Timed up and go performance improved to a greater degree in the eccentric training group than the TRT group ($P < 0.05$).

Acute Effects of Resistance Training

Although the benefits of resistance training for older adults have been well established by the studies discussed above, there is some evidence to suggest that older adults may be at an increased risk of experiencing an adverse event immediately after a training session. These areas of increased risk may fall into two broad categories: cardiovascular and neuromuscular. With regards to cardiovascular risk, this review will focus on platelet reactivity and activation, and arterial stiffness. With regards to neuromuscular risk, the areas of focus will be muscle force steadiness and postural stability.

Blood platelets play a critical role in atherothrombotic events, such as heart attack and stroke, with an increased platelet activation or responsiveness to stimulation being associated with an increased risk of acute cardiovascular events (182). A small number of studies have reported increased platelet reactivity and activation after weight training in young healthy adults (2, 4). There have been no studies to date investigating the acute effects of a weight training session on platelet function in older adults. However, one study by Hulmi and colleagues (72) found that platelet count increased ($P < 0.05$) in 11 healthy older men (average age 60.9 ±

5.0 years) immediately after 5 sets of 10 repetitions of leg press at 10RM. As mentioned earlier, Ahmadizad and El-Sayed (2) observed increased platelet count, platelet aggregation in response to a high concentration (2×10^{-5} M) of adenosine diphosphate (ADP), and activation (as measured by plasma concentrations of beta-thromboglobulin [B-TG]) after a bout of heavy resistance training at 80% of 1RM in young adults. However, in a follow-up study, Admadizad, El-Sayed and MacLaren (4) corrected platelet aggregation in response to ADP and plasma concentrations of B-TG for changes in plasma volume and platelet count after exercise. This was done as changes in plasma volume due to dehydration, for example, will affect the concentration of B-TG in the plasma and platelet aggregation (4). They found that platelet aggregation and plasma concentrations of B-TG corrected for plasma volume were not affected by a bout of resistance training at 80% of 1RM in young adults. However, platelet count corrected for changes in plasma volume did increase significantly ($P < 0.001$) after resistance training, and this may have thrombogenic side effects, especially in populations at high risk of cardiovascular events (72). Therefore, from the limited number of studies available, it seems that platelet aggregation and activation are not affected by resistance training in young adults, but there is an acute increase in platelet count after resistance training in older and young adults. This limited evidence illustrates that more research is needed to elucidate the acute effects of resistance training on platelet function and count in older adults.

Arterial stiffness immediately after weight training has been investigated more widely (9, 33, 37, 60, 185), with most of these studies finding an increase, and only Heffernan et al. (60) finding no change in arterial stiffness following weight training in young adults. The reason for this discrepancy may be that participants performing resistance training in the study by Heffernan and colleagues (60) were

instructed to refrain from the Valsalva manoeuvre, whilst this is not usually controlled for in other studies. Interestingly, Heffernan et al. (60) found that arterial stiffness increased in a group that performed a straining Valsalva manoeuvre bout without resistance training. Therefore, the large increases in blood pressure that occur during Valsalva manoeuvres may contribute to acute increases in arterial stiffness following resistance training. Arterial stiffness in response to weight training has not been investigated in older adults.

With regards to postural stability, defined as the neuromuscular maintenance of equilibrium (105), Moore, Korff, and Kinzey (105) have demonstrated that conventional weight training has an acute negative effect on postural stability in 21 older adults (average age 71.2 ± 3.8 years), as measured by static balance on a force plate. This may then increase the risk of falls in older adults immediately after a weight training session. However, no studies to date have investigated the acute effects of other resistance training modalities on postural stability in older adults.

Force fluctuations, or reduced steadiness, of muscles during voluntary contractions are higher in older adults compared to young individuals, and this reduced ability to exert an intended force can affect the ability of older adults to control leg movements, for example, during stair descent (171). Although 16 weeks of weight training reduces force fluctuations in older adults (171), it has been shown that fatiguing weight training increases force fluctuations in the quadriceps muscles of young adults immediately after a training session (155). Again, there is a lack of data in this area on older adults, highlighting the need for more research to identify whether older adults experience greater force fluctuations immediately after resistance training.

Summary

In general, TRT increases isometric and concentric strength, thus shifting the f-v curve upwards in the concentric portion of the relationship. However, there seems to be contradicting evidence as to whether V_{max} increases as a result of TRT in older adults. Muscle fascicle pennation angle increases with TRT, but increases in fascicle length have not been observed in all studies. Power training in older adults has been found to increase both strength and power. Although V_{max} has not been investigated in PT studies involving older adults, increases in RFD and impulse indicate greater contraction velocity of muscles. Older adults have also been found to perform better in functional tests after PT. Eccentric resistance training has not been widely investigated in older adults, but the limited data available shows that functional capacity can be improved with this approach and that potentially favourable increases in muscle fascicle length may occur. There is limited evidence to suggest that older adults may be at a greater risk of an adverse event immediately after a resistance training session. However, the lack of data with regards to the acute effects of resistance training on platelet function, arterial stiffness, muscular force steadiness and postural stability in older adults means that more research is needed is these areas.

CONCLUSION

The decrease in muscular strength and contraction velocity with age, as illustrated by changes in the force-velocity and power-velocity relationships, leads to a loss of mobility and independence that is often observed in older adults. This is of mounting concern with an aging population as the potential increased demand on our healthcare system may compromise its capacity to cope in the future.

Due to the high social relevance of this issue, much research has focused on interventions that increase muscular strength and power in older adults. In light of recent evidence that contractile velocity impairments have a significant role to play in mobility loss with age, it is recommended that future research investigate interventions that not only increase strength and power but also increase the concentric contraction speed at which power is maximised. Eccentric training is an intervention that shows potential in this regard while also having possible advantages over other training modes. Specifically, eccentric training improves function as effectively as other training modes while possibly having no detrimental effects on arterial stiffness, in contrast to traditional resistance training. Also, eccentric training may lead to greater hypertrophy than traditional resistance training. However, more research is needed to elucidate the effects of this strength training mode on contraction velocity and functional capacity in older adults to determine if this mode is indeed the most efficacious.

STATEMENT OF THE BROAD OBJECTIVES OF THE STUDIES COMPRISING THIS THESIS

With the knowledge gained from the literature review, the major objectives of the studies comprising this thesis were confirmed and key outcome measures identified. The major objectives were: (i) to compare the acute effects of eccentrically-biased and conventional resistance training on arterial stiffness, platelet reactivity, activation and count, postural stability and isometric force steadiness in older men and women; and (ii) to compare the effects 16-weeks of eccentrically-biased versus conventional resistance training on muscle architecture, 1 repetition maximum, isometric strength, isokinetic force-velocity characteristics, functional capacity and pulse wave velocity in older men and women. Additionally the general designs of the intervention studies (Chapters 5 and 6) were drafted, including proposed protocols and methodologies. However, before commencing any intervention it was necessary to determine the reliability of the proposed outcome measures. The studies described in Chapters 3 and 4 were therefore undertaken to determine the reliability of strength, functional capacity and muscle architecture measures.

CHAPTER 3: Reliability of Maximum Voluntary Strength Tests of the Knee Extensors and a Range of Functional Tests in Older Adults

ABSTRACT

Objectives: To determine whether two familiarisation sessions enable reliable measurements of maximal voluntary muscular strength and functional capacity of older adults to be obtained, and whether coefficients of variation (CVs) of individuals obtained at the first familiarisation can predict repeatability of performance in subsequent tests.

Measurements: Isometric and isokinetic quadriceps strength were tested on an isokinetic dynamometer. Functional capacity tests employed were the 6 metre fast walk (6mFWT), timed up and go (TUG), stair climb and descent, and vertical jump.

Results: Intraclass correlation coefficients ranged from 0.976 to 0.991 for the dynamometer tests and 0.952 to 0.997 for the functional tests after two familiarisations. 95% ratio limits of agreement (LOAs) for the isometric, 60º/s, 120º/s, 240º/s and 360º/s dynamometer tests were 1.01 ×/÷ 1.10, 1.02 ×/÷ 1.20, 1.06 ×/÷ 1.21, 1.04 ×/÷ 1.18 and 1.02 ×/÷ 1.15 respectively. 95% ratio LOAs for the 6mFWT, TUG, stair climb, stair descent and vertical jump tests were 0.99 ×/÷ 1.14, 0.99 ×/÷ 1.10, 0.97 ×/÷ 1.07, 0.96 ×/÷ 1.14 and 1.01 ×/÷ 1.14 respectively. Significant linear relationships were observed between CVs in familiarisation 1 and percentage difference between familiarisations 1 and 2 for 6mFWT, stair climb, 120º/s and 240º/s tests.

Conclusion: The tests appear to have sufficient reliability for the detection of realistic amounts of change of the magnitude that may be attainable from an intervention at group level after two familiarisations. The isometric test and TUG also have potential to detect real change on an individual level. CVs can be used to predict repeatability of performance in individuals in some tests, but more research is required.

INTRODUCTION

The loss of skeletal muscle mass with aging is the main cause of the loss of muscular strength and power in older adults (98). Loss of muscular strength and power leads to slower walking speeds, increases the risk of falling and causes a loss of functional capacity (40, 120). Therefore, interventions to prevent or ameliorate the losses are important and in this context measures of maximal voluntary muscle strength and functional capacity in older adults are important for quantifying the outcomes of intervention studies (151).

It is essential to be able to obtain reliable measures of maximal voluntary muscle strength and functional capacity when studying older adults in order to have confidence in the data, thus allowing clear conclusions to be made (67). However, few studies have obtained multiple assessments of maximal voluntary muscle strength prior to an intervention, which may lead to an overestimation of the effectiveness of an intervention due to familiarisation with the testing procedures. This is especially important in studies involving older adults where gains in strength may be small, but may have functional significance (151). Also, to the knowledge of the authors, no studies have evaluated the reliability of isokinetic and isometric strength measures as well as functional capacity measures in the same population of older adults after two familiarisations.

However, it is not always feasible to perform multiple familiarisations prior to test sessions in clinical settings or in studies involving a large number of participants due to time or financial constraints (163). Therefore, a method to predict the ability of individual participants to produce reliable results in subsequent test sessions would be useful as clinicians or researchers could allow highly reliable

participants to proceed to training or subsequent test sessions without the need for further familiarisation sessions.

The aims of the current study were to determine whether two familiarisation sessions and the testing methods employed enable reliable measurements of maximal voluntary muscular strength and functional capacity of older adults to be obtained, and whether coefficients of variations (CVs) for each participant at each test obtained at the first familiarisation session can predict repeatability of performance in subsequent tests.

METHODS

Participants

Twenty-three healthy community-dwelling older adults (13 men and 10 women) participated in this study. Participants were excluded from the study if they were identified during a preliminary health screening as having any relevant cardiovascular or orthopaedic problem or if they had undertaken resistance training that included leg exercises in the previous six months. Written informed consent was obtained from all participants before entry into the study, which was approved by the RMIT University Human Research Ethics Committee and was conducted according to the Declaration of Helsinki (132). Participants were instructed to maintain their regular level of physical activity throughout the experimental period and not to participate in any vigorous physical activity in the two days prior to test sessions. None of the participants reported having prior experience performing knee extensor strength tests on an isokinetic dynamometer.

Study Design

During the study each participant completed a total of 4 sessions (Figure 2). These comprised of 2 familiarisation sessions (F1 & F2) followed by a test session (T1) and a retest session (T2). During the familiarisation sessions the participants performed the activities as they would in the subsequent test and retest sessions. The two familiarisation sessions were conducted to minimise possible remaining learning effects between T1 and T2. The familiarisation, test and retest sessions were separated by 7 to 14 days and were undertaken at the same time of day.

| F1 | ←— 7 – 14 days —→ | F2 | ←— 7 – 14 days —→ | T1 | ←— 7 – 14 days —→ | T2 |
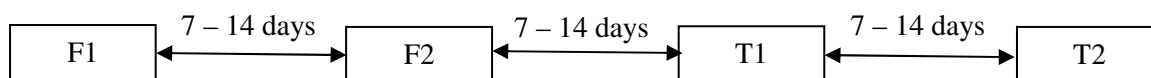
Figure 2. Study design. F1 = familiarisation 1; F2 = familiarisation 2; T1 = test 1; T2 = test 2.

Isokinetic and Isometric Testing

Isokinetic and isometric strength testing of the quadriceps muscles were carried out on an isokinetic dynamometer (Biodex System 4 Quick Set, Biodex Medical Systems, Shirley, New York, USA). The leg to be tested was selected at random to reduce any bias due to leg dominance and the same leg was tested in all subsequent sessions. Participants sat in the dynamometer seat in an upright position and stabilisation was provided by waist and torso straps (see Figure 3). The axis of rotation of the dynamometer was visually aligned with the lateral epicondyle of the femur, which was considered to represent the axis of rotation of the knee joint. The lever arm length was adjusted so that the ankle pad was positioned above the medial malleolus and attached to the lower leg by a strap. The position of the seat base, seat back and length of lever arm were recorded at the first familiarisation session and replicated for the subsequent familiarisation and testing sessions. Participants were instructed to hold onto handles positioned on either side of the seat during contractions.

A standardised warm-up of the quadriceps muscles was carried out before each session. This involved two sets of six contractions of the quadriceps muscles at a speed of 30º/s. The first set involved six sub-maximal contractions. In the second set of warm-ups, participants were instructed to perform four sub-maximal contractions of increasing intensity before performing two maximal contractions.

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Participants were given a rest period of one minute after the warm-up before commencement of the test protocol. The test protocol consisted of concentric contractions at 60, 120, 240 and 360º/s, and isometric contractions. The speeds chosen represent everyday tasks such as rising from a chair slowly (60º/s) to recovering from a stumble (360º/s). Five different test sequences, each with a different order of contraction speeds, were employed. Participants were randomly assigned a sequence at the first familiarisation session. This sequence was then used for the second familiarisation, test, and re-test sessions. Isokinetic contractions were performed between a knee joint range of movement of 105º to 5º, with 0º representing full extension of the knee. Joint angles were confirmed using a goniometer. Isometric contractions were performed at a knee joint angle of 60º for 5 seconds. Participants were required to perform five contractions at each speed with 30 seconds rest between each contraction and one minute rest between each speed. Participants were instructed to provide maximal effort and given loud verbal encouragement during each contraction. Visual feedback of the torque signal was provided to participants via a computer screen.

Figure 3. Dynamometer set-up.

Isokinetic and Isometric Signal Sampling and Analysis

During all isokinetic and isometric tests, data were sampled into an external computer at a frequency of 1000Hz. All data were gravity-corrected to account for the weight of the lower leg. Average torque data of each isokinetic contraction between knee joint angles of 30 and 70º were analysed. Any torque data in this range of motion that did not occur at the pre-set isokinetic velocity were discarded. The torque data from the five contractions performed at each isokinetic speed and isometrically were then averaged and used for statistical analysis.

Functional Tests

Five functional tests were undertaken. They were: the 6 metre fast walk test (6mFWT), the Timed Up and Go test (TUG), stair climb and stair descent tests, and the vertical jump test.

The 6 metre fast walk test involved the timing of participants as they walked as quickly as possible a distance of 6 metres (49, 63). Light gates were used as a means of accurately measuring walk time.

The Timed Up and Go test measures the time taken for an individual to rise from a chair, walk 3 metres, turn 180 degrees, return to the chair, and sit down (22). A standard chair was used for all tests and a marker was placed on a wall at a distance of 3 metres from the chair. A tester instructed participants to begin on the word, "Go!" and started the stopwatch at the same time. The timing stopped when participants returned to the chair and sat down. Participants were instructed not to use their hands when rising from or sitting back down on the chair. A spotter was situated at the chair to ensure the participants' safety as they rose from and sat down on the chair.

The timed stair climb and descent involved participants climbing a flight of stairs as quickly as possible and then descending the same flight of stairs (98). Stair climbing and descent time were assessed separately using a stopwatch. The flight of stairs utilised in this study comprised of 16 steps, each with a height of 15cm. The participants were not allowed to hold the handrails during this test, but were accompanied by one or two "spotters" to reduce the risk of falling.

The vertical jump height test was performed on a force plate (Kistler Type 9286AA, Kistler Instruments, Winterthur, Switzerland). Participants were instructed to stand on the force plate with both feet shoulder width apart, perform a counter-movement by bending the knees, then jump as high as possible. A spotter stood near the participants in case they lost balance on landing. The vertical force data from the force plate was used to obtain the jump height attained by each participant. Methods for signal sampling are described elsewhere (29).

All participants performed each functional test three times during familiarisation and test sessions. The average of the three results from each functional test was used for further statistical analysis.

Statistical Analyses

One-way repeated measures ANOVAs were used to evaluate differences in the mean values of the first familiarisation (F1), second familiarisation (F2), first test (T1) and second test (T2) for each contraction speed and functional test. If the main effect was found to be significant, paired *t*-tests were used to assess between-group differences. In this way, systematic bias between T1 and T2 was evaluated.

In order to assess test-retest reliability, intraclass correlation coefficients (ICC) were calculated for each contraction speed and functional test. Since the average of five contractions and the average of three results from the dynamometer test and functional tests respectively were used for analysis, the two-way mixed model of average-measure reliabilities ($ICC_{3,1}$) was used. If there was evidence of non-normality in the data, as assessed by the Kolmogorov-Smirnov test, the data were natural log-transformed before calculation of ICCs (8).

In addition, Bland-Altman plots (15) of the difference in results between T1 and T2 against the mean of T1 and T2 for each participant were generated to calculate the 95% limits of agreement (LOA). The presence of heteroscedasticity in the data sets was objectively assessed by plotting the absolute differences against the mean of T1 and T2, and calculating the correlation coefficient (8). If heteroscedasticity was not present, the LOA were calculated as described elsewhere (8). If heteroscedasticity was found to be present, the ratio of the two results from T1 and T2 for each participant was calculated and plotted against the mean of T1 and

T2. The 95% ratio LOA were then calculated as described by Bland and Altman (14) and Eksborg (43).

The CVs of each participant in each test during F1 were determined by dividing the standard deviation of the five (for dynamometer tests) or three results (for functional tests) from each test by their average and multiplying by 100. The relationships between the CVs in F1 and the percentage difference in results between F1 and F2 were evaluated by means of Pearson correlation coefficients. If significant correlations existed, linear regression analyses were performed to characterise these relationships.

Results were considered significant at $P < 0.05$, and statistical analyses were performed using SPSS 17.0 (SPSS, Chicago, IL).

RESULTS

Participants' demographics are summarised in Table 4. One participant was unable to reach the target velocity of 360º/s during the dynamometer tests, so data from this subject at this velocity was excluded. Another participant was unable to perform the vertical jump height test due to a pre-existing neck injury, so the data from the remaining 22 participants were analysed for this test.

Table 4

Participant demographics

Participants	n	Age (years)	Height (cm)	Weight (kg)
Males	13	66.8 ± 4.9	169.4 ± 9.4	77.2 ± 11.0
Females	10	67.8 ± 6.6	160.6 ± 4.5*	69.8 ± 9.5
Overall	23	67.2 ± 5.6	165.6 ± 8.7	74.0 ± 10.9

Data presented as mean ± SD; n = number of participants; Asterisk indicates a significant difference between males and females ($P < 0.05$).

With regards to the dynamometer tests, no significant between-group (between F1, F2, T1 and T2) main effect was observed. However, a significant between-group main effect ($P < 0.05$) was observed in all the functional tests, except for vertical jump height. In the 6mFWT, post-hoc paired t-tests revealed significant differences in the mean times between the familiarisations and the two tests sessions, but no difference between F1 and F2 or T1 and T2. In the TUG, there was a significant difference in the mean times between F1 and all the other sessions and F2 and the other sessions, but there was no significant difference between T1 and T2.

