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Rapid torque development in older female fallers and nonfallers: A comparison across lower-extremity muscles

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ABSTRACT

The objective of this study was to compare reaction time, joint torque, rate of torque development, and magnitude of neuromuscular activation of lower-extremity muscles in elderly female fallers and nonfallers. Participants included 11, elderly, female fallers (71.3 ± 5.4 years) and twelve nonfallers (71.3 ± 6.2 years) who completed a fall risk questionnaire. Then, maximal, voluntary, isometric contractions of the knee and ankle muscles were performed in reaction to a visual cue to determine joint torque, rate of torque development, reaction time, and nervous activation of agonists and antagonists. Results indicated that significantly more fallers reported "dizziness upon rising", "use of balance altering medications", "stress or depression", "not enough sleep", "arthritis in lower body", "chronic pain in lower body", and "tiring easily while walking" (all $P < 0.05$). Normalized dorsiflexion and plantarflexion strength scores (summation of peak torque, rate of torque development and impulse) were lower in fallers than in nonfallers ($P < 0.05$). When summed across lower-extremity muscle groups, fallers demonstrated 19% lower peak torque and 29% longer motor time ($P < 0.05$). In conclusion, comprehensive fall risk screening and prevention programs should address both neuromuscular and non-muscular factors, and, weakness of the ankle dorsiflexors and plantarflexors should be further studied as potential contributors to falls in older adults.

1. Introduction

Falling in older adults is a multifactorial problem with environmental as well as sensory, nervous, and muscular causes (AGS, 2001). Extrinsic factors such as visual impairments, cognitive deficits, prescription medication use, depression, and arthritis have all been reported to increase the risk of falling (AGS, 2001; Lipsitz et al., 1991; Sieri and Beretta, 2004). Nevertheless, a metanalysis of available fall-risk studies indicates that falling is associated with muscle weakness (odds ratio (OR) = 4.4) more so than gait (OR = 2.9), balance (OR = 2.9), vision (OR = 2.5) or use of psychotropic medication (OR = 1.7) (AGS, 2001).

In addition to increasing fall risk, loss of muscular performance in the aged leads to inability to perform activities of daily living and a loss of independence (Close et al., 2003; Nevitt et al., 1989; Skelton et al., 2002; Bean et al., 2002; Petrella et al., 2004). Maximum joint torque, rate of torque development, and joint torque at fast angular velocities are variables that are compromised in the lower extremities of older adults, particularly in fallers (Whipple et al., 1987; Pijnappels et al., 2008; Thelen et al., 1996). For example, rate of torque development in the knee and ankle musculature has been reported to be 20–40% lower in fallers than in nonfallers (Skelton et al., 2002; Pijnappels et al., 2008; Perry et al., 2007). The importance of lower extremity strength in recovery from an induced trip has also been demonstrated as those with low strength fall due to inability to support the body after reactive stepping (Pavol et al., 2002). The cause of the decline in muscle strength and rate of torque development is thought to be due to muscle atrophy but may also be due to reduced relative force output per muscle fiber, slower shortening velocity, and reduced neural drive to the muscle (Hakkinen and Hakkinen, 1991; D'Antona et al., 2007; LaRoche et al., 2008; Kostka, 2005). Muscular weakness has been identified in all of the major lower-extremity muscles including the knee extensors, knee flexors, ankle plantarflexors and dorsiflexors, but reports of which muscles are weakest in fallers vary (Sieri and Beretta, 2004; Skelton et al., 2002; Whipple et al., 1987).

With respect to nervous system functioning, recovery from a loss of balance requires effective sensorimotor integration, rapid conduction of nerve impulses to the periphery and appropriate implementation of postural control. An impaired ability to quickly activate skeletal muscle with aging has been well documented including longer reaction time, longer latency of muscle activation, lower motor unit activity, and increased antagonist coactivation (LaRoche et al., 2008; Fozard et al., 1994; Tang and Woollacott,

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1998). This results in older fallers demonstrating a slowed reaction to postural disturbances resulting in the need for greater muscular forces during recovery (Sieri and Beretta, 2004; van den Bogert et al., 2002; Kemoun et al., 2002; Thelen et al., 1997, 2000).

