MASTER OF SCIENCE BY RESEARCH

Effect of eccentric flywheel training on musculoskeletal characteristics and physical function in older adults

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Award date:
2020

Awarding institution:
Coventry University

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MSc (R)

September 2019

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A thesis submitted in partial fulfilment of the University's requirements for the Degree of Master of Research

Certificate of Ethical Approval

Applicant:

Matthew Roberts

Project Title:

The effects of flywheel training on musculoskeletal characteristics and physical function in healthy older adults - a randomised control trial.

This is to certify that the above named applicant has completed the Coventry University Ethical Approval process and their project has been confirmed and approved as Medium Risk

Date of approval:

26 March 2019

Project Reference Number:

P79002

Content removed on data protection grounds

Content removed on data protection grounds

Content removed on data protection grounds

Content removed on data protection grounds

Content removed on data protection grounds

Acknowledgements

I would like to thank my supervisor’s Dr Mathew Hill and Dr Mike Price for their guidance, ongoing support and belief in me over the last year. Their experience and knowledge enabled me to complete tasks efficiently and to my greatest ability. I’d like to thank the Exxentric team for providing the Kbox 4, Professor Tony Kay and University of Northampton for the collaboration, providing ultrasound equipment and training, Hilton Northampton for providing facilities for training and testing over the whole training period and all participants for their involvement hard work and dedication. I’d also like to acknowledge the contribution of Melanie Wood, Sue and Steve Roberts who assisted with this study along with ongoing support and patience with me over the last year.

Abstract

Falls among older adults represent a major public health problem, often leading to progressive functional decline, the start of dependency and the development of comorbidities. However, falls are not random events and are often preventable by targeting intrinsic risk factors such as reduced muscle size and strength contributing to poor postural control. Traditional resistance training has been shown to provide benefits to older adults for mobility and strength, improving quality of life. However, evidence suggests performing exercises in an upright position provides a greater stimulus, such as eccentric resistance exercise. Therefore, the aim of the study was to determine the effects of flywheel training on muscle thickness/quality, physical functioning, postural stability and fear of falling among older people. Twenty-one physically activity participants (10 females and 11 males, age 62.52 years ± 6.72, 75.4 ± 12.9kg, 170.6 ± 9.4m) were split into groups, intervention (n = 13) and control (n = 8) with both groups completing muscle thickness and quality (ultrasonography), posturography, timed-up-and-go (TUG), sit to stand (30 secs STS and 5 x STS), strength dynamometer and fear of falling (FOF), six weeks apart from pretesting. The intervention group completed 6 weeks of eccentric flywheel training (ECC), performing between four sets of eight to twelve throughout the intervention, on squats and plantarflexion movements. Following ECC intervention, results showed no significant group × time interactions were found for muscle thickness (all $P > 0.05$), muscle quality (all $P > 0.05$), posturography (all $P > 0.05$), TUG (all $P > 0.05$), 30 secs STS (all $P > 0.05$), 5 x STS (all $P > 0.05$), strength (all $P > 0.05$) and FOF (all $P > 0.05$). However, we observed a large magnitude reduction in the 30-s STS ($d = 1.07$) and moderate reduction in TUG ($d = 0.77$) and 5 x STS ($d = 0.61$) with a moderate magnitude of change from pre to post intervention left vastus lateralis ($d = 0.70$) and for left gastrocnemius medial ($d = 0.47$). From the first to final training sessions, squat average power (54%), concentric (115%) and eccentric peak power (115%) improved throughout the six weeks. Furthermore, plantarflexion average power (28%), concentric (62%) and eccentric peak power (59%) improved throughout the six weeks. The results highlight that eccentric flywheel training may have the potential to elicit beneficial effects on physical function outcomes in older adults. A greater understanding of the effects of eccentric flywheel training of a greater dose on these outcomes would further contribute to the evidence-based practice in older people.

List of Abbreviations

30 secs STS - 30 seconds sit to stand

5 x STS - 5 repetition sit to stand

ANOVA - analysis of variance

CM - centimetres

COP - centre of pressure

COP_{AP} - total displacement in the anteroposterior directions

COP_{ML} - total displacement in the mediolateral directions

COP_{PL} - COP path length

COV - coefficients of variation

DA - deep aponeurosis

EA - ellipse areas

EC - eyes closed

ECC - Eccentric flywheel training

EI - Echo Intensity

EO - eyes open

ES - Cohen’s *d* effect sizes

FOF - Fear of falling

GM - gastrocnemius medial

ICC - intraclass correlation coefficients

KG - Kilograms

MF - muscle fascicle

PARQ - pre-medical readiness questionnaire

ROM - range of motion

SA - superficial aponeurosis

SD - standard deviation

TUG - Timed up and go

VL - Vastus Lateralis

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1. Literature review

Falls among older adults represent a major public health problem, often leading to progressive functional decline, the start of dependency and the development of comorbidities (Okubo et al. 2016). More than forty percent of community dwelling adults over 65 years of age fall at least once annually (Peeters et al. 2009). The aetiology of falls is complex, involving multiple intrinsic (i.e. reduced strength and balance) and extrinsic (i.e. environmental) factors (Bueno-Cavanillas et al. 2000). However, falls are not random events and are often preventable by targeting intrinsic risk factors. For example, age-related increases in fall-risk can be attributed to reduced lower body strength/power (Benichou and Lord 2016), muscle atrophy and diminished balance control (Granacher et al. 2012) all of which are potentially reversible with exercise intervention (Orr et al. 2008). This literature review aims to provide a brief overview of the current evidence regarding ageing and the role of strength training in counteracting age-related changes in balance and functional performance. The review will conclude by describing the potential applications of a novel and low-cost mode of eccentric exercise, termed flywheel training. Reviews are available regarding the effects of traditional resistance training (Orr et al. 2008) and eccentric resistance training (Roig et al. 2009) on functional outcomes in older people. The principle aim of this chapter is to provide a more specifically focused review integrating the area of flywheel training in older people.

1.1 Aging and Physical Function

Muscle mass is associated with the amount of force produced (i.e. strength) (Lexell, Taylor and Sjostrom, 1988). Age-related loss of muscle mass results in marked reduction in strength and power (Mitchell et al. 2012). Muscular strength is classically defined as the maximal amount of force a muscle or group of muscles can produce during a single contraction or repetition (Sapega and Drillings, 1983). A product of strength is power, defined as the greatest amount of force achieved from muscular contraction (power = work/time), and is dependent upon strength (Brown and Weir, 2001; Bonder and Dal Bello-Haas, 2017). The progressive decline of strength with advancing age (typically accelerating after 65 years) might expose older people to falls, because strength influences multiple biological risk factors for falls, such as gait speed, dynamic balance, endurance and fall recovery (Ward et al. 2015). A reduction in strength and power makes day to day tasks such as standing up and climbing stairs more challenging and fatiguing, potentially augmenting the risk of falling (Laybourne, Biggs and Martin, 2008). For example, Wang et al. (2016) reported that quadricep strength is significantly correlated with dynamic and static balance. Balance is classically defined as maintaining an upright position to complete activities in daily life (Vuillerme et al. 2002) with postural control, an essential component of balance. Proprioception, vestibular and visual systems are key contributors to maintain of the centre of mass within the base of support (Paillard and Noé, 2015). Several studies have found that balance is influenced by multiple factors including strength, history of falls, fear of falling, environmental hazards, visual impairments, neurologic disorders and gait characteristics (Rubenstein, 2006; Deandrea et al. 2013; Ambrose, Paul and Hausdorff, 2013). Muscle power is reported to be more important than muscular strength for dynamic balance, physical function and fall prevention and in situations such as reacting rapidly when balance is threatened (Pavol and Pai, 2007). Power of the lower limbs is reported to decline from 30 years of age with the progressive loss of power accelerated beyond 60 years (Kostka, 2005). As ageing is associated with a consistent and progressive reduction in muscle mass, strength and power, appropriately targeted interventions may be able to slow down age-related deteriorations in these biological risk factors.

1.2 Sarcopenia and Traditional Resistance Training

The multifactorial causes of sarcopenia are understood to be mainly intrinsic risk-factors (reduced motor neurons and activity/nutrition, changes in hormones and increased inflammation) (Walston, 2012: 625). The reduction in muscle fibre size has been suggested to be fibre type specific, research suggests older adults have 10-40% smaller type II fibres when compared to young adults (Dreyer et al. 2006; Verdijk et al. 2007). The specific reduction could be related to the order of recruitment, as type I fibres are recruited first (more often) and are responsible for endurance activities (walking), type II fibres are recruited after type I (less often) for higher intensity activities (lifting heavy objects) which may not be viable for older adults. Therefore, seeing a potential decline in muscle strength and number of type II fibres (Tieland, Trouwborst and Clark, 2018). Importantly, the progressive decline in sarcopenia can be slowed down (Johnston, De Lisio and Parise, 2007) with appropriately targeted interventions. For example, meta-analytical evidence points towards significant increases in muscle mass and strength following traditional resistance training among older people (Granacher, Zahner and Gollhofer, 2008). Although traditional lower extremity resistance training (i.e. moderate intensity concentric and eccentric contractions) is widely utilised in exercise-based fall prevention interventions (Granacher Zahner and Gollhofer, 2008; 2011), the effects of traditional strength training are often not transferred to balance and mobility among older adults (Orr et al. 2008). It is likely that traditional resistance training alone, particularly when performed in the seated position, is not a robust intervention to improve postural control. The key muscle groups responsible for controlling upright stance are the ankle dorsiflexors and plantarflexors, knee extensors and flexors and hip abductor and adductors (Orr et al. 2008). Thus, resistance training that targets these key postural muscles, performed in the standing position, is likely to provide a greater neuromuscular stimulus relevant to balance control than exercise performed in the seated position (Okubo, Schoene and Lord, 2017).

High-intensity training may best deliver the stimulus required to increase muscle strength and to elicit neuromuscular benefits to enhance balance (Hess and Woollacott 2005; Liu-Ambrose et al. 2004; Schlicht et al. 2001). However, the training demands of traditional resistance training, involving high-intensity concentric contractions, are often not practical or feasible because of the high cardiovascular and metabolic costs. Therefore, it remains an important goal in ageing research to develop exercise training that is well accepted (tolerated) and effective in concomitantly targeting intrinsic fall risk factors among older people. Eccentric exercise training has received a growing interest over the last decade, particularly in light of the emerging health related benefits of improved muscle mass and strength (Hody et al. 2019). Indeed, the superiority of eccentric resistance training has been demonstrated repeatedly in young adult populations with greater increases in muscle mass (Roig et al. 2009) strength (Hortobagyi et al. 1996). Collectively, these findings suggest that eccentric exercise might provoke improvements in important risk factors for falls.

1.3 Low Metabolic Demands of Eccentric Training

There is good evidence that metabolic, neural and cardiovascular demands are lower during eccentric resistance exercise compared to traditional resistance exercise (i.e.

concentric contractions) (Vallejo et al. 2006). For example, the energetic cost of eccentric resistance exercise is approximately four times less than that of concentric exercise of a comparable external workload (LaStayo et al. 1999). The lower metabolic cost of eccentric resistance exercise results in a reduced perceived effort (LaStayo et al. 2003) and is therefore potentially better tolerated and safer for exercise intolerant groups (i.e. older adults and patients with cardiorespiratory impairments) (Gault and Willems 2013; Hortobagyi et al. 2003; LaStayo et al. 2003). Furthermore, there appears to be a preservation of eccentric strength in older adults (Hortobagyi et al. 1995), suggesting that the aged muscle is well suited for eccentric resistance exercise. When performed in isolation, eccentric muscle contractions produce greater muscle force than concentric contractions (Lindstedt et al. 2001). Since high-force production is a key driver for increases in muscle mass and strength (Roig et al. 2009), the greater forces produced by eccentric contractions could provide the best stimulus to promote balance performance among older people. Given that greater levels of strength and power can be produced during eccentric contractions when compared to concentric contractions, training with an emphasis on eccentric overload may produce a more potent stimulus for improvement in balance and functional performance among older adults (Bonder and Dal Bello-Haas, 2017). Indeed, several studies suggest that eccentric resistance training elicits comparable (Gault et al. 2012; Mueller et al. 2009) or superior (LaStayo et al. 2003) improvements in balance and mobility (i.e. Timed Up and Go Test; TUG) performance compared to traditional resistance training. However, the improvement in TUG in these studies was rather modest (Gault et al. 2012 [22%]; LaStayo et al. 2003 [~28%]; Mueller et al. 2009 [7.5%]).

