RESEARCH ARTICLE

Isometric strength and steadiness adaptations of the knee extensor muscles to level and downhill treadmill walking in older adults

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Abstract An ageing related decline in muscle strength and steadiness decreases quality of life and increases the risk for falls. Downhill treadmill walking (DTW) may enhance muscle strength and steadiness in older adults. Eighteen healthy older adults (age: 67 ± 4, body mass: 75 ± 14 kg) completed 12-weeks of level treadmill walking (LTW, 0 %, $n = 8$) or DTW (-10 %, $n = 10$) (30 min, 3 days per week) at a self-selected walking speed (re-adjusted in week 4 and 8). Maximal voluntary isometric force (MVIF) and electromyography (EMG) of the *m. quadriceps femoris* (QF) were measured at baseline, 4, 8 and 12 weeks. Steadiness of submaximal (5, 10 and 20 % MVIF) isometric contractions (i.e. coefficient of variation of the force signal) and EMG of QF were measured at baseline and 12 weeks. Baseline MVIF of LTW (340 ± 112 N) and DTW (368 ± 128 N) increased equally by 14 ± 6 and 5 ± 6 % ($p < 0.05$). Steadiness at 5 %MVIF improved following 12 weeks of LTW (baseline: 0.04 ± 0.01; 12 weeks: 0.03 ± 0.01) and DTW (baseline: 0.04 ± 0.02; 12 weeks: 0.03 ± 0.01 ($p < 0.05$). EMG root mean square of *m. vastus lateralis* during MVIF increased by 38 % following 12 weeks of LTW only ($p < 0.05$). The potential implications for an exercise modality, such as DTW, with a lower oxygen demand, to improve muscle strength could serve as a rehabilitative countermeasure for older adults.

Keywords Older adults · Steadiness · Isometric · Strength · Electromyography

Introduction

Sarcopenia is not fully understood, but is associated with a lower skeletal muscle mass, a change in the peripheral nervous system and a lower physical activity level (Deschenes 2004). An imbalance between rate of muscle protein synthesis and breakdown of muscle protein, and a decline in growth hormones, limits the ability of older adults to increase muscle mass (Marcell 2003; Yarasheski 2003). And, as the number of muscle fibres decrease, motor units are lost, increasing the size of remaining motor units (Doherty 2003; Marcell 2003). Ageing related changes not only decrease maximal strength, but also decrease muscle control and steadiness (Carville et al. 2006). The reduction in muscle mass and decline in motor neurons increases innervation ratio and motor unit size (Doherty et al. 1993). This increases mechanical output of the active motor neurons' discharge rate, and a summation of motor unit forces, leading to force fluctuations and a lower force control (Keen et al. 1994). Overall, information provided by the sensory system (visual, vestibular and somatosensory), to

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generate a motor response, becomes impaired with age, resulting in poor force control and an increased risk for falls (Gauchard et al. 1999). The greatest deficit in force control of older adults may be found during submaximal work (Tracy and Enoka 2002; Seynnes et al. 2005). For example, impaired force control, i.e. steadiness, was shown in elderly (65–79 years), healthy, sedentary adults during sub-maximal isometric contractions of 2–10 % maximal voluntary isometric force (MVIF) (Tracy and Enoka 2002). Performance in sub-maximal isometric steadiness tasks can independently predict functional performance in older women (Seynnes et al. 2005). And, because older adults have an increased level of postural-control during functional tasks, e.g. sit-to-stand and stair climbing, sub-maximal isometric force-control capacity may be a critical factor in assessing risk for falls during functional tasks (Seynnes et al. 2005). A sub-maximal isometric steadiness test for a period beyond 30-s may be a sensitive indicator of early muscle dysfunction related to functional limitations.

Maintenance of muscle strength and steadiness is important for older adults to enable independent living, a better quality of life and reducing the risk for falls (Carville et al. 2006; Doherty 2003). Regular exercise has been recognized as an important means to reduce the effects of *sarcopenia* (Dreyer et al. 2006; Mueller et al. 2009; Trappe et al. 2002). In general, resistance training is utilised to improve muscle strength and steadiness of older adults (Esposito et al. 2005; Hortobágyi et al. 2001). For example, maximal voluntary isometric strength of the *m. quadriceps femoris* muscles, in older women, increased by 14 % following 18 weeks of a combined concentric and eccentric resistance training programme (Sipilä et al. 1996). Additionally, 10 weeks of resistance training improved anisometric steadiness of the *m. quadriceps femoris* by 37 % (Manini et al. 2005). These changes are the result of individual fibre hypertrophy—increased muscle protein synthesis creating more myofibrils (Evans 1997; Yarasheski 2003)—and increased electrical activity-motor unit recruitment, synchronization and/or firing frequency (Klass et al. 2007).

Participation in endurance exercise is not generally associated with improvements in muscular strength or steadiness (Sipilä et al. 1996). However, elderly endurance athletes and physically active older women have higher isometric muscle strength than untrained controls of the same age (Rantanen et al. 1993; Sipilä et al. 1991).