With regards to the stair climb and descent tests, there were significant differences between F1 and the two test sessions (T1 and T2), F2 and T2, and T1 and T2.

Table 5 details the descriptive statistics of the dynamometer tests and functional tests. Systematic bias, as revealed by paired t-tests, was detected between T1 and T2 for the contractions performed at 120º/s on the dynamometer and for the stair climb and descent tests ($P < 0.05$). Systematic bias is also illustrated graphically, along with the 95% LOA, in the Bland-Altman plots for the dynamometer tests (see Figure 4) and functional tests (see Figure 5).

Table 5

Descriptive statistics for dynamometer and functional tests

Test Name	Test 1	Test 2	% Diff	P-value
0º/s	154.7 ± 41.3 Nm	156.6 ± 41.9 Nm	1.2	0.276
60º/s	97.5 ± 28.7 Nm	99.4 ± 30.2 Nm	1.9	0.323
120º/s	79.2 ± 24.6 Nm	82.5 ± 23.6 Nm	4.2*	0.021
240º/s	56.5 ± 18.7 Nm	57.9 ± 16.8 Nm	2.5	0.115
360º/s [a]	45.3 ± 13.4 Nm	45.8 ± 13.0 Nm	1.1	0.508
6mFWT (s)	2.69 ± 0.45	2.64 ± 0.43	-1.9	0.237
TUG (s)	4.63 ± 0.96	4.57 ± 1.03	-1.3	0.308
Stair climb (s)	5.07 ± 1.94	4.91 ± 1.74	-3.2*	0.012
Stair descent (s)	5.74 ± 2.32	5.48 ± 2.15	-4.5*	0.014
VJ (cm) [†]	25.63 ± 8.85	25.87 ± 9.06	0.9	0.575

Data presented as mean ± SD; % Diff = percent mean difference; 6mFWT = 6 meter fast walk test; TUG = Timed up and go test; VJ = Vertical jump; [a] indicates $n = 22$; Asterisk indicates a significant difference between test 1 and test 2 ($P < 0.05$).

The ICCs between F2 and T1, and T1 and T2 are presented in Table 6. The upper and lower 95% confidence limits for ICCs between T1 and T2 and the 95% ratio LOAs for all dynamometer and functional tests are also included in Table 6. In general, the ICCs between T1 and T2 were higher than the ICCs between F2 and T1, except for the stair descent and 240º/s isokinetic tests. The ICCs for all tests were high between T1 and T2, ranging from 0.976 to 0.991 for the dynamometer tests and 0.952 to 0.997 for the functional tests. The 95% ratio LOAs for the isometric, 60º/s, 120º/s, 240º/s and 360º/s dynamometer tests were 1.01 ×/÷ 1.10, 1.02 ×/÷ 1.20, 1.06 ×/÷ 1.21, 1.04 ×/÷ 1.18 and 1.02 ×/÷ 1.15 respectively. The 95% ratio LOAs for the 6mFWT, TUG, stair climb, stair descent and vertical jump test were 0.99 ×/÷ 1.14, 0.99 ×/÷ 1.10, 0.97 ×/÷ 1.07, 0.96 ×/÷ 1.14 and 1.01 ×/÷ 1.14 respectively.

Table 6

Reliability measures for dynamometer and functional tests

Test	ICC F2-T1	ICC T1-T2	Lower confidence limit	Upper confidence limit	95% ratio LOA (%)
6mFWT	0.824	0.952	0.886	0.980	14.32
TUG	0.977	0.979	0.951	0.991	10.36
Stair climb	0.993	0.997	0.992	0.999	7.28
Stair descent	0.991	0.989	0.974	0.995	13.72
VJ [a]	0.986	0.988	0.971	0.995	13.53
Isometric	0.978	0.991	0.978	0.996	9.87
60º/s	0.964	0.976	0.943	0.990	20.28
120º/s	0.951	0.982	0.958	0.992	20.92
240º/s	0.985	0.984	0.962	0.993	18.21
360º/s	0.967	0.984	0.960	0.993	14.91

ICC F2-T1 = intraclass correlation coefficient between familiarisation 2 and test 1; ICC T1-T2 = intraclass correlation coefficient between test 1 and test 2; Lower and upper confidence limits correspond to ICC T1-T2; 6mFWT = 6 meter fast walk test; TUG = Timed up and go test; VJ = Vertical jump; 95% ratio LOA = 95% ratio limits of agreement; [a] indicates $n = 22$.
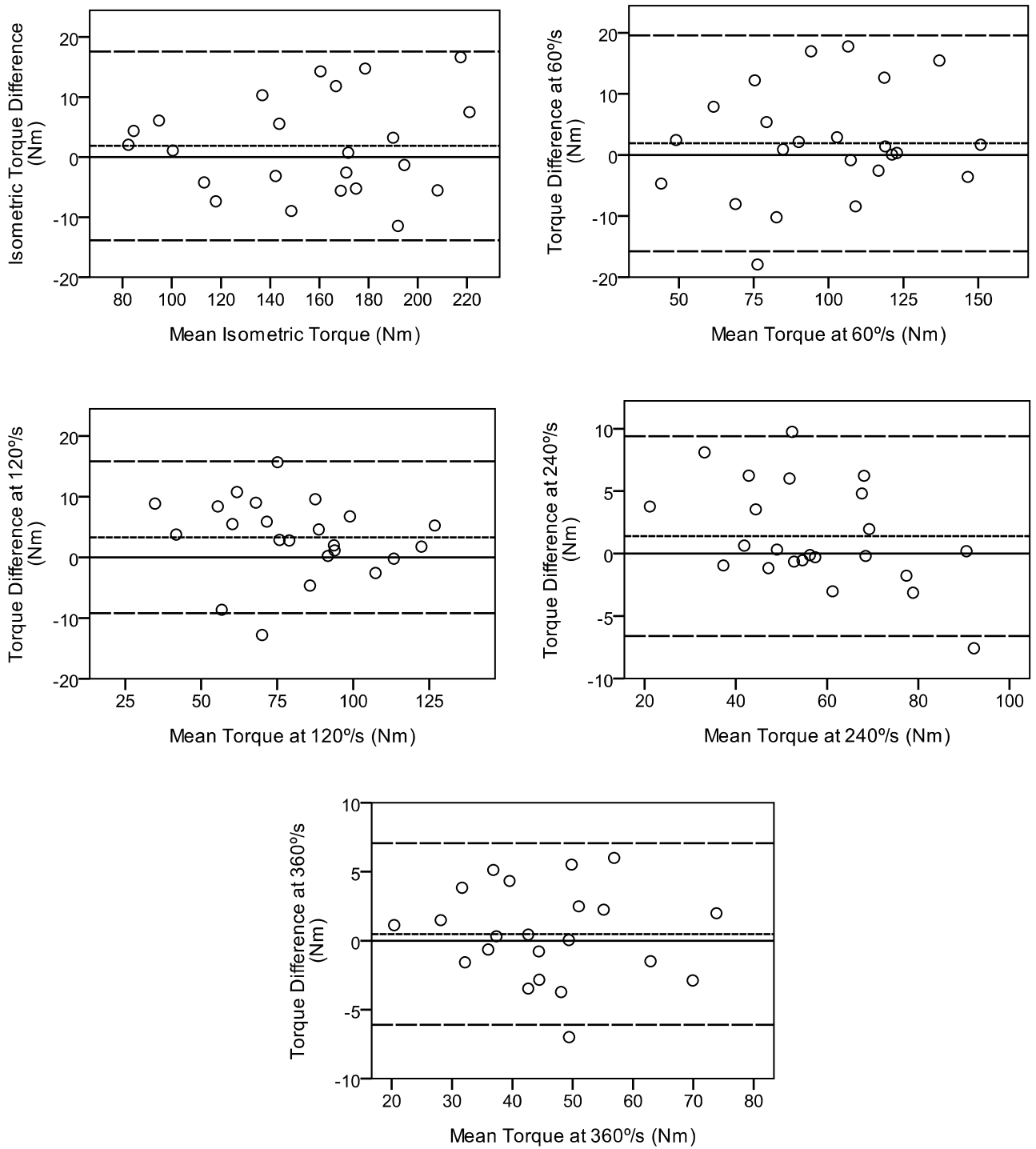
Figure 4. Bland-Altman plots of torque during isometric and concentric contractions at 60, 120, 240 and 360°/s. Long dashes represent upper and lower 95% limits of agreement. Short dashes represent the systematic bias.
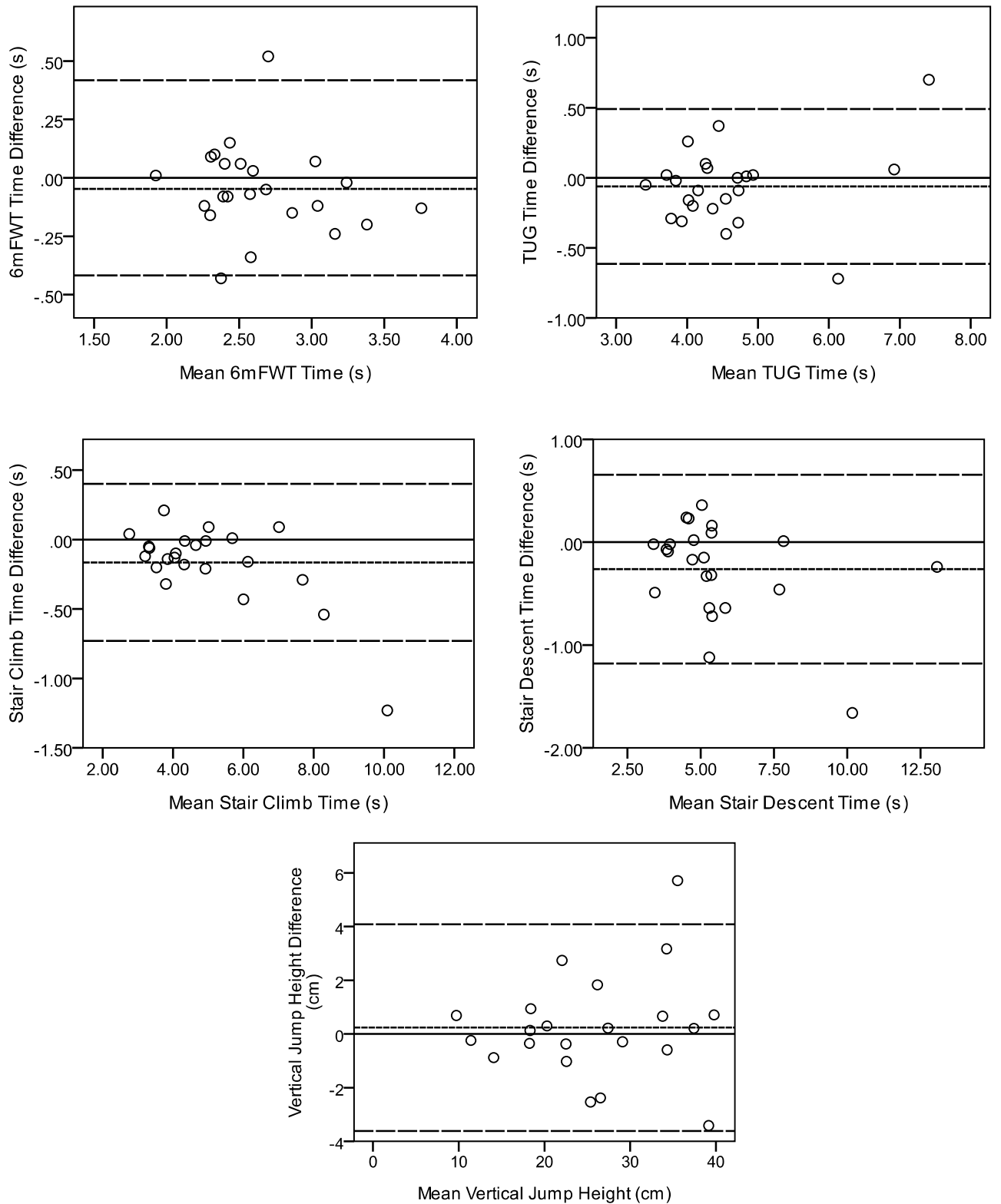
Figure 5. Bland-Altman plots of results of 6mFWT, TUG, stair climb, stair descent and vertical jump

tests. Long dashes represent upper and lower 95% limits of agreement. Short dashes represent the

systematic bias.

Correlation analyses revealed significant positive associations between CVs in F1 and percentage difference between F1 and F2 in the 6mFWT (Pearson's $r = 0.706$; $P < 0.01$), stair climb test (Pearson's $r = 0.485$; $P = 0.022$), 120º/s (Pearson's $r = 0.673$; $P < 0.01$) and 240º/s (Pearson's $r = 0.554$; $P = 0.007$) dynamometer tests. The linear regressions were statistically significant ($P < 0.05$) for the 6mFWT ($y = 0.755 + 0.809x$; $r^2 = 0.498$; SEE = 3.36), stair climb test ($y = 2.610 + 0.399x$; $r^2 = 0.235$; SEE = 3.72), 120º/s ($y = 4.969 + 0.832x$; $r^2 = 0.453$; SEE = 12.4) and 240º/s ($y = 4.390 + 0.634x$; $r^2 = 0.307$; SEE = 8.51) dynamometer tests. The linear regression analyses showed a trend for the percentage difference in results between F1 and F2 to increase with increasing CVs in F1. Participants who achieved CVs of less than 5.23% and 5.99% in the 6mFWT and stair climb test respectively in F1 were likely to have a percentage difference of less than 5% between F1 and F2. Participants who achieved CVs of less than 6.05% and 8.85% in the 120º/s and 240º/s dynamometer tests respectively in F1 were likely to have a percentage difference of less than 10% between F1 and F2.

DISCUSSION

The first aim of this study was to determine the relative and absolute reliability of an isokinetic and isometric strength testing protocol of the knee extensors and performance in a battery of functional tests in the same population of older adults following two familiarisation sessions. The second aim was to determine whether coefficients of variation for each participant at each dynamometer and functional test obtained during F1 can predict repeatability of performance in subsequent tests.

The results of the study demonstrated very good relative reliabilities for all dynamometer and functional tests. Absolute reliability was satisfactory for all measures. The ratio LOAs for the dynamometer tests ranged from 1.10 or 9.87% for the isometric contractions to 1.21 or 20.92% for isokinetic contractions at 120º/s. This means that for isokinetic contractions at 120º/s for example, the torque measurements for an individual would need to change by more than 20.92% to be 95% confident of detecting a real change. The ratio LOAs for the functional tests ranged from 1.07 or 7.28% for the stair climb test to 1.14 or 14.32% for the 6mFWT.

In general, the relative reliabilities of the dynamometer and functional tests were similar, but interestingly, ratio LOAs of the functional tests were slightly narrower than almost all the dynamometer tests except for the isometric contractions. This was not entirely unexpected, as the functional tests all involved movements that the participants were familiar with in everyday life, while none of the participants had previously performed a strength test on a dynamometer prior to F1.

Isokinetic and Isometric Strength Tests

The magnitudes of average torque for the isometric and isokinetic knee extension contractions observed in this present study were comparable to those in previous studies involving older adults (26, 59, 67, 84, 121, 164).

The two familiarisation sessions conducted prior to the testing sessions seem to have eliminated any residual learning effect between T1 and T2 in most dynamometer strength tests, as demonstrated by the lack of systematic bias. This finding concurs with that of another study that conducted a familiarisation session before testing and re-testing isokinetic and isometric knee extension strength (59). Although the mean torque during T2 was significantly greater than T1 for the knee extension contractions at 120º/s, the percentage difference between T1 and T2 was small (4.2%).

It could be argued that the lack of a between-group main effect for all contraction velocities means that familiarisations are not needed prior to a test session. Furthermore, in some cases (60º/s, 240º/s, 360º/s), mean torque decreased between F1 and T1 before increasing slightly in T2. For contractions at 120º/s, mean torque increased from F1 to F2, but decreased from F2 to T1 before increasing between T1 and T2. However, when Symons et al. (164) investigated the reliability of a single-session isokinetic and isometric strength test of the knee extensors by conducting test and re-test sessions without familiarisations, they found that the ratio LOAs for isometric and isokinetic contractions at 90º/s were 22.85% and 33.27% respectively. They also reported that the ratio LOAs in their study were higher than expected, and recommend one or two familiarisation sessions prior to a test session. Therefore, despite the indications of the study described in this chapter, it would seem that including familiarisation sessions would be prudent. In another

comparable study by Hartmann et al. (59), where one familiarisation session was conducted before the test and re-test sessions, the ratio LOAs for knee extension contractions at 60º/s and 120º/s were 22.3% and 23.7% respectively. The ratio LOAs in the present study for isometric and isokinetic contractions after two familiarisation sessions are slightly lower, ranging from 9.87% for isometric contractions to 20.92% for dynamic contractions at 120º/s. However, the ratio LOAs for the isokinetic strength measurements are still slightly greater than desirable. According to Rankin and Stokes (137), the 95% LOAs will be too wide if there are less than 50 participants in a reliability study. Therefore, the ratio LOAs may have been wider than desirable due to the small sample size in the current study.

Relative reliability in the present study for isometric and isokinetic contractions was high, with an ICC of 0.991 for isometric contractions and ICCs of 0.976 to 0.984 for isokinetic contractions. This compares favourably with those obtained by Symons et al. (164), who reported an ICC of 0.92 for isometric contractions and 0.90 for isokinetic contractions at 90º/s. The ICCs in the present study are also slightly higher than those observed by Hartmann et al. (59) who reported ICCs of 0.93 and 0.94 for contractions at 60º/s and 120º/s. In fact, the ICCs observed in the present study are generally higher than those typically reported for isokinetic strength tests (25, 54, 92). This supports the suggestion that two familiarisation sessions allow for greater reliability when testing older adults. This point is further illustrated by the fact that ICCs in the present study are generally higher after two familiarisations than after one familiarisation (see Table 3).

One limitation of the current study is that although none of the participants reported any prior experience of performing knee extensor strength tests on an isokinetic dynamometer, participants were not asked if they had prior experience

with knee extension exercises in other settings. Therefore, some participants may have had more experience than others in performing this type of exercise.

Functional Tests

The results obtained in the functional tests were also similar to those obtained in other studies (29, 63, 127, 159, 161). No studies to date have reported LOAs or ratio LOAs for any of the functional tests assessed in the present study.

The ICCs for all functional tests were high after two familiarisations, ranging from 0.952 to 0.997. This compares favourably to the ICC of 0.78 obtained by Tager, Swanson, and Satariano (165) for a walking test in adults over the age of 55. It should be noted, however, that participants in their study were not given a familiarisation prior to the test and re-test sessions (165). A study of the relative reliability of the TUG in 60 frail older adults (mean age 79.5 years) reported ICCs of 0.99, which is similar to the value of 0.979 obtained in the present study (127). Henwood and Taafe (64) administered the 6mFWT and stair climb test to older adults aged between 65 and 84 years to assess the effectiveness of a short-term resistance training program. They did not calculate ICCs for these tests, but reported coefficients of variations of 5.1% and 4.2% for the 6mFWT and stair climb time.

The results of the repeated measures ANOVAs suggest that two familiarisation sessions are needed for the 6mFWT and the TUG before older adults are able to produce reliable results in these tests. This is supported by the finding that the ICCs are higher after two familiarisation sessions than after one familiarisation session. However, it seems that two familiarisation sessions are insufficient to eliminate the learning effect for the stair climb and descent tests, as illustrated by the significantly faster mean times recorded in T2 compared to T1. This is not

unexpected given that many participants expressed apprehension at performing the stair climb and descent tests at the beginning of the study due to a fear of falling. Although the participants became more comfortable with performing these tests with practice and improved with each session, it appears that they were still improving after three sessions. This must be taken into account in future studies and effort must be put in to reassure participants and increase safety so that they feel comfortable to perform to their maximum ability.