The mechanisms surrounding the preservation of eccentric strength in the elderly are understood to be neurological (reduced agonist activation during concentric contractions), mechanical (increased connective tissue and muscle passive stiffness) and cellular (preserved tension in muscle fibres) (Roig et al. 2009). Furthermore, eccentric resistance training has been shown to improve muscle quality, as deduced by changes in muscle echogenicity (improvements in muscle strength, thickness and function) (Fukumoto et al. 2012; Reimers et al. 1993). The echo intensities (EI) measured using the ultrasound technique can delineate functioning/normal to diseased muscle (Reimers et al. 1993; Scholten et al. 2003). Lower calculations/values (from histogram analysis) of muscle echogenicity have also been linked with measures of high muscle density in older women (Sipilä & Suominen, 1993). Grey histogram analysis is usually applied to clinical settings via ultrasonography machines. The analysis of muscle quality can be executed using paid software services such as Photoshop (Adobe Systems, San Jose, CA) and freely available service ImageJ (LOCI, University of Wisconsin). Both software services have been broadly used for clinical applications of skeletal muscle damage in older adults (Saad et al. 2008; Watanabe et al. 2013; Casella et al. 2015).

1.4 Eccentric Training and Physical Function

Improvements in balance are task specific; therefore, to improve balance, we must stimulate the balance control system (Zech et al. 2010). Indeed, approximately thirty minutes of balance training per week can provoke marked improvements in postural control (Lesinski et al. 2015). Alternatively, there is convincing evidence that walking can reduce fall risk (Okubo et al. 2016). However, most falls occur during ambulatory activities (Talbot et al. 2005), thus walking interventions are only best suit to physically abled and less frail older people. A more common approach to reduce fall risk is to improve strength through traditional resistance training, because strength is correlated with static and dynamic balance (Wang et al. 2016). Previous research suggests following traditional for 12 weeks (40 minutes per week) may improve lower limb strength, balance and mobility in the elderly (Rydwik et al. 2008). However, ECC targeted interventions indicates training twice a week for 12 weeks of ECC could improve timed-up-and-go time by 7% and isometric strength by 7% (Mueller et al. 2009). These results imply ECC could improve mobility from eccentric strength training in elderly using specialist equipment. Research employing Yo-Yo device (a variable inertial leg extensor performed seated) to improve strength, suggest that training thrice a week for 12 weeks may improve single leg stance time (balance) by 46%, which was likely induced by the marked improvements in plantarflexion strength (15%) and tendon stiffness (136%) allowing for greater control of the ankle joint throughout balance trials (Onambélé et al. 2008). Furthermore, dynamic knee extension power improved by 28%. However, no mobility data was recorded, but because strength is vital for functional performance, mobility would be expected to improve following flywheel ECC. Although the benefits of eccentric resistance training are indisputable, devices used to train the muscles eccentrically (isokinetic dynamometers) are generally prohibitively expensive and not portable. Therefore, it is important to find training approaches that can provide a marked eccentric training stimulus while also targeting several performance factors such as strength, mass, balance and mobility all at the same time.

1.5 Potential Applications of Flywheel Training in Older Adults

Flywheel training is employed to improve muscle strength, size and mobility, very similar to traditional resistance training (Petré, Wernstål and Mattsson, 2018). However, flywheel training utilises kinetic energy gained through concentric actions and transferred to a flywheel, allowing for greater emphasis on the eccentric phase. The efficacy of portable flywheel ECC device has previously been demonstrated in young adults, with marked improvements reported in quadriceps muscle mass (8.6%) and power (48%) following ten training sessions of 10 x 5 flywheel squats over a 4 week period (Illera-Dominguez et al. 2018). The use of the flywheel is more feasible compared to other specialist and expensive equipment (e.g. isokinetic dynamometers). Flywheel training devices costs a fraction of price, more transportable with similar results experienced. Testing the efficacy of flywheel devices will be important for future definitive trials as the device is transportable and could potentially be used in the home, hotel room, or office. Thus, there is a reasonable basis for the expectation that flywheel training might be effective in combating functional consequences of ageing, such as improve muscle mass, strength, balance and mobility. This research is important because it will allow us to provide the evidence base necessary to employ this mode of exercise in larger, more definitive randomised control trials.

1.6 The Effect of Flywheel Training on Physical Function and Muscle Mass

The majority of ECC training studies in older adults focus on training squat movements to improve mobility or reduce fall risk. Recently Sañudo et al. (2019) investigated the effect of ECC compared with a non-training control group, focusing on mobility, balance and power in older adults. Participants trained on a flywheel device two to three times per week, performing four sets of nine squats for six weeks. The training group demonstrated improved balance, mobility and muscle power, which could be important to prevent falls in older adults (Sañudo et al. 2019). This is the only research to date to employ the squat exercise, mimicking the sit to stand movement, which is a vital mobility component of daily activities enabling older adults to maintain independence. The present study will employ a similar strategy with squats and calf raises (plantarflexion). Training the plantarflexor muscles is likely to elicit increased tendon stiffness and greater control of ankle movements, potentially reducing fall risk and improving mobility (Onambélé et al. 2008). Although the present study does not intend to compare the effectiveness of flywheel training to traditional progressive resistance training, this proof of concept study that seeks to determine the feasibility of this exercise mode in older people. Specifically, the present study will determine the effects of 6-weeks of flywheel training on mobility (Timed-up-and-go), physical function (Sit to stand 5 reps and 30 seconds), strength (back dynamometer), muscle mass and quality (ultrasound), balance (postural sway) and fear of falling.

The key objectives of the present study are to; (1) determine the effectiveness of a short period of eccentric resistance training using a portable device on health-related outcomes, and (2) compare changes in muscle function (strength and mass), physical function and fall risk between the experimental and control group. It was hypothesised that flywheel eccentric training would increase quadricep size and strength, improve muscle quality and improve balance/mobility and reduce the fear of falling score in elderly.

2. Methods

2.1 Participants

An *a priori* power analysis (statistical power = 0.80, alpha = 0.05, effect size = 1.60) was conducted for knee extension power (Onambélé et al. 2008) and revealed that 10 participants would be sufficient for finding statistically significant effects of flywheel training on physical functional performance. A total of 25 older adults were recruited, but four adults withdrew from the control group due to factors not associated with the study (i.e. lack of time and unavailability). Given the onerous nature of the study, participants were selected based on convenience recruitment. More specifically of the 25 older adults initially approached, 13 expressed an interest to participate in the training intervention. We acknowledge that this approach may lead to bias effects. To account for possible drop outs (typical attrition; 20%), a convenience sample of twenty-one physically activity participants volunteered to participate in the study after providing written informed consent and completing a pre-medical questionnaire. Twenty-one community-dwelling older adults volunteered for the study with subjects assigned to either a training (n = 13, 7 females, age = 62.0 ± 7.7 years, height = 169 ± 8.4 cm, mass = 74.8 ± 14.2 kg) or control (n = 8, 3 females, age = 63.25 ± 5 years, height = 172.7 ± 11.2 cm, mass 76.5 ± 11.3 kg) group. Subjects were moderately active (training group 2.1 ± 1.3 $h \cdot wk^{-1}$, control = 2.0 ± 0.8 $h \cdot wk^{-1}$). Given the pragmatic and exploratory nature of the present trial, we chose to include only healthy abled-bodied individuals without high risk of falls. All participants were healthy and free from musculoskeletal, neurological, and/or cardiovascular or pulmonary diseases that would prevent them from safely performing a 6-week flywheel training intervention. The study was completed in accordance with guidelines summarised in the declaration of Helsinki (1964) and ethical approval was granted by Coventry Universities Ethics Committee.

2.2 Pre and Post Training Testing Procedures

Prior to pre-testing assessments, participants' height (Seca, 213 Portable Stadiometer, Birmingham, UK), mass (Seca, 710 mechanical column scales, Birmingham, UK) age and activity levels were ascertained on pre-medical readiness questionnaire (PARQ). Following the completion of a pre-medical questionnaire, fear of falling scale and informed consent participants completed a battery of balance, physical function and strength assessments. The same procedures were repeated for post-testing.

2.2.1 Muscle Thickness

Thickness of the vastus lateralis (VL) and gastrocnemius medial (GM) was recorded using ultrasonography probe and system (GE LogiqBook XP pro portable ultrasound machine, GE Healthcare, Chicago, USA) with ultrasound gel. To locate the thickest point of the VL, participants sat in a chair with hips and knees at 90º and feet were shod and flat on the floor, with heels resting against chair leg. The lateral border of the greater trochanter and the lateral proximal border of the patella were located. Using a tape measure (Korbond, tape measure 150cm Lincolnshire, UK) from these locations, the 50% point was measured three times for accuracy and marked using a pen for reference. To locate the thickest point of the GM participants stood upright, the popliteal fossa and the muscle tendon junction were located. Using a tape measure the same procedures were followed for GM. To record GM thickness, participants sat in a chair with hips at 90º and one leg at full extension resting against a wall and other leg/knee resting at 90º. To record

GM thickness, ultrasound gel was applied evenly to the probe, the midpoint of the probe was placed with little pressure (landscape orientation) on the GM reference point (50% mark) with orientation marker pointing distal and aimed towards the achillies tendon, allowing for greater imaging of GM. Each participant had a unique participant number and account created on the ultrasound system to record and store images from both sides of VL. To record VL thickness, ultrasound gel was applied evenly to the probe, allowing for clear imaging, midpoint of the probe was placed with little pressure (landscape orientation) on the VL reference point (50% mark) with orientation marker pointing distal. Imaging of VL was projected on the ultrasound screen (Figure 1), allowing for data collector to view skin, subcutaneous fat, superficial aponeurosis (SA), muscle fascicle (MF) and deep aponeurosis (DA). Once a clear image of SA, MF and DA was imaged at the midpoint of muscle, the image was frozen and saved. This process was repeated three times in total per leg for accurate and consistent recordings. Imaging of muscles were projected on the ultrasound screen. The images were carefully analysed using the software built in the system, which records the thickness of muscle in centimetres (cm) (Figure 2). Recording of images was measured from the lowest point of the SA and the highest point of the DA, this measurement determined the thickness of the VL and GM muscles respectively. Recording settings were set at 8.0 MHz frequency with a depth of 4.0cm for all images.