In addition, older women experienced a 19 % improvement in maximal isometric force of the *m. quadriceps femoris* following 18-weeks of track walking and step-aerobics (Sipilä et al. 1996). Level treadmill walking (LTW) is an activity biased towards muscle-shortening contractions, whereas downhill treadmill walking (DTW), an activity that is biased towards voluntary muscle-lengthening contractions of the *m. quadriceps femoris*, may have greater potential to improve isometric strength and steadiness of the knee extensors in older adults. Unaccustomed muscle-lengthening exercise initially results in damaged muscle, an associated strength loss (Gault et al. 2011) and greater force fluctuations (Semmler et al. 2007). However, it is well established that a repeated bout of the same or similar muscle-lengthening activity, when the muscle is fully recovered or not, results in a reduction of the symptoms, no further loss in strength and protection against further damage—known as the 'repeated bout effect' (McHugh 2003). This may promote muscle repair and improve knee extensor strength of the elderly (Hameed et al. 2008). Additionally, the lower energy demand and oxygen cost of eccentric contractions ensures a lower stress on the cardiovascular system, which may be of particular interest to older adults and other clinical populations due to their lower aerobic capacity and increased risk of cardiac issues (Gault et al. 2012b; Navalta et al. 2004).

Recent studies have focused on the effects of cycling with muscle-lengthening contractions. For example, 12 weeks of cycling (muscle-lengthening contractions) by older adults improved MVIF of the knee extensors by 8 %, with an 11 % improvement by coronary artery disease patients following 8 weeks (42–66 years) (Mueller et al. 2009; Steiner et al. 2004). Such improvements in isometric strength were associated with neuronal adaptations rather than muscle hypertrophy (Mueller et al. 2009; Steiner et al. 2004). DTW has been shown to substantially improve functional mobility of older adults; however, these changes were not explained by changes in dynamic strength of the *m. quadriceps femoris* (Gault et al. 2012a). Despite these findings, it has also been established that performance in functional mobility tasks is associated with sub-maximal steadiness of the knee extensor muscles (Seynnes et al. 2005). And, as far as we know the effects of DTW, on isometric strength and steadiness of older adults has not been examined.

Therefore, we examined in older adults, the effects of LTW and DTW on MVIF, steadiness of sub-maximal voluntary isometric contractions and electromyographic (EMG) activity during maximal and sub-maximal isometric contractions of the knee extensor muscles (*m. quadriceps femoris*). It was hypothesized that 12-weeks of DTW and LTW would improve MVIF and steadiness of knee extensor muscles during sub-maximal voluntary isometric contractions, reflected in an increased EMG activity of the *m. quadriceps femoris*.

Methods

Participants

Twenty-three independent older adults, free from illness and disease, volunteered to take part in the study. Participants had not previously completed a structured exercise programme and each individual completed a health history questionnaire and provided written informed consent before starting the programme. Ethical approval for all procedures and protocols was provided by the University of Chichester Ethics Committee. All participants were in good health with four on medication to lower cholesterol.

Preliminary measures and familiarisation

Resting heart rate (RHR) and blood pressure (BP) (Omron 705 IT, Medisave, UK) were measured after subjects were seated for 20-min followed by measurement of height (Holtain Ltd, Crymych, UK) and body mass in normal clothing without shoes (Seca Model 880, Seca, UK). Body fat analysis (BC418 MA, Tanita, UK) was determined using bioelectrical impedance analysis (BIA) and body mass index (BMI) was calculated by the following equation: BMI = body mass (kg) $\div$ height^2(m). Predicted maximal oxygen uptake ($\dot{V}O_{2max}$) was determined by the rockport fitness walking test (RFWT), a 1-mile overground walk that has been validated for older adults (Fenstermaker et al. 1992). Participants were familiarised for all testing procedures with the exception of downhill walking. A full testing session, where participants completed three knee extensor maximal voluntary isometric contractions and three knee extensor isometric steadiness tests of 60-s (20, 10 and 5 % of MVIF) was also completed as part of the

familiarisation (described below). Following treadmill familiarisation, self-selected walking speed (SSWS) for LTW was determined by each individual (Gault et al. 2012a).

Experimental protocol

Participants were assigned to a DTW group ($n = 12$) or LTW group ($n = 11$). The LTW participants acted as the control group and DTW as the experimental group. A physically active control group was used as opposed to a sedentary control, because a healthy, physically active group of participants are at a reduced risk of illness, and physical inactivity is a major cause of disease and lower level of functional capacity (Booth and Lees 2006). Anthropometric and physiological characteristics were similar between groups ($p > 0.05$; Table 1). All participants visited the laboratories for three 30-min supervised treadmill (Woodway Ergo ELG 70, Cranlea & Co., Birmingham, UK; HP Cosmos Pulsar, Bodycare products, Warwicks, UK) walking sessions per week for up to 12 consecutive weeks, at their SSWS (Gault et al. 2012a). Participant drop-out was low, two participants (1 LTW and 1 DTW) stopped the programme after 4 weeks and a further three after 8 weeks (2 LTW and 1 DTW). The chosen SSWS was re-established every 4 weeks. The LTW and DTW groups had a treadmill gradient of 0 and -10 % respectively. A gradient of -10 % is the point at which minimum total body energy cost occurs for downhill walking (Wanta et al. 1993). Participants performed the maximal voluntary isometric contraction tasks of the knee extensors on their non-dominant leg on four occasions—baseline and after 4, 8, and 12 weeks of the treadmill walking intervention. Knee extensor isometric steadiness tasks were completed on the non-dominant leg (5, 10, 20 % MVIF) following the maximal contractions on two occasions—baseline and after 12 weeks—in a randomised order (described in detail below).