Ambiguity in the literature exists as to which muscle groups have the greatest loss of function and which neuromuscular performance variables are most affected in fallers. Therefore the purpose of this study was to determine how timing of muscle activation, nervous drive to the muscle, and muscle strength are related to a history of falls making comparisons across the knee flexors, knee extensors, ankle plantarflexors and dorsiflexors. The researchers hypothesized that fallers would have slower muscle activation times, lower strength and rate of torque development, and reduced nervous drive to the muscle, and that these deficits would be greatest in the rarely trained ankle dorsiflexors. Moreover, we aim to identify those muscles groups most in need of exercise in the elderly and to highlight which aspects of neuromuscular performance are mostly impaired in elderly fallers.

2. Methods

2.1. Subjects

A total of 23 women aged 65–85 years participated in this experiment. There were no significant differences between fallers and nonfallers for age, height, mass, BMI or the reported volume of physical activity (see Table 1). The women were categorized as fallers and nonfallers based on the protocol used by Skelton et al. (2002), and were then age-matched across groups. Fallers were defined as women who had fallen, or nearly fallen but caught themselves with their upper body, three or more times within the last year and nonfallers had no history of unexplained falls. Participants were independent women capable of ambulating without assistive devices and had no known neurological or muscular disorders. Volunteers were excluded from the study if they had any of the following conditions: severe arthritis, severe osteoporosis, uncontrolled blood pressure over 160/90 mm Hg, neurological disorders, knee or hip replacement in the dominant leg, and evidence of severe heart disease or dysrhythmia. All volunteers were required to provide written consent from their physician prior to participation and gave their own written informed consent. The protocol was approved by the University's Institutional Review Board for the use of human subjects.

Table 1
Subject descriptive characteristics.

	Fallers $n = 11$	Nonfallers $n = 12$	P-value
Age (year)	71.3 ± 5.4	71.2 ± 6.2	0.500
Mass (kg)	73.7 ± 17.6	65.1 ± 12.4	0.163
Height (cm)	163.1 ± 6.2	160.5 ± 6.7	0.203
Body mass index (kg m^{-2})	27.6 ± 5.7	25.2 ± 4.1	0.178
Activity (METs h week^{-1})	27.9 ± 22.2	29.6 ± 31.5	0.379

2.2. Procedures

Subjects reported to the laboratory on two separate days. The first visit was reserved for completion of interviews, assessment of leg dominance, familiarization of equipment and experimental procedures, and for recording age, height, mass, and body mass index (BMI). Interviews were conducted to obtain fall history, assess fall risk factors, and determine the volume of physical activity performed over the previous ten years. A fall risk assessment questionnaire (Table 2) was developed using the "Guideline for the Prevention of Falls in Older Persons" by the American Geriatrics Society, British Geriatrics Society, and American Academy of Orthopedic Surgeons Panel on Falls Prevention (AGS, 2001). This questionnaire identified factors most closely associated with falls. Physical activity volume over the previous ten years was estimated according to the methods of Kriska et al. (1990) using published energy costs for common physical activities (Ainsworth et al., 1993).

A second visit was scheduled approximately seven days later and included assessments of premotor time, motor time, total reaction time, peak joint torque, time to peak torque, rate of torque development, impulse, the magnitude of nervous stimulation of the agonists, and antagonist coactivation in a visually cued reaction task. These measures were obtained during maximal voluntary isometric contractions (MVC) of the dominant limb and were performed separately for the knee flexors (KF), knee extensors (KE), ankle plantarflexors (PF) and ankle dorsiflexors (DF). The investigators measured isometric strength as opposed to dynamic strength so that the time domain variables (premotor time, motor time, reaction time, time to peak torque, rate of torque development, and impulse) would not be influenced by movement of the resistance arm or changes in the length–tension relationship of the muscle during shortening. All measurements were completed using a HUMAC Norm dynamometer (*CSMI*, Stoughton, MA, USA) integrated with a BIOPAC MP100 data acquisition system that recorded joint torques from the analog output of the dynamometer. Prior to each data collection, the dynamometer was calibrated according to the manufacturer's recommendations. Torque

Table 2
Results of a questionnaire developed to assess the prevalence of factors associated with increased fall risk.