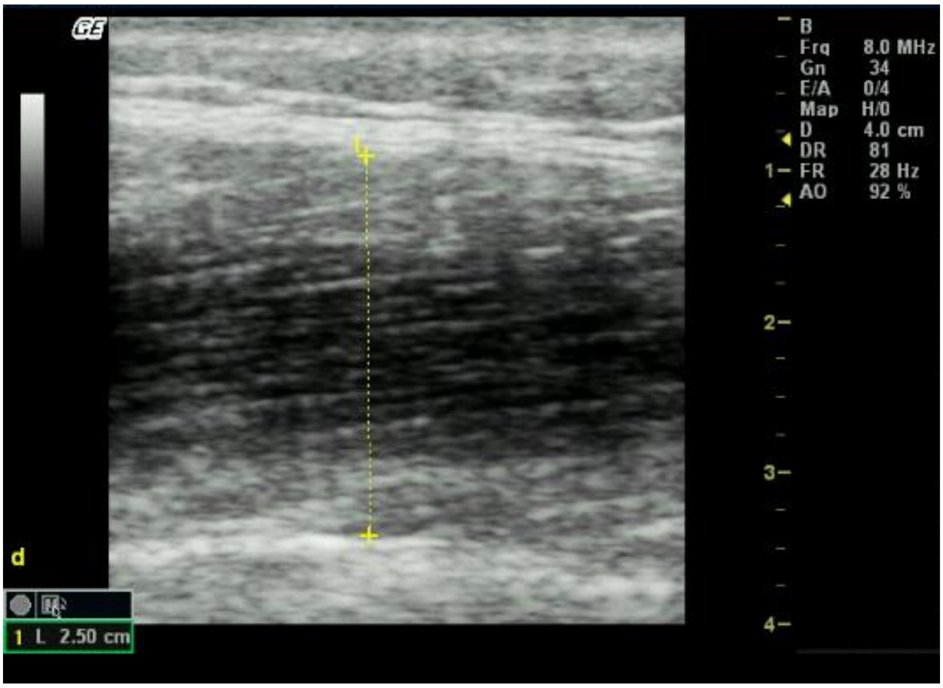

Figure 1. Image of VL measurement from lowest point of SA (top cursor) and highest point of DA (bottom cursor)

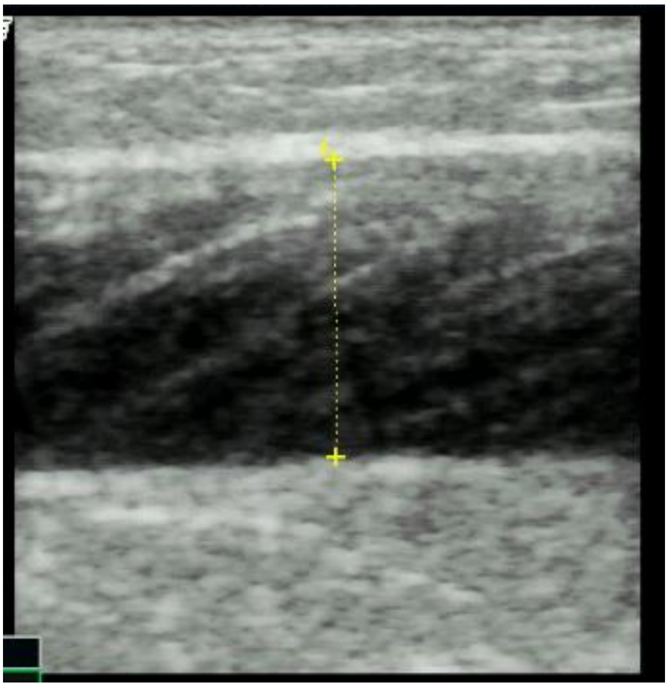

Figure 2. Image of GM measurement from lowest point of SA (top cursor) and highest point of DA (bottom cursor)

2.2.2 Muscle Quality

Muscle quality was analysed by exporting ultrasonography images from the ultrasound device onto a laptop using a memory stick. Using free photo editing software (ImageJ, LOCI, University of Wisconsin), images were analysed by drawing the muscle shape using the polygon selections, and not including the lighter in colour superior muscle facia (Figure 3). Imaging the muscle quality using polygon selections has been suggested to be as accurate as drawing the muscle using the free hand tool (Harris-Love et al. 2016). Once the polygon shape was created, histogram of the image reveals the mean greyscale of white and black within the muscle, signifying muscle quality (Reimers et al. 1993; Scholten et al. 2003). Histogram of EI on muscles were expressed for the region of interest in values from 0 to 255. The lower EI values signify greater muscle quality and function (Watanabe et al. 2013).

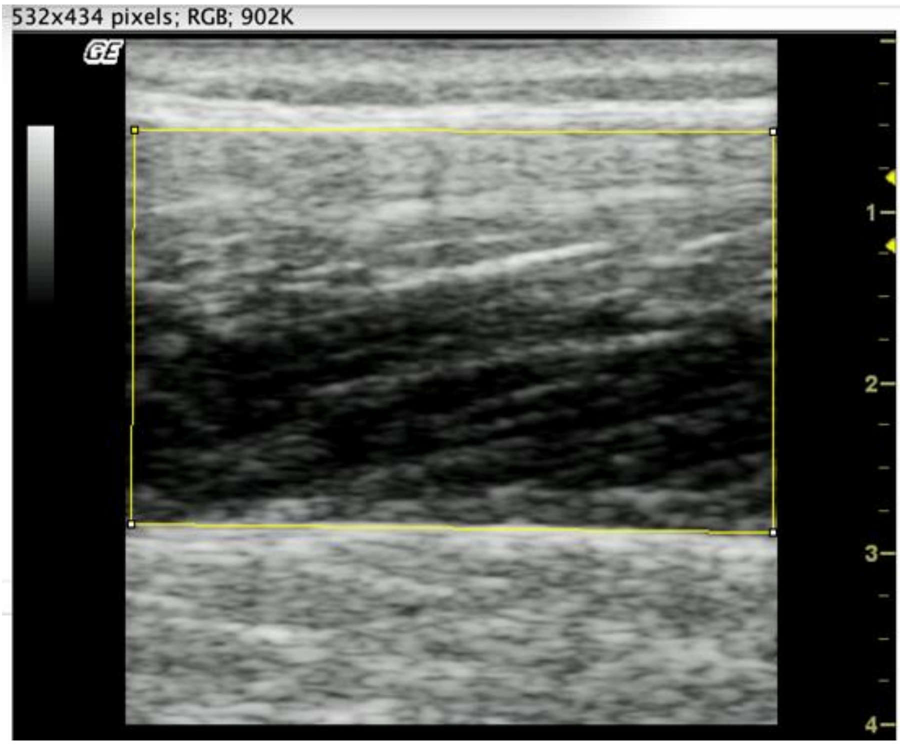

Figure 3. ImageJ software utilised to analyse greyscale histogram for ultrasonography images.

2.2.3 Sit-to-stand tests

A five rep sit-to-stand test (5 x STS) was completed following posturographic trials. Prior to the recorded test, instructions and visual demonstrations were provided by the principal investigator. Participants were instructed to start in the seated position, with hips and knees at 90º and the arms crossed across the chest and hands resting on the contralateral shoulders. The objective of the test was to perform five sits to stands repetitions in the quickest possible time without assistance (Figure 4). A submaximal practice effort was permitted prior to the recorded test, to familiarise the participants to the protocol and serve as a warm up. The test commenced once the participants' back left the backrest of the chair. A repetition consisted of the participant standing up and sitting back down returning to the starting position. The protocol was followed and timed for five reps with a stopwatch. The participants continued to STS until thirty seconds was completed for the endurance STS, and both results were recorded (30-s STS).

Figure 4. Participant completing 5 x STS and 30-s STS during pre-testing.

2.2.4 Timed up and go

The Timed up and go (TUG) test was employed to test mobility. To test TUG, participants were asked to wear trainers or comfortable walking shoes. Three meters were measured from the chair (starting point) using a tape measure (Stanley Powerlock 5 metre steel tape measure, Connecticut, USA) and a cone, signalling the turning point for participants. A demonstration was given prior to the participants familiarising and practising the TUG. Participants were initially seated on a back supported chair (seat height 46cm) with their arms resting on the lap. To begin the test, knees were at 90º and without using the arms to assist, on the word "go" had to stand up, walk to the cone at a normal comfortable speed, walk around the cone and return to the chair (Figure 5). The time taken to complete the test was measured in seconds with a stopwatch. Participants were aware that each trial would be timed. Timing began as soon as the participants back left the chair and ended when the back returned to the same position. A practice trial was performed followed by three timed trials, the fastest of which was used for analysis.

Figure 5. Participant completing TUG during pre-testing.

2.2.5 Isometric Strength

The back-dynamometer isometric test served as a global measure of muscle strength with the Takei 5402 digital back and leg isometric dynamometer (HaB International Ltd, Southam UK). Measurement of isometric strength was recorded in kilograms (kg) of force. Participants observed a demonstration of the test prior to a sub-maximal practice test. Participants stood on the base of the dynamometer with the bar in their hands (overhand grip), arms fully extended, with knees and hips flexed slightly (Figure 6). From this position, the range of motion (ROM) was set for the participants. To test strength, participants were asked to lift in a vertical direction by providing continuous isometric contractions with the extensors of the knees, hips and lower back. The maximal contractions were completed in a gradual manner, with participants gradually increasing isometric pull for three seconds. Following demonstration and familiarisation, participants completed three trials with thirty seconds rest between each trial. Maximal strength was recorded and used for analysis.

Figure 6. Isometric back strength dynamometer test.

2.2.6 Fear of falling

A fear of falling questionnaire (Greenberg, 2011) was completed pre and post intervention at the participants own leisure, providing they returned the questionnaire on the days of pre and post testing. Sixteen day to day scenarios were given, each with a score from 1-4 (1 being lowest concern vs 4 being greatest concern of falling). A total score was given after adding the scores of all scenarios. A low concern of falling score was considered between 16-19, moderate concern was 20-27 and high concern was 28-64.

2.2.7 Posturography

Static postural stability assessments were completed on a force platform (AMTI, AccuGait, Watertown, MA). All trials were completed in silent conditions with participants unshod and data collector nearby to prevent any risk of falling through a loss of balance. Three trials were completed with the feet together (Romberg stance) with the eyes open (EO) and eyes closed (EC) for thirty seconds per trial. During the EO trials, participants were instructed to rest their arms in front of hips, focus on a large circular object fixed on the wall (eye level) 1.5 metres from the force platform and stay as still as possible for the duration of the test. The same instructions were followed for EC, apart from the participants eyes were closed throughout trials (Figure 7). Data were sampled at 100Hz (AMTI, Netforce, Watertown, MA) and the total displacement (cm) of centre of pressure (COP), in the anteroposterior (COP_{AP}) and mediolateral (COP_{ML}) directions, ellipse areas (EA) and COP path length (COP_{PL}) were subsequently calculate (AMTI, BioAnalysis, Version 2.2, Watertown, MA) and served as measure of postural sway. All forces were filtered with a 4th order low-pass Butterworth filter with a cut off frequency of 6Hz. An average result of the three trials were analysed for all parameters, and analysed using SPSS version 25.0 software (IBM Inc., Chicago, IL).

Figure 7. Posturography examination during pre-testing.

2.3 Characteristic of Kbox Flywheel Device

Traditional forms of training require resistance provided by gravity-dependent free weights, machines, or elastic recoil; however, flywheel resistance is provided by iso-inertial momentum (Carroll et al. 2019). A thorough review of the physical properties of flywheel exercise is not within the scope of the current review (Kowalchuk and Butcher, 2019). However, a brief overview follows. The participant provides the muscular force concentrically through a connection to a rope that is attached and wrapped around the axis of the flywheel, which causes the flywheel to spin against its inertia throughout the concentric phase. Upon reaching the maximum amount of displacement of the knees and ankles (squat and plantarflextion), the flywheel strap wraps back around the axis, this momentum provides the resistance during the eccentric phase. The amount of eccentric energy recovered from the concentric phase is slightly less, because the laws of conservation of energy- with friction and heat loss reducing the eccentric energy slightly. Therefore, the overall power created concentrically during the movement is very similar to that achieved eccentrically. However, the resistance and peak powers can be greater during the eccentric phase, depending on when in the eccentric phase most amount of effort is exerted. If the participant exerts most of the effort in decelerating the flywheel (eccentrically), the peak power and resistance will be greater in the eccentric phase compared to the concentric phase.