This significant improvement in performance in the stair climb and descent tests between T1 and T2 highlights difficulties in interpreting the results of these tests after a training intervention. This is because it is impossible to distinguish between learning and training effects when an improvement is observed. As most intervention studies do not familiarise their participants twice before testing, there may be a false impression as to the effect of any intervention. This is especially true in the absence of a control group. Therefore, it is advisable that older adults are familiarised on at least two occasions before testing is carried out to minimise this learning effect.

Linear Regression Analyses

This study is the first to investigate the relationship between CVs obtained by individuals in each test in one session and percentage difference between the first and second sessions. In this way, the CVs obtained by individuals in F1 can be used to determine if they are able to produce reliable results and are therefore ready to proceed to further test sessions or training. In the current study, positive linear relationships were observed between CVs in F1 and percentage difference between F1 and F2 in the 6mFWT, stair climb test, and 120º/s and 240º/s dynamometer tests.

Therefore, participants who achieved CVs of less than 5.23% and 5.99% in the 6mFWT and stair climb test respectively in F1 were likely to have a percentage difference of less than 5% between F1 and F2 while participants who achieved CVs of less than 6.05% and 8.85% in the 120º/s and 240º/s dynamometer tests respectively in F1 were likely to have a percentage difference of less than 10% between F1 and F2. However, a limitation of this study is the small sample size, and further research is warranted with a larger number of participants to draw clearer conclusions about the ability of CVs of individuals to predict repeatability in subsequent tests.

Conclusion

In conclusion, for the isometric and isokinetic strength measurements, 6mFWT, TUG and vertical jump, two familiarisations produce more reliable results than one familiarisation, while two familiarisations may be insufficient for the stair climb and descent test. Overall, the results suggest that all the tests in the present study have high relative reliability after two familiarisation sessions for older adults. However, the LOAs and ratio LOAs for the isokinetic strength measurements are wider than desirable. Consequently, a relatively large change in torque will need to be observed in a new participant before being able to state with 95% confidence that a real change in strength has occurred. Therefore, the ability of these tests to determine a real change in strength and functional capacity is good on a group level, while the isometric strength test and TUG have the potential to detect real change on an individual level as well. The current findings suggest that for future intervention studies or strength and functional testing in the clinical setting, two familiarisations will provide greater reliability than one or no familiarisations. When two

familiarisations are not feasible, it may be possible that CVs at F1 can be used to predict repeatability of results in individuals, but more research is needed in this area before clear conclusions can be drawn.

CHAPTER 4: Reliability of Ultrasonographic Measurement of the Architecture of the Vastus Lateralis and Gastrocnemius Medialis Muscles in Older Adults

An earlier version of this chapter has been accepted for publication:

Raj IS, Bird SR, Shield AJ. Reliability of Ultrasonographic Measurement of the Architecture of the Vastus Lateralis and Gastrocnemius Medialis Muscles in Older Adults. *Clin Physiol Funct Imaging*. 2011. DOI: 10.1111/j.1475-097X.2011.01056.x

ABSTRACT

Objective: To determine the test-retest reliability of measurements of thickness, fascicle length (L_f) and pennation angle (θ) of the vastus lateralis (VL) and gastrocnemius medialis (GM) muscles in older adults.

Participants: Twenty-one healthy older adults (11 men and 10 women; average age 68.1±5.2 years) participated in this study.

Methods: Ultrasound images (probe frequency 10MHz) of the VL at two sites (VL site 1 and 2) were obtained with participants seated with knee at 90º flexion. For GM measures, participants lay prone with ankle fixed at 15º dorsiflexion. Measures were taken on two separate occasions, 7 days apart (T1 and T2).

Results: The ICCs (95% CI) were: VL site 1 thickness =0.96(0.90-0.98); VL site 2 thickness =0.96(0.90-0.98), VL θ =0.87(0.68-0.95), VL L_f =0.80(0.50-0.92), GM thickness =0.97(0.92-0.99), GM θ =0.85(0.62-0.94) and GM L_f =0.90(0.75-0.96). The 95% ratio limits of agreement (LOAs) for all measures, calculated by multiplying the standard deviation of the ratio of the results between T1 and T2 by 1.96, ranged from 10.59 to 38.01%.

Conclusion: The ability of these tests to determine a real change in VL and GM muscle architecture is good on a group level but problematic on an individual level as the relatively large 95% ratio LOAs in the current study may encompass the likely magnitude of intervention-induced changes in architecture observed in other training studies. Therefore, the current findings suggest that B-mode ultrasonography can be used with confidence by researchers when investigating changes in muscle architecture in groups of older adults, but its use is limited if seeking to determine possible changes over time within individuals.

INTRODUCTION

Skeletal muscle architecture plays an important role in the function of muscles in humans (19, 110). Specifically, muscle fascicle length plays a role in force generation during high-speed contractions, while fascicle pennation angle and muscle thickness are important factors for overall force generation (8). Ultrasonography has become a popular method for characterising muscle architecture due to its safety and minimally invasive nature (110). The reliability of ultrasound measures of muscle architecture is influenced by a number of factors including the ability to accurately re-locate examination sites at re-test, the experience level of the examiner and whether complete fascicles can be imaged or extrapolation is required. Previous research has demonstrated the reliability of muscle architecture measurements by B-mode ultrasound imaging in adults (17, 101, 111) and young children (90), but there is a lack of data in this area in older adults. However, cross-sectional studies have demonstrated that muscle architecture, or specifically, muscle thickness, fascicle length (L_f) and fascicle pennation angle (θ) are reduced in older adults compared to their young counterparts (106, 113, 166). These differences mean that the reliability measures established for young adults and children may not be applicable to older adults. Additionally, since the aforementioned age associated changes result in a decline in functional capacity, health and quality of life, a number of exercise studies have been undertaken to investigate the effects of various resistance training modalities on muscle architecture in older adults and to assess whether the age associated changes can be ameliorated or reversed (108, 140, 142, 144, 146, 161). Therefore, information on the reliability of ultrasound measures of muscle architecture in older adults is needed to provide researchers with an indication of the magnitude of any changes required in order to be confident of

reporting significant differences between or within groups, and help in the planning of future research studies (90).

The aim of the current study was to determine the reliability of measurements of muscle thickness, fascicle length and pennation angle of the vastus lateralis (VL) and gastrocnemius medialis (GM) muscles in older adults using B-mode ultrasound imaging.

METHODS

Participants

The study was approved by the University Human Research Ethics Committee and was conducted according to the Declaration of Helsinki (133). Participants were recruited from local retirement villages via flyers. Twenty-one healthy community-dwelling older adults (11 men and 10 women) participated in this study. Participants were excluded from the study if they were identified during a preliminary health screening as having any relevant orthopaedic problem or if they were undertaking resistance training that included leg exercises. Written informed consent was obtained from all participants before entry into the study. Participants were instructed to maintain their regular level of physical activity throughout the experimental period.

Study Design

A single experienced investigator acquired the images from all participants on two separate test sessions (T1 and T2), which were separated by 7 to 14 days. Test sessions were held at the same time of day for each participant. A second investigator, who was blinded to the identity of the participants, was then employed to analyse the images.

Muscle Architecture

Real-time B-mode ultrasonography (LOGIQ I, GE Healthcare, Wauwatosa, Wisconsin, USA) was used to measure fascicle pennation angle, fascicle length and muscle thickness of the vastus lateralis and gastrocnemius medialis muscles. The leg to be tested was chosen at random, and the same leg was tested at both test sessions.

The 42 mm long, 10 MHz linear-array ultrasound transducer was coated with sufficient water-based transmission gel to ensure that clear images of the muscles were obtained without the need to compress the muscles during examination.

A site 62% proximal between the anterior superior iliac spine and the superior aspect of the patella on the mid-sagittal plane of the thigh was marked (VL site 1) on the skin. Another site at the same position along the thigh as VL site 1 on the mid-coronal plane on the lateral side of the thigh was also marked (VL site 2). Participants then sat with the knee angle fixed at 90º (see Figure 6). All joint angles were confirmed using a goniometer. These sites were chosen for examination as pilot testing revealed minimal fascicle curvature at these sites when participants sat in this position. The ultrasound transducer was placed over the muscle at VL site 2 and when clear images of the muscle fascicles, and the superficial and deep aponeuroses were obtained, three images were recorded. These images, recorded to a depth of 6 cm from the transducer surface, were used to measure VL fascicle length and pennation angle. To measure vastus lateralis muscle thickness clear images of the superficial and deep aponeuroses and the femur were obtained and another three images were each recorded to a depth of 9 cm at both VL site 1 and VL site 2 (18). The greater recording depth was chosen for muscle thickness measurements as pilot testing revealed that this depth was required to visualise the femur.
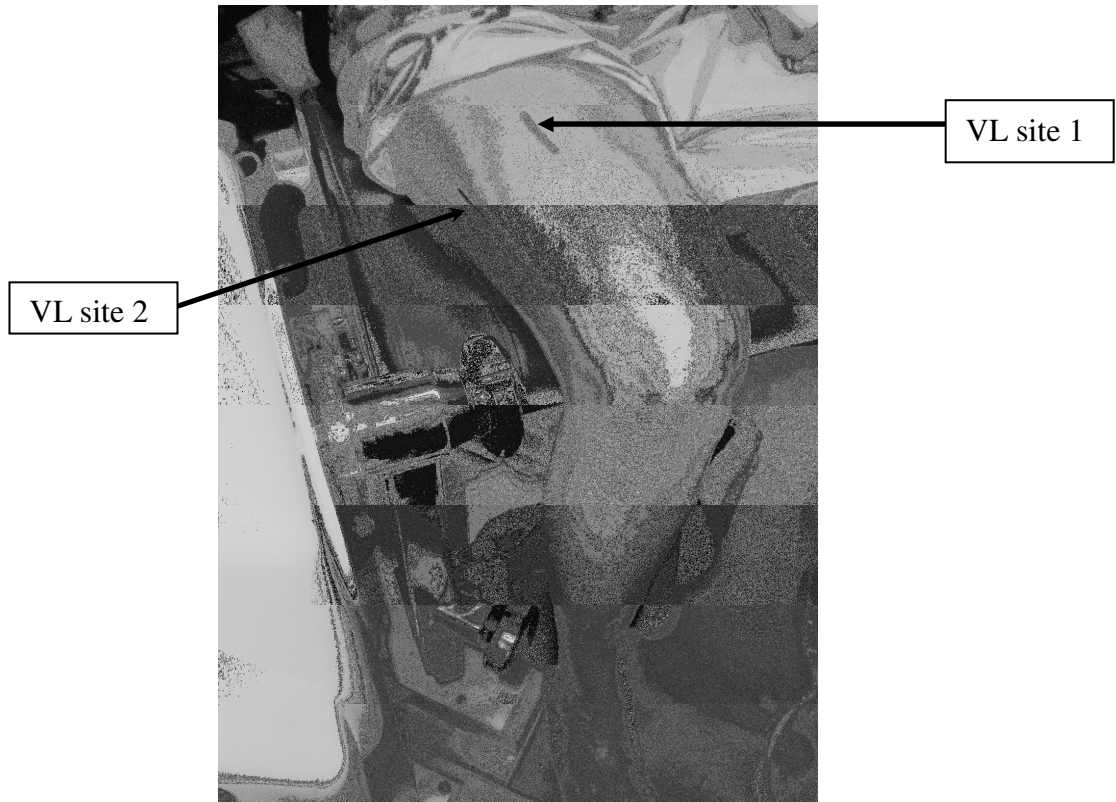
Figure 6. Photograph of the vastus lateralis (VL) examination set-up.

To assess gastrocnemius medialis muscle architecture and thickness, participants were asked to lie prone on the bench with their feet hanging off the edge (113). A modified night splint was placed on the foot and lower leg to fix the ankle joint angle at 15º dorsiflexion. The ultrasound transducer was placed on a site on the muscle 30% proximal between the lateral malleolus of the fibula and the lateral condyle of the tibia (see Figure 7). This site was chosen for examination as pilot testing revealed minimal fascicle curvature at this site when participants were lying in this position. Once clear images of the muscle fascicles, and the superficial and deep aponeuroses were obtained, three images were recorded to a depth of 6 cm from the surface of the transducer.
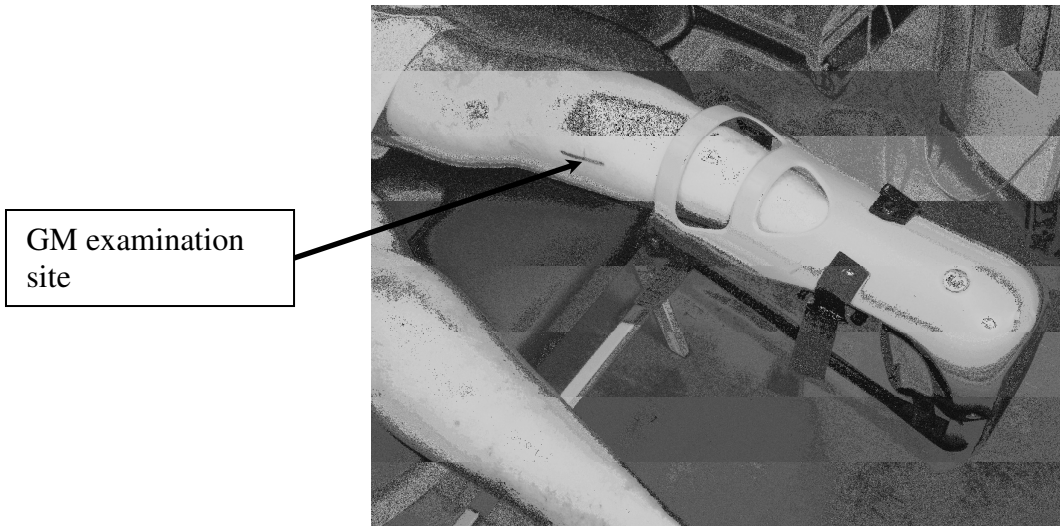
Figure 7. Photograph of the medial gastrocnemius (GM) examination set-up.

After the first test session, a clear plastic sheet was placed over the participants' anterior thigh and posterior lower leg and the examination sites and any permanent blemishes on the skin, as well as the examination sites, were marked on the sheet (18). Before the second test session, holes were made on the clear plastic sheets at the marked examination sites. The sheets were then placed over the skin and aligned with the marked blemishes before the examination sites were marked with a pen on the skin. All images were recorded digitally and analysed using computer software (ImageJ, U. S. National Institutes of Health, Bethseda, Maryland, USA).

Vastus lateralis muscle thickness was defined as the distance between the superficial aponeurosis and the femur, and gastrocnemius medialis muscle thickness was defined as the distance between the superficial and deep aponeuroses. Pennation angle was measured as the angle between the muscle fascicles and the deep aponeurosis, and fascicle length was measured as the length of a fascicle between its insertions at the superficial and deep aponeurosis. Where the fascicles extended beyond the recorded image, fascicle length was estimated from muscle thickness and fascicle pennation angle using the following equation (1):

$$\text{Fascicle length} = \text{muscle thickness} \cdot \sin\theta^{-1}$$

where θ is muscle fascicle pennation angle determined by ultrasonography.

Statistical Analyses

To assess reliability, intraclass correlation coefficients (ICC) were calculated for each measure of muscle thickness, pennation angle and fascicle length. Since the average results from three images were used for analysis, the two-way mixed model of average-measure reliabilities ($ICC_{3,1}$) was used. If there was evidence of non-normality in the data, as assessed by the Kolmogorov-Smirnov test, the data were natural log-transformed before calculation of ICCs (8).

In addition, Bland-Altman plots (15) of the difference in results between T1 and T2 against the mean of T1 and T2 for each participant were generated to calculate the 95% limits of agreement (LOA). The presence of heteroscedasticity in the data sets were objectively assessed by plotting the absolute differences against the mean of T1 and T2, and calculating the correlation coefficient (8). The presence of heteroscedasticity can lead to the 95% limits of agreement to be underestimated at the higher end of measured values, and overestimated at the lower end of measured values (8). If heteroscedasticity was not present, the LOA were calculated as described elsewhere (8). If heteroscedasticity was found to be present, the ratio of the two results from T1 and T2 for each participant was calculated and plotted against the mean of T1 and T2. The 95% ratio LOA were then calculated as described by Bland and Altman (14) and Eksborg (43). Paired *t*-tests with equal variances assumed were used to assess systematic bias in the results from T1 and T2.

Results were considered significant at $P < 0.05$, and statistical analyses were performed using SPSS 17.0 (SPSS, Chicago, IL).

RESULTS

Participants' demographics are summarised in Table 7. The descriptive statistics of the ultrasound measures are detailed in Table 8. Paired t-tests revealed no systematic bias in any of the measures. The 95% LOA are illustrated graphically in the Bland-Altman plots (see Figure 8).

The ICCs between T1 and T2 are presented in Table 9. The upper and lower 95% confidence limits for the ICCs and the 95% ratio LOAs are also included in Table 9. In general, the ICCs for the thickness measures were higher than the ICCs for L_f and θ for both the VL and GM muscles. The 95% confidence intervals for the ICCs tended to be narrower for the thickness measures than for L_f and θ measures. The ICCs for all measures were good, ranging from 0.80 to 0.97.

The 95% ratio LOAs for VL site 1 thickness, VL site 2 thickness, VL θ, VL L_f, GM thickness, GM θ and GM L_f were 0.99 ×/÷ 1.17, 0.98 ×/÷ 1.11, 1.04 ×/÷ 1.34, 1.05 ×/÷ 1.38, 1.01 ×/÷ 1.13, 1.03 ×/÷ 1.24 and 1.00 ×/÷ 1.22 respectively.

Table 7

Participant demographics

Participants	n	Age (years)	Height (cm)	Mass (kg)
Males	11	67.1 ± 4.8	168.5 ± 10.0	78.5 ± 11.0
Females	10	69.3 ± 5.6	160.7 ± 5.5*	68.3 ± 6.3*
Overall	21	68.1 ± 5.2	164.8 ± 8.9	73.7 ± 10.3

Data presented as mean ± SD; n = number of participants; Asterisk indicates a significant difference between males and females ($P < 0.05$).