Isometric strength and steadiness protocols

For all isometric contractions of the knee extensor muscles, participants were secured in a custom built chair, with hip and knee at 90° flexion. Velcro straps were placed around the participant's chest and waist to restrict movement of the upper body and hips. A cuff was placed around the participant's ankle (proximal to

Table 1 Anthropometric and physiological characteristics of LTW and DTW participants (mean ± SD)

	Age (years)	Height (m)	Weight (kg)	BMI (kg$\bullet$m^{-2})	BF (%)	RHR (b$\bullet$min^{-1})	Blood pressure (mmHg)	$\dot{V}O_2$max (mL$\bullet$kg$^{-1}\bullet$min^{-1})
LTW (n = 11)	65 (±4)	1.68 (±0.10)	75.1 (±18.5)	26.3 (±4.5)	30.1 (±7.5)	77 (±11)	147/86 (±25/10)	29.8 (±7)
DTW (n = 12)	69 (±4)	1.68 (±0.09)	74.4 (8.7)	26.2 (±3.5)	30.4 (±7.1)	76 (±8)	142/84 (±18/10)	28.8 (± 7.6)

BMI body mass index, *BF* body fat, *RHR* resting heart rate, *Blood pressure*, systolic and diastolic; $\dot{V}O_2$max, predicted from the rockport fitness walking test

the *fibular* notch and *medial malleolus*) and attached to an s-beam load cell (RS250 kg, Tedea Huntleigh, Cardiff, UK) via a steel chain at the base of the chair. The signal from the strain gauge was amplified, with a sampling frequency of 1,000 Hz using Chart 4 V4.1.2 (AD Instruments, Oxford, UK). The signal was displayed on a monitor placed in the view of the subjects (1-m).

As part of a warm-up participants were asked to produce three progressive sub-maximal isometric contractions (3–5 s) with 60-s rest between. Participants then performed three maximal voluntary isometric contractions, each lasting 3-s, with 3-min rest between each effort (Seynnes et al. 2005). If these were progressively increasing in amplitude or were of very different amplitudes then further efforts were made until the force generated had plateaued. This only affected 2-individuals. The highest force generated was taken as the MVIF. Verbal encouragement and visual feedback of the analogue force signal on a PC monitor were used.

Sub-maximal isometric tasks were used to assess knee extensor steadiness during a constant isometric force exertion (Carville et al. 2006; Seynnes et al. 2005). Such muscle contractions were utilised due to their ability to independently predict, stressful functional-performance in older women (Seynnes et al. 2005). Using the participant's knee extensor MVIF, achieved during that session, a 20, 10 and 5 % force was calculated (Carville et al. 2006). In comparison to younger adults, older adults had significantly greater force fluctuations whilst maintaining low submaximal isometric force contractions (2–10 % MVIF) in comparison to high contractions (50 % MVIF) (Tracy and Enoka 2002) and, older adults with a history of falls were less steady than both young adults and older adults who were non-fallers during sub-maximal isometric contractions (Carville et al. 2006). Horizontal lines were drawn on the monitor at the calculated 20, 10 and 5 % force, in a random order, and used as a target. Participants were asked to generate the target force, and maintain it as steadily as possible for 60-s. This duration was selected as Seynnes et al. (2005) suggests that sub-maximal contractions beyond 30-s may prove to be a more stressful test paradigm and therefore a more sensitive indicator of early muscle dysfunction related to functional limitations, whilst at the same time avoiding muscle fatigue. Two initial attempts at each force were performed to insure the

participant could achieve the target force within 3-s. A 3-min rest period was given between contractions.

Surface electromyography

Electromyography (EMG) activity during knee isometric extension tasks (MVIF and sub-maximal steadiness) were taken from the *m. rectus femoris* (RF), *m. vastus lateralis* (VL), *m. vastus medialis* (VM), and *m. biceps femoris* (BF). Electrode positions were selected by determining the muscle belly, palpating the muscle when relaxed and contracted (Gregoire et al. 1984). To ensure accurate positioning in subsequent trials, electrode positions were marked and recorded on lines running from the centre of the base of the patella to the inguinal crease (RF and VL only). The site for electrode attachment was shaved and dead skin removed with an abrasive patch then cleaned with an alcohol wipe. Electrodes (Bagnoli DE-2.1 Parallel Bar Electrodes, Delsys Inc, Boston, USA) were positioned using one layer of thin medical tape (Transpore 3 M Surgical Tape, 3 M, Minnesota, USA). The EMG activity was recorded (Bagnoli 8-Channel EMG System, Delsys Inc, Boston, USA) at 1,000 Hz during the MVIF and each 60 s sub-maximal isometric steadiness task.

Data analysis

Maximal voluntary isometric force was calculated using as the highest value maintained for 1-s during the contraction (Microsoft Excel, 2007). Coefficient of variation (CV = SD/mean) was calculated over each 60-s task (5, 10 and 20 %) to determine sub-maximal isometric knee extensor steadiness. Coefficient of variation indicates relative variation of the distribution of data and is shown to reflect force fluctuations during sustained sub-maximal isometric contractions (Tracy and Enoka 2002). The larger this figure is the greater the force fluctuations and the less steady an individual is.