2.4 Training Program

Prior to starting the training program, participants completed two familiarization sessions, involving harness fitting, safety guidelines and the practising of squat training with the ECC device (Kbox 4, Exxentric AM TM, Bromma, Sweden). The flywheel was initially fitted with one flywheel with a moment inertia of 0.025 $kg \cdot m^{-2}$. Participants trained two times per week with each session separated by a minimum of 48 hours for 6 weeks. Training consisted of four sets of eight repetitions. Before each set, participants completed three pre-repetitions to accelerate the flywheel to desired speed. Average power (W), concentric peak and eccentric peak power (W) were recorded using the kMeter 2 feedback system, sending real time data to the Exxentric mobile application. These measures were selected due to recent evidence of reliability for the platform selected (Weakley et al. 2019). Training was progressed by increasing the number of repetitions by two, every two weeks with the final weeks performing four sets of twelve repetitions for both squat and plantarflexion exercises (Onambélé et al. 2008). Exercises were performed at a maximal voluntary speed for each repetition at the chosen flywheel inertia. The flywheel inertia that participants began the training with was selected following the initial familiarisation session. To begin the squat exercise, the body harness was fitted, and ROM was set to ensure consistent tension throughout the movement. Foot position was self-selected. Participants were instructed to squat to their desired range, whilst holding the squat the flywheel was spun, until the belt was fully wound (loading the wheel). The participant was instructed to stand up at their maximal voluntary speed and resist the flywheel inertia on the eccentric phase each rep, allowing the flywheel to gain greater speeds of inertia (Figure 8). This speed should be matched throughout the whole set through verbal feedback from the data collector via live information from the K meter 2 and Exxentric mobile application. Throughout the squats, participants had the data collector nearby, and were able to hold onto a secure structure, if required for additional support/balance. Upon completion of each set, participants had to resist the flywheel inertia on the eccentric phase to bring the flywheel inertia to a halt.

Figure 8. A training session with flywheel squats being demonstrated.

The calf press movement was performed using a foot block attachment, allowing the participants to elevate their heel off the floor to perform plantarflexion at their self-selected range. All repetitions were completed with participants holding onto a secure structure for support/balance (Figure 9). Following each set, participants were asked to rate the difficulty of exercise from 1-10 using the CR-10 rating of perceived exertion scale (Zamunér et al. 2011). To allow participants to learn flywheel movements, Exxentrics recommend at least 5 familiarisation sessions prior to initial training. In present study we followed the protocol recommended, allowing participants to learn movements before intervention started.

Figure 9. A training session with plantarflexion being demonstrated.

2.5 Statistical Analysis

The statistical analyses were completed using SPSS version 25.0 software (IBM Inc., Chicago, IL). All outcome measures were analysed using a with a 2 (group; treatment vs. control) × 2 (time; pre vs. post) mixed model repeated measures analysis of variance (ANOVA). For all analyses, normality (Shapiro–Wilk Test) and homogeneity of variance/sphericity (Mauchly Test) were performed and confirmed prior to parametric analyses. Post hoc analyses with the Bonferroni-adjusted α for multiple comparisons were conducted to follow up significant effects. For ANOVA, effect sizes are reported as partial eta-squared value (η^2) where appropriate. Cohen's *d* effect sizes (ES) are reported for the post hoc comparisons, presented with effect sizes where 0.2, 0.5 and 0.8 indicate small, medium and large effects. Statistical significance was accepted at $P \leq 0.05$ for all outcomes, with data reported as mean ± standard deviation (SD).

2.6 Reliability Data

Test-retest reliability was determined for all outcomes to ensure that any observed differences post intervention represent a real physiological change, and not a systematic error. Within-session reliability was examined using intraclass correlation coefficients (ICC) and coefficients of variation (COV) during pre-training experimental session between the second and third trials. No significant differences ($P > 0.05$) were detected in TUG time, or any measure of postural sway, muscle quality or thickness. A high degree of reliability was found for muscle thickness (ICC = 0.98 to 1.00, COV =1.19 to 1.83%) (Figure 10), TUG (ICC = 0.97, COV = 2.0%), postural sway (ICC = 0.84 to 0.97, COV = 4.9 to 11.1%) and muscle quality (ICC = 0.96 to 0.97, COV = 1.30 to 1.99%). Due to the nature of the sit-to-stand test, participants completed one before training (due to fatigue), therefore, within-session reliability could not be reported for this outcome.

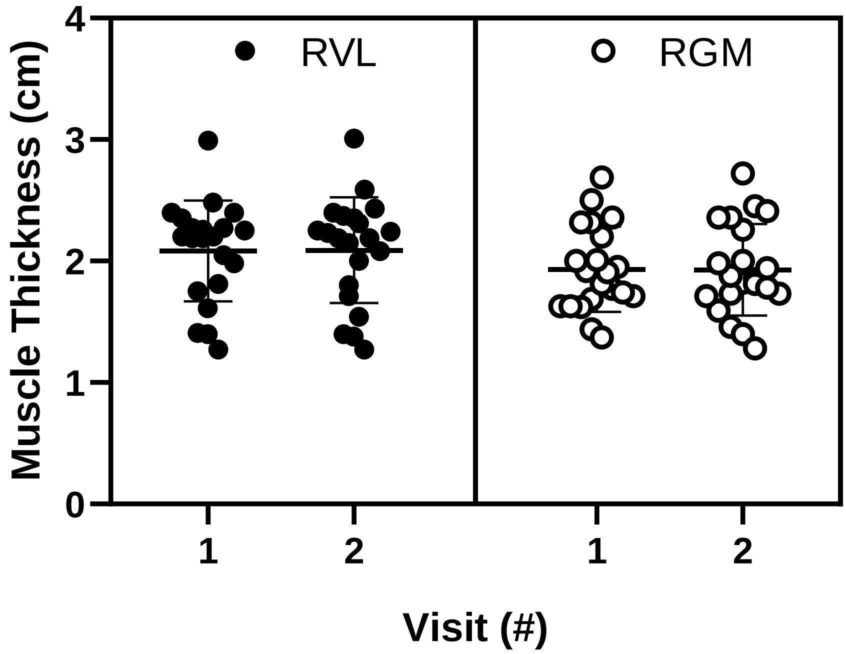

Figure 10. Muscle thickness of the RVL and RGM measured during two separate visits.

Ultrasonography data was utilised for reliability in muscle quality, to ensure data was collected from reliable locations from the ultrasound images recorded. Control group images were analysed twice, the examiner analysed each image and revisited the same images at a later time, recording the mean greyscale and standard deviation. Data was analysed using a COV calculator (Microsoft Excel, Redmond, Washington, USA) and Cronbach's Alpha (SPSS), with an COV average score of 1.2% and Cronbach's Alpha of 0.985.

3. Results

3.1 Posturography

During eyes open conditions, no significant group × time interactions were observed for COP_{AP} (F = 0.290; P = 0.593; η^2 = 0.008), COP_{ML} (F = 0.001; P = 0.972; η^2 = 0.000), COP_{PL} (F = 0.589; P = 0.448; η^2 = 0.448), or EA (F = 0.002; P = 0.962; η^2 = 0.000). Similarly, during eyes closed conditions, no significant group × time interactions were observed for COP_{AP} (F = 0.002; P = 0.960; η^2 = 0.000), COP_{ML} (F = 0.000; P = 0.991; η^2 = 0.000), COP_{PL} (F = 0.088; P = 0.769; η^2 = 0.002) and EA (F = 0.242; P = 0.625; η^2 = 0.006).

Table 1. Mean posturography data with eyes open and eyes closed.

	Treatment		Control	
Variable	Pre	Post	Pre	Post
Eyes open				
$COP_{AP\ (cm)}$	1.91 ± 0.30	1.91 ± 0.41	5.22 ± 2.24	4.73 ± 2.41
$COP_{ML\ (cm)}$	2.11 ± 0.57	1.88 ± 0.88	2.86 ± 0.70	2.60 ± 0.77
$COP_{PL\ (cm)}$	69.00 ± 12.04	66.98 ± 10.34	63.20 ± 4.50	65.97 ± 8.44
EA $_{(cm^2)}$	2.94 ± 1.27	3.00 ± 1.49	4.47 ± 1.66	4.48 ± 2.35
Eyes closed				
$COP_{AP\ (cm)}$	3.27 ± 0.70	3.25 ± 0.47	5.66 ± 2.25	5.70 ± 2.21
$COP_{ML\ (cm)}$	3.25 ± 0.88	2.94 ± 1.09	3.76 ± 1.00	3.53 ± 0.98
$COP_{PL\ (cm)}$	93.09 ± 25.27	92.14 ± 16.72	76.43 ± 2.45	78.70 ± 4.14
EA $_{(cm^2)}$	6.91 ± 2.52	7.29 ± 1.65	10.84 ± 4.26	10.21 ± 4.67

COP: centre of pressure excursions; COP_{AP}: anteroposterior axis; COP_{ML}: mediolateral axis; COP_{PL}: centre of pressure path length; EA: ellipse area.

3.2 Mobility

No significant group × time interactions were observed for the 5 times STS (F = 0.759; P = 0.389; η^2 = 0.020), 30-s STS (F = 1.379; P = 0.248; η^2 = 0.035), strength dynamometer (F = 0.341; P = 0.562; η^2 = 0.009) and TUG (F = 2.081; P = 0.157; η^2 = 0.052). However, for the treatment group, there was a large magnitude reduction in the 30-s STS (d = 1.07), and a moderate magnitude reduction (Figure 11) in TUG (d = 0.77) and 5 times STS (d = 0.61).

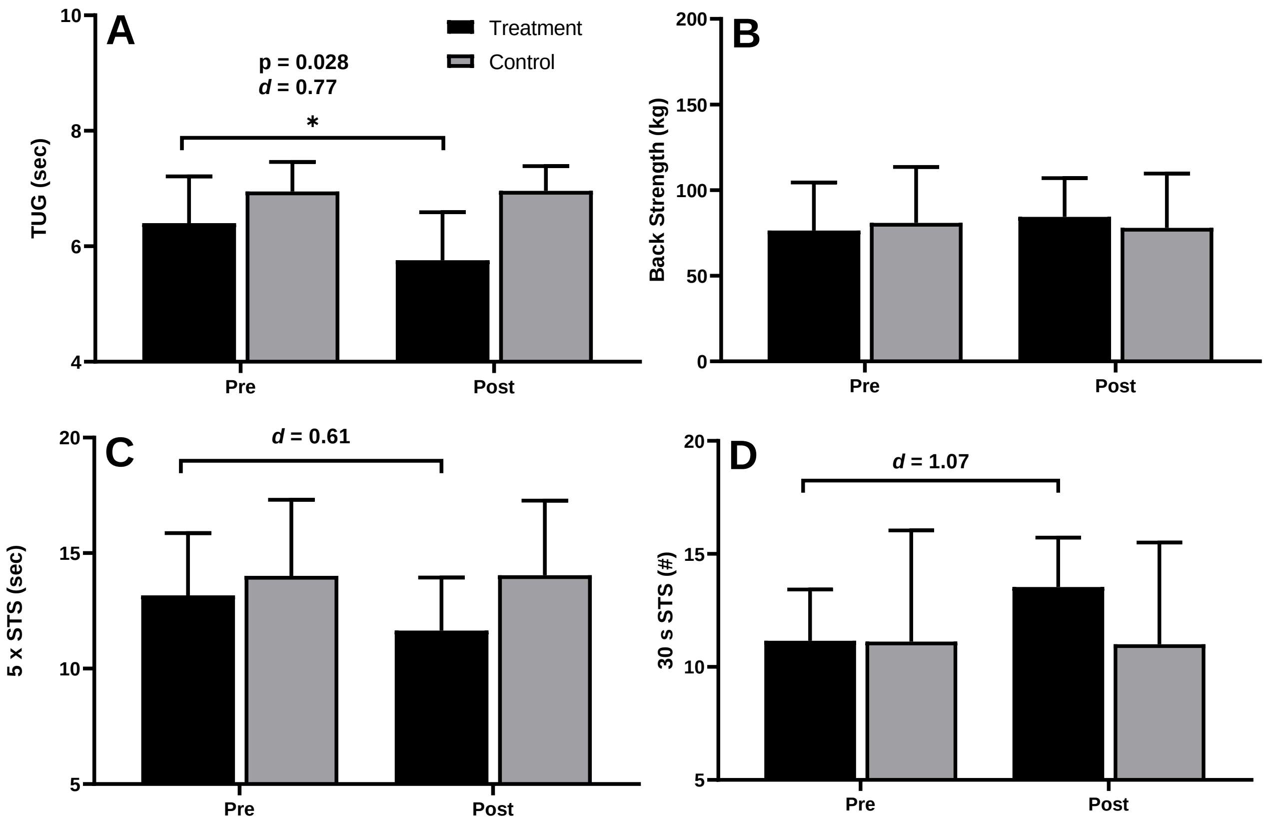

Figure 11. TUG (A), back strength (B), 5 x STS (C) and 30 s STS (D) pre and post 6 weeks of ECC flywheel training.