Table 8

Descriptive statistics for muscle architecture measures

Test Name	Test 1	Test 2	% Diff	*P*-value
VL site 1 thickness	3.80 ± 0.74 cm	3.76 ± 0.80 cm	-1.1	0.42
VL site 2 thickness	4.50 ± 0.57 cm	4.42 ± 0.63 cm	-1.8	0.13
VL θ	11.2 ± 3.0º	11.4 ± 2.5º	1.8	0.51
VL L_f	11.1 ± 2.9 cm	11.4 ± 2.6 cm	2.7	0.41
GM thickness	1.79 ± 0.28 cm	1.80 ± 0.31 cm	0.7	0.57
GM θ	17.8 ± 2.9º	18.2 ± 2.7º	2.2	0.38
GM L_f	5.99 ± 1.15 cm	5.96 ± 1.15 cm	-0.5	0.84

Data presented as mean ± SD; % Diff = percent mean difference; VL = vastus lateralis muscle; GM = gastrocnemius medialis muscle; θ = muscle fascicle pennation angle; L_f = muscle fascicle length. *P*-values refer to paired *t*-test between Test 1 and Test 2.
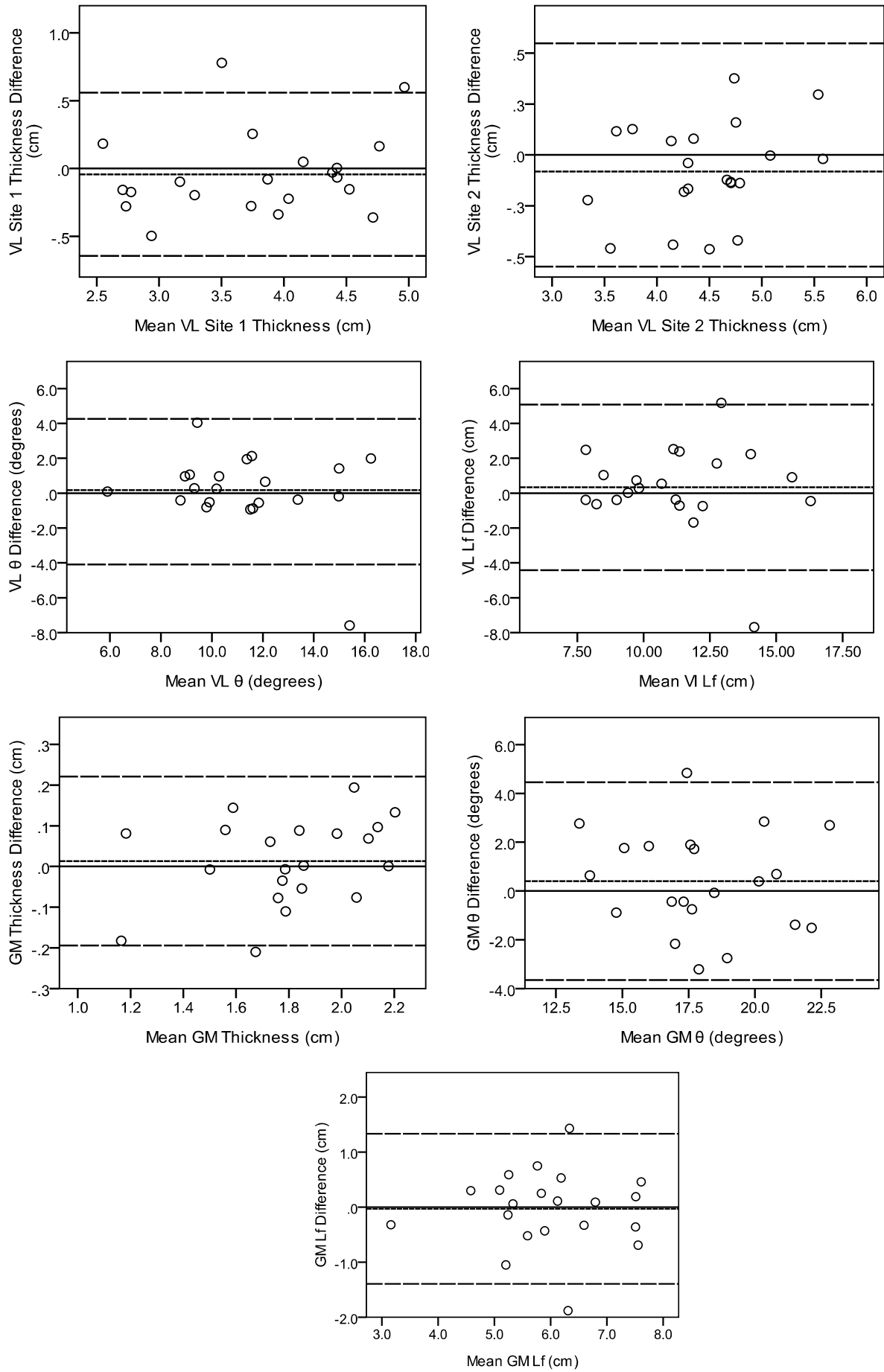
Figure 8. Bland-Altman plots of muscle architecture measurements. Long dashes represent upper and lower 95% limits of agreement. Short dashes represent the systematic bias.

Table 9

Reliability statistics for muscle architecture measures

Test	ICC	Lower confidence limit	Upper confidence limit	95% ratio LOA (%)
VL site 1 thickness	0.96	0.90	0.98	17.25
VL site 2 thickness	0.96	0.90	0.98	10.59
VL θ	0.87	0.68	0.95	33.74
VL L_f	0.80	0.50	0.92	38.01
GM thickness	0.97	0.92	0.99	12.56
GM θ	0.85	0.62	0.94	24.18
GM L_f	0.90	0.75	0.96	22.25

VL = vastus lateralis muscle; GM = gastrocnemius medialis muscle; θ = muscle fascicle pennation angle; L_f = muscle fascicle length; 95% ratio LOA = 95% ratio limits of agreement, calculated by multiplying the standard deviation of the ratio of the results between Test 1 and Test 2 by 1.96.

DISCUSSION

The muscle architectural measurements obtained in the current study are in close agreement with measurements of the VL and GM muscles obtained in previous studies in older adults using B-mode ultrasonography (106, 113, 140, 161, 166). The ultrasound measurements of GM muscle architecture in this study also agree closely with direct measurements of GM muscle architecture in a cadaver of a 62 year old male (111). It should be noted, however that the reliability data presented here are specific to the data collection protocol followed in the current study.

The results of the study demonstrated good to very good relative reliability, ranging from 0.96 to 0.97 for thickness measurements, 0.85 to 0.87 for θ measurements and 0.80 to 0.90 for L_f measurements. However, the 95% confidence intervals of the ICCs for the L_f and θ measurements tended to be wider than those for the thickness measurements. This indicates that a larger sample size may be needed to attain greater precision of estimates of ICCs for L_f and θ measurements (7). The measurements were comparable to the ICCs of 0.88 to 0.97, 0.90 to 0.99 and 0.76 to 0.86 for VL muscle thickness, θ and L_f respectively obtained by Blazevich et al. (17) in young adults. The results also agree closely with those obtained by Legerlotz and colleagues (90) from the GM muscles of young children aged four to 10 years old. This suggests that, despite the varying ages of the participants and differing knee and ankle joint positions during measurements in these studies, B-mode ultrasonography and the analysis of the images from this method is a reliable method of characterising muscle architecture on a group level.

However, as observed by Legerlotz et al. (90), muscle architecture measurements have a high degree of inter-individual variability, which can result in higher ICCs than expected. Therefore, to gain a better understanding of the reliability

of using B-mode ultrasonography to measure muscle architecture, we have produced Bland-Altman plots (15) and calculated 95% ratio LOAs for each measure. In this way, we were able to characterise the absolute reliabilities of these measures and illustrate systematic bias, if present, between T1 and T2. For example, the 95% ratio LOA for GM thickness was 1.13 or 12.56%. This means that for a new individual from this older adult population, there is a 95% probability any two tests would differ due to measurement error by no more than 12.56% in either the positive or negative direction. This result is comparable to the 95% ratio LOA of 1.13 or 13% observed by Legerlotz et al. (90) for thickness measures of the GM muscle in young children. Unfortunately, Legerlotz et al. (90) did not report 95% LOAs for θ and L_f. To the knowledge of the authors, no other studies have reported 95% LOAs or ratio LOAs for muscle architecture measurements, illustrating the need for more research in this area.

An interesting observation of the results of the current study is that the L_f measurements of the GM muscle are more reliable (both absolute and relative reliability) than L_f measurements of the VL muscle. This could be because of the shorter fascicle lengths in the GM muscle, meaning that less extrapolation outside the field of view of the ultrasound transducer is necessary to quantify fascicle lengths.

Although the very limited evidence available seems to suggest that the reliability of the methods of characterising VL and GM muscle architecture in the current study is comparable to other studies, the absolute reliabilities of VL and GM θ and L_f may be wider than desirable. This is because typical average changes observed in previous studies involving 14 weeks of resistance training with elderly adults are up to 35% for VL θ and up to 20% for VL L_f (140, 142), while 95% ratio LOAs for VL θ and VL L_f observed in the current study are 33.74% and 38.01%

respectively. These results therefore indicate that these measures may not be sensitive enough to detect real θ and L_f changes in individuals. One reason for this could be the method of using clear plastic sheets to trace the examination sites as well as permanent blemishes on the skin surface at T1 to use as reference points in order to examine the same sites on the muscles at T2. Some participants had very few or no blemishes on their skin, making it very difficult to find reference points. This reduced the precision with which measurement sites could be relocated and therefore reduced the accuracy of this method in some cases. Also, Klimstra and colleagues (80) have previously demonstrated that changes in the orientation of the ultrasound transducer can have an effect on muscle architectural measurements. Since the orientation of the transducer was not standardised between T1 and T2 in the current study, this may have been another factor that contributed to the ratio LOAs being wider than desirable.

Conclusion

In summary, the method of using B-mode ultrasonography described in the current study to characterise VL and GM muscle architecture in older adults has high relative reliability. However, the 95% LOAs and ratio LOAs are wider than desirable. Therefore, the ability of these tests to determine a real change in VL and GM muscle architecture is good on a group level but problematic on an individual level as the relatively large LOAs and ratio LOAs observed in the current study may encompass the likely magnitude of changes in architecture as indicated from the results of other training studies. Hence, the current findings suggest that B-mode ultrasonography can be used with confidence by researchers when investigating

changes in muscle architecture in groups of older adults, but it may not be sensitive

enough to detect small longitudinal changes in muscle architecture in individuals.

SUBSEQUENT STEPS

Consequently, and with the availability of the above reliability measures, these assessments were utilised in the intervention study described in Chapter 6. And the results used to inform the determination of appropriate group sizes from statistical power calculations. However, prior to the intervention study, it was determined that a study examining the relative acute post-exercise safety of eccentrically-biased versus conventional resistance training should be conducted. This was done to determine if there were any safety risks immediately post-resistance training for older adults that should be taken into consideration.

CHAPTER 5: The Acute Effects of an Eccentrically-biased versus Conventional Resistance Training Session in Older Adults

ABSTRACT

Introduction: The acute effects of eccentrically-biased (EB) and conventional (CONV) resistance training on: arterial stiffness; platelet reactivity, activation and count; postural stability; and isometric force steadiness were compared.

Methods: Ten older adults (7 males and 3 females; mean ± S.D. age, 69 ± 4 years) participated in this study. EB involved three sets of 10 concentric lifts at 50% of 1RM with the eccentric portion of repetitions performed unilaterally, alternating between limbs with each repetition. CONV involved two sets of 10 repetitions at 75% of 1RM. EB and CONV were matched for total work. Arterial stiffness was measured by means of pulse wave velocity (PWV). Platelet reactivity was measured using an optical platelet aggregometer and platelet activation was evaluated using flow cytometry. Postural stability was evaluated using mean velocity (Vm) of the centre of pressure and isometric force steadiness was measured on an isokinetic dynamometer.

Results: Platelet count was significantly higher immediately after EB than after the control condition ($232 \pm 32 \times 10^9$/L after EB versus $206 \pm 29 \times 10^9$/L after control; *P* < 0.05), and the difference in platelet count immediately after training or control between CONV and the control condition approached significance ($232 \pm 44 \times 10^9$/L after CONV versus $206 \pm 29 \times 10^9$/L after control; *P* = 0.09). A significant condition by time effect was observed for Vm (*P* < 0.05). Post-hoc tests revealed that mean Vm decreased, albeit not reaching statistical significance, in CONV (3.02 ± 1.24 m/s pre versus 2.75 ± 1.00 m/s post; *P* = 0.09) and control (3.17 ± 1.29 m/s pre versus

2.89 ± 1.16 m/s post; $P = 0.28$) while increasing, but again not reaching statistical significance in EB (2.82 ± 1.16 m/s pre versus 3.26 ± 1.72 m/s post; $P = 0.22$). No significant changes were observed in any other measures.

Conclusion: Overall, the results suggest that CONV and EB do not seem to have any acute adverse effect on platelet function, arterial stiffness, knee extensor force steadiness in older adults. However, the possibility of increased platelet count after both training modalities and decreased postural stability after EB mean that more research is needed to fully understand the acute effects of these modalities in older adults.

INTRODUCTION

Resistance training has been identified as an important component of exercise programs for older adults to maintain health and physical function (30), and as mentioned in the thesis introduction, programs emphasising the eccentric phase of resistance training exercises are gaining interest. Careful management of these programs will ensure that the benefits to older adults are maximised while any risks arising from participation in these programs are minimised. Although the benefits of resistance training for older adults are well-established (40, 98), there is some evidence to suggest that older adults may be at an increased risk of experiencing an adverse event immediately after a training session (2, 4, 9, 33, 37, 60, 105, 155, 185). These areas of increased risk may fall into two broad categories: cardiovascular and neuromuscular.

With regards to increased risk of cardiovascular events immediately post a resistance training session, the current study focused on arterial stiffness and platelet reactivity and activation. Increased platelet function is associated with an increased risk of acute cardiovascular events (182) and a small number of studies have reported increased platelet reactivity and activation after conventional resistance exercise in young healthy adults (2, 4). However, there have been no studies to date investigating the acute effects of a resistance training session on platelet function in older adults. Arterial stiffness immediately after conventional resistance exercise has been investigated more widely (9, 33, 37, 60, 185), with most of these studies finding an increase, and only Heffernan et al. (60) finding no change in arterial stiffness following resistance exercise in young adults. Arterial stiffness in response to resistance exercise has not been investigated in older adults.

The neuromuscular risk factors that were a focus of the current study were postural control and force steadiness. Moore, Korff, and Kinzey (105) have demonstrated that conventional resistance exercise has an acute negative effect on postural stability in older adults. This may then increase the risk of falls in older adults immediately after a resistance training session. However, no studies to date have compared the acute effects of conventional versus eccentrically-biased resistance exercise. Force fluctuations of muscles during voluntary contractions are higher in older adults compared to young individuals, and this reduced ability to exert an intended force can affect the ability of older adults to control leg movements, for example, during stair descent (171). Although 16 weeks of conventional resistance training reduces force fluctuations in older adults (171), it has been shown that fatiguing conventional resistance exercise increases force fluctuations in the quadriceps muscles of young adults immediately after a training session (155). However, there are no studies investigating the acute effect of resistance exercise on the force steadiness of quadriceps muscles in older adults.

The aim of the current study was to compare the acute effects of a single session of conventional (CONV) versus eccentrically-biased (EB) resistance training on platelet function, arterial stiffness, postural stability and knee extensor force steadiness in older adults. It was hypothesised that a single session of CONV would increase platelet function and arterial stiffness, and decrease postural stability and knee extensor force steadiness to a greater extent than EB.

METHODS

Participants

Ten community-dwelling older adults (7 males and 3 females; mean ± S.D. age, 69 ± 4 years; body mass, 71.0 ± 11.5 kg; height, 166.3 ± 9.1 cm) participated in this study. Participants were excluded from the study if they had relevant cardiovascular or orthopaedic problems, if they had undertaken any resistance training in the preceding six months or if they were taking any medication that affected platelet function. Written informed consent was obtained from all participants before entry into the study, which was approved by the University Human Research Ethics Committee.

Study Design

A randomised controlled cross-over design was used for this study. Participants attended the laboratory on four occasions in total. The overall study design is illustrated in Figure 9. During the first session, maximum voluntary isometric strength of the knee extensors was quantified before participants were familiarised with the exercises to be performed during the resistance training sessions. One-repetition maximum (1RM) was then quantified for each exercise to be performed in the training sessions. Participants were given a food diary to record their normal diet the day before and on the morning of the first trial session. They were then instructed to replicate this diet for the subsequent two trial sessions. Participants were also instructed to avoid fatiguing physical activity during the 48 hours prior to trial sessions. After a 14 day washout period, participants returned to the laboratory for the first trial session. Before the start of this session, participants were randomised to one of three conditions: CONV, EB or control. Details of the

trial sessions are provided in Figure 10. Blood samples were obtained first at each data collection timepoint, followed by measurement of pulse wave velocity, postural control and force steadiness respectively. The control condition involved participants sitting quietly in the laboratory for 45 minutes. During the subsequent two trial sessions, the testing protocol was replicated and participants were randomised to the remaining conditions. Participants reported to the laboratory for the trial session in the morning between 7:00am and 8:00am.
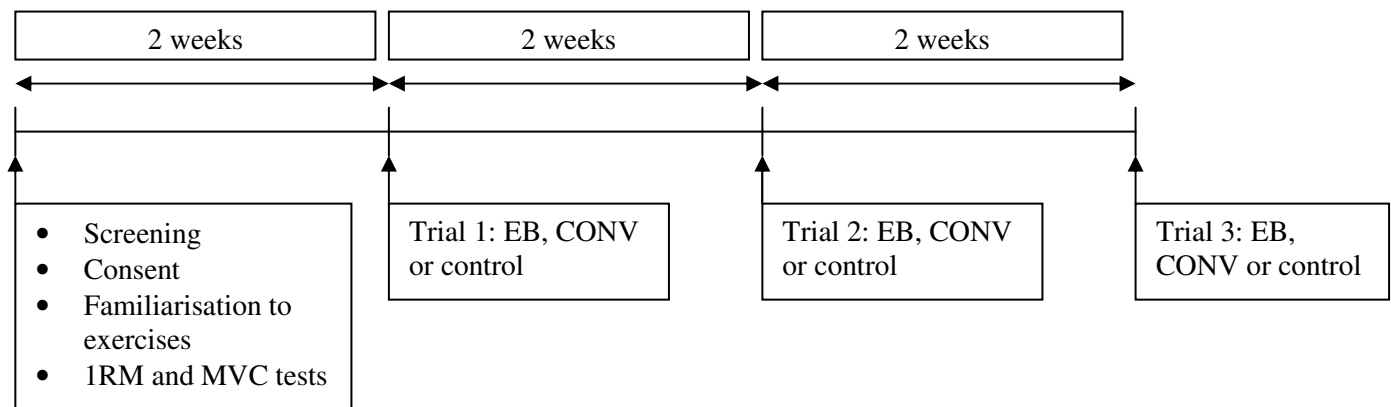
Figure 9. Overall study timeline. EB = eccentrically-biased resistance training; CONV = conventional resistance training; 1RM = one-repetition maximum test; MVC = maximum voluntary isometric contraction.

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┌─────────────────┐
│ EB, CONV or control │
│   (~45 minutes)    │
└─────────────────┘
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Baseline	Post (0 min)	Post (30 min)	Post (120 min)
• Blood sample • Arterial Stiffness • Postural control • Force steadiness	• Blood sample • Postural control • Force steadiness	• Arterial stiffness	• Blood sample
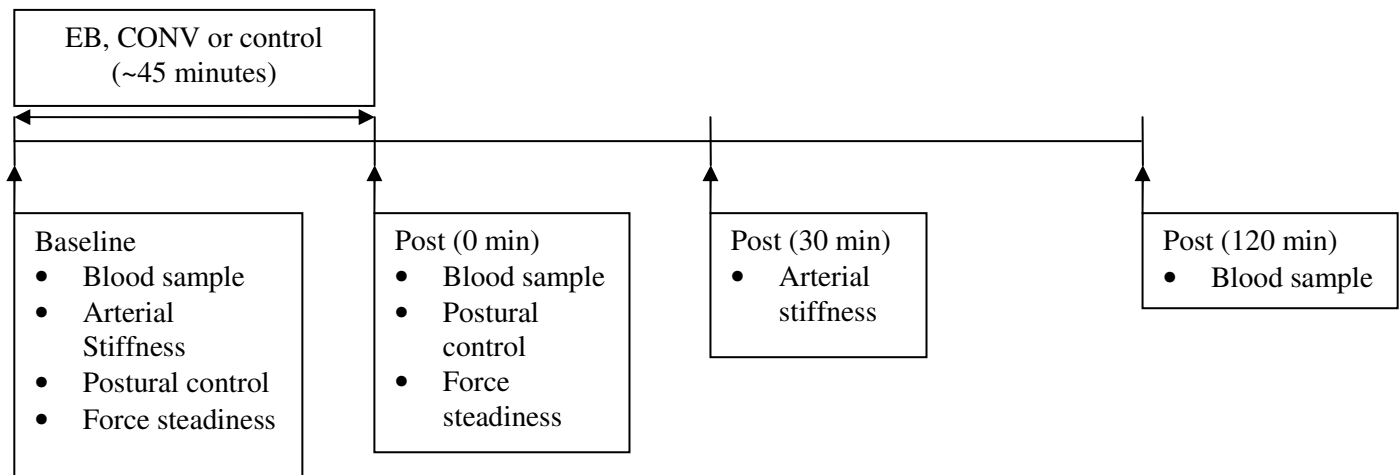
Figure 10. Trial timeline. EB = eccentrically-biased resistance training; CONV = conventional resistance training.