Raw EMG signals were filtered using a 2nd order Butterworth band-pass filter (low 10 Hz, High 350 Hz) (as recommended by the guidelines of the Journal of Electromyography and Kinesiology, 2000). The RMS of the filtered data was calculated using a moving window (window length 0.05-s, window overlap 0.025-s) (Tseng et al. 2007). EMG root mean square (RMS) was calculated using Delsys EMGworks

Analysis V3.6 (Delsys INC, Boston, USA) and Microsoft Excel 2002 for Windows (Microsoft, Redmond, Washington). The peak RMS value was recorded over each MVIF for the VL, RF and VM. During the 60-s submaximal isometric steadiness task a mean RMS was calculated for each *m. quadriceps femoris* muscle (VL, RF and VM) and presented as a percentage of the peak RMS during the MVIF. This data was only taken from those participants that completed 12-weeks of walking. Participant dropout led to missing MVIF data, therefore a method described by Little and Rubin (1989) was used to correct for this.

Statistical analysis

Statistical analysis was undertaken using SPSS for Windows V16.0 (SPSS, Chicago, Illinois). Normal distribution of the data was tested using a Kolmogorov–Smirnov test. A two-way repeated measures analysis of variance (ANOVA) was used to examine the change from baseline values across time and between conditions (level walking vs. downhill walking) for all parameters. When the two-way ANOVA showed a significant difference between conditions or over time, pre-planned paired and independent sample t-tests with Bonferroni corrections were used to compare the change over time and values at each time point ($p < 0.05$). All data are presented as the mean ± SD, significance was accepted at $p < 0.05$ and presented with degrees of freedom (df) and effect size (partial eta squared, η^2).

Results

Maximal voluntary isometric force (MVIF)

Maximal voluntary isometric force of the *m. quadriceps femoris* was similar at all time points for both LTW and DTW (Fig 1) ($F_{(1,21)} = 0.03$, $p = 0.86$, $\eta^2 = 0.002$). MVIF of knee extensor muscles increased only after 12-weeks LTW and DTW ($F_{(2,44)} = 6.44$, $p = 0.003$, $\eta^2 = 0.24$). LTW resulted in a 14 ± 6 % (baseline: 340 ± 112 N, 12 weeks: 395 ± 130 N) increase in MVIF and DTW elicited a 5 ± 6 % (baseline: 368 ± 128 N, 12 weeks: 388 ± 132 N) improvement (Fig 1, $t_{(22)} = -2.73$, $p = 0.01$).
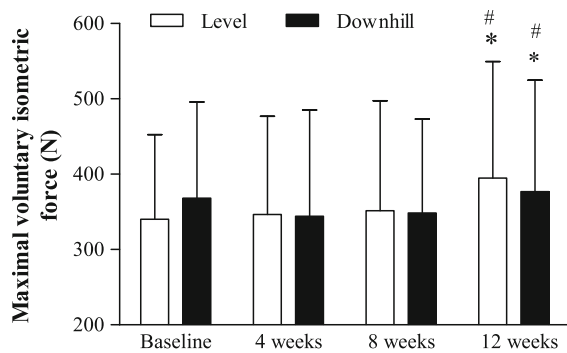
Fig. 1 Maximal voluntary isometric force of the knee extensor muscles at baseline, and following 4, 8, and 12 weeks of LTW (0 %) and DTW (−10 %), three times per week. Data presented as mean ± SD. *Asterisk* difference from baseline measurements ($p < 0.05$) and *Ash* difference from the preceding weeks test ($p < 0.01$)

20 % of maximal voluntary isometric force

Isometric steadiness (i.e. coefficient of variation) of a 60-s contraction at 20 % of MVIF of the knee extensor muscles was not different between LTW and DTW ($F(1,16) = 0.17$, $p = 0.18$, $\eta^2 = 0.01$). A main effect for time ($F(1,16) = 4.57$, $p = 0.048$, $\eta^2 = 0.22$) and an interaction effect were reported ($F(1,16) = 5.74$, $p = 0.03$, $\eta^2 = 0.26$) (Table 2). This would suggest that 12 weeks of LTW and DTW walking intervention

Table 2 Force and steadiness (i.e. coefficient of variation) during submaximal isometric contractions at different intensities (i.e. 5, 10 and 20 %) for 60-s at baseline and following 12-weeks of LTW and DTW

	Baseline		Post	
	Force (N)	CV (SD/ mean)	Force (N)	CV (SD/ mean)
Level % MVIF ($n = 8$)				
20 %	70 ± 25	0.04 ± 0.02[a]	79 ± 29[b]	0.02 ± 0.01
10 %	34 ± 12	0.04 ± 0.01	40 ± 10[b]	0.03 ± 0.02
5 %	17 ± 6	0.04 ± 0.01	20 ± 8[b]	0.03 ± 0.01[b]
Downhill % MVIF ($n = 10$)				
20 %	74 ± 26	0.03 ± 0.003[a]	70 ± 32	0.03 ± 0.008
10 %	38 ± 12	0.05 ± 0.03	40 ± 16	0.03 ± 0.01
5 %	19 ± 6	0.04 ± 0.02	21 ± 8	0.03 ± 0.01[b]

Data presented as mean ± SD

CV coefficient of variation, *SD* standard deviation, *Force* mean force over 60-s, *MVIF* maximal voluntary isometric force