3.3 Muscle Thickness

No significant group × time interactions were observed for muscle thickness of the RVL (F = 0.031, P = 0.860, η^2 = 0.001), LVL (F = 0.259, P = 0.614, η^2 = 0.007), RGM (F = 2.557, P = 0.118, η^2 = 0.063) and LGM (F = 1.335, P = 0.255, η^2 = 0.034) (Figure 12). However, there were main effects of group for each muscle (all P< 0.05). Post hoc analysis revealed that for each muscle measured, the control group had a significantly greater muscle thickness than the training group at pre and post training points (Figure 12). A representative imagine of muscle quality is illustrated in Figure 14.

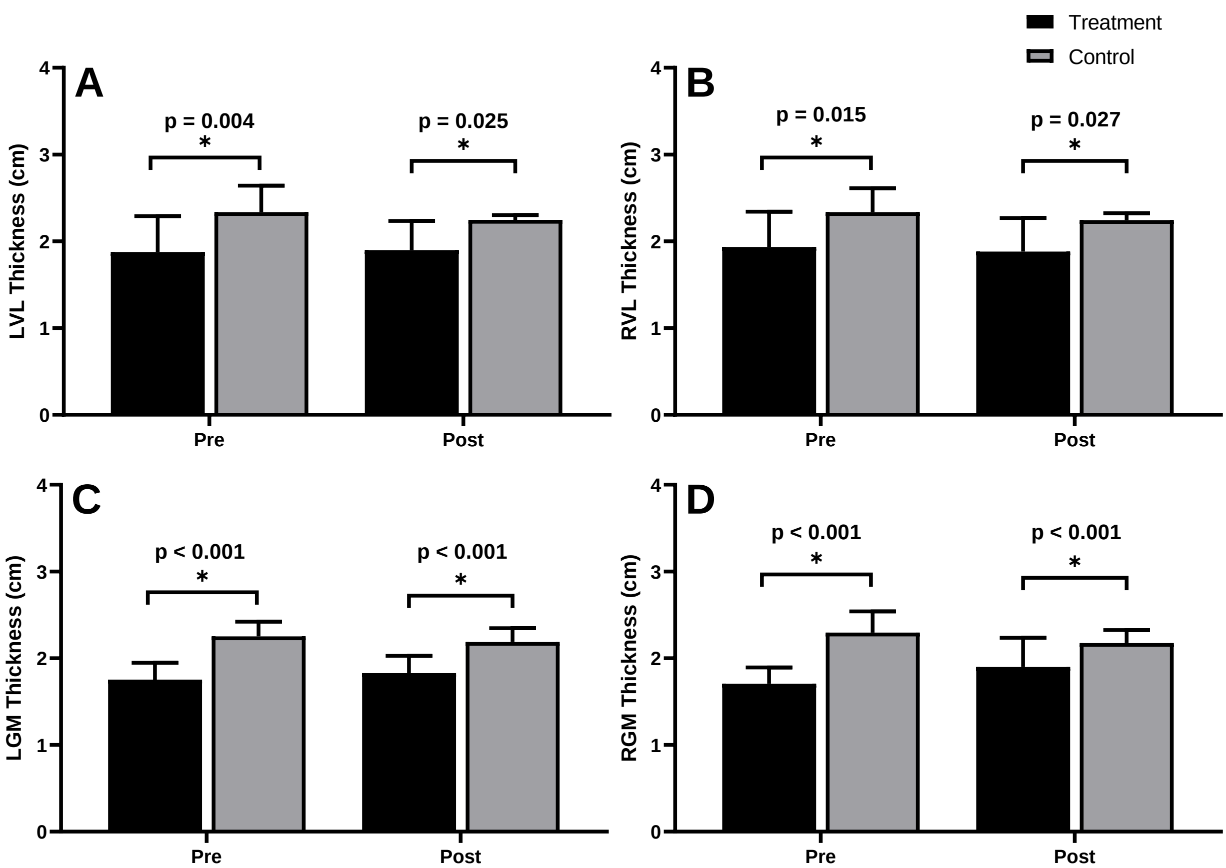

Figure 12. Charts demonstrating changes in muscle thickness for LVL (A), RVL (B), LGM (C) and RGM (D).

3.3.1 Muscle Quality

No significant group × time interactions were observed for muscle quality for the RVL (F = 0.837, P = 0.366, η^2 = 0.022), LVL (F = 1.895, P = 0.177, η^2 = 0.047), RGM (F = 0.215, P = 0.646, η^2 = 0.006) and LGM (F = 0.459, P = 0.502, η^2 = 0.012). However, we did observe a moderate magnitude of change (Figure 13) from pre to post eccentric flywheel training for LVL (d = 0.70) and for LGM (d = 0.47).

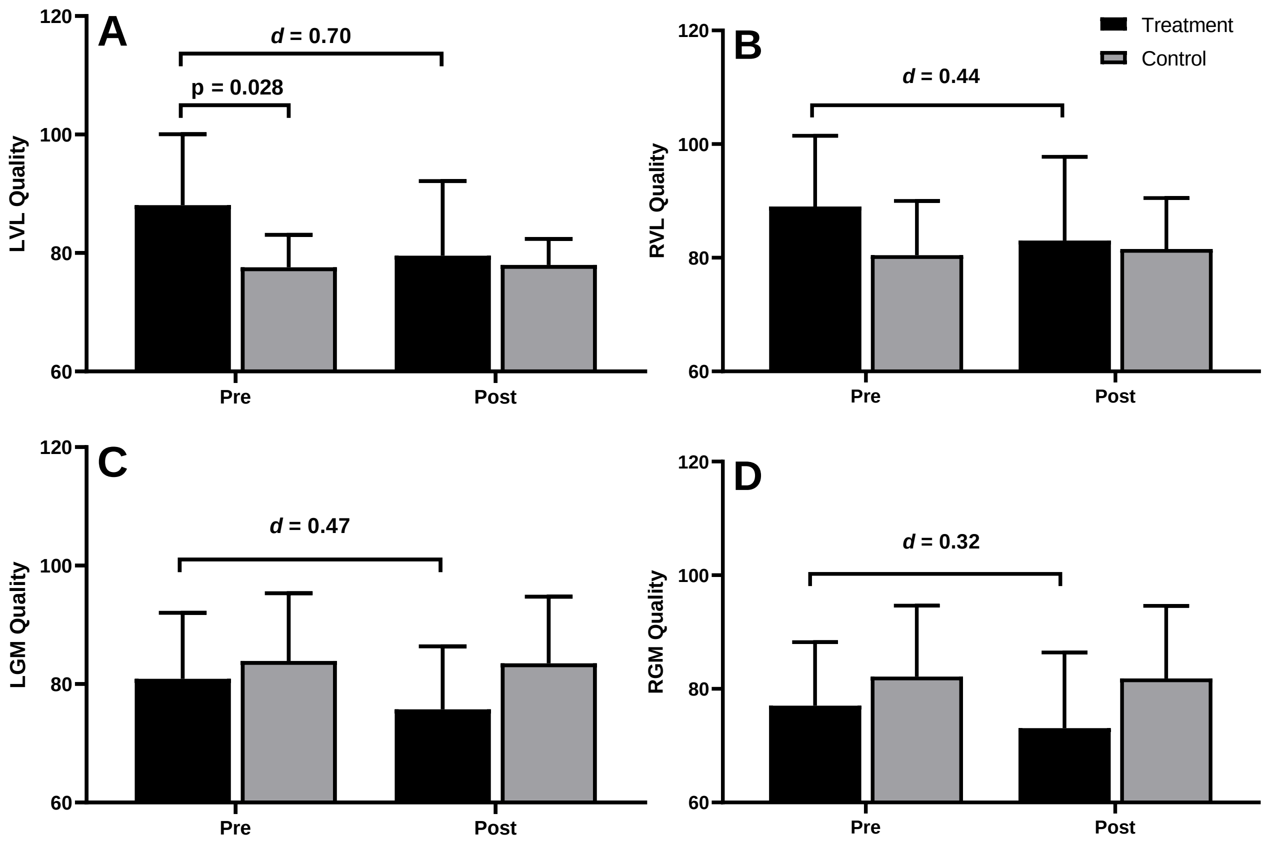

Figure 13. Charts demonstrating changes in muscle quality for LVL (A), RVL (B), LGM (C) and RGM (D).

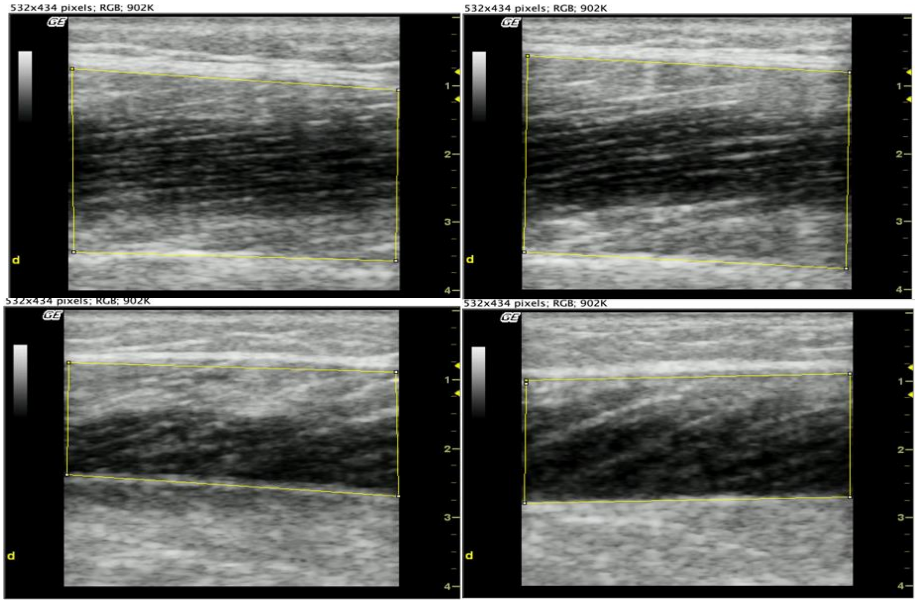

Figure 14. Ultrasonography images during greyscale muscle quality analysis using Image J software of (A) LVL, (B) RVL, (C) LGM and (D) RGM.

3.4 Training improvements

Throughout training period, average power (W), concentric and eccentric peak power was recorded. From the first to final training sessions, squat average power (54%), concentric (115%) and eccentric peak power (115%) improved throughout the six weeks (illustrated in Figure 15). Furthermore, plantarflexion average power (28%), concentric (62%) and eccentric peak power (59%) improved throughout the six weeks (illustrated in Figure 16). Throughout the training intervention, there were strong positive correlations for squat between CR-10 and average power (Table 2.). Throughout the intervention, rep time (seconds) was recorded, improvements of 28% for squats and 27% for plantarflexion, illustrated in Figure 17.