	Fallers (% responding yes)	Nonfallers (% responding yes)	P-value
Do you ever feel dizzy after getting up from a seated or lying down position?	27	0	0.029*
Do you ever feel dizzy for no apparent reason?	36	8	0.055
Do you take medications for depression, anxiety, seizure prevention or as a sleep aid?	45	8	0.024*
Do you take two or more medications (excluding vitamins and supplements)?	73	42	0.071
Do you have Diabetes?	9	0	0.148
Do you suffer from high levels of stress or depression?	27	0	0.029*
Do you wear visual aids?	100	100	0.50
Do you have trouble sleeping which results in not enough sleep?	64	8	0.004*
Do you have arthritis in the spine or lower limbs?	82	25	0.004*
Have you been diagnosed with osteoporosis?	18	17	0.463
Do you have chronic muscle pain in the torso or lower limbs?	27	0	0.029*
Do you have difficulty walking or use a gait aid to help you walk?	0	0	0.500
Do you have trouble getting up out of a chair or getting up when you are lying down?	18	0	0.066
Do you tire easily when you walk on a flat surface?	27	0	0.029*

* $P \leqslant 0.05$.

from the load cell of the dynamometer was sampled at 1 kHz, and smoothed using the mean torque calculated over overlapping 50-sample (20 ms) epochs to minimize noise in the precontraction torque signal such that the onset of torque could be easily and reliably detected.

For KE and KF muscle testing, participants were placed on the dynamometer in a seated position with a hip angle of 90° and knee angle of 75° (full KE equal to 0°). Participants were secured to the dynamometer in a prone position for DF and PF muscle testing with a 90° angle at the ankle. The participants' torso and active leg were restrained using nylon straps to prevent changes in joint angle that would influence the length of the tested muscle and subsequently joint torque. This restraint also served to limit the biarticular muscles to the desired joint action. After the participants were secured, they performed a MVC, with no time constraints, in order to record peak EMG so that the reaction task trial EMG could be normalized to peak. Participants were then asked to produce a MVC as quickly as possible in reaction to a visual cue. Three trials were completed for each of the four muscle groups with the first being used for practice and the mean of the last two trials used for analysis. The duration of the visual cue was 2 s; so each muscular contraction lasted approximately 2 s with 60 s rest between each trial. Because of the required high rate of torque development in this task, the term *peak torque* is used in this manuscript to indicate that the highest trial torque may not be representative of the true maximum torque. The sequence of muscle groups tested was conducted in stratified random order to prevent any order effect.

Electromyograms (EMG) were recorded from the surface of the skin using disposable, self-adhesive, 1 cm in diameter, silver-silver-chloride, wet gel electrodes (*Vermed, Inc.*, Bellows Falls, Vermont, USA). After the skin was cleaned and abraded to achieve a skin impedance of <5 kΩ, the electrodes were placed centrally superficial to the rectus femoris and biceps femoris muscles 10 cm proximal to the muscle–tendon junction and superficial to the tibialis anterior and medial gastrocnemius 4 cm proximal to the muscle–tendon junction. The electrodes had an inter-electrode distance of 20 mm and a ground electrode was placed over the proximal head of the fibula. The surface EMG signal was recorded at the skin and differentially amplified (×1000) using a BIOPAC TEL100M DC amplifier (Goleta, California, USA) with a common mode rejection ratio of 110 dB and a signal to noise ratio of 75 dB. The DC signal was then imported to a personal computer via the BIOPAC MP100 data acquisition system where it was band pass filtered (30–500 Hz) using the software's online digital filtering, full wave rectified and integrated; sampled at 1 kHz; and stored on the computer's hard drive using data acquisition software (BIOPAC AcqKnowledge software).