[a] Difference between LTW and DTW at baseline

[b] Difference from baseline measurements

in older adults improved steadiness at 20 %MVIF. Although pre-planned t-tests show no change in steadiness at 20 %MVIF from baseline to post for both groups, both groups showed a trend towards significance (LTW, $t(7) = 22$, $p = 0.06$; DTW, $t(9) = −2.29$, $p = 0.06$). In addition, the significant interaction effect was present because the level walkers performed better in the steadiness task at baseline in comparison to the downhill walkers ($t(16) = −1.53$, $p = 0.02$) (Table 2). In addition, LTW participants had an increase in the mean force of 20 % sub-maximal steadiness over 60-s ($t(7) = −2.97$, $p = 0.02$) from baseline to post, with a trend towards significance for DTW participants ($t(9) = −2.29$, $p = 0.06$) (Table 2).

10 % of maximal voluntary isometric force

Steadiness at 10 % MVIF of the knee extensor muscles was similar between LTW and DTW at baseline ($F(1,16) = 0.57$, $p = 0.46$, $\eta^2 = 0.03$), with no change from baseline to post ($F(1,16) = 1.70$, $p = 0.19$, $\eta^2 = 0.11$) (Table 2). There was an increase in the 10 % MVIF force produced by the LTW participants following 12-weeks of treadmill walking ($t(7) = −3.42$, $p = 0.01$) with no change for DTW participants ($t(9) = −1.70$, $p = 0.12$) (Table 2).

5 % of maximal voluntary isometric force

Steadiness at 5 %MVIF of the knee extensor muscles was similar between groups at all time points ($F(1,16) = 2.09$, $p = 0.17$, $\eta^2 = 0.12$) (Table 2). There was a significant improvement in 5 % steadiness for both groups following 12-weeks of LTW and DTW ($F(1,16) = 8.37$, $p = 0.01$, $\eta^2 = 0.34$). The force maintained during 5 % MVIF over 60-s was increased from baseline to post for the LTW group ($t(7) = −2.88$, $p = 0.02$) with no change for the DTW group ($t(9) = −1.86$, $p = 0.10$).

Surface electromyography (EMG) activity

Root mean square for the *m. vastus lateralis* (VL) during the production of a MVIF did not change from baseline ($F(1,16) = 3.65$, $p = 0.07$, $\eta^2 = 0.02$) and was similar for both LTW and DTW groups ($F(1,16) = 0.46$, $p = 0.51$, $\eta^2 = 0.03$) (Fig 2a). However, an interaction effect ($F(1,16) = 12.00$, $p < 0.01$,
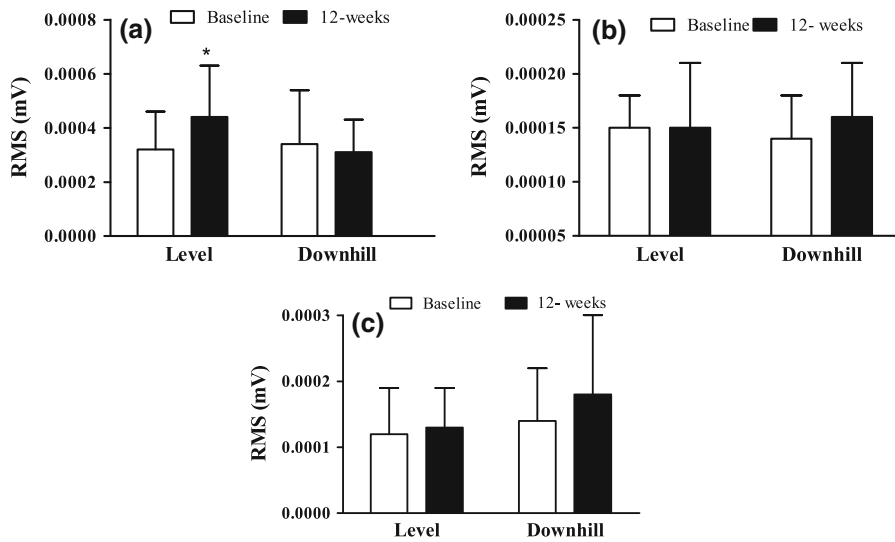
Fig. 2 Root mean square (RMS, mV) for the *m. vastus lateralis* (**a**), *m. rectus femoris* (**b**), and *m. vastus medialis* (**c**) muscles during the production of a maximal voluntary isometric force at baseline and following 12-weeks of level (0 %) and downhill (−10 %) treadmill walking at a self-selected intensity. Data presented as mean ± SD. *Asterisk* a difference from baseline measurements ($p < 0.05$)

$\eta^2 = 0.43$) showed that following 12 weeks of LTW RMS of the VL was increased from baseline. Both the RF (F(1,16) = 0.36, $p = 0.56$, $\eta^2 = 0.02$) and VM (F(1,16) = 1.20, $p = 0.29$, $\eta^2 = 0.07$) RMS during the production of a MVIF were similar from baseline to 12-weeks and between groups (RF: F(1,16) = 0.001, $p = 0.98$, $\eta^2 = 0.00$; VM: F(1,16) = 0.97, $p = 0.34$, $\eta^2 = 0.06$) (Fig 2b, c).