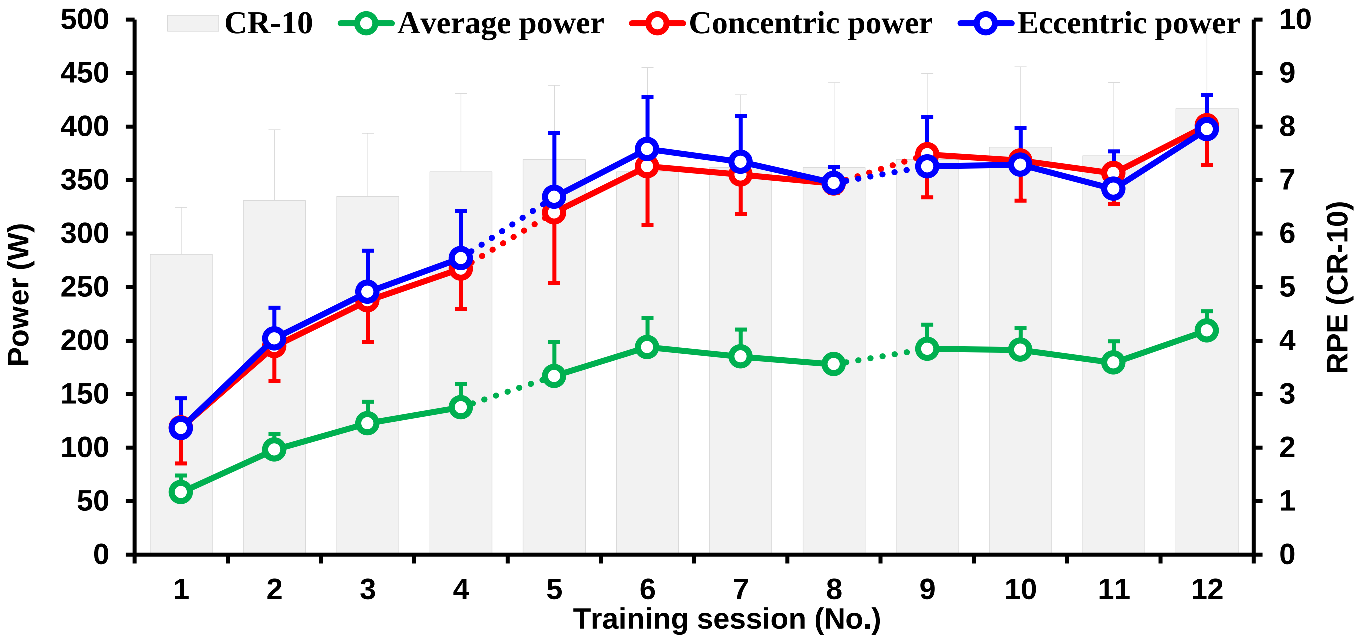

Figure 15. Average watts, concentric and eccentric peak power throughout each training session for squats. Dotted line represents increase in training intensity.

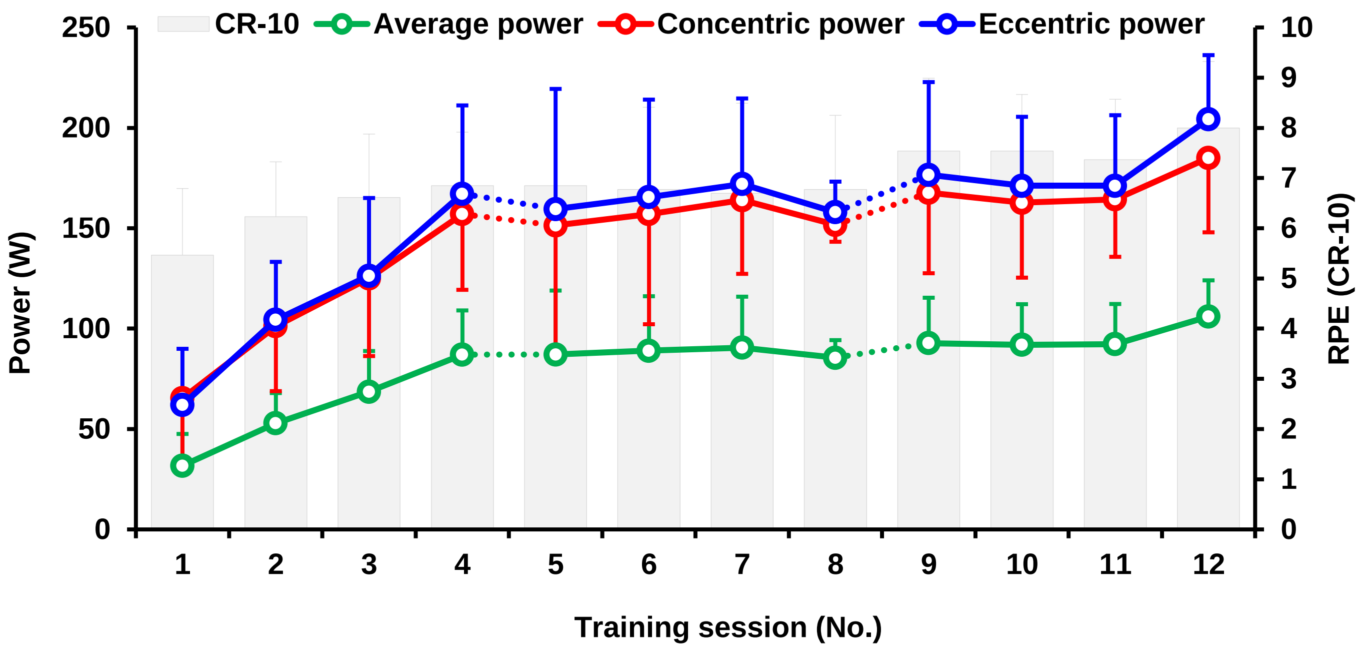

Figure 16. Average watts, concentric and eccentric peak power throughout each training session for plantarflexion. Dotted line represents increase in training intensity.

Table 2. Pearson's correlation coefficients between squat and plantarflexion RPE on power (W).

	Squat RPE		Plantarflexion RPE	
	p	*r*	*p*	*r*
Average power output (W)	< 0.001	.907	< 0.001	.903
Concentric peak power (W)	< 0.001	.911	< 0.001	.903
Eccentric peak power (W)	< 0.001	.903	< 0.001	.910

Correlation is significant at $p < 0.05$ between squat and plantarflexion RPE on average power, concentric peak power and eccentric peak power (W).

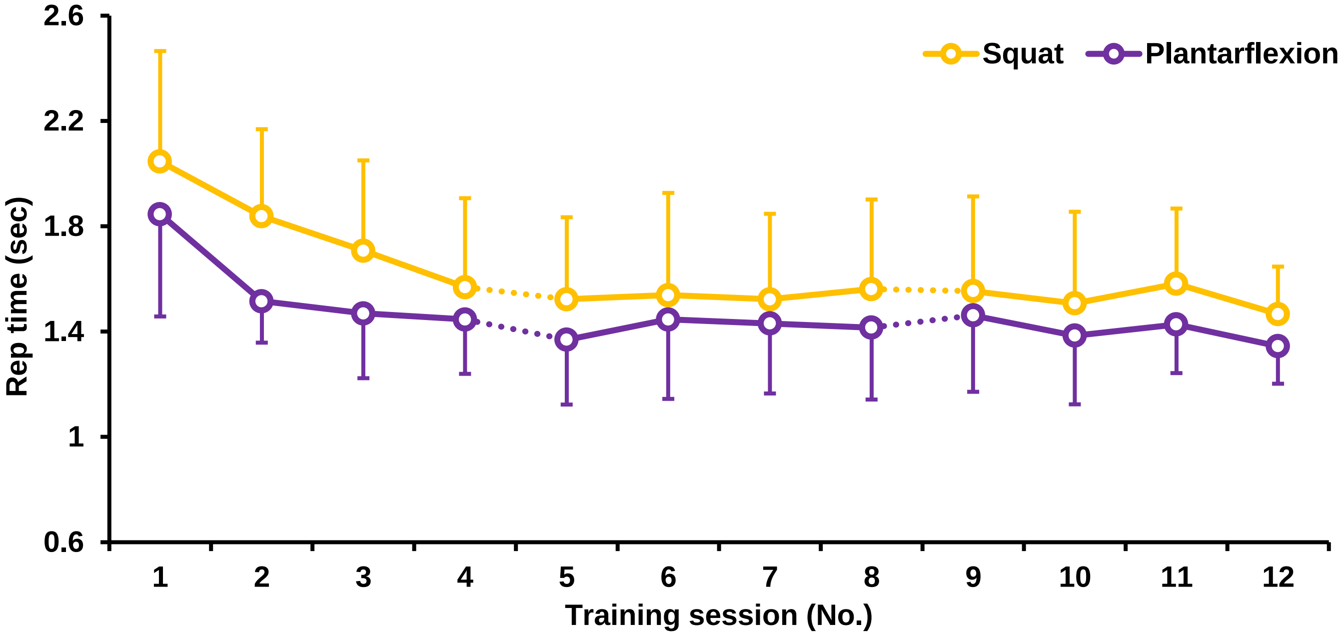

Figure 17. Improvements of rep time (seconds) for squat and plantarflexion. Dotted line represents increases in training intensity.

3.5 Fear of Falling

FOF results revealed no significant change in the questionnaires for treatment group from pre (17.3 ± 1.8) to post (17.3 ± 1.8) training. No significant changes were found in control group for pre (16.1 ± 0.35) and post (16.1 ± 0.35). Both groups had no significant changes from pre to post training FOF ($P > 0.05$).

4. Discussion

The aim of the present study was to determine the effects of flywheel training on muscle thickness/quality, physical functioning, postural stability and fear of falling among older people. We initially hypothesised that flywheel eccentric training would elicit improvements in quadricep size and strength, balance, mobility and FOF. The current findings indicate that ECC had no effect on balance outcomes, mobility, FOF, physical function and muscle thickness or quality. Therefore, we must reject our hypotheses.

4.1 Mobility and Physical Function

As with previous studies, we examined the effects of ECC on physical function markers such as TUG (Onambélé et al. 2008), 30-s STS (Van Roie et al. 2013), 5 x STS (Schlicht, Camaione and Owen, 2001) and strength dynamometer (Onambélé et al. 2008). Although we did not find a statistically significant improvement in TUG or STS, it is important to note that the analyses revealed large magnitude increase in 30-s STS (d = 1.07) and a moderate magnitude reduction in TUG (d = 0.77) following ECC flywheel training. These findings are consistent with previous literature which reported improvements TUG ranging from 7-29% in (LaStayo et al. 2003; Mueller et al. 2009; Sañudo et al. 2019). These findings are important because impaired mobility is associated with falls, with individuals recording TUG times of >13.5 s having a 90% probability of being a faller (Shumway-Cook, Brauer, Woollacott, 2000). Participants in the present study initially completed the TUG in ~6.5 s, times at the faster end of the normative spectrum (7.1-9.0 s) for community-dwelling older adults aged 60-69 years (Bohannon, 2006). Nevertheless, the 10% improvement in TUG occurred, placing the participants well above the expected range. The reductions in TUG time could be due to the nature of ECC training and might be important in improving activities of daily living (i.e. sitting, standing, accelerating or decelerating).

In addition to TUG, we found a 21% increase in the number of sit-to-stand repetition performed during 30 s, and an 12% reduction in the time taken to achieve 5 sit-to-stand repetitions. Accordingly, Van Roie et al. (2013) found that high-intensity strength training in significantly improved 30-STS (8.6% ± 8) results among older people. The 30-s STS is a widely used tool to assess fitness levels (Okamoto et al. 2010), monitor training (Özkaya et al. 2005) and for rehabilitation in elderly population (Nyland et al. 2007). Furthermore, the test is a reliable and valid indicator of lower body muscle strength, mobility and activity levels in older people (Jones, Rikli and Beam, 1999). This improved STS performed found in the present study implies a reduced risk of falls, given that lower reps during this test is associated with falls (Applebaum et al. 2017). Completing a greater number of repetitions suggests the training has reduced fatiguability for participants, which is an important risk factor for falls (Millor et al. 2013). Within the context of the 5 times STS test, Schlicht, Camaione and Owen (2001) found that strength training alone does not appear to improve 5 x STS performance. A reduction in the time to achieve 5 reps points towards an increase in strength, which might be associated with a reduced fall risk because increased strength is linked with greater balance control (Applebaum et al. 2017).