2.3. Data processing

BIOPAC AcqKnowledge software (Goleta, California, USA) was used to calculate dependent measures offline. The rate of joint torque development (RTD, N m s^{-1} kg^{-1}) was calculated in real time as the slope of the torque versus time curve. BIOPAC AcqKnowledge software was used to determine the instantaneous rate of change in the torque–time curve calculated using overlapping 50-sample (20 ms) epochs according to Eq. (1)

$$\mathrm{RTD}_{(1,50)} = \frac{(\mathrm{Torque}_{n=50} - \mathrm{Torque}_{n=1})}{(1000\ \mathrm{Hz}/50\ \mathrm{samples})} \quad (1)$$

Therefore, the slope of the torque–time curve was calculated from sample 1 to sample 50, followed by sample 2–51, 3–52, etc. The resultant RTD data were simultaneously sampled at 1 kHz along with torque and EMG, and during data processing, the peak instantaneous RTD observed in the first 200 ms of contraction was recorded for analysis. The contractile impulse (N m s kg^{-1}) from the onset of torque production until 200 ms was obtained by integrating the torque versus time curve over this period. Peak torque (N m kg^{-1}) was recorded as the greatest torque achieved during the muscular contraction. All torque measures were scaled to each participant's body mass to account for size differences among the participants and to more accurately reflect the muscles' functional performance relative to the individual's mass.

Total reaction time was measured as the time between the start of the visual cue until a torque threshold of 0.5 N m was exceeded. Reaction time was further fractionated into premotor time and motor time. Premotor time represented the amount of time needed by the central nervous system to recognize the visual signal and send the motor command to the periphery and was measured by calculating the time from the start of the visual stimulus to the beginning of the EMG burst. Motor time was measured by calculating the time from the beginning of the EMG burst until the 0.5 N m torque threshold was exceeded and represented the latency of excitation–contraction coupling and tensioning of the muscle–tendon unit. Time to peak torque was defined as the duration of time between the visual stimulus and the greatest torque achieved during the muscular contraction.

To assess nervous stimulation, the mean amplitude of integrated EMG was measured from the onset of torque production until 200 ms. This was measured for both the agonist and antagonist muscle groups for each of the four muscle groups tested. Data were then normalized to the peak EMG amplitude obtained from each muscle's MVC completed before the reaction task and were expressed as a percentage.

2.4. Statistical analysis

Descriptive measures included age, height, body mass, body mass index, volume of physical activity, and the reported prevalence of: dizziness after getting up from a seated or lying down position, dizziness for no apparent reason, taking balance altering medications, taking two or more medications, diabetes, high levels of stress or depression, use of visual aids, sleep deprivation, arthritis in the spine or lower limbs, osteoporosis, chronic muscle pain in the torso or lower limbs, difficulty walking, trouble getting up out of a chair or from a lying down position, and tiring easily when walking on a flat surface. Dependent variables included: reaction time, premotor time, motor time, time to peak torque, peak torque, rate of torque development, impulse, and integrated EMG of the agonist and antagonist muscle groups.

For each subject, for each dependent variable, individual *Z*-scores were determined using the formula:

$$Z = \frac{\text{individual score} - \text{mean}}{\text{standard deviation}} \quad (2)$$

To answer the question of whether the constructs of muscle activation timing, nervous drive to the muscle, or strength are related to a history of falls, and to facilitate comparison of dependent measures across muscle groups, composite *Z*-scores were calculated. A composite score for muscle activation timing was determined by obtaining the mean *Z*-score from total reaction time, motor time, premotor time, and time to peak torque from the individual *Z*-scores for these variables. Similarly, a composite *Z*-score was calculated for nervous system factors by obtaining the mean *Z*-score from the level of nervous stimulation of both agonists and antagonists, and a third composite *Z*-score was calculated from the muscle strength variables, rate of torque development, impulse, and peak torque. To provide an examination of lower-extremity muscle function summed across the KE, KF, PF, and DF, composite *Z*-scores were also calculated for the dependent measures: premotor time, motor time, total reaction time, time to peak torque, peak torque, rate of

torque development, impulse, nervous stimulation of agonists, and antagonist coactivation. Differences between groups were assessed using a Mann–Whitney test and the rejection criterion was set at $P \leqslant 0.05$. This statistical test was chosen because of the inclusion of ordinal scale variables and lack of normal distribution for a number of dependent variables.