Resistance Training

The resistance training sessions consisted of four exercises: 45° leg press, toe press, bench press and latissimus dorsi pulldowns. For the toe press, participants sat on the leg press machine with knees fully extended and with the balls of their feet on the bottom edge of the foot-plate, lifted and lowered the resistance with the plantar flexors. Bench press was performed using a Smith machine and lat-pulldowns were performed on a pin-loaded machine with a 'V-bar' handgrip, comprising of two parallel handles approximately 9 cm apart. These exercises were chosen as they constitute a full-body workout commonly prescribed for older adults.

At the first session, participants were familiarised with each exercise and were instructed on proper technique. Participants then performed a bilateral 1RM test for each exercise. After each successful lift, the resistance was increased and participants were given at least one minute to recover before the next attempt. Small

increments of no more than 5 kg were used to improve the accuracy of 1RM determination. No more than five lifts were needed to determine 1RM.

For CONV, participants performed two sets of each exercise, with three minute rests between sets. Each set involved 10 completely bilateral repetitions at 75% of the 1RM. For EB, participants performed three sets of each exercise, with three minute rests between sets. Each set involved 10 concentric lifts performed bilaterally with 50% of the 1RM. Participants then lowered the weight unilaterally, alternating between left and right limbs with each repetition, thus performing five unilateral eccentric contractions per limb per set. The difference in the number of sets employed in CONV and EB in the current study was necessary to match the volume of work performed by each training group. The training protocols were designed to ensure that participants performed the same amount of work for each limb relative to individual 1RMs in EB and CONV (see Table 10). Actual total concentric work for each limb was calculated by multiplying the actual relative intensity (% of 1RM) by the number of repetitions performed in each set, then summing concentric work performed in each set over the whole training period. Actual total work (concentric and eccentric) for each limb was calculated by multiplying actual concentric work by 2.

Training method	Contraction mode	Sets	Reps	Relative Intensity[1]	Volume-load[2]
CONV	Concentric	2	10	75%	1500
	Eccentric (bilateral)	2	10	75%	1500
EB	Concentric	3	10	50%	1500
	Eccentric (unilateral)	3	5	100%	1500

Table 10. Volume-load in conventional and eccentrically-biased training
CONV = conventional resistance training; EB = eccentrically-biased training

1 Relative intensity = % of 1RM

2 Volume-load = sets × repetitions × relative intensity

Arterial Stiffness

Arterial stiffness was quantified from the pulse wave velocity (PWV). Reliability analyses on 13 healthy community-dwelling older adults (7 men and 6 women, average age 67 ± 5 years) revealed an ICC (95% CI) of 0.835 (0.427 – 0.953) and 95% ratio LOA (limits of agreement) of 23.29%. Participants lay supine for 20 minutes before digital pulse detectors were strapped to their right index finger and right second toe. A three-lead electrocardiogram was obtained concurrently to use as a reference point for each pulse. Data were collected for 5 minutes and sampled at 1000Hz (PowerLab 4/25; AD Instruments, Bella Vista, New South Wales, Australia). The difference between the distances from the sternal notch to the

index finger and the sternal notch to the second toe was taken as the difference in the distance travelled by the pulse wave. Five pulse waves, separated by 1 minute, were selected for analysis on a computer software program (Chart 5; ADInstruments, Bella Vista, New South Wales, Australia). The mean difference in time taken for the five separate pulse waves to travel from the sternal notch to finger versus the sternal notch to the toe was used to calculate PWV (m/s) using the following equation:

$$PWV = \Delta D / \Delta T$$

where ΔD is the distance in metres and ΔT is the time interval in seconds. The time interval between pulses was measured from the 'foot' of the waveforms. This method of determining pulse wave velocity has been validated by Tsai et al. (175). All PWV data was analysed by a single investigator.

Blood Sample Collection

A total of 16 ml of venous blood was collected from the antecubital vein at each blood sample collection timepoint into tri-potassium ethylene-diamine-tetra acetic acid (EDTA 1.8 mg/ml) and tri-sodium citrate (3.8%) tubes using a 21-gauge needle. Care was taken to ensure minimal platelet activation while drawing blood samples.

Platelet Reactivity

Platelet reactivity was evaluated using an optical aggregometer (Chrono-Log Corp, Model 700, Philadelphia, USA). Blood samples collected in tri-sodium citrate tubes were centrifuged (Beckman Coulter Allegra X-15R Centrifuge, Fullerton,

California) at 300×gravitational constant (G) for 10 minutes at a temperature of 21°C

to separate platelet rich plasma (PRP). Subsequently, the remaining contents of the

tube were centrifuged at 2500×G for ten minutes at a temperature of 21°C to obtain

platelet poor plasma (PPP). Five hundred micro litres of PRP was transferred to glass

cuvettes and heated to 37°C in the aggregometer for 5 minutes and subsequently

mixed separately with three agonists (arachidonic acid, adenosine triphosphate and

collagen) to trigger platelet-to-platelet aggregation. The final concentrations of

arachidonic acid, adenosine triphosphate and collagen in the solution equaled

0.5mM/L, 10μM/L and 2μg/mL respectively. Mixing was aided by adding

siliconised stir bars (Chrono-Log, Philidelphia, USA) to the solution. PPP was used

to calibrate the aggregometer to 100% aggregation. Data was recorded for six

minutes and the maximum levels of percent platelet aggregation with respect to PPP

(100% aggregation) were documented. The concentrations of agonists were

determined from pilot testing and were guided by standard concentrations

recommended by the distributors. Percent platelet aggregation was corrected for

plasma volume (38) to account for hydration status. Coefficients of variation,

calculated using the baseline data from the three conditions (EB, CONV and control)

for arachidonic acid, adenosine triphosphate and collagen were 2.54, 0.46 and 1.80%

respectively. A single investigator completed all analyses to reduce operator

dependant variability.

Platelet Activation

Platelet activation was evaluated using flow cytometry (93). Whole blood

samples collected in tri-sodium citrate tubes were diluted 1:5 in HEPES buffered

saline (pH 7.3) and incubated for 15 minutes with fluorescently labeled monoclonal

antibodies that bind to: integrin $\alpha_{IIb}\beta_3$ that has undergone conformational change due to platelet activation (PAC-1); P-selectin, which is only present on the surface of activated platelets that have undergone degranulation (CD62P); and CD42B, which is present on the surface of all platelets. The samples were then fixed with 1% formaldehyde before being analysed on a flow cytometer (BDFACS Canto 2, BD Biosciences, San Jose, California, USA). Platelets were identified by their characteristic forward and side scatter, and the presence of CD42A on their surface. Once identified, the percentage of platelets with PAC-1 and CD62P bound to their surface was determined by analysing 10 000 platelets at a rate of 50 – 100 events per second. Data were collected and stored on computer (BD FACSDiva Software, BD Biosciences, San Jose, California, USA). Coefficients of variation, calculated using the baseline data from the three conditions (EB, CONV and control) for percent platelets positive for PAC1 and CD62P were 35.30 and 23.88% respectively. A single investigator completed all analyses to reduce operator dependant variability.

Platelet Count

Blood samples collected in EDTA tubes were analysed for platelet count using an automated differential cell counter (Coulter AcT 5 Diff CP, Coulter Electronics Inc, Hialeah, Florida, USA). Platelet count was corrected for plasma volume (38) to account for hydration status. Coefficients of variation, calculated using the baseline data from the three conditions (EB, CONV and control) for platelet count was 0.79%.

Postural Stability

Participants stood quietly barefoot on a force-plate (Kistler Type 9286AA, Kistler Instruments, Winterthur, Switzerland) with their arms comfortably by their sides, their eyes fixed on a point in front of them, their feet abducted 10º and their heels separated medio-laterally by a distance of 6cm. Markings were made on the surface of the force plate to standardise the position of the feet (139). The force-plate was used to obtain the coordinates of the centre of pressure (COP) in the medial-lateral (x) and anterior-posterior (y) directions. Each trial lasted for 30s and data was sampled at a rate of 100Hz and stored on computer (BioWare 3, Kistler Instruments, Winterthur, Switzerland). However, analysis was performed using coordinate pairs obtained at consecutive 0.1s intervals so that a sampling frequency of 10Hz was simulated (139).

Displacement velocity (m/s) of each coordinate pair of the COP (Vd) was calculated using the following formula:

$$Vd = \frac{\sqrt{(x_i - x_{i-0.1})^2 + (y_i - y_{i-0.1})^2}}{t_i - t_{i-0.1}}$$

where x_i and y_i are a coordinate pair at time i.

Mean velocity of COP (Vm) was calculated as follows:

$$Vm = \frac{\sum Vd}{n}$$

where n is the number of paired observations.

Force Steadiness

Determination of maximum voluntary isometric strength

Maximum voluntary isometric knee extensor strength (MVC) of a randomly chosen limb was determined on a Biodex System 4 Quick Set dynamometer (Biodex Medical Systems, Shirley, New York, USA). Reliability analyses on 23 healthy

community-dwelling older adults (13 men and 10 women, average age 67.2 ± 5.6 years), revealed that the ICC (95% CI) for isometric strength test was 0.991 (0.978 – 0.996) and 95% ratio LOA was 9.87% (refer to Chapter 3, Table 6). Participants sat upright in the dynamometer secured by waist and torso straps. The dynamometer's axis of rotation was visually aligned with the lateral epicondyle of the femur. The dynamometer's ankle pad was positioned above the medial malleolus. The position of the seat base, seat back and length of lever arm were recorded at the first session and replicated for the subsequent trial sessions. Participants were instructed to hold onto handles positioned on either side of the seat during contractions. A standard warm-up of the quadriceps involving one set of six isometric contractions of increasing intensity was carried out before the test. Participants rested one minute between the warm-up and the commencement of the test. Maximum voluntary isometric contractions were performed at a knee joint angle of 60º. Participants performed five contractions with 30 seconds rest between each contraction. Participants were given loud verbal encouragement, and visual feedback of the torque signal in each repetition. Torque, corrected for limb weight, was sampled at a frequency of 1000Hz (PowerLab 4/25; AD Instruments, Bella Vista, New South Wales, Australia) and stored on computer. Torque was analysed on a computer software program (Chart 5; ADInstruments, Bella Vista, New South Wales, Australia). The torque data from the five contractions were averaged to determine 100% MVC.

Assessment of force steadiness

During trial sessions, participants underwent evaluations of steadiness of the knee extensors during isometric contractions at 50 and 10% of MVC. Participants sat

in the dynamometer in the same position as for the evaluation of MVC and the same limb used for evaluating MVC was used for quantifying steadiness of the knee extensors. Participants were asked to match the target torque level, which was displayed on a computer screen, as steadily and accurately as possible. Real-time visual feedback was provided by overlaying active torque over the target torque level on the screen. Participants were given two practice contractions at each intensity prior to two trial contractions, each lasting 30s. Participants were given 30s rest between contractions.

Since the first 7s and last 2s of each trial involved initiation and termination of the target torque, a 6s block of data beginning 7s after the start of the trial, was used for data analysis. All torque measures were normalised to each participant's MVC. Accuracy of torque production was evaluated by means of the normalised mean absolute error (NMAE), calculated as the average value of the absolute difference between torque produced and the target torque level. Force steadiness, or fluctuation, was evaluated by means of the normalised standard deviation of absolute error (NSAE), calculated as the standard deviation of the absolute difference between torque produced and the target torque level. Maximum deviation from the target torque level was evaluated by means of the normalised peak absolute error (NPAE) of the torque produced (155).

Statistical Analyses

Normality of the data was assessed using the Kolmogorov-Smirnov test, and non-normal data were natural log-transformed. Two-tailed paired samples *t*-tests were used to compare work done for each exercise and total work done in CONV and EB. Two-way (condition * time) repeated measures analyses of variance

(ANOVA) were used to evaluate any effect of EB, CONV or the control condition on arterial stiffness, platelet reactivity, platelet activation, platelet count, postural stability and force steadiness. Post-hoc tests with a Bonferroni correction were used to further analyse significant main interactions. Data are presented as mean ± standard deviation (SD). Results were considered significant at $P < 0.05$, and statistical analyses were performed using IBM SPSS Statistics 19.0 (IBM, Somers, NY). A priori power analysis based on the most conservative effect size of all outcome measures of 0.28 with regards to platelet activation data from flow cytometry (percentage of platelets positive for PAC1) revealed that 12 participants were needed to obtain statistical power of 0.95 (47).

RESULTS

Resistance Training Data

The estimates of amount of work performed in each exercise and total amount of work did not differ significantly between CONV and EB (see Table 11).

Table 11

Estimates of mean work overall and for each exercise

	Group	Work (A.U.)	P-value
Leg press	CONV	3000 ± 0	-
	EB	3000 ± 0	
Toe press	CONV	3009 ± 28	0.34
	EB	3000 ± 0	
Bench press	CONV	2876 ± 170	0.06
	EB	3168 ± 332	
Lat pulldown	CONV	2972 ± 101	0.91
	EB	2967 ± 105	
Overall	CONV	11857 ± 229	0.09
	EB	12134 ± 359	

CONV = conventional resistance training; EB = eccentrically-biased training; A.U. = arbitrary units. *P*-values are for two-tailed paired *t*-tests performed to compare work performed in EB and CONV. Dash indicates that *t*-test was not performed as values in EB and CONV were identical.

Arterial Stiffness

Pulse wave velocity data are summarised in Table 12. Data from eight participants were analysed as clear pulse wave traces were not obtainable in two participants. There was no significant difference ($P > 0.05$) in pulse wave velocity at baseline between the three conditions. No significant condition ($P = 0.45$), time ($P = 0.54$) or condition by time ($P = 0.13$) effect was observed.

Platelet Reactivity

Platelet aggregometry data are summarised in Table 12. For arachidonic acid, data from eight participants were analysed while for adenosine diphosphate and collagen data from six participants were analysed due to haemolysis of samples or participants declining to have blood samples taken. There was no significant difference ($P > 0.05$) in platelet reactivity to all three agonists at baseline between the three conditions. No significant condition ($P = 0.75$), time ($P = 0.89$) or condition by time ($P = 0.26$) effect was observed for arachidonic acid. No significant condition ($P = 0.74$), time ($P = 0.69$) or condition by time ($P = 0.80$) effect was observed for adenosine diphosphate. No significant condition ($P = 0.93$), time ($P = 0.72$) or condition by time ($P = 0.95$) effect was observed for collagen.

Platelet Activation

Flow cytometry data are summarised in Table 12. Data from seven participants were analysed due to sample haemolysis or participants declining to have blood samples taken. There was no significant difference ($P > 0.05$) in percent platelets positive for PAC-1 or CD62P at baseline between the three conditions. No significant condition ($P = 0.16$), time ($P = 0.41$) or condition by time ($P = 0.08$)

effect was observed for percent platelets positive for PAC-1. No significant condition ($P = 0.45$), time ($P = 0.44$) or condition by time ($P = 0.57$) effect was observed for percent platelets positive for CD62P.

Platelet Count

Platelet count data are summarised in Table 12. Data from eight participants were analysed due to two participants declining to have blood samples taken. There was no significant difference ($P > 0.05$) in platelet count at baseline between the three conditions. A significant condition by time effect ($P < 0.05$) was observed. Post-hoc tests revealed that platelet count in the control condition decreased significantly ($P < 0.05$) from baseline to immediately post-control while not changing significantly in CONV ($P = 0.25$) or EB ($P = 0.23$). Platelet count was significantly higher ($P < 0.05$) in EB than in the control condition immediately post resistance training. Mean platelet count immediately after CONV was also higher than the control condition, but this difference was not statistically significant ($P = 0.09$).

Table 12

Changes in pulse wave velocity, and platelet reactivity, activation and count

	Condition	Baseline	Post 0	Post 120
Pulse wave velocity (m/s)	CONV	9.2 ± 2.3	11.1 ± 3.3	
	EB	10.6 ± 2.5	11.4 ± 4.6	
	Control	10.7 ± 2.6	9.3 ± 3.4	
AA (%)	CONV	84.1 ± 3.6	84.9 ± 6.3	85.4 ± 6.7
	EB	86.1 ± 7.8	87.7 ± 6.5	85.7 ± 7.1
	Control	88.5 ± 11.6	83.0 ± 6.8	85.8 ± 5.2
ADP (%)	CONV	84.5 ± 9.6	81.6 ± 8.2	80.5 ± 6.7
	EB	83.8 ± 8.8	84.1 ± 10.4	81.7 ± 7.5
	Control	84.5 ± 5.6	81.4 ± 6.4	85.1 ± 13.3
Collagen (%)	CONV	81.3 ± 4.1	85.0 ± 7.5	84.6 ± 5.5
	EB	84.0 ± 5.7	85.5 ± 8.2	84.4 ± 9.8
	Control	83.8 ± 6.3	83.9 ± 8.5	83.2 ± 10.7
Platelet count (10^9/L)	CONV	224 ± 46	232 ± 44	235 ± 35
	EB	224 ± 37	232 ± 32	228 ± 30
	Control	221 ± 36	206 ± 29*	217 ± 32
% Positive PAC-1	CONV	7.3 ± 4.9	6.6 ± 4.4	10.0 ± 6.2
	EB	4.0 ± 1.4	6.1 ± 3.5	5.4 ± 4.3
	Control	4.3 ± 3.3	6.0 ± 5.8	6.0 ± 6.1
% Positive CD62P	CONV	2.1 ± 1.1	2.0 ± 0.7	1.9 ± 0.5
	EB	1.5 ± 0.7	1.8 ± 0.6	1.5 ± 0.6
	Control	2.5 ± 1.9	2.5 ± 1.7	1.7 ± 1.1

Data presented as mean ± SD; AA = percent aggregation in response to arachidonic acid; ADP = percent aggregation in response to adenosine diphosphate; Collagen = percent aggregation in response to collagen; Post 0 = immediately post training; Post 120 = 2 hours post training. Asterisks indicate significant difference from baseline (*$P < 0.05$).

Postural Stability

Mean velocity of COP data is summarised in Table 13. Data from eight participants were analysed as data from two participants was incorrectly collected due to a computer malfunction. There was no significant difference ($P > 0.05$) in Vm at baseline between the three conditions. A significant condition by time ($P < 0.05$) interaction was observed. Post-hoc tests revealed that Vm decreased non-significantly in CONV ($P = 0.09$) and control ($P = 0.28$) while the mean increased, albeit not being statistically significant, in EB ($P = 0.22$).

Force Steadiness

Force steadiness and accuracy data is summarised in Table 13. Data from nine participants were analysed due to loss of data from one participant. There were no significant differences ($P > 0.05$) in 50% MVC NMAE, 50% MVC NSAE, 50% MVC NPAE, 10% MVC NMAE and 10% MVC NPAE. However, there was a significant difference between CONV and EB in 10% MVC NSAE at baseline ($P = 0.03$).

There were no significant condition ($P = 0.40$), time ($P = 0.11$) or condition by time ($P = 0.44$) effects for 50% MVC NMAE. There were no significant condition ($P = 0.80$), time ($P = 0.69$) or condition by time ($P = 0.72$) effects for 50% MVC NSAE. There were no significant condition ($P = 0.49$), time ($P = 0.27$) or condition by time ($P = 0.84$) effects for 50% MVC NPAE. There were no significant condition ($P = 0.12$), time ($P = 0.99$) or condition by time ($P = 0.37$) effects for 10% MVC NMAE. There were no significant condition ($P = 0.24$), time ($P = 0.66$) or condition by time ($P = 0.58$) effects for 10% MVC NPAE. However, there was a significant condition effect for 10% MVC NSAE ($P < 0.01$). Post-hoc tests revealed

that this was due to the significant difference between CONV and EB at baseline (P < 0.05).