Previous research on ECC interventions has shown an increase in strength (Kowalchuk and Butcher, 2019). The present study is not in agreement with prior research as no improvement is isometric strength was found. Findings from recent meta-analysis by Kowalchuk and Butcher, (2019) on flywheel training noted beneficial changes in muscle strength and muscle power in older adults, which are related to increases in postural stability (Sañudo et al. 2019). There are a number of possible explanations for the null findings in strength reported here. For example, the cohort recruited for the present study were very active. Therefore, the stimulus provided from ECC may have not been strong enough to elicit significant improvements in strength (Okubo, Schoene and Lord, 2017). Given that Sañudo et al. (2019) did not provide any familiarisation sessions to their cohort, no improvements were seen in power output (W) until the 8th training session. However, in the present study we observed improvements of power output (W) found in the 2nd session following the recommended sessions (n =5). Finally, the measure of strength may not have been valid for testing concentric and eccentric strength. The isometric dynamometer is not considered a valid measure of concentric and eccentric strength because it only tests the isometric contractions. However, due to the nature of the study (testing in the field) this was the most practical test of strength. We would welcome future studies which determine the effects of flywheel training on isokinetic measures of muscle strength and power.

4.2 Effects of Flywheel Training on Muscle Thickness and Quality

To our knowledge, this is the first study to investigate changes in muscle quality and muscle thickness following eccentric flywheel training among older people. As with our measures of mobility, balance and physical function, we found no (statistically significant) increases in superficial-to-deep muscle thickness. Given that increases in muscle thickness often accompany increases in muscle volume (i.e. cross-sectional area) (Kawakami et al. 1995), we suggest that it is unlikely that eccentric flywheel training substantially increased muscle size in the present study. The lack of increase in muscle thickness is not an uncommon finding following relatively short duration training studies (Akima et al. 1999; Blazevich et al. 2007; Moritani and DiVries, 1979; Narici et al. 1996). Accordingly, the moderate magnitude improvements in TUG and STS cannot be explained by improved muscle thickness. However, the underlying mechanisms under which this lack of response occurs are unclear. It is plausible that the early adaptations to strength training occur largely by alterations in muscle recruitment of additional motor units, increased firing rate and inter- and intramuscular coordination (Blazevich et al. 2007). Although we did not measure muscle activation patterns in the present study, rapid changes in muscle recruitment in response to traditional eccentric-concentric resistance training have previously been reported (Moritani and DiVries, 1979; Frontera et al. 2000; Caserotti et al. 2008; Granacher et al. 2009; Cadore et al. 2013). Given that muscle mass is associated with both fall risk (Benichou and Lord, 2016) and mortality (Chuang et al. 2014), identifying exercise modalities that can limit or even reverse functional decline remains a top priority in geriatric research. We would encourage future studies to determine the effects of a longer period of flywheel training on morphological muscle measures.

Older adults demonstrate reduced muscle quality, which is associated with poor physical function (Misic et al. 2007) and a greater risk of future functional limitations (Vissers et al. 2005). The reduced muscle quality with ageing is most likely explained by a decline in the proportion of type II muscle fibres, an increase in intramuscular connective tissue, an infiltration of fat deposits and alterations in muscle metabolism (Pinto et al. 2014). In corroboration with the muscle thickness results, we found no statistically significant changes in muscle quality following flywheel training. However, the training group showed moderate magnitude reductions (~10%) in echo intensity values after 6-weeks of flywheel training, suggesting an improvement in muscle quality. Similar to the present study, Pinto et al. (2014) found that a strength training program (leg press and knee extension, 12 – 15 reps) lasting only 6-weeks (2 days/week) was sufficient to improve muscle quality by 14%. It should be noted that the technique to assess muscle quality differed to the study of Pinto and colleagues. More specifically, we measured muscle quality using echogenicity (i.e. greyscale), while Pinto et al. (2014) measured muscle quality expressed as the force produced per unit of active muscle mass. Nevertheless, the present findings provide promising evidence that flywheel training might be effective in combating morphological reductions associated with ageing and subsequently improve functional performance. The mechanism responsible for improved muscle quality remains an issue of debate in the literature. The most likely explanation is that resistance trained provoked a decline in adipose tissue within the muscle. Indeed, high echo intensity values are associated with the amount of fat tissue (Reimers et al. 1993). Although we observed only moderate magnitude ($d = 0.41$ to 0.77) reductions in echo intensity (inferring better muscle quality), additional sets, at a higher intensity and over longer periods of training mat promote an even high reduction.

Given the lack of morphological change shown in the present study, it is appropriate to discuss the precision of our ultrasound measurements. The validity of ultrasound techniques to assess in vivo muscle thickness and quality has previously been confirmed by several studies (Harris-Love et al. 2016; Ismail et al. 2015; Kawakami et al. 1993). We measured the reliability of our ultrasound procedure and they were found to be highly accurate for both the (right side only) VL (ICC = .995) and GM (ICC = .978). We believe that these reliabilities are very high and therefore the lack of change in muscle thickness and quality are unlikely a result of measurement unreliability. Instead, we argue that the lack of improvement was most likely a result of the low training volume, low statistical power, and large standard deviations. Moreover, the absence of significant changes in muscle thickness and quality may be explained by high variability in performance and the physical characteristics at baseline. We cannot rule out the possibility that a higher training volume may have resulted in greater improvements in muscle quality and thickness.

4.3 Effects Flywheel Training on Postural Control

Despite moderate to large magnitude (albeit non-significant) improvements in mobility (TUG) and physical function (STS), no significant reductions in postural sway outcomes were observed after flywheel training (Table 1). Although unexpected, these findings are in agreement with previous systematic reviews (Orr et al. 2008) and meta-analysis (Low et al. 2017) examining the effect of traditional resistance training on static balance performance. In light of recent evidence showing that 6-weeks of flywheel training (using the squat technique) elicited marked reductions in COP measure of postural sway among older adults (Sanudo et al. 2019), we initially hypothesised that flywheel training, involving both squat (knee muscles) and plantarflexion (ankle muscles) exercises performed in the standing position, would provoke considerable reductions in postural sway. Thus, the underlying mechanisms explaining the null findings reported here are not clear. The disparate findings reported between the present study and those of Sanudo et al. (2019) might be related to the type of balance assessment. In the present study, participants performed quiet bipedal standing tasks with the eyes open or eyes closed. In the study by Sanudo and colleagues participants also stood in a bipedal position, but concurrently performed a cognitive interference task. Thus, the most likely explanation for the null findings in the present study could be the presence of a ceiling effect. More specifically, body oscillations were already close to the “physiological minimum” for this particular group. In contrast, postural stability in more challenging scenarios (i.e. performing an attentional demanding task) has more room to improve, and therefore changes are more noticeable. It should be noted that Sanudo et al. (2019) reported a reduction in only one out of ten postural sway outcomes following flywheel training. Indeed, the ~1.5 mm reduction they reported in the COP displacement in the anteroposterior direction is unlikely to represent a clinically significant/relevant improvement in the context of falls-risk.

Previous research has suggested that the lack of transfer effects of strength training to improve static balance is related to different underlying neuromuscular control mechanisms governing muscle strength and postural control (Orr et al. 2008). More specifically, it is likely that balance is a distinct neuromuscular quality which likely needs to be targeted separately in order for any noticeable improvements (Kiss et al. 2018). Although our training programme was performed in the standing position which likely stressed key postural musculature, we cannot exclude the possibility that the relatively short 6-week training programme may not be sufficient to improve standing balance. Alternatively, the null findings reported here might be related to the disparity in the type of muscle fibre recruitment during eccentric exercise compared to quiet standing. For example, eccentric training preferentially recruits fast twitch (type II) motor units (Douglas et al. 2017) which would logically improve performance during the fast velocity dynamic tasks (i.e. TUG, STS), but not during quiet standing as the antigravity muscles that minimise body sway show a greater predominance of type I muscle fibres (Paillard, 2017). Furthermore, participants in the intervention group in the present study also demonstrated good static balance performance upon commencing training, as evidenced by the smaller postural sway when compared to the control group. Thus, the null findings for postural sway could be related to a ceiling effect (Orr et al. 2008), where the intervention group may have had little room for improvement. Further research is needed to assess whether flywheel training is effective in balance impaired individuals, over a longer duration (does-response adaptations), and employ more challenging static (i.e., unipedal or standing on foam) or reactive (i.e. perturbations) balance scenarios.

4.4 Implications

There are several important implications to be garnered from the present study. The current investigation determined the effects of eccentric flywheel training on physical function, muscle mass and quality, and balance performance among older adults. Although we did not observe statistically significant improvements in most outcome measures following 6-weeks of eccentric flywheel training, the moderate to large magnitude improvements in TUG, STS, VL quality suggest that this type of training offers a promising approach to elicit an eccentric training stimulus outside of the laboratory. This type of training is well tolerated (low RPE, low dropouts and high attendance), is easy to perform (mimics ADL's) and uses portable and low-cost equipment. Consequently, flywheel training appears to provide a practical means to exercising with older people because this device can be used in exercise classes, retirement facilities, personal residence or care/rehabilitation settings. Further, flywheel training devices are portable and inexpensive, and therefore might provide an alternative to isokinetic training devices, which are often not portable and prohibitively expensive. Additionally, this training approach mimics the same functional movement patterns that older adults experience during their activities of daily living (i.e. standing up from a chair, climbing stairs, picking up objects or getting into or out of the car). A unique feature of the current eccentric flywheel training used in the present study is the ability to produce an eccentric overload while also potentially manipulating balance difficulty. We argue that the null findings found for balance improvements might be attributed to the lack of balance training stimulus. To stress the sensorimotor system during balance activities, it is necessary to progressively increase the training intensity (Calatayud et al. 2015). Increasing the balance training difficulty on the flywheel device could be achieved by various combinations of sensory modulation (i.e. adding a foam pad to the surface of the platform) (Muehlbauer et al. 2012) or stance manipulation (i.e. reducing the size of the base of support) (Donath et al. 2016). Although we did not test whether sensory and/or stance manipulations could render flywheel training more challenging for balance control, future studies would be welcome which address this issue. Overall, we believe that from a practical standpoint, the moderate to large magnitude effect sizes (albeit non-significant) for TUG, STS, VL thickness and quality might provide valuable information for physical therapists, care providers and trainers who work with older people.

4.5 Limitations and Future Directions

A few limitations in this study should be acknowledged and the results should be interpreted with some caution. Firstly, the lack of statistically significant improvement in some outcome measures might be a result of an insufficient training dose (intensity, frequency and duration) to elicit marked neuromuscular adaptations, or the training failed to target the key postural musculature. The choice of a 6-week training intervention was based on previous research which showed marked benefits in similar outcome measures following a 6-week flywheel training intervention (Sanudo et al. 2019). Given the lack of previous research using flywheel training devices, and the potentially negative effects of eccentric induced muscle damage (i.e., pain, soreness, reduced function), we intentionally adopted a cautious and safe approach to the initial training volume and progression. We believe that this progression method may have impaired improvements in the training group. Future studies should identify the most appropriate dose response trends for flywheel training systems to optimise improvements in muscle mass/quality, physical function and balance. More specifically, further research is needed to determine if a longer training (i.e. 12 weeks) and greater load increments could elicit improvements in similar outcomes.

It is also possible that the outcome measures selected may have lacked sensitivity/ were not responsive to change or were subject to ceiling effects. Additionally, the generalisability of the results is uncertain, as the sample was highly selected (convenience sampling). Indeed, we recruited members of a private health club who were already highly physically active. Thus, although our older adults may have been on the verge of physical decline, their high physical activity levels prevented this decline. Future studies should determine the effectiveness of eccentric flywheel training in those with physical decline, frail older people, or those with mild to large balance impairments.