3. Results

Significantly more fallers reported dizziness upon rising, use of balance altering medications, stress or depression, not enough sleep, arthritis in lower body, chronic pain in lower body, and tiring easily while walking (Table 2). Comparison of composite scores between muscles for muscle activation timing, strength, and nervous activation indicated that only dorsiflexion and plantarflexion strength scores (summation of peak torque, rate of torque development and impulse) were different between fallers and nonfallers ($P = 0.048$, $P = 0.01$ respectively). When comparing the composite scores for each of the measured variables summed across lower-extremity muscle groups, only peak torque and motor time were significantly different between fallers and nonfallers ($P = 0.022$, $P = 0.014$). No differences between groups were found for total reaction time, premotor time, time to peak torque, rate of torque development, impulse, or levels of agonist or antagonist activation. Means and standard deviations for the temporal components of muscle activation may be seen in Table 3, strength parameters in Table 4, and muscle activation parameters in Table 5.

4. Discussion

There were several important findings in this study. First, fallers reported more non-muscular fall risk factors including experiencing dizziness upon rising, taking balance altering medications, suffering from stress and/or depression, sleep deprivation, fatigue while walking on a flat surface, chronic pain, and arthritis in the lower extremities. The fallers demonstrated lower strength (peak torque) when summed across all muscle groups in comparison to nonfallers. Specifically, fallers had the greatest deficits in peak torque, rate of torque development, and impulse in the ankle dorsiflexors and plantarflexors with no differences between groups for these variables in the knee flexors and extensors. Thirdly, fallers exhibited longer motor times than their non-falling peers. These results suggest the presence of multiple non-muscular risk factors, slowed excitation–contraction coupling, and strength and rate of torque development deficits in the ankle musculature in these subjects.

4.1. Non-muscular fall risk factors

The current study supports previous findings that have indicated that stress, depression, the use of balance altering medications, and vertigo upon rising are risk factors related to falls in older persons (AGS, 2001; Lipsitz et al., 1991; Sieri and Beretta, 2004). These factors are likely interrelated with depression leading to the use of anti-depressants and their deleterious effects. Antidepressants (Ryynanen et al., 1993), along with sedatives (Speechley and Tinetti, 1991), psychotropic (Campbell, 1990) and anti-seizure medications can impair the central or peripheral nervous system, can cause postural hypotension, drowsiness and decreased awareness of surroundings (Cranwell-Bruce, 2008). Additionally, the present study reported that 64% of the fallers suffered from sleep deprivation while only 8% of nonfallers did. Although a lack of sleep has been linked to stress and depression, it has been identified as an independent fall risk factor (AGS, 2001). Perhaps elderly

Table 3
Premotor time, motor time, reaction time, and time to peak torque in the leg muscles of fallers and nonfallers obtained from a visually cued maximal voluntary isometric contraction. Values are mean ± SD. Composite *Z*-score by muscle = mean of premotor time, motor time, reaction time, and time to peak torque *Z*-scores. Composite score by variable = mean of knee extensors, knee flexors, dorsiflexors, and plantarflexors *Z*-scores for a given variable.

		Knee extensors	Knee flexors	Dorsiflexors	Plantarflexors	Composite *Z*-score by variable (sd)	*P*-value
Premotor time (ms)	Fallers	179 ± 51	194 ± 54	196 ± 55.6	192 ± 58	−0.10 ± 0.28	0.269
	Nonfallers	207 ± 46	204 ± 40	193.5 ± 26	193 ± 16	0.09 ± 0.11	
Motor time (ms)	Fallers	99 ± 51	122 ± 56	64 ± 31	109 ± 41	0.31 ± 0.22	0.014*
	Nonfallers	78 ± 31	88 ± 30	52 ± 12	88 ± 23	−0.29 ± 0.10	
Reaction time (ms)	Fallers	279 ± 34	317 ± 44	261 ± 81	301 ± 42	0.16 ± 0.22	0.134
	Nonfallers	284 ± 34	291 ± 54	248 ± 30	279 ± 28	−0.14 ± 0.10	
Time to peak (ms)	Fallers	1624 ± 453	1499 ± 434	1369 ± 369	1515 ± 397	−0.11 ± 0.20	0.088
	Nonfallers	1714 ± 23	1545 ± 421	1420 ± 401	1690 ± 476	0.10 ± 0.13	
Composite *Z*-score by muscle (sd)	Fallers	−0.05 ± 0.14	0.12 ± 0.18	0.09 ± 0.29	0.10 ± 0.17		
	Nonfallers	0.05 ± 0.15	−0.11 ± 0.17	−0.08 ± 0.10	−0.10 ± 0.10		
P-value		0.088	0.212	0.427	0.070		

* Difference in composite *Z*-score between groups; $P \leqslant 0.05$.