During the 20 % isometric contraction of the *m. quadriceps femoris* muscle, RMS for the VM (F(1,16) = 0.09, $p = 0.79$, $\eta^2 = 0.01$), RF (F(1,16) = 0.17, $p = 0.21$, $\eta^2 = 0.10$), and VL (F(1,16) = 0.04, $p = 0.85$, $\eta^2 = 0.002$) were similar from baseline to 12-weeks and between groups (VM: F(1,16) = 0.67, $p = 0.42$, $\eta^2 = 0.04$; RF: F(1,16) = 0.85, $p = 0.37$, $\eta^2 = 0.05$; VL: F(1,16) = 0.04, $p = 0.85$, $\eta^2 = 0.09$) (Table 3). At 10 % of MVIF RMS of the VL was similar from baseline to 12-weeks (F(1,16) = 1.44, $p = 0.25$, $\eta^2 = 0.08$) (Table 3). A between-subjects difference was shown at baseline were the DTW (13 ± 8 %) group had a larger RMS compared to the LTW group (6 ± 2 %) (F(1,16) = 6.43, $p = 0.02$, $\eta^2 = 0.29$). The RF (F(1,16) = 0.64, $p = 0.44$, $\eta^2 = 0.04$) and VM (F(1,16) = 0.15, $p = 0.70$, $\eta^2 = 0.01$) muscles had no change in % of maximal RMS from baseline to 12-weeks and between group (RF: F(1,16) = 1.55, $p = 0.23$, $\eta^2 = 0.09$; VM:

Table 3 Root mean square (RMS, mV), expressed as a percentage of the RMS during a maximal voluntary isometric contraction, of the *m. vastus medialis* (VM), *m. rectus femoris* (RF) and *m. vastus lateralis* (VL) during a 60-s submaximal isometric force task at 20, 10 and 5 % of maximal voluntary isometric force

	Baseline		Post	
	LTW (%)	DTW (%)	LTW (%)	DTW (%)
20 % MVIF				
VL	11 ± 4	13 ± 4	10 ± 4	16 ± 10
RF	11 ± 6	13 ± 8	13 ± 9	22 ± 25
VM	22 ± 8	25 ± 18	22 ± 11	28 ± 15
10 % MVIF				
VL	6 ± 2	13 ± 8[a]	6 ± 3	9 ± 5
RF	6 ± 3	13 ± 12	9 ± 7	14 ± 14
VM	17 ± 7	24 ± 24	15 ± 12	23 ± 18
5 % MVIF				
VL	4 ± 1	10 ± 10	4 ± 2	7 ± 4
RF	6 ± 3	11 ± 15	7 ± 5	14 ± 14
VM	14 ± 9	20 ± 26	11 ± 13	21 ± 18

Data was recorded at baseline and following 12 weeks of LTW ($n = 8$) and DTW ($n = 10$). Data presented as mean ± SD

VM: *vastus medialis*, RF: *rectus femoris*, VL: *vastus lateralis*

LTW level treadmill walking, *DTW* downhill treadmill walking, *MVIF* maximal voluntary isometric force

[a] Difference between baseline measurements

F(1,16) = 0.91, $p = 0.35$, $\eta^2 = 0.05$) (Table 3). During the 5 % sub-maximal isometric contraction the VL (F(1,16) = 0.64, $p = 0.44$, $\eta^2 = 0.04$), RF (F(1,16) = 1.27, $p = 0.28$, $\eta^2 = 0.07$) and VM (F(1,16) = 0.05, $p = 0.83$, $\eta^2 = 0.003$) had no change in baseline RMS, following 12-weeks of LTW or DTW (Table 3). There was also similar values between groups at baseline and post (VL: F(1,16) = 4.01, $p = 0.06$, $\eta^2 = 0.20$; RF: F(1,16) = 1.49, $p = 0.24$, $\eta^2 = 0.09$; VM: F(1,16) = 1.06, $p = 0.32$, $\eta^2 = 0.06$).

Discussion

This study examined, in older adults, the effects of a novel exercise intervention (i.e. regular DTW). It was found that 12-weeks of LTW and DTW, exercise modes biased toward voluntary muscle-shortening and muscle-lengthening contractions respectively, of the *m. quadriceps femoris*, had similar improvements in MVIF and steadiness at 5 % MVIF of the knee extensors. The mechanisms for MVIF adaptation appear to be different, as LTW, but not DTW participants, demonstrated an improved neural activation in the VL during maximal voluntary isometric contractions. Interestingly, the steadiness of sub-maximal isometric contractions of the knee extensor muscles was intensity-dependent, with an improvement in the CV only for 5 % MVIF and without a change in neural activation.

Maximal voluntary isometric force

Knee extensor MVIF was increased for the current group of older adults following 12-weeks of LTW (+14 %) and DTW (+5 %). Endurance based exercise interventions are not usually associated with changes in MVIF. However, when older adults completed 18-weeks of track walking (2 × 30-min) and step aerobics (1 × 40-min) knee extensor MVIF improved by 19 % (Sipilä et al. 1996), and 7 % following 12-weeks of cycling with muscle-lengthening contractions (40-mins, twice weekly) (Mueller et al. 2009). Strength-training studies have however led to more significant gains in isometric knee extensor strength (Esposito et al. 2005; Hortobágyi et al. 2001). This could be attributed to a number of parameters. For example, endurance exercise may not overload the *m. quadriceps femoris* muscles

sufficiently (Bompa 1965). And, the training protocol implemented by Esposito et al. (2005) isolated the knee extensor muscles—maximal isokinetic contractions—therefore more specific to the test protocol than treadmill walking.