Another limitation was that the assessor was not blind to treatment allocation, which may have led to biased effect of treatment estimates for some of our outcome measures (Wood et al., 2008). Additionally, sample size was small (*n* = 21), but is similar to the sample sizes used in other exercise training studies among older people (~10–20 participants) (e.g. Sanudo et al. 2019). Because of the small sample size, we are precluded from exploring potential moderator variables such as sex or baseline physical activity levels. Additionally, although we included a control group, we lacked a traditional resistance training group (i.e. parallel comparison). This approach may have allowed us to determine whether flywheel training adds value as an exercise intervention given that traditional resistance training is often prescribed to older adults as an effective and appropriate way to exercise. Incorporating an isokinetic training group should be investigated. Another important limitation in the present study was that the test used to assess maximum muscle force (isometric back strength dynamometer) did not evaluate eccentric or concentric muscle force. Finally, the present study did not measure other aspects of physical function like reactive balance, cognitive function or gait. Thus, it is possible that eccentric flywheel training can affect fall-risk by mechanisms other than those ascertained in the present study.

5. Conclusion

In summary, this is the first study to investigate the effects of eccentric flywheel training on muscle thickness and muscle quality in older people, in addition to physical function and balance outcomes. The results highlight that eccentric flywheel training may have the potential to elicit beneficial effects on physical function outcomes in older adults. A greater understanding of the effects of eccentric flywheel training of a greater dose on these outcomes would further contribute to the evidence-based practice in older people.

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Appendix 1- Participant Information Sheet

The effects of flywheel training on musculoskeletal characteristics and physical function in healthy older adults - a randomised control trial.

PARTICIPANT INFORMATION SHEET

You are being invited to take part in research on the effects of flywheel training on muscular characteristics and physical function in older adults. Matthew Roberts (masters by research student) at Coventry University is leading this research. Before you decide to take part it is important you understand why the research is being conducted and what it will involve. Please take time to read the following information carefully.

What is the purpose of the study?
The purpose of the study is to determine the effects of eccentric flywheel training and detraining on muscle function, physical functioning, postural stability and fear of falling in the elderly. The objectives are to determine the effectiveness of a short period of eccentric resistance training using a portable device, on health-related outcomes and to compare changes in muscle function (strength and mass), physical function and fall risk. The project will involve 6 weeks of eccentric flywheel training (12 sessions), including a pre and post assessment of independent variables (balance, ultrasound, sit to stand, timed up and go, back strength dynamometer and fear of falling). The training sessions will require participants to perform squats and calf raises at maximal (voluntary) speed with 4 sets of 8 for initial 2 weeks, 4 sets of 10 (3-4 weeks) and 4 sets of 12 (5-6 weeks), which will take approximately 30 minutes.

Why have I been chosen to take part?
You are invited to participate in this study because you are active, healthy, within the suitable age range and not had a lower limb injury 6 months prior to the study, and/or severe lower limb muscle injury (strains) in the previous 2 months.

What are the benefits of taking part?
By sharing your experiences with us, you will be learning about various training methods to improve strength, balance and potentially reducing fall risk following the training. Furthermore, you will be helping Matthew Roberts and Coventry University to better understand the effects of eccentric flywheel training and detraining on muscle function, physical functioning, postural stability and fear of falling in the elderly.

Are there any risks associated with taking part?
This study has been reviewed and approved through Coventry University's formal research ethics procedure. There are no significant risks associated with participation. However, because the training is classed as maximal, the usual risks of exercise are

present throughout the study, so any issues prior or during participation must be addressed immediately.

Do I have to take part?

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What will happen if I decide to take part?

You will be asked a number of questions regarding training status, current health and previous experience in training. The training intervention will take place in a safe environment at a time that is convenient to you. The training sessions should take around 20-30 minutes per session to complete.

Data Protection and Confidentiality

Your data will be processed in accordance with the General Data Protection Regulation 2016 (GDPR) and the Data Protection Act 2018. All information collected about you will be kept strictly confidential. Unless they are fully anonymised in our records, your data will be referred to by a unique participant number rather than by name. If you consent to being audio recorded, all recordings will be destroyed once they have been transcribed. Your data will only be viewed by the researcher/research team. All electronic data will be stored on a password-protected computer file. All paper records will be stored in a locked filing cabinet at Coventry university. Your consent information will be kept separately from your responses in order to minimise risk in the event of a data breach. The lead researcher will take responsibility for data destruction and all collected data will be destroyed on or before 6 months following the final training session.

Data Protection Rights

Coventry University is a Data Controller for the information you provide. You have the right to access information held about you. Your right of access can be exercised in accordance with the General Data Protection Regulation and the Data Protection Act 2018. You also have other rights including rights of correction, erasure, objection, and data portability. For more details, including the right to lodge a complaint with the Information Commissioner's Office, please visit www.ico.org.uk. Questions, comments and requests about your personal data can also be sent to the University Data Protection Officer - enquiry.ipu@coventry.ac.uk

What will happen with the results of this study?
The results of this study may be summarised in published articles, reports and presentations. Quotes or key findings will always be made anonymous in any formal outputs unless we have your prior and explicit written permission to attribute them to you by name.

Making a Complaint

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Appendix 2 – Informed Consent Sheet

Participant No.

INFORMED CONSENT FORM:
The effects of flywheel training on musculoskeletal characteristics and physical function in healthy older adults - a randomised control trial.

You are invited to take part in this research study for the purpose of collecting data on determining the effects of flywheel training on muscle function, physical functioning, postural stability and fear of falling in the elderly.

Before you decide to take part, you must **read the accompanying Participant Information Sheet.**

Please do not hesitate to ask questions if anything is unclear or if you would like more information about any aspect of this research. It is important that you feel able to take the necessary time to decide whether or not you wish to take part.

If you are happy to participate, please confirm your consent by circling YES against each of the below statements and then signing and dating the form as participant.

1	**I confirm that I have read and understood the Participant Information Sheet for the above study and have had the opportunity to ask questions**	**YES**	**NO**
2	**I understand my participation is voluntary and that I am free to withdraw my data, without giving a reason, by contacting the lead researcher and the Research Support Office at any time until the date specified in the Participant Information Sheet**	**YES**	**NO**
3	**I have noted down my participant number (top left of this Consent Form) which may be required by the lead researcher if I wish to withdraw from the study**	**YES**	**NO**
4	**I understand that all the information I provide will be held securely and treated confidentially**	**YES**	**NO**
5	**I am happy for the information I provide to be used (anonymously) in academic papers and other formal research outputs**	**YES**	**NO**
6	**I am happy for training sessions to be recorded and posted on social media for the purpose of promoting the study and company providing training equipment**	**YES**	**NO**
7	**I agree to take part in the above study**	**YES**	**NO**

Thank you for your participation in this study. Your help is very much appreciated.

Participant's Name	**Date**	**Signature**
Researcher	**Date**	**Signature**

Appendix 3 – Poster

Coventry University

Are you interested in reducing your fall risk?

Are you aged 55 or over and otherwise healthy?

If yes, join our trial to look at the effects of flywheel training on strength and balance control

What does the study involve?

We will divide volunteers into two groups (a) training group and (b) control group. The control group will complete testing before the intervention, 3 weeks into intervention and at the end of the intervention, equalling three visits. The testing will take approximately 30 minutes.

The training group will complete 2 training sessions per week for 6 weeks. The training group will complete a brief warm up, followed by a specific amount of reps and sets on selected exercises lasting no more than 25 minutes per session.

The aim of the study is to determine the effects of eccentric flywheel training and detraining on muscle function, physical functioning, postural stability and fear of falling in the elderly.

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Appendix 4 – Fear of Falling Questionnaire

SUPPLEMENTARY DATA

Translators'/Interviewers' notes for FES-I

The text of the FES-I below is the final version agreed by the authors on completion of the development study, prior to subsequent translation and validation in different languages. It became clear during the process of translation that there was no wording of the questionnaire that would translate easily into every EC language using exactly the same words and phrases. Consequently, these notes are intended to assist translators of the FES-I to express the same *meaning* of items, even if they cannot use quite the same words in their language. They may also assist interviewers who are asked for clarification of the meaning of items when the FES-I is administered by interview.

Participants should answer items thinking about how they usually do the activity – for example, if they usually walk with an aid they should answeritemsaboutwalkingtoshowhowconcernedtheywouldbeaboutfallingw henusingthataid. Some translators may find it helpful to clarify in the instructions (after the sentence on circling an opinion) 'The opinions you can choose from are: 1 = not at all concerned 2 = somewhat concerned 3 = fairly concerned 4 = very concerned.' In some languages it is better to translate the word 'opinion' as 'statement'.

The word 'concerned' expresses a cognitive or rational disquiet about the possibility of falling, but does not express the emotional distress that would be expressed by terms such as 'worried', 'anxious' or 'fearful'. It is important to use a similar unemotional term, as respondents may be less willing to admit to emotions, which might be viewed as signs of weakness.

Item 3. In some EC languages 'simple' meals are best translated as 'everyday' meals, but the intention is to refer to a meal that does not require complex preparation, rather than one that is prepared every day.

Item 5. This item is intended to refer to shopping that is not extensive or recreational. In some languages the best translation is 'shopping for groceries'.

Item 7. This item refers to *any* stairs, not necessarily the flight of stairs in one's own house.
Item 8. In some languages 'neighbourhood' may be difficult to translate, and so 'walking around outside' can be used instead.

Item 12. In some languages it is necessary to add the term ‘acquaintances’ to friends and relatives, since this is a more common and casual category of relationship than friends. (see also comment on items 12, 13 and 16 below)

Item 13. ‘Crowds’ can be translated as ‘many people’ if necessary. (see also comment on items 12,13 and 16 below)

Item 14. It was found to be necessary to give examples of what is meant by uneven ground, but no examples could be found that were appropriate for all countries. Consequently, translators should choose any TWO examples from the following: cobblestones; poorly maintained pavement; rocky ground; unpaved surface.

Items 12, 13, 16. These items contain a greater element of ambiguity than many of the items assessing functional capabilities, because the physical activities involved in these social events may differ greatly for different respondents. However, it was decided that this ambiguity was acceptable because it is important to assess effects of fear of falling on social activities.

Now we would like to ask some questions about how concerned you are about the possibility of falling. For each of the following activities, please circle the opinion closest to your own to show how concerned you are that you might fall if you did this activity. Please reply thinking about how you usually do the activity. If you currently don’t do the activity (e.g. if someone does your shopping for you), please answer to show whether you think you would be concerned about falling IF you did the activity.

		Not at all concerned 1	Somewhat concerned 2	Fairly concerned 3	Very concerned 4
1	Cleaning the house (e.g. sweep, vacuum or dust)	1	2	3	4
2	Getting dressed or undressed	1	2	3	4
3	Preparing simple meals	1	2	3	4
4	Taking a bath or shower	1	2	3	4
5	Going to the shop	1	2	3	4
6	Getting in or out of a chair	1	2	3	4
7	Going up or down stairs	1	2	3	4
8	Walking around in the neighbourhood	1	2	3	4
9	Reaching for something above your head or on the ground	1	2	3	4
10	Going to answer the telephone before it stops ringing	1	2	3	4
11	Walking on a slippery surface (e.g. wet or icy)	1	2	3	4
12	Visiting a friend or relative	1	2	3	4
13	Walking in a place with crowds	1	2	3	4
14	Walking on an uneven surface (e.g. rocky ground, poorly maintained pavement)	1	2	3	4
15	Walking up or down a slope	1	2	3	4
16	Going out to a social event (e.g. religious service, family gathering or club meeting)	1	2	3	4

Appendix 5 – Risk Assessment

STUDENT RESEARCH PROJECT RISK ASSESSMENT
SPORT AND EXERCISE BASED PROJECTS
DEPARTMENT OF BIOMOLECULAR AND SPORT SCIENCES

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SECTION 2 DETAILS OF RISK ASSESSMENT

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