Table 4
Peak torque, power and impulse in the leg muscles of fallers and nonfallers obtained from a visually cued maximal voluntary isometric contraction. Values are mean ± SD. Composite *Z*-score by muscle = mean of peak torque, rate of torque development, and impulse *Z*-scores. Composite score by variable = mean of knee extensors, knee flexors, dorsiflexors, and plantarflexors *Z*-scores for a given variable.

		Knee extensors	Knee flexors	Dorsiflexors	Plantarflexors	Composite *Z*-score by variable (sd)	*P*-value
Peak torque (N m kg^{-1})	Fallers	1.49 ± 0.46	0.59 ± 0.73	0.32 ± 0.06	0.76 ± 0.14	−0.38 ± 0.16	0.021*
	Nonfallers	1.72 ± 0.56	0.72 ± 0.25	0.38 ± 0.09	1.04 ± 0.27	0.34 ± 0.26	
Rate of torque development (N m s^{-1} kg^{-1})	Fallers	6.97 ± 2.9	4.02 ± 2.17	1.57 ± 0.36	3.18 ± 1.14	−0.20 ± 0.20	0.212
	Nonfallers	6.90 ± 3.86	4.50 ± 2.67	1.93 ± .55	4.12 ± 1.89	0.18 ± 0.31	
Impulse (N m s kg^{-1})	Fallers	0.096 ± 0.039	0.045 ± 0.018	0.030 ± 0.007	0.046 ± 0.018	−0.11 ± 0.17	0.269
	Nonfallers	0.095 ± 0.058	0.043 ± 0.021	0.032 ± 0.009	0.064 ± 0.029	0.10 ± 0.29	
Composite *Z*-score by muscle (sd)	Fallers	−0.07 ± 0.25	−0.13 ± 0.21	−0.29 ± 0.19	−0.42 ± 0.17		
	Nonfallers	0.07 ± 0.29	0.12 ± 0.28	0.27 ± 0.29	0.38 ± 0.29		
P-value		0.403	0.178	0.049*	0.014*		

* Difference in composite *Z*-score between groups; $P \leqslant 0.05$.

Table 5
Nervous activation for agonist and antagonist muscles in the leg of fallers and nonfallers obtained from a visually cued maximal voluntary isometric contraction. Values are mean ± SD. Composite *Z*-score by muscle = mean of agonist integrated EMG and the inverse of antagonist integrated EMG *Z*-scores. Composite score by variable = mean of knee extensors, knee flexors, dorsiflexors, and plantarflexors *Z*-scores for a given variable.

		Knee extensors	Knee flexors	Dorsiflexors	Plantarflexors	Composite *Z*-score by variable (sd)	*P*-value
EMG agonist (% of peak EMG)	Fallers	46 ± 13	55 ± 19	52 ± 9	62 ± 26	0.11 ± 0.10	0.249
	Nonfallers	34 ± 15	44 ± 17	51 ± 11	73 ± 27	−0.10 ± 0.13	
EMG antagonist (% of peak EMG)	Fallers	53 ± 33	13 ± 10	19 ± 9	16 ± 11	0.14 ± 0.17	0.121
	Nonfallers	47 ± 33	12 ± 5	17 ± 12	15 ± 12	−0.13 ± 0.23	
Composite *Z*-score by muscle (sd)	Fallers	0.16 ± 0.22	0.07 ± 0.30	−0.04 ± 0.07	−0.13 ± 0.19		
	Nonfallers	−0.15 ± 0.12	−0.06 ± 0.17	0.04 ± 0.22	0.12 ± 0.22		
P-value		0.088	0.212	0.403	0.212		

fallers are fatigued during the day or up at night while nonfallers are resting well.