One male LTW participant in the current study, with the highest MVIF at baseline, increased his knee extensor MVIF by 26 % after 12-weeks. Six out of eight LTW participants and two out of ten DTW participants had a 10 % or greater increase. DTW participants had up to a 17 % improvement in MVIF. The large standard deviation in the DTW group was due to two participants showing a -2 and -4 % change in MVIF following 12-weeks. However, when we assess these individuals at 8-weeks their results show a similar MVIF to baseline (+2 and +4 %), therefore, a lack of motivation during the final testing session may be the cause of their lower MVIF values at 12-weeks (Warren et al. 1999). Previous research (LaStayo et al. 1999) has shown similar variability in adaptations to muscle-lengthening contractions in younger adults (18–34 years), with longer error bars in the group that completed cycling with muscle-lengthening contractions versus cycling with muscle-shortening contractions. Therefore, such variability in the current study may reflect differing individual adaptations to novel endurance exercise with predominately muscle-lengthening contractions. Overall, both LTW and DTW groups had similar increases in MVIF, and the increased muscle strength for the DTW group indicates no further muscle damage, caused by the initial bout of DTW (Gault et al. 2011). Studies have shown that satellite cells of aged subjects are still able to make about 15-divisions, which is enough to repair exercise induced muscle damage (Thornell et al. 2003). In addition, exercise that induces muscle damage increases the expression of IGF-I in older adults, which is correlated to the increase in developmental myosin (Fiatarone-Singh et al. 1999). However, Close et al. (2005) review evidence to suggest that older adults are more susceptible to muscle damage from muscle-lengthening contractions in comparison to young adults, with a longer recovery period, due to an impaired ability to regenerate—with a reduced number of satellite cells that have a diminished proliferative capacity—challenging the suggestions of Thornell et al. 2003. Future research needs to confirm the reduced number of satellite cells with age, and if those satellite cells that are left have

enough remaining cell divisions to ensure repair following exercise induced damage, specifically in the very old.

Strength gains in MVIF can primarily be linked to two mechanisms, muscle hypertrophy (Fiatarone et al. 1990) and/or neural adaptations (Esposito et al. 2005). In the past, strength gains associated with endurance exercise were shown to be the result of neuronal adaptations (Sipilä et al. 1996). However, Harridge et al. (1997) raise the question of specificity of muscle usage, and its effect on skeletal muscle function, suggesting that endurance-based physical exercise may be of little value in maintaining muscle strength and speed of contraction in old age. The current study, in part, supports the findings of Sipilä et al. (1996), as the 14 % increase in MVIF following LTW, coincided with a 38 % increase in VL RMS. An increase in RMS at near maximal or maximal intensities of contractions can be attributed to the underlining motor units firing rate increment and better retrieval of fast twitch fibre motor units (Esposito et al. 2005). Isometric resistance training increased RMS of the RF, suggesting training effects may vary from one part of the *m. quadriceps femoris* to the other (Rabita et al. 2000). This high variability could be explained by the fact that the *m. quadriceps femoris* is a large muscle having several components, thus, the neural control is complex and compartmentalized. Therefore, different components of the *m. quadriceps femoris* will have inter-individual responses to different exercise strategies (Rabita et al. 2000). Watanabe and Akima (2009) indicate neuro-muscular activation of the VL was relatively higher than activation of the VM and RF muscle during the production of a moderate force. It may be that LTW, at a SSWS, requires the muscles to produce a moderate force, with the VL, potentially, having the greatest neuromuscular activation. In addition, the VL has a relatively high percentage (68 %) of type II muscle fibres (Edgerton et al. 1975), the predominant muscle fibre affected by sarcopenia (Harridge 2003). Exercise can help restore innervation of such muscle fibres that have been lost through the ageing process, increasing the number of fast-twitch motor units, resulting in an improved maximal muscular strength (Esposito et al. 2005).

An increased MVIF (+5 %) for DTW participants occurred without a change in EMG RMS. Unlike LTW, DTW resulted in muscle damage following the initial 30-min bout of exercise (Gault et al. 2011).

Damage from muscle-lengthening contractions causes structural change, which can promote hypertrophy (Hameed et al. 2008). Although hypertrophy was not assessed in the current study, there is evidence from previous research, using cycling with muscle-lengthening contractions (Mueller et al. 2009; LaStayo et al. 2000), that such an activity can increase fibre cross-sectional area. Muscle-lengthening contractions can produce up to 4-times as much force as muscle-shortening contractions (LaStayo et al. 2000), which has been shown to stimulate a change in type IIX/type II ratio, following 12-weeks of cycling (Mueller et al. 2009). Further to this, the growth hormone IGF-I mRNA—stimulant for myofibril protein synthesis and satellite cell activation—was increased following cycling with muscle-lengthening contractions (Zoll et al. 2006). Such mechanisms may account for the improved MVIF in DTW, in addition to an improved muscle co-ordination (Tracy and Enoka 2006); and increased tendon stiffness (Reeves et al. 2003).