Table 13

Changes in mean displacement velocity and force steadiness measures

	Condition	Baseline	Post	% Diff
$Vm \times 10^{-3}$ (m/s)	CONV	3.02 ± 1.24	2.75 ± 1.00	-9
	EB	2.82 ± 1.16	3.26 ± 1.72	16
	Control	3.17 ± 1.29	2.89 ± 1.16	-9
50% MVC NMAE ($\times 10^{-2}$)	CONV	1.75 ± 0.95	2.10 ± 0.73	20
	EB	1.80 ± 1.38	1.57 ± 0.51	-13
	Control	2.03 ± 1.20	2.06 ± 0.93	1
50% MVC NSAE ($\times 10^{-2}$)	CONV	0.95 ± 0.43	0.87 ± 0.31	-9
	EB	0.87 ± 0.52	0.90 ± 0.31	3
	Control	0.95 ± 0.35	0.92 ± 0.34	-2
50% MVC NPAE ($\times 10^{-2}$)	CONV	4.17 ± 1.87	4.27 ± 1.47	3
	EB	3.97 ± 2.23	4.03 ± 1.27	2
	Control	4.40 ± 1.54	4.51 ± 1.80	3
10% MVC NMAE ($\times 10^{-2}$)	CONV	0.83 ± 0.45	1.03 ± 0.76	25
	EB	0.74 ± 0.49	0.74 ± 0.42	0
	Control	1.51 ± 1.79	1.35 ± 1.62	-11
10% MVC NSAE ($\times 10^{-2}$)	CONV	0.29 ± 0.12	0.29 ± 0.10	0
	EB	0.19 ± 0.08	0.24 ± 0.07	23
	Control	0.20 ± 0.12	0.20 ± 0.08	-1
10% MVC NPAE ($\times 10^{-2}$)	CONV	1.53 ± 0.52	1.70 ± 0.87	11
	EB	1.26 ± 0.63	1.36 ± 0.41	8
	Control	1.94 ± 1.80	1.89 ± 1.65	22

Data presented as mean ± SD; Vm = mean velocity of centre of pressure; MVC = maximum voluntary isometric contraction; NMAE = normalised mean absolute error of torque produced with respect to target torque level; NSAE = normalised standard deviation of absolute error; NPAE = normalised peak absolute error. Asterisks indicate significant difference from baseline (*$P < 0.05$).

DISCUSSION

The current study is the first to compare the acute effects of eccentrically-biased and conventional resistance exercise on arterial stiffness, platelet function and count, postural stability and knee extensor force steadiness in older adults. The baseline data for arterial stiffness, platelet aggregometry and count, mean velocity of COP displacement and force steadiness parameters agree well with those observed in previous studies (2, 139, 155, 175).

The lack of change in pulse wave velocity immediately after resistance exercise observed in the current study is in contrast to the results of previous studies that have observed an increase in arterial stiffness (9, 33, 37, 185). One reason for this discrepancy could be that previous studies that observed increases in arterial stiffness following resistance exercise measured central arterial stiffness, while the method used in the current study takes into account peripheral as well as central arteries. Heffernan et al. (61) found that peripheral arterial stiffness decreased in the exercised limb following resistance exercise. Therefore, there is a possibility that if opposing changes in central and peripheral arterial stiffness occurred, they may have nullified each other and consequently no overall changes in arterial stiffness were detected. Also, differences in the resistance training protocols employed in the previously referred to studies (7) that observed an increase in arterial stiffness compared to the current study may partly explain the difference in results. For example, DeVan et al. (37) employed an exercise protocol consisting of nine exercises performed at 75% of 1RM to exhaustion. In the current study, participants performed 10 repetitions of four exercises at 75% of 1RM in CONV, but not necessarily to exhaustion. MacDougall, Tuxen, Sale, Moroz, and Sutton (99) have shown that for two training protocols utilising equivalent relative intensities, the

protocol that requires the greater number of repetitions per set elicits a greater blood pressure response, which may lead to increased arterial stiffness (37).

The lack of change in platelet aggregation in response to selected agonists following resistance exercise in the current study is also in contrast to the increase observed in previous studies (2, 4). However, in order to be able to draw accurate conclusions with regards to the effect of resistance exercise on platelet aggregation, data should be corrected for plasma volume in order to account for hydration status (169). When platelet aggregation was corrected for plasma volume in the previous studies, no changes in platelet aggregation were observed (2, 4). This was also the conclusion of Ahmadizad, El-Sayed, and MacLaren (3), who also found no change in platelet aggregation corrected for plasma volume after resistance exercise.

There have been no previous studies investigating the effects of resistance exercise on platelet activation by means of flow cytometry. However, Ahmadizad et al. (4) measured plasma concentrations of beta-thromboglobulin, a soluble marker of platelet activation, and found no change in its concentration following resistance exercise after correcting for plasma volume. This finding agrees with our observations of no change in the percentage of platelets expressing PAC-1 or CD62P following CONV or EB.

The finding of higher platelet count immediately after EB and CONV when compared to the control condition agrees with the results of previous studies showing an increase in platelet count following resistance exercise (2-4). This is most likely due to a release of fresh platelets from the spleen and bone marrow during resistance exercise (150). Although increased platelet count may be associated with cardiovascular disease (44), heavy resistance exercise is generally well-tolerated

among older adults and the evidence suggests that the benefits of resistance training outweigh the risks (30, 168).

The finding that the mean velocity of centre of pressure did not change significantly after CONV is in contrast to that observed by Moore et al. (105), who reported a decline in postural control immediately after resistance exercise in older adults. However, the training protocol employed by Moore et al. (105) consisted of six exercises, all for the legs, and designed to fatigue the leg muscles. In contrast, the resistance training protocol employed in the current study was designed to replicate a typical resistance training session an older adult may undertake for muscle mass and strength gain. Therefore, the training protocol in the current study may have led to less fatigue of the leg muscles than the training protocol employed by Moore et al. (105), thereby explaining the lack of a significant change in Vm in CONV. Although the increase in Vm in EB and decrease in CONV and the control condition were not statistically significant, there was a significant condition by time interaction. This indicates that EB may elicit greater postural instability in older adults than CONV. A possible reason for this may be the higher intensity during eccentric contractions in EB than CONV, which may have led to greater muscle disruption (89). This may increase the risk of an adverse event such as a fall immediately after resistance exercise. However, it should be noted that the participants in the current study were unconditioned, so would most likely become more accustomed to eccentrically-biased exercise with training over time. Therefore, any increased risk of falls might be transient.

The lack of change in submaximal knee extensor isometric force accuracy and steadiness after EB and CONV is in contrast to the decreased accuracy and steadiness observed by Singh et al. (155) after 11 sets of 8 repetitions of squats in

young adults. Again, this discrepancy can be explained by the larger training volume for the legs employed by Singh et al. (155) as compared to the current study. The current exercise volumes are more realistic and have proven effective in increasing strength in this population, as shown in Chapter 6.

One limitation of the current study is that it is underpowered, as the required number of participants was not achieved. However, the current study was powered to show an effect size of 0.28 or greater. Therefore, it could be speculated that while the current study cannot rule out effect sizes smaller than 0.28, such small effect sizes would be unlikely to be of clinical significance.

Conclusion

Overall, the results suggest that conventional and eccentrically-biased resistance exercise do not seem to have any acute adverse effect on platelet function, arterial stiffness, knee extensor force steadiness in older adults. However, the possibility of increased platelet count after both training modalities and decreased postural stability after eccentrically-biased training mean that older adults should exercise caution with regards to cardiovascular events and balance immediately after a resistance training session.

SUBSEQUENT STEPS

With the knowledge gained from the previous study with regards to the safety of eccentrically-biased and conventional resistance training for older adults, the intervention study was conducted. The aim of the next study was to compare the effectiveness of 16 weeks of eccentrically-biased versus conventional resistance training in older adults.

CHAPTER 6: The Chronic Effects of Eccentrically-biased versus Conventional Resistance Training in Older Adults

An earlier version of this chapter has been accepted for publication:

Raj IS, Bird SR, Westfold BA, Shield AJ. Effects of eccentrically-biased versus conventional weight training in older adults. *Medicine and Science in Sports and Exercise*.

ABSTRACT

Introduction: The effects 16-weeks of eccentrically-biased (EB) versus conventional (CONV) resistance training on: muscle architecture, 1 repetition maximum (1RM), isometric strength, isokinetic force-velocity characteristics, functional capacity and pulse wave velocity (PWV) in older men and women was compared.

Methods: Twenty-eight older adults participated in the study (mean±S.D; age 68±5 years). Of these, 13 were allocated to a wait-list control, 10 of whom progressed to training (CONV n=12; EB n=13). Training was twice a week for 16 weeks. EB involved three sets of 10 concentric lifts at 50% of 1RM with the eccentric portion of repetitions performed unilaterally, alternating between limbs with each repetition. CONV involved two sets of 10 repetitions at 75% of 1RM. EB and CONV were matched for total work. Isokinetic knee extensor strength was assessed across a range of velocities (0-360º/s). Functional capacity was assessed via 6 metre fast walk (6MFWT), timed up and go (TUG), stair climb and descent power and vertical jump tests. Vastus lateralis and gastrocnemius medialis architecture were assessed using ultrasonography.

Results: Both EB and CONV improved 1RM (Δ23-35%, $P<0.01$). Compared to the control group, both training regimens improved 6MFWT (Δ5-7%, $P<0.01$) and concentric torque at 60º/s and 120º/s (Δ6-8%, $P<0.05$). Significant improvements were evident in EB for: isometric and concentric torque at 240º/s and 360º/s (Δ6-11%, $P<0.05$), vastus lateralis thickness (Δ5%, $P<0.05$) and stair climb (Δ5%,

$P<0.01$). TUG (Δ5%, $P<0.01$), stair descent (Δ4%, $P<0.05$) and vertical jump (Δ7%, $P<0.01$) improved in CONV. PWV, pennation angle and fascicle length remained unchanged in both training groups.

Conclusion: Both training modalities were effective at increasing torque at slow contraction velocities but EB appears superior to CONV at increasing torque at high contraction velocities while CONV appears more effective at improving some functional performance measures and vertical jump. This has important implications for preserving functional capacity.

INTRODUCTION

For the reasons outlined in the thesis introduction (Chapter 1), this study was designed to compare the effects of 16 weeks of eccentrically-biased versus conventional resistance training in older adults.

It was hypothesised that eccentrically-biased resistance training (EB) would lead to a greater increase in fascicle length and muscle thickness of the knee extensors and plantar flexors while also increasing concentric knee extensor strength of older adults at fast contraction speeds to a greater extent than conventional resistance training (CONV). This study also sought to compare the effects of EB and CONV on functional capacity and pulse wave velocity (PWV).

METHODS

Participants

Twenty-eight community-dwelling older adults (17 males and 11 females) participated in this study (see Figure 11). Of these, seven males and six females were assigned to the wait-list control group (mean ± S.D. age, 67 ± 5 years; body mass, 78.7 ± 13.7 kg; height, 167.0 ± 8.6 cm), 10 of whom progressed to one of the two training groups. Seven males and five females performed CONV (age, 68 ± 5 years; body mass, 77.8 ± 15.5 kg; height, 168.3 ± 11.6 cm), and eight males and five females performed EB (age, 68 ± 5 years; body mass, 77.4 ± 13.4 kg; height, 167.8 ± 8.8 cm). Participants were excluded from the study if they had relevant cardiovascular or orthopaedic problems or if they had undertaken any resistance training in the preceding six months. Written informed consent was obtained from all participants before entry into the study, which was approved by the University Human Research Ethics Committee.
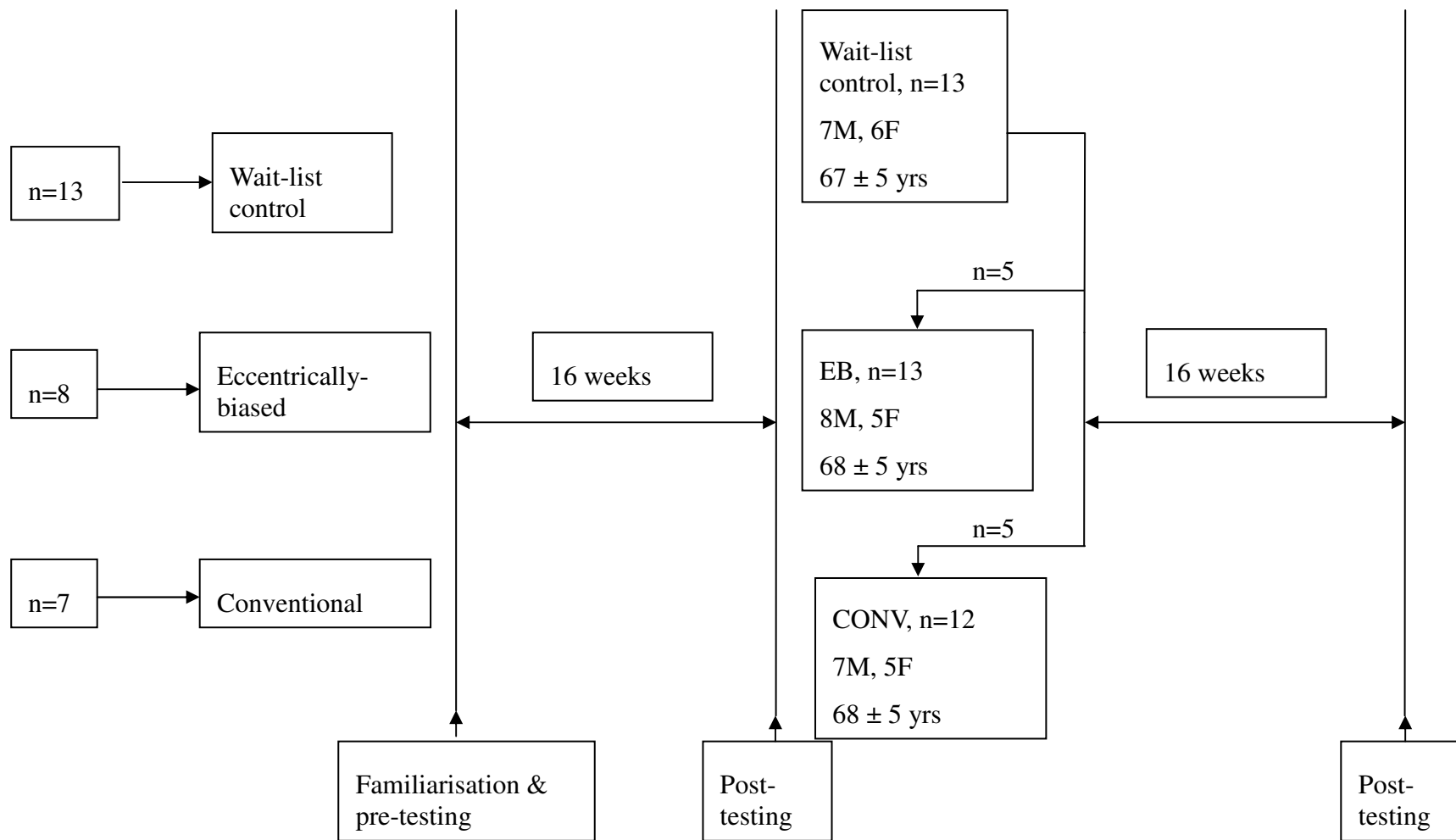
Figure 11. Participant allocation and study design.

Study Design

A randomised controlled design was used for this study (see Figure 11). To reduce any potential bias of sex and age, participants were stratified according to age (60 to 70 and 71 to 80 years old) and gender before being randomly assigned to CONV, EB or a wait-list control group. Participants randomised to EB and CONV underwent pre-training testing of isometric and isokinetic knee extensor strength, quadriceps and medial gastrocnemius muscle architecture, arterial stiffness and functional capacity. Prior to baseline testing participants attended the laboratory on two occasions to be familiarised with the isometric and isokinetic strength and functional capacity tests. The familiarisation sessions and test session were separated by seven to 14 days. Participants then commenced the 16-week resistance training program, after which they underwent post-training testing. Participants randomised to the wait-list control group underwent pre-control testing and were then instructed to maintain their regular level of physical activity and avoid heavy resistance training for 16 weeks before post-control testing. They were then randomised to either EB or CONV and performed 16 weeks of resistance training before post-training testing.

Resistance Training

EB and CONV participants performed resistance training twice weekly on non-consecutive days for 16 weeks. Both programs consisted of the 45° leg press, toe press, bench press and latissimus dorsi pulldown exercises. For the toe press, participants sat on the leg press machine with knees fully extended and with the balls of their feet on the bottom edge of the foot-plate, lifted and lowered the resistance with the plantar flexors. Bench press was performed using a Smith machine and lat-

pulldowns were performed on a pin-loaded machine with a 'V-bar' handgrip, comprising of two parallel handles approximately 9 cm apart.

At the first training session, participants were familiarised with each exercise and were instructed on proper technique. Participants then performed a 1RM test for each exercise. After each successful lift, participants were given at least one minute to recover before the next attempt. No more than five lifts were needed to determine 1RM. 1RM tests were repeated two weeks later, then every three weeks subsequently and training weights were adjusted accordingly. When 1RM tests were performed, one less set than usual of each exercise was performed.

CONV participants performed two sets of each exercise, with three minute rests between sets. Each set involved 10 completely bilateral repetitions at 75% of the 1RM. For EB, participants performed three sets of each exercise, with three minute rests between sets. Each set involved 10 concentric lifts performed bilaterally with 50% of the 1RM. Participants then lowered the weight unilaterally, alternating between left and right limbs with each repetition, thus performing five unilateral eccentric contractions per limb per set. The difference in the number of sets employed by CONV and EB in the current study was necessary to match the volume of work performed by each training group. The training protocols were designed to ensure that participants in EB and CONV performed the same amount of work for each limb relative to individual 1RMs (see Table 14). Actual total concentric work for each limb was calculated by multiplying the actual relative intensity (% of 1RM) by the number of repetitions performed in each set, then summing concentric work performed in each set over the whole training period. Actual total work (concentric and eccentric) for each limb was calculated by multiplying actual concentric work by 2.

Table 14. Volume-load in conventional and eccentrically-biased training.

Training method	Contraction mode	Sets	Reps	Relative Intensity[1]	Volume-load[2]
CONV	Concentric	2	10	75%	1500
	Eccentric (bilateral)	2	10	75%	1500
EB	Concentric	3	10	50%	1500
	Eccentric (unilateral)	3	5	100%	1500

CONV = conventional resistance training; EB = eccentrically-biased training

1 Relative intensity = % of 1RM

2 Volume-load = sets × repetitions × relative intensity

Rating of Perceived Exertion

Borg's Rating of Perceived Exertion (RPE) Scale with values from 6 – 20 (21) was used to obtain RPE after each set of exercise throughout the 16 weeks. Mean RPE for each exercise for each participant was then calculated. Mean RPE for each exercise in weeks 4, 8, 12 and 16 of training were also calculated.

Pulse Wave Velocity

Arterial stiffness was quantified from the pulse wave velocity (PWV) prior to strength and functional capacity tests. Reliability analyses on the data from the control group revealed an ICC (95% CI) of 0.835 (0.427 – 0.953) and 95% ratio LOA (limits of agreement) of 23.29%. Participants lay supine for 20 minutes before digital pulse detectors were strapped to their right index finger and right second toe.