In the present study, 82% of fallers reported arthritis in the lower extremities compared to only 25% of nonfallers, and, 27% of fallers reported having chronic pain in the legs while no nonfallers reported chronic pain. It has been demonstrated that arthritic symptoms are associated with low levels of physical activity (Heesch et al., 2007). Therefore, arthritis probably leads to a decline in physical activity, which leads to deconditioning, which increases the likelihood of falls. In support of this hypothesis, this study showed impaired muscular performance in fallers and 27% of fallers reported fatiguing easily while walking on a flat surface while none of the nonfallers did. These results are in accordance with others (Kemoun et al., 2002; Verghese et al., 2006; Luukinen et al., 1994) and provide further support for the link between arthritic pain, fatigue, and fall risk in older adults.

4.2. Muscle strength and power

Joint rate of torque development is important in fall prevention (Overend et al., 1992) because it allows an individual to react quickly to a postural perturbation and to support their body weight during reactive stepping (Lanza et al., 2003). Previous researchers have shown that low levels of composite strength and power of the leg muscles contribute to fall incidents (Whipple et al., 1987; Perry et al., 2007). Similarly, the current study shows that, averaged across all muscle groups, peak torque was 19% lower in older female fallers. This lends further support for the relationship between muscle weakness and a history of falls. However, there are disparities in the literature as to which muscles contribute most to increase the risk for falls in the elderly. Some studies have found the DF to be the most impaired in fallers (Skelton et al., 2002; Whipple et al., 1987); others found the greatest deficiency in the PF (Sieri and Beretta, 2004; Perry et al., 2007), while others found weakness in the KE and/or the KF (Sieri and Beretta, 2004; Takazawa et al., 2003). Such disparities may be attributed to the different methodologies used, age and gender differences, different types of contractions performed, and, during dynamic contractions, varying velocities and range of motions. This study, for example, used isometric contractions that elicit repeatable strength measurement over time, but are not characteristic of the dynamic movements required during locomotion and recovery from a loss of balance.

Nonetheless, the results obtained in the present study are consistent with those obtained by Skelton et al. (2002), Whipple et al. (1987) and Perry et al. (2007) in that DF and PF strength and rate of torque development were lower in fallers than in nonfallers. Specifically, older female fallers had 16% lower DF peak torque, 27% lower PF torque, 19% lower DF rate of torque development, 23% lower PF rate of torque development, 6% lower DF impulse, and 28% lower PF impulse during a rapid contraction. It is likely that these two particular muscle groups are associated with falling for two reasons: (1) the PF and DF muscles are critical for maintaining balance after a postural disturbance and (2) the PF and DF muscles are required for normal walking gait. It has long been known that the DF and PF muscles are the first line of defense in standing postural control (Nashner, 1977) and more recent research suggests that during reactive stepping the ankle muscles are activated first before the muscles of the knee and hip (Thelen et al., 1997). If strength in the ankle musculature is insufficient to control balance, individuals must then adopt hip or stepping strategies. These strategies require larger gross movements and displacement of the center of mass, require higher forces, possibly leading to further loss of balance and falls.

As for walking gait, Kemoun et al. observed that during the "swing" and "toe off" phases the ankles of fallers moved through a lower range of motion than nonfallers and display delayed DF activation (Kemoun et al., 2002). The lower DF peak torque seen in the current study may be associated with foot drop when walking which would reduce the ability to clear obstacles possibly increasing the frequency of tripping. The lower PF peak torque, rate of torque development and impulse seen in this study more likely attenuate propulsion during walking and inhibit recovery during loss of balance as has been previously demonstrated (Kerrigan et al., 1998; Mueller et al., 1995; Nadeau et al., 1999; Pijnappels et al., 2005). Specifically, Pijnappels et al. (2005) demonstrated that during push-off following a trip, older fallers showed the greatest deficits in ankle and hip rate of torque development and demonstrated lower peak torque only for ankle plantarflexion. These weaknesses translated into an inability to control forward momentum leading to falls for these subjects. The current study is in agreement with these findings. Since no deficiencies were found for the muscles of the knee in the falling group, performance of the ankle musculature appears to be more associated with a history of falling in this experimental group. It is possible that by performing activities of daily living (sit to stand, stair climbing) or through participation in recreational activities like walking and gardening, the knee muscles are exercised to a greater degree than the ankle muscles. In fact, a secondary examination of the data indicated that by separating participants into the most and least active (ignoring fall history), KE and KF strength and rate of torque development tracked well with reported physical activity level while DF and PF performance did not.