Steadiness of sustained sub-maximal isometric contractions

In comparison to previous studies (Laidlaw et al. 1999; Manini et al. 2005), the current group of older adults had a higher level of functional mobility before participating in any exercise intervention (Gault et al. 2012a). And, because performance in sub-maximal isometric steadiness tasks can independently predict functional performance (Seynnes et al. 2005), this would indicate a more stable group of older adults, with a lower risk of falls (Laidlaw et al. 1999; Manini et al. 2005).

Twelve-weeks of LTW and DTW increased knee extensor isometric steadiness of older adults by 25 %, whilst maintaining 5 % MVIF for 60 s. Previous studies examining the effects of resistance training on sub-maximal isometric steadiness of the knee extensors observed no change in isometric force fluctuations (Bellew 2002; Tracy and Enoka 2006). Contrary to this, the current study is the first endurance based exercise intervention, to our knowledge, that improves sub-maximal isometric steadiness of the knee extensors. And, as indicated before, force steadiness improvements at such a low force may be important (Seynnes et al. 2005). Most daily activities occur at a fraction of maximal strength and older adults become more unsteady with decreasing levels of force

production, therefore increasing the risk of falls (Galganski et al. 1993; Grabiner and Enoka 1995). Also, there is evidence to suggest that muscle-lengthening contractions during DTW did not impair neuromuscular function when performing isometric steadiness tasks. The earlier reported increase in MVIF suggests that muscle damage is no longer present and not an issue when assessing steadiness following the 12-week intervention.

The observed increase in steadiness cannot be linked to an increase in strength per se, as both light- and heavy- load resistance training have shown similar steadiness improvements (Hortobágyi et al. 2001; Laidlaw et al. 1999). Four features of motor output from the spinal cord could contribute to the observed improved steadiness: (1) average force produced by motor unit; (2) pattern of co-activation; (3) amount of motor unit synchronization and; (4) discharge rate of motor unit (Laidlaw et al. 2000). An improved discharge rate variability may originate from an increase in the descending motor output or decreased sensory feedback caused by pre-synaptic inhibition of afferent inputs at the spinal cord (Manini et al. 2005). These may consequently influence polarisation of the cell membrane controlling the timing of discharged action potentials and, therefore, improve steadiness (Kernell 1983). However, because there were no parallel changes in EMG RMS this may not be the case. Motor unit recruitment (small and large motor units), discharge frequency and synchronization influence EMG activity (Kamen and Gabriel 2010). It is possible that LTW and DTW decreased discharge frequency, and because a small force is required, eliciting a better recruitment of smaller motor units, there is a more efficient synchronization, which would result in a similar EMG RMS to baseline, but an improved steadiness (Kamen and Gabriel 2010). Although synchronization has been shown to improve with training this requires further investigation (Manini et al. 2005). Additionally, antagonist co-activation (*m. biceps femoris*) during the 5 % steadiness was not different following LTW and DTW (unpublished observation), contradicting previous research that showed antagonist co-activation to be more extensive in older than younger adults, which improved with exercise participation (Laidlaw et al. 1999).

Ten and twenty percentage MVIF was similar before and after 12-weeks of LTW and DTW. And there are suggestions that because participants in the current study were at a low risk for falls, they had a limited ability to improve steadiness further (Bellew 2002). Training modality may also influence steadiness adaptations (Laidlaw et al. 1999; Manini et al. 2005) as exercise induced improvements in steadiness are shown to be task-specific (Hortobágyi et al., 2001). Training with isometric contractions would improve isometric steadiness, and dynamic training anisometric steadiness (Bellew 2002; Hortobágyi et al. 2001). For example, participants that completed a 12-week resistance and functional based training programme improved anisometric, but not isometric steadiness of the knee extensors (Manini et al. 2005). Future investigations should include anisometric steadiness at various intensities, giving a better understanding of improved steadiness and how it reflects an improved functional mobility of older adults. A 14 % increase in 10 and 20 % MVIF load, for LTW, is a reflection of the14 % increase in MVIF. An increased target force would require individuals to maintain a greater load, recruiting a greater number of motor units and therefore potentially greater force fluctuations and no steadiness improvements. 5 % steadiness had improved with similar increases in load (17 %) to 10 and 20 %, but this is an extremely small change. A 17 % load increase for 5 % is approximately a 3 N increase, whereas a 14 % load increase for 10 and 20 % would be 6 N (2×5 % increase) and 9 N (3×5 % increase) respectively, which may have caused greater force fluctuations.

In conclusion, 12-weeks of LTW and DTW, at a self-selected intensity, increased MVIF of the knee extensor muscles. We can therefore, in-part, accept our hypothesis, however, we reject that the mechanisms of adaptations are the same for both groups. An increased MVIF (14 %) for the LTW was due to an increased neural activation of the VL. However, changes in MVIF for DTW were not explained by changes in EMG activity. Further to this, LTW and DTW improved force fluctuations at 5 % MVIF without signs of an improvement in motor unit discharge rate and motor unit recruitment patterns. Overall, current improvements in isometric strength and steadiness could support the enhanced functional ability of the same group of older adults in Gault et al. (2012a). Therefore, as many older adults, especially those with cardiovascular disease, cannot exercise at intensities sufficient to provoke improvement in skeletal muscle mass and function, the potential of

DTW is worth further work. DTW dominated by muscle-lengthening contractions to increase muscle strength, and with lower cardiac demand in comparison to LTW, may be suited to this population and serve as a rehabilitative countermeasure.

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