A three-lead electrocardiogram was obtained concurrently to use as a reference point for each pulse. Data were collected for 15 minutes and sampled at 1000Hz. The difference between the distances from the sternal notch to the index finger and the sternal notch to the second toe was taken as the difference in the distance travelled by the pulse wave. Five pulse waves, separated by 1 minute, were selected for analysis on a computer software program (Chart 5; ADInstruments, Bella Vista, New South Wales, Australia). The mean difference in time taken for the five separate pulse waves to travel from the sternal notch to finger versus the sternal notch to the toe was used to calculate PWV (m/s) using the following equation:

$$PWV = \Delta D / \Delta T$$

where ΔD is the distance in metres and ΔT is the time interval in seconds. The time interval between pulses was measured from the 'foot' of the waveforms. Timing was made from the 'foot' of the waveforms (57). All PWV data were analysed by a single investigator.

Muscle Architecture

Real-time B-mode ultrasonography (LOGIQ I, GE Healthcare, Wauwatosa, Wisconsin, USA) with a 42 mm long, 10 MHz linear-array transducer, was used to measure fascicle pennation angle, fascicle length and muscle thickness of the vastus lateralis (VL) and medial gastrocnemius (GM) muscles on a single randomly chosen limb. The reliability of the following protocol for measuring VL and GM architecture has been previously demonstrated in Chapter 4 (136). A single investigator acquired

the images from all participants. A second investigator, who was blinded to the identity of the participants, was then employed to analyse the images.

Ultrasound images were obtained from sites 62% along the length between the anterior superior iliac spine and the superior aspect of the patella in the mid-sagittal (VL site 1) and mid-coronal (VL site 2) planes of the thigh. Participants were seated on the edge of the bench with knee angles fixed at 90º, a position associated with minimal fascicle curvature (18).

Medial gastrocnemius architecture and thickness were measured 30% of the distance between the lateral malleolus of the fibula and the lateral condyle of the tibia while participants lay prone on the bench with their feet hanging off the edge (113) in a modified night splint that fixed the ankle at 15º of dorsiflexion. Consistent positioning of the ultrasound transducer before and after training was obtained by use of a transparent plastic sheet onto which the examination sites and any permanent skin blemishes were marked (18). Three ultrasound images from each site were recorded digitally and analysed using freely available software (ImageJ 1.38x, National Institutes of Health, USA).

Quadriceps thickness was defined as the distance between the superficial aponeurosis and the femur, and medial gastrocnemius muscle thickness was defined as the distance between the superficial and deep aponeuroses. Pennation angle was determined between the muscle fascicles and the deep aponeurosis, and fascicle length was measured between its insertions on the superficial and deep aponeuroses. Where the fascicles extended beyond the recorded image, their length was estimated from muscle thickness and fascicle pennation angle using the equation (1):

$$L_f = T \times \sin\theta^{-1}$$

where L_f is fascicle length, T is muscle thickness and θ is pennation angle.

Isokinetic and Isometric Testing

Isokinetic and isometric knee extensor strength of a randomly chosen limb was determined on a Biodex System 4 Quick Set dynamometer (Biodex Medical Systems, Shirley, New York, USA). Reliability analyses on 23 healthy community-dwelling older adults (13 men and 10 women, average age 67.2 ± 5.6 years), 13 of whom participated in the current study, revealed that the ICCs (95% CI) for the dynamometer strength tests were: Isometric = 0.991 (0.978 – 0.996); 60º/s = 0.976 (0.943 – 0.990); 120º/s = 0.982 (0.958 – 0.992); 240º/s = 0.984 (0.962 – 0.993); 360º/s = 0.984 (0.960 – 0.993). 95% ratio LOAs for the isometric, 60º/s, 120º/s, 240º/s and 360º/s dynamometer tests were 9.87, 20.28, 20.92, 18.21 and 14.91% respectively (refer to Chapter 3, Table 6).

Participants sat upright in the dynamometer secured by waist and torso straps. The dynamometer's axis of rotation was visually aligned with the lateral epicondyle of the femur. The dynamometer's ankle pad was positioned above the medial malleolus. The position of the seat base, seat back and length of lever arm were recorded at the first familiarisation session and replicated for the subsequent familiarisation and testing sessions. Participants were instructed to hold onto handles positioned on either side of the seat during contractions.

A standard warm-up of the quadriceps, involving two sets of six concentric efforts at 30º/s was carried out before each session. Participants rested one minute between the warm-up and the commencement of the test. The test consisted of maximal concentric contractions at 60, 120, 240 and 360º/s, and isometric contractions (0º/s). One of five different test sequences, each with a different order of contraction speeds, was randomly assigned to participants at the first familiarisation session and used for all subsequent sessions. Isokinetic contractions were performed

between knee joint angles of 105º to 5º, with 0º representing full extension. Isometric contractions were performed at a knee joint angle of 60º. Participants performed five contractions at each speed with 30 seconds rest between each contraction and one minute rest between speeds. Participants were given loud verbal encouragement, and visual feedback of the torque signal in each repetition.

Torque, corrected for limb weight, was sampled at a frequency of 1000Hz (PowerLab 4/25; AD Instruments, Bella Vista, New South Wales, Australia) and stored on computer. Only torques from the isokinetic portion of each dynamic contraction were analysed on a computer software program (Chart 5; ADInstruments, Bella Vista, New South Wales, Australia). The torque data from the five contractions performed at each velocity were averaged and used for statistical analysis.

Functional and Vertical Jump Tests

Five functional tests were undertaken. They were: the 6 metre fast walk test (6MFWT), the Timed Up and Go test (TUG), stair climb and stair descent power tests, and the vertical jump test. Reliability analyses on 23 healthy community-dwelling older adults (13 men and 10 women, average age 67.2 ± 5.6 years), 13 of whom participated in the current study, revealed that the ICCs (95% CI) were: 6MFWT = 0.952 (0.886 – 0.980); TUG = 0.979 (0.951 – 0.991); Stair climb = 0.997 (0.992 – 0.999); stair descent = 0.989 (0.974 – 0.995); vertical jump = 0.988 (0.971 – 0.995). 95% ratio LOAs for the 6MFWT, TUG, stair climb, stair descent and vertical jump tests were 14.32, 10.36, 7.28, 13.72, and 13.53% respectively (refer to Chapter 3, Table 6).

The 6 metre fast walk test, performed between two sets of light gates, involved the timing of participants as they walked as quickly as possible (49, 63).

The Timed Up and Go test measures the time taken for an individual to rise from a chair, walk 3 metres to touch a marker on a wall, turn 180 degrees, return to the chair, and sit down (22). Time was recorded by stopwatch. Participants were instructed not to use their hands when rising from or sitting back down on the chair.

The stair climb and descent power tests involved participants climbing and descending a flight of stairs as quickly as possible (98). This measure of stair descent performance is a pseudo representation of stair descent power since displacement is negative during stair descent. Stair climb and descent time were assessed separately using a stopwatch. The flight of stairs utilised in this study comprised of 16 steps, each with a height of 15cm. The participants were not allowed to hold the handrails during this test. Stair climb and descent power were calculated using the following equation:

$$Power(W) = \frac{m \times g \times d}{t}$$

Where m is the mass (kg) of the participant, g is acceleration (m/s^2) due to gravity, d is vertical displacement (m) and t is stair climb or descent time (s).

The vertical jump test was performed on a force plate (Kistler Type 9286AA, Kistler Instruments, Winterthur, Switzerland). Participants were instructed to stand on the force plate with both feet shoulder width apart, perform a counter-movement by bending the knees, then jump as high as possible. Arm swing was allowed during performance of the jump. Vertical jump height and peak jumping power were estimated from vertical take-off velocity derived from impulse data by means of data analysis software (BioWare 3, Kistler Instruments, Winterthur, Switzerland). Methods for signal sampling are described elsewhere (29).

Participants performed each functional and vertical jump test three times during familiarisation and test sessions. The average of the three results from each

test was used for statistical analysis. All functional capacity and vertical jump tests were supervised by the same investigator.

Statistical Analyses

Normality of the data were assessed using the Kolmogorov-Smirnov test, and non-normal data were natural log-transformed. One-way ANOVAs were used to determine whether there were any differences between groups for any of the variables at baseline. Repeated measures ANOVAs were used to determine differences in RPE for each exercise between weeks 4, 8, 12 and 16. Two-way (group * time) analyses of variance (ANOVA) were used to determine any effect of the exercise interventions on arterial stiffness, muscle architecture, isometric and isokinetic strength, angle of peak torque, functional capacity and 1RM. Two-way (group * velocity) analyses of variance (ANOVA) were also used to evaluate if the exercise interventions differed in their efficacy at differing isokinetic speeds. Post-hoc tests with a Bonferroni correction were used to further analyse significant main interactions. Two-tailed unpaired t-tests were used to determine whether there were any differences in RPE and work performed between training groups. Data are presented as mean ± standard deviation (SD). Results were considered significant at $P < 0.05$, and statistical analyses were performed using IBM SPSS Statistics 19.0 (IBM, Somers, NY). A priori power analysis based on the most conservative effect size of 0.34 with regards to dynamometer tests of strength (torque data at $60^{\circ} \cdot s^{-1}$) revealed that 13 participants were needed per group to obtain statistical power of 0.95 (47).

RESULTS

Three participants assigned to the wait-list control group decided not to participate in the resistance training intervention. The other 10 participants from the wait-list control group were randomly assigned to either EB or CONV after the control period. There were no significant differences between the three groups with regards to any variables at baseline.

Resistance Training Data

Estimates of total work performed by each limb for leg press, toe press, bench press and latissimus dorsi pulldowns were not significantly different between EB and CONV (see Table 15). EB and CONV participants completed 95.9% and 95.8% of the total planned training sessions, respectively. Changes in 1RM as a result of training are summarised in Table 16. Significant time effects were observed for changes in 1RM for all exercises ($P < 0.01$). Post-hoc tests revealed significant differences ($P < 0.01$) between pre- and post-training 1RM for all exercises in both exercise groups. There were no significant group by time effects for 1RM between EB and CONV for any exercise, indicating that there was no significant difference between training modalities with regards to changes in 1RM.

Table 15

Estimates of total work for each limb

	Group	Total work (A.U.)	*P*-value
Leg press	CONV	76320 ± 6147	0.17
	EB	79507 ± 4876	
Toe press	CONV	74623 ± 8296	0.18
	EB	78463 ± 5396	
Bench press	CONV	75244 ± 6098	0.77
	EB	73866 ± 15012	
Lat pulldown	CONV	75673 ± 5199	0.34
	EB	77685 ± 5122	

Data are mean and SD. CONV = conventional resistance training; EB = eccentrically-biased training; A.U. = arbitrary units. *P*-values are for two-tailed independent *t*-tests performed to compare total work performed both groups.

Table 16

Changes in 1RM as a result of training

	Group	Pre-training	Post-training	% Difference
Leg press 1RM (kg)	CONV	159 ± 38	195 ± 45	23**
	EB	171 ± 51	211 ± 61	23**
Toe press 1RM (kg)	CONV	200 ± 50	263 ± 64	31**
	EB	196 ± 37	265 ± 54	35**
Bench press 1RM (kg)	CONV	36 ± 13	46 ± 15	30**
	EB	37 ± 14	47 ± 14	24**
Lat pulldown 1RM (kg)	CONV	48 ± 17	58 ± 18	23**
	EB	50 ± 14	61 ± 15	24**

Data presented as mean ± SD; 1RM = one repetition maximum; % Difference = percentage difference between pre- and post-training data. Asterisks indicate significant difference between pre- and post- training (**$P < 0.01$).

Rating of Perceived Exertion

Mean RPE for each set tended to be higher in CONV than EB for all exercises. This difference was non-significant for leg press (12.8 ± 1.6 versus 12.5 ± 1.4 respectively; $P = 0.59$) and toe press (13.3 ± 1.8 versus 12.2 ± 1.4; $P = 0.11$), but statistically significant for bench press (14.8 ± 2.0 versus 13.3 ± 1.4; $P < 0.05$) and latissimus dorsi pulldowns (15.1 ± 2.2 versus 12.8 ± 1.2; $P < 0.01$). RPE did not change significantly between weeks 4, 8, 12 and 16 in CONV for all exercises ($P > 0.05$). RPE did not change significantly between weeks 4, 8, 12 and 16 in EB for leg press, bench press and latissimus dorsi pulldowns. A significant time effect was observed for toe press in EB ($P < 0.05$). Post-hoc tests revealed that RPE was

significantly lower in week 16 than week 4 for toe press in EB (11.8 ± 1.5 in week 16 versus 12.6 ± 1.9 in week 4).

Pulse Wave Velocity

Pulse wave velocity data for the three groups are summarised in Table 17. The three groups did not differ significantly at baseline. No significant time ($P = 0.38$) or group by time ($P = 0.30$) effects were observed.

Table 17

Changes in pulse wave velocity and functional capacity

	Group	Pre-training	Post-training	% Difference
Pulse wave velocity (m/s)	CONV	14.5 ± 10.3	16.0 ± 10.8	10
	EB	10.8 ± 3.7	12.1 ± 7.4	12
	Control	11.7 ± 4.2	13.3 ± 5.5	14
6MFWT (s)	CONV	2.79 ± 0.57	2.66 ± 0.61	-5**
	EB	2.79 ± 0.32	2.60 ± 0.29	-7**
	Control	2.74 ± 0.40	2.86 ± 0.38	4*
TUG (s)	CONV	4.55 ± 0.81	4.34 ± 0.64	-5**
	EB	4.51 ± 0.43	4.39 ± 0.38	-3
	Control	4.58 ± 0.54	4.50 ± 0.48	-2
Stair climb power (W)	CONV	400 ± 117	412 ± 121	3
	EB	433 ± 138	456 ± 141	5**
	Control	404 ± 101	410 ± 99	1
Stair descent power (W)	CONV	376 ± 83	392 ± 81	4*
	EB	366 ± 105	380 ± 111	4
	Control	362 ± 62	360 ± 60	-1
Vertical jump height (cm)	CONV	25.4 ± 9.1	27.3 ± 8.6	7**
	EB	28.1 ± 5.7	28.9 ± 5.3	3
	Control	25.9 ± 4.9	25.2 ± 6.0	-2
Peak jumping power (W)	CONV	985 ± 466	1055 ± 499	7
	EB	1085 ± 453	1085 ± 458	0
	Control	1083 ± 344	1040 ± 422	-4

Data presented as mean ± SD; 6MFWT = six metre fast walk test; TUG = Timed up and Go test; % Difference = percentage difference between pre- and post-training or post-control data. Asterisks indicate significant difference between pre- and post-training or post-control (*$P < 0.05$; **$P < 0.01$).

Muscle Architecture

Muscle architecture data for all three groups are summarised in Table 18. The three groups did not differ significantly in any architecture measurements at baseline. A significant group by time effect was observed for VL site 1 thickness ($P < 0.01$). Post-hoc tests revealed that VL site 1 thickness increased significantly by 5% in EB ($P < 0.05$), while thickness did not change significantly in CONV ($P = 0.41$) and decreased significantly by 6% in the control group ($P < 0.05$). No significant main effects were observed for other muscle architecture measures in either muscle.

Table 18

Muscle architecture data

	Group	Pre-training	Post-training	% Difference
GM θ (º)	CONV	19.9 ± 3.6	20.6 ± 2.7	4
	EB	19.6 ± 1.4	18.9 ± 3.2	-3
	Control	19.9 ± 3.5	18.0 ± 2.7	-10*
GM L_f (cm)	CONV	5.56 ± 0.97	5.38 ± 0.81	-3
	EB	5.67 ± 0.76	5.92 ± 0.83	4
	Control	5.85 ± 1.07	6.17 ± 1.25	5
GM Thickness (cm)	CONV	1.87 ± 0.28	1.87 ± 0.21	0
	EB	1.89 ± 0.24	1.89 ± 0.25	0
	Control	1.94 ± 0.25	1.87 ± 0.29	-3
VL Site 1 Thickness (cm)	CONV	3.88 ± 0.46	3.96 ± 0.47	2
	EB	4.03 ± 0.62	4.22 ± 0.68	5*
	Control	4.18 ± 0.74	3.95 ± 0.55	-6*
VL Site 2 Thickness (cm)	CONV	4.71 ± 0.50	4.71 ± 0.62	0
	EB	4.49 ± 0.53	4.64 ± 0.52	3
	Control	4.50 ± 0.49	4.47 ± 0.46	-1
VL θ (º)	CONV	12.9 ± 2.8	11.9 ± 3.6	-8
	EB	11.5 ± 4.4	11.9 ± 3.1	3
	Control	11.9 ± 3.2	11.1 ± 3.5	-7
VL L_f (cm)	CONV	11.1 ± 2.6	11.5 ± 3.6	4
	EB	12.3 ± 3.8	12.9 ± 5.1	5
	Control	12.3 ± 4.3	12.1 ± 4.5	-2

Data presented as mean ± SD; GM = medial gastrocnemius; VL = vastus lateralis; θ = pennation angle; L_f = fascicle length; % Difference = percentage difference between pre- and post-training or post-control data. Asterisks indicate significant difference between pre- and post-training or post-control (*$P < 0.05$).

Knee Extensor Torque-Velocity Relationship

The knee extensor torque data are presented in Table 19. Change in (Δ) torque at each velocity in each group is illustrated in Figure 12. The main group effect for the mean change in torque (post – pre, for all velocities combined) showed a trend between the groups with (mean) Control = 1.6 Nm, CONV = 5.2 Nm, and EB = 7.6 Nm. The difference between these means bordered on being statistically significant between the control group and EB ($P = 0.13$).

The main effect for the amount of change in torque (post – pre, Δ torque) differed between velocities. Essentially the 5 velocities formed 2 clusters. The three slower velocities (0, 60 and 120º/s) displayed a greater change in torque (mean of all 3 groups) than the two faster velocities (240 and 360º/s). The amount of change (Δ torque) was: 5.9, 6.3 and 6.3 Nm for the three slower velocities and 2.8 and 2.3 Nm for the two faster velocities. These differences were statistically significant ($P < 0.05$) between 120º/s and the two faster velocities (240 and 360º/s). For the two other slower velocities (0 and 60º/s) the difference with the two faster velocities (240 and 360º/s) displayed the same trend (see means) but did not reach statistical significance.

Further analyses revealed that the differences in the change in torque (i.e. the 3 slower velocities displaying greater overall increases in torque than the two faster velocities) were largely attributable to the differences in delta torque displayed at different velocities in CONV, where the differences between velocities within the group were statistically significant ($P < 0.05$). This was due to CONV producing relatively large changes at the three slowest velocities, but little or no improvement at the two fastest velocities. Conversely in EB the Δ torque at different velocities did not differ statistically as they all displayed an improvement of similar and relatively

large magnitude, and in the control group the Δ torque at different velocities again did not differ statistically, as the changes were also consistent but of small magnitude or non-existent across all velocities.

Further analysis of the difference between groups, revealed a group by velocity interaction with the change in torque being statistically significant ($P < 0.05$) at 360º/s, with EB producing a greater change in torque at this fastest velocity than either CONV or control.

With regards to the two-way (group * time) ANOVA performed using the absolute torque values, significant time effects were detected for torque during isometric contractions and all concentric contraction speeds ($P \leq 0.01$). A significant group by time effect was also detected for torque during concentric contractions at 360º/s ($P < 0.05$). Post hoc tests revealed that for isometric contractions, torque increased significantly in EB by 7% ($P < 0.01$). For contractions at 60º/s, torque increased significantly in both EB and CONV by 6% and 7% respectively ($P < 0.05$). For contractions at 120º/s, torque increased significantly in both EB and CONV by 7% and 8% respectively ($P < 0.01$). For contractions at 240º/s and 360º/s, torque increased significantly only in EB by 5% ($P < 0.05$) and 11% ($P < 0.01$) respectively.

A significant group by time effect ($P < 0.05$) was detected for angle of peak torque during contractions at 240º/s. Post-hoc tests revealed that the angle of peak torque during contractions at 240º/s decreased significantly (Δ5%, $P < 0.05$) in the control group but did not change significantly in CONV ($P = 0.36$) or EB ($P = 0.225$). No significant main effects ($P > 0.05$) were observed for angle of peak torque at all other contraction speeds.