4.3. Time course of muscle activation

A slow response time has been linked to falls (Maki, 1997; Larsson et al., 1979) and difficulty recovering loss of balance (Thelen et al., 1997), but there is little research on muscle activation time of individual muscle groups in older fallers. When the temporal factors of muscle activation (premotor time, motor time, total reaction time, and time to peak torque) were summated and compared *between* muscle groups there were no significant differences in muscle activation latencies between fallers and nonfallers. This indicates that in response to a visual cue during isolated, uniaxial

contractions, muscle activation time in the muscles studied is not strongly associated with a history of falls. However, when each temporal component was summed *across* muscle groups and examined independently, motor time was 22 ms longer (29%) in fallers. Motor time, the time from nervous activation to torque production, is longer in less active individuals (Bunce et al., 2004; LaRoche et al., 2007) and it increases with age (Bunce et al., 2004). Likely, the slowed motor time of fallers is representative of diminished excitation–contraction coupling including slowed calcium release or reuptake from the sarcoplasmic reticulum and decreased activity of metabolic enzymes such as creatine kinase and actomyosin ATPase (Prochniewicz et al., 2005; Kaczor et al., 2006; Pastoris et al., 2000). Alternatively, if fallers had reduced muscle mass and cross-sectional area, the slower motor time may have been due to reduced musculotendinous stiffness that would result in less immediate transfer of force from the muscle to the bone (Magnusson et al., 1997). In fact, elderly have been shown to have tendons that are less stiff than young yet have the capacity to increase stiffness by more than 60% following resistance training (Reeves et al., 2003). It is therefore logical that the longer motor time seen in elderly fallers covaries with reduced strength.

4.4. Muscle EMG activity

Because aging (LaRoche et al., 2008; Laughton et al., 2003) and low levels of physical activity (LaRoche et al., 2007) have been associated with decreased neural drive, it was hypothesized that decreased agonist activation might contribute to the lower strength and rate of torque development seen in older female fallers. Unexpectedly, the magnitude of neuromuscular activation of the agonist muscles in the first 200 ms of contraction was not different between fallers and nonfallers for any of the actions performed. Also, it was hypothesized that greater levels of antagonist coactivation in older female fallers might contribute to reduced net joint torque, slowed movements, and their inability to appropriately respond to postural disturbances but this too was not supported by the current study. These findings indicate that in this group of women, when performing simple, single joint strength tasks, that performance of the motor system does not distinguish between fallers and nonfallers.

4.5. Limitations

A major limitation of this study was that it was cross-sectional in nature and did not prospectively determine the relationship between neuromuscular performance and fall risk. A significant health disparity was identified between fallers and nonfallers with fallers reporting more medication use, arthritis, pain, and fatigue. Because of the study design, it is not possible to differentiate to what extent the neuromuscular performance deficits or impaired general health contributed to the greater history of falls. Lastly, the performance of the hip musculature was not assessed in this study despite its documented importance in recovery from loss of balance (Thelen et al., 2000).

5. Conclusions

This study indicates that poor health and poor muscular fitness are comorbid conditions likely to be seen in elderly fallers. This was demonstrated by diminished lower extremity strength and a higher prevalence of non-muscular fall risk factors in older female fallers. The results suggest that strength, speed of movement, and power of the ankle dorsiflexors and plantarflexors should be further studied as potential contributors to falls in older adults. Secondly, interventions designed to reduce falls might help control the number and type of medication use, as well as reduce fatigue, stress and chronic pain. Finally, the determination of specific muscular weaknesses and fall risk factors should be used to design individualized fall prevention programs that are likely to be more successful than generalized fall prevention programs (Tinetti et al., 1994).

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Conflict of interest

None.

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