Table 19

Knee extensor isometric and isokinetic torque data

Velocity	Group	Pre-training (Nm)	Post-training (Nm)	% Difference
Isometric	CONV	160 ± 40	166 ± 46	4
	EB	175 ± 38	187 ± 44	7*
	Control	162 ± 40	162 ± 41	0
60º/s	CONV	126 ± 36	135 ± 39	7*
	EB	129 ± 30	137 ± 32	6*
	Control	125 ± 25	128 ± 29	2
120º/s	CONV	101 ± 31	109 ± 32	8**
	EB	101 ± 24	108 ± 26	7**
	Control	98 ± 19	101 ± 20	3
240º/s	CONV	75 ± 26	77 ± 26	3
	EB	74 ± 21	78 ± 22	5*
	Control	70 ± 16	72 ± 18	3
360º/s	CONV	59 ± 21	60 ± 24	1
	EB	56 ± 16	62 ± 19	11**
	Control	56 ± 12	56 ± 11	0

Data presented as mean ± SD; % Difference = percentage difference between pre- and post-training or post-control data. Asterisks indicate significant difference between pre- and post-training or post-control (*$P < 0.05$; **$P < 0.01$).
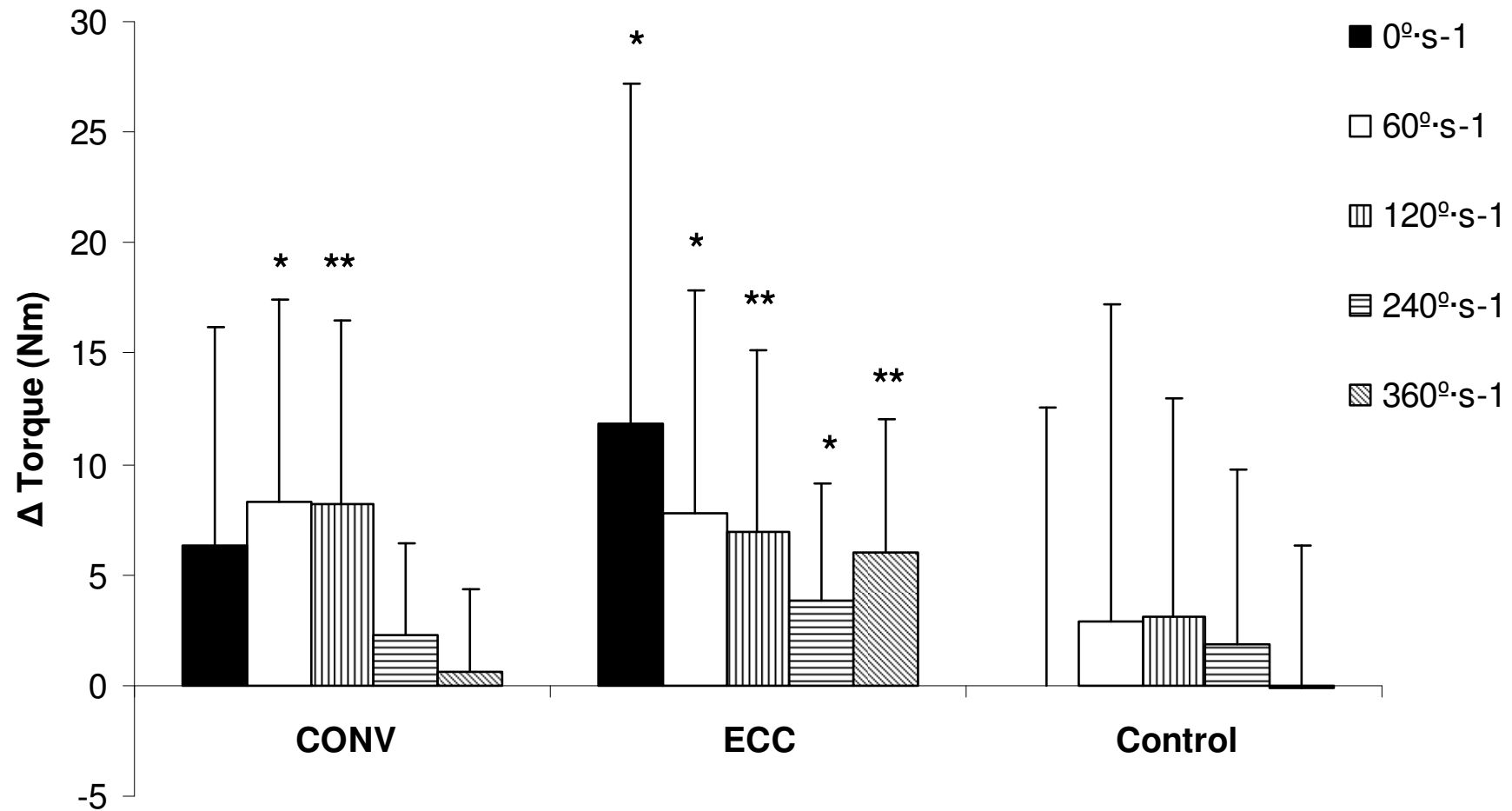
Figure 12. Change (Δ) in torque for knee extensors for conventional training (CONV), eccentrically-biased training (ECC) and the control group.

Values are means and SD. Asterisks indicate significant difference between pre- and post-training or post-control (*$P < 0.05$; **$P < 0.01$).

Functional and Vertical Jump Tests

Results of the functional and vertical jump tests data are summarised in Table 17. Significant time ($P < 0.05$) and group by time ($P < 0.01$) effects were detected for the 6MFWT. Post-hoc tests revealed that 6MFWT time decreased significantly ($P < 0.01$) in both EB and CONV but increased significantly in the control group ($P < 0.05$). A significant time effect was detected for the TUG ($P < 0.01$). Post-hoc tests revealed that TUG time decreased significantly in CONV ($P < 0.01$) and approached significance in EB ($P = 0.08$). There was no significant change in the control group ($P = 0.25$). When data were pooled across experimental groups, a significant improvement in TUG performance (4.54s pre versus 4.41s post; $P < 0.01$) was observed from pre- to post-condition. A significant time effect was detected for the stair climb power test ($P < 0.01$). Post-hoc tests revealed that stair climb power increased significantly only in EB ($P < 0.01$) with no significant change in CONV ($P = 0.10$) or the control group ($P = 0.53$). When data were pooled across experimental groups, a significant improvement in stair climb power (417 W pre versus 430 W post; $P < 0.01$) was observed from pre- to post-condition. A significant time effect was detected for the stair descent power test ($P < 0.05$). Stair descent power increased significantly in CONV ($P < 0.05$) and approached significance in EB ($P = 0.06$). There was no significant change in the control group ($P = 0.96$). When data were pooled across experimental groups, a significant improvement in stair descent power (373 W pre versus 382 W post; $P < 0.05$) was observed from pre- to post-condition. A significant group by time effect was detected for the vertical jump height ($P < 0.05$). Post-hoc tests revealed that vertical jump height increased significantly in CONV ($P < 0.01$) but did not change significantly in EB ($P = 0.33$)

or the control group ($P = 0.22$). No significant time ($P = 0.83$) or group by time ($P = 0.525$) effects were detected for peak jumping power.

DISCUSSION

This is the first study to compare eccentrically-biased resistance training, a more practically applicable training modality than eccentric-only resistance training, and conventional training in older adults. The main findings are: (i) EB and CONV lead to similar increases in 1RM strength; (ii) EB leads to increases in strength across a range of isokinetic contraction velocities while CONV leads to strength gains only at slower contraction velocities; (iii) EB and CONV induce similar improvements to the performance of a number of functional capacity assessments; (iv) EB and CONV seem to have no significant impact on arterial stiffness; (v) EB may be more effective than CONV at increasing muscle mass; (vi) RPE is similar to or lower in EB than in CONV training.

The changes to the torque-velocity relationship of the knee extensors after training confirm our hypothesis that EB would be more effective than CONV at increasing torque production during faster concentric contractions. The observed increase in torque production at isometric and slower concentric contractions (0, 60 and 120º/s) but not at the faster velocities (240 and 360º/s) in CONV is expected as the relatively heavy weights demanded that concentric contractions in all exercises, and specifically, the leg press, were performed at relatively slow speeds. This finding is consistent with the concept of velocity-specificity in resistance training (12). The significant increase in torque at fast concentric contractions (240 and 360º/s) is encouraging for its application to training programs for older adults. This increased torque at fast contraction speeds may be an advantage when rapid movements of the

limbs are necessary, such as recovering from a stumble or trip (184). The increase in torque across all concentric contraction velocities and during isometric contractions after EB is intriguing as it does not conform to the concept of velocity-specificity. The previously reported elongation of muscle fascicles after eccentric-only resistance training (140) would conceivably increase muscle force and power output at relatively high shortening velocities although increases in fascicle lengths were not observed here. It is therefore difficult to pinpoint a reason for the positive effects of eccentric resistance training on high velocity concentric strength in EB. However, the increase in vastus lateralis thickness in EB may partly explain this observation. One issue arising from the EB training modality is that of the bilateral strength deficit. The influence of the bilateral strength deficit would mean that participants in the EB group possibly performed slightly less work overall during the training program in the eccentric phase, which was performed unilaterally, than those in the CONV group. This is because the 1RM tests were performed bilaterally, meaning that the unilateral 1RM may have been slightly underestimated. This may have been more predominant at the start of the training program, since the bilateral strength deficit is reduced with training, and it may have declined less in the EB group, who performed the bilateral concentric phase of exercises at 50% of 1RM compared to 75% of 1RM in the CONV group. This could have potentially biased the bilateral tests towards the CONV group and the unilateral tests towards the EB group. However, both groups performed bilateral concentric phases so the effects of the training should not have differed too drastically between groups. To illustrate this, torque still increased at all contraction speeds in EB while only increasing at slow contraction speeds in CONV. In addition, 1RM strength, which was performed bilaterally, increased to a similar degree in both EB and CONV groups.

Although more functional capacity measures improved significantly in CONV than EB, performance improvements in the TUG and stair descent power test in EB approached significance ($P = 0.08$ and $P = 0.06$ respectively) thereby suggesting that the two training modalities might be similarly effective at improving functional performance. It was surprising to observe a significant decline in 6MFWT performance in the control group after only 16 weeks in this healthy community-dwelling older adult population. However, similar declines in function have been observed in the control groups of other studies (153, 159) so this finding is not a unique anomaly and may be indicative of real functional declines. Another interesting observation was that the increase in knee extensor strength across all contraction velocities in EB did not translate into better performance in the vertical jump test than CONV. However, it should be noted that older adults perform vertical jumps with relatively low joint angle velocities (56) and conventional resistance training has been shown to have a positive effect on vertical jump performance in older men (77). Also, participants in CONV lifted heavier loads in the concentric phase, which were possibly more specific to body mass, than those in EB, and vertical jump is a movement with a bilateral stretch shorten cycle which finishes with a concentric effort rather more similar to the CONV training than the EB. This may suggest that velocity and contraction mode specificity are important for this task. Nevertheless, it could be argued that the superior improvements in vertical jump performance, which is a bilateral method of assessing power, in CONV is more functionally significant than the increases in unilateral, isokinetic strength seen in the EB group.

The lack of familiarisation prior to 1RM testing is a limitation of the current study and may have over-estimated 1RM gains as a result of training. However, the

percentage increase in leg press 1RM (23% for CONV and EB), for example, is similar to the increase (23%) in leg press 5RM observed by Reeves, Maganaris, Longo and Narici (140) after 14 weeks of conventional training in 9 older adults (average age 67 ± 2 years) with 2 weeks of familiarisation prior to 1RM testing. Also, the similar increases in 1RM strength in both training groups indicate that both modalities are equally effective at increasing maximal strength, and the improvements in isokinetic and isometric strength, and functional capacity measures in both groups independently illustrate the effectiveness of the CONV and EB training protocols employed in this study.

Medial gastrocnemius (GM) and vastus lateralis (VL) muscle fascicle length and pennation angle did not change significantly in either training group. This is in contrast to the observations of Reeves et al. (140), who reported increases in VL fascicle length and pennation angle following 14 weeks of either eccentric-only or conventional resistance training performed 3 times a week by older adults. However, there were significant decreases in GM pennation angle and VL thickness at site 1, and non-significant decreases in GM fascicle length, VL pennation angle and VL fascicle length in the control group in the current study. While the degree of deterioration in muscle architecture measures in the control group is surprising, the fact that the reliability of these muscle architecture measures has been recently demonstrated (136) makes this observation difficult to explain. Also, the lack of change in angle of peak torque in the training groups supports the finding of a lack of change in fascicle lengths in CONV and EB (17). These observations may suggest that both training modalities had a protective effect against the potentially detrimental age-related changes in GM and VL muscle architecture, and that the increases in torque at fast contraction speeds in EB may be due to mechanisms other

than changes in fascicle length. Nevertheless, the fact that fascicle length was only measured at one site on each muscle is a limitation of the current study as it is recognised that muscular adaptation to training may be heterogeneous along the length of a muscle and may differ between vastii (114). With regards to muscle thickness, the fact that EB brought about an increase in VL thickness while thickness in CONV did not change and thickness in the control group decreased over time is consistent with numerous previous studies which suggest that eccentric resistance training is more effective at increasing muscle hypertrophy than concentric training (66, 152, 180). The lack of change in GM thickness with both training modalities is consistent with the finding that soleus muscle protein synthesis responds relatively poorly to an acute bout of resistance training when compared to VL protein synthesis (174).

The lower RPE in upper body exercises in EB compared to CONV concurs with the findings of Reeves and colleagues (140), who compared conventional training to eccentric-only training in older adults. Lower ratings of exertion may be important for resistance training program compliance. The lack of change in RPE over time in both training groups for most exercises is expected due to the adjustment of training weights with every 1RM test conducted throughout the training program, so that participants exercised at the same intensity throughout the programs. The decrease in RPE over time in EB for toe press is most likely due to participants becoming more familiar with performing the exercise, rather than an actual decrease in exertion, due to the unusual nature of the exercise.

The finding that neither training modality had a significant impact on the combined central and peripheral arterial pulse wave velocity supports the findings of Maeda et al. (100), who found that 12 weeks of isokinetic (concentric and eccentric)

leg resistance training had no effect on carotid and femoral artery pulse wave velocities in healthy young females. On the other hand, Okamoto and colleagues (119) reported higher brachial-ankle pulse wave velocity after 8 weeks of concentric-only resistance training, but no change after eccentric-only resistance training in older men. Other studies have found evidence of decreased central arterial compliance as a result of conventional resistance training in men (103, 104). As previously discussed in Chapter 5 (page 104), one reason for this discrepancy could be that previous studies that observed increases in arterial stiffness following resistance training measured central arterial stiffness, while the method used in the current study takes into account central as well as peripheral arteries. Heffernan et al. (61) found that peripheral arterial stiffness decreased in the exercised limb following resistance training. Therefore, if there were any opposing changes in central and peripheral arterial stiffness they may have counteracted each other thereby resulting in no overall changes in arterial stiffness in the current study. The index of arterial stiffness employed in the current study is one of a number of methods to describe arterial stiffness (57) and there are limitations to this method. For example, the method of measuring the distance travelled by the pulse wave does not take into account differences in body shape and assumes that the aorta is straight. Even though this method has been validated by Tsai and colleagues (175), more research may be needed before the effects of EB and CONV on arterial stiffness are more clearly understood.

CONCLUSION

This study suggests that eccentrically-biased resistance training is a viable alternative to conventional resistance training for older adults. Whilst improvements

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in one repetition maximum and functional capacity were similar for both training modalities, quadriceps thickness and torque at higher isokinetic velocities increased only after EB. While longer term studies are required, these findings suggest that EB may be particularly valuable for a population that is prone to sarcopenia and falls (40). Generally lower ratings of perceived exertion in eccentrically-biased training may also have implications for program compliance. Furthermore, whilst eccentric-only training is impractical in a real-world gym setting due to the consistent need for assistance from a spotter to aid with the lifting of the weights, this study has demonstrated that eccentrically-biased training can be successfully performed without assistance, using resistance training machines that are widely available.

CHAPTER 7: Summary and Conclusion

The major objectives of this thesis were: (i) to compare the acute effects of eccentrically-biased and conventional resistance training on arterial stiffness, platelet reactivity, activation and count, postural stability and isometric force steadiness in older men and women; and (ii) to compare the effects 16-weeks of eccentrically-biased versus conventional resistance training on muscle architecture, 1 repetition maximum, isometric strength, isokinetic force-velocity characteristics, functional capacity and pulse wave velocity in older men and women.

The results of the two reliability studies (Chapters 3 and 4) show that: (i) the chosen dynamometer and functional tests appear to have sufficient reliability for the detection of realistic amounts of change of the magnitude that may be attainable from an intervention at group level after two familiarisations; (ii) B-mode ultrasonography can be used with confidence by researchers when investigating changes in muscle architecture in groups of older adults. The study investigating the acute effects of a single bout of eccentrically-biased versus conventional resistance training (Chapter 5) demonstrated a small acute increase in platelet count and postural instability after eccentrically-biased resistance training. The results of the intervention study (Chapter 6) showed that both eccentrically-biased and conventional resistance training are effective at increasing strength and improving function in older adults. However, only eccentrically-biased resistance training improved strength during quick isokinetic contractions of the knee extensors and increased thickness of the vastus lateralis muscle. Also, participants performing eccentrically-biased resistance training reported generally lower ratings of perceived exertion than those performing conventional resistance training.

From these results, it can be concluded that the outcome measures have sufficient reliability to be used by researchers in intervention studies involving groups of older adults, allowing the results from the subsequent studies to be interpreted with confidence. The results demonstrated in Chapter 5 mean that older adults should exercise caution with regards to balance and cardiovascular events immediately after eccentrically-biased resistance training. However, appropriate management should decrease these risks. With regards to the results from Chapter 6, the improvements in strength during quick isokinetic contractions of the knee extensors after eccentrically-biased resistance training may have implications for functional movements that require rapid movements of the limb, such as recovering from a stumble. Also, the lower ratings of perceived exertion in eccentrically-biased training may have implications for program compliance. Overall, eccentrically-biased resistance training is a viable alternative to conventional resistance training for older adults.

With regards to the prescription of exercise for older adults in the future, this research contributes to our understanding of a novel resistance training modality, which can be feasibly performed by older adults and may have advantages over conventional resistance training when aiming to increase muscle mass or improve function.

Future research should aim to investigate the effects of eccentrically-biased resistance training on the ability of older adults to recover from mechanical postural perturbations and the acute and chronic effects of eccentrically-biased resistance training on central arterial stiffness.

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APPENDIX: List of Publications

Literature review:

Raj IS, Bird SR, Shield AJ. Aging and the force-velocity relationship of muscles. *Exp Gerontol*. 2010;45(2):81-90.

Reliability of Ultrasonographic Measurement of the Architecture of the Vastus Lateralis and Gastrocnemius Medialis Muscles in Older Adults:

Raj IS, Bird SR, Shield AJ. Reliability of Ultrasonographic Measurement of the Architecture of the Vastus Lateralis and Gastrocnemius Medialis Muscles in Older Adults. *Clin Physiol Funct Imaging*. 2011; DOI: 10.1111/j.1475-097X.2011.01056.x

The Chronic Effects of Eccentrically-biased versus Conventional Resistance Training in Older Adults:

Accepted for publication

Raj IS, Bird SR, Westfold BA, Shield AJ. Effects of eccentrically-biased versus conventional weight training in older adults. *Medicine and Science in Sports and Exercise*.

Conference proceeding:

Raj IS, Bird SR, Westfold BA, Shield AJ. Effects of eccentrically-biased versus conventional resistance training in older adults. *Australian Conference of Science and Medicine in Sport 2011.*