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Altered muscle activation characteristics associated with single volitional forward stepping in middle-aged adults

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ABSTRACT

Background: Middle-aged adults show a higher incidence of falls compared to young adults when performing outdoor physical activities. This study investigated whether or not the patterns and quantitative characteristics of the trunk and lower extremity muscle activations associated with stepping, which represents an important movement for arresting falls, differ between middle-aged adults and young adults.

Methods: Nine healthy young adults (age = 22[3] years) and nine healthy middle-aged adults (age = 52[8] years), performed a single-step, volitional, fast forward stepping movement with each leg. The stepping movement was divided into the step-initiation, single-leg-support, and landing phases based on footswitch signals. The activation sequence, occurrence rate, onset latency, burst duration, and normalized co-contraction duration of the tibialis anterior, medial gastrocnemius, rectus femoris, biceps femoris, and gluteus medius of the stance and swing legs and that of bilateral erector spinae muscles were analyzed using surface electromyography. We defined the essential muscle activation as exhibiting an occurrence rate of 90% or more in all of these trials.

Findings: As compared to young adults, the middle-aged adults demonstrated several additional essential bursts throughout the stepping movement. Middle-aged adults also displayed significantly longer burst durations of the biceps femoris and medial gastrocnemius of the swing leg after landing, as well as longer co-contraction of the rectus femoris and biceps femoris of the stance leg in the single-leg-support phase ($P < 0.05$).

Interpretation: Age-related changes in step-related neuromuscular control exist in healthy middle-aged adults. We propose that training focused on improving or maintaining neuromuscular control associated with volitional leg movements may benefit middle-aged individuals.

1. Introduction

Recent large-scale surveys on accidental falls have revealed that middle-aged adults have a higher incidence of falls (21%) than young adults (18%) do (Talbot et al., 2005). Most of these falls occur in the forward direction and occur outdoors when middle-aged individuals are performing physical activities and/or encountering potential postural threats in the environment (Li et al., 2006; Talbot et al., 2005). From the preventive medicine perspective, middle-aged adults are encouraged to be engaged in more physical activities in order to secure better mobility and to reduce the incidence of falls later in life (Patel et al., 2006; Talbot et al., 2005). However, it is worth noting that engaging in leisure-time physical activity is itself one of the independent risk factors for outdoor falls (Li et al., 2006). These public health findings have shed light on the importance of examining the ability of middle-aged adults to respond to potential environmental postural threats while performing dynamic physical tasks.

Both reactive and proactive volitional stepping are two effective protective balance strategies used by an individual in everyday life (Maki et al., 2000; Rogers and Mille, 2003). While reactive stepping is evoked after an individual experiences an unexpected postural perturbation during dynamic tasks and is a powerful mechanism in preventing an impending fall (Maki et al., 2000; Pai et al., 2000; Pavol et al., 2004a; Thelen et al., 1997; Wojcik et al., 1999), volitional stepping requires anticipatory neural mechanisms that allow an individual to detect potential environmental hazards, such as a ball flying towards him, and initiate postural adjustments from a static posture or ongoing movement in order

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to prevent postural threats (Lyon and Day, 1997; Rogers and Mille, 2003). Both reactive and proactive stepping abilities have been shown to be impaired in older adults (Cho et al., 2004; Luchies et al., 1999; Maki et al., 2000; Medell and Alexander, 2000; Schulz et al., 2007; Thelen et al., 1997, 2000). In addition, tests using volitional fast stepping and its various forms have also been found to be valid predictors of falls in the elderly population (Cho et al., 2004; Dite and Temple, 2002; Lord and Fitzpatrick, 2001). However, little is known about the volitional stepping ability of middle-aged individuals.

Although volitional stepping is less dynamic than reactive stepping, the former nevertheless requires that one maintains his or her dynamic equilibrium while changing from a symmetric double-limb-support stance to a single-limb-support stance, and ultimately to an asymmetric double-limb-support stance (Patla et al., 1993). The base-of-support (BoS) and center-of-mass (CoM) are simultaneously varied throughout this period of rapid adjustment. The execution of successful volitional stepping involves a complex neuromuscular control mechanism during the initiation, single-limb-support, and termination phases of this movement in order to maintain an individual's dynamic equilibrium.

Previous studies have shown that in young adults, the initiation of volitional stepping activates distal leg muscle contraction patterns that are similar to those observed during gait initiation. During these two activities, the tonic contraction of the gastrocnemius (GA) and soleus (SoL) muscles is typically inhibited, followed by activation of the bilateral tibialis anterior (TA) muscles prior to the toe-off of the swing foot (Brunt et al., 1999; Crenna and Frigo, 1991; Elble et al., 1994; Mann et al., 1979). The magnitude of the TA activation is highly correlated with the backward displacement of the center-of-pressure (CoP) (Crenna and Frigo, 1991) and the time-integral of the backward CoP shift (Polcyn et al., 1998) during gait initiation, as well as with the step velocity during step-initiation (Ito et al., 2003). Yet despite these similarities, Gantchev et al. (1996) reported different timing of the phases between these two tasks in healthy adults. Specifically, they found that the two tasks were characterized by a similar duration of initiation, but that the step-initiation had a longer single-limb-support phase compared to the gait initiation.

In contrast to the well-documented activation patterns of the distal leg muscles, the activation patterns of the more proximal muscles during the step or gait initiation are less frequently reported and quantified. Wang et al. (2006) and Mann et al. (1979) found that the medial gluteus (MGLU) muscles of the swing and stance legs were sequentially activated before the foot-off of the swing leg during rapid stepping and gait initiation. It was hypothesized that this sequential activation of the MGLU muscles serves to shift the CoP laterally in preparation for the foot-off.

Termination is also an important process for stepping and gait initiation, since effective and safe termination can prevent a forward fall. Two biomechanical mechanisms have been proposed as causal in the rapid termination during walking (Hase and Stein, 1998). The first mechanism involves a reduction in the push-off power of the trailing (stance) leg, a phenomenon that can be achieved by decreasing the GA and SoL activation and increasing the TA activation. The second mechanism involves the braking force, which is generated by increased activation of the GA and SoL of the leading (swing) leg. This activation then creates a backward momentum after the leading leg makes heel contact (Hase and Stein, 1998). Furthermore, activation of the proximal muscles [the biceps femoris (BF) and MGLU of the trailing leg, vastus lateralis, MGLU of the leading leg, and bilateral erector spinae (ES)] is also observed during gait termination and is thought to stabilize the knee, hip, and trunk (Hase and Stein, 1998). However, the mechanisms by which the trunk and lower extremity muscles are involved in step termination remains unresolved.

Previous research has demonstrated age-related changes in muscle activation during volitional stepping, gait initiation, and gait termination, however, this research was mostly performed in older adults. Thus, there is lack of information regarding these important aspects in middle-aged individuals. Previous studies have indicated that in gait initiation healthy older adults present the sequence of GA inhibition followed by TA activation prior to the toe-off less frequently than young adults do (Halliday et al., 1998; Polcyn et al., 1998). Healthy older adults also more frequently present TA/GA co-activation prior to the toe-off (Polcyn et al., 1998) and sustained GA activation of the stance leg during the single-leg-support phase (Henriksson and Hirschfeld, 2005; Mickelborough et al., 2004) than young adults do in gait initiation. Such alterations may lead to a smaller backward shift to the CoP (Halliday et al., 1998) and slower forward acceleration of the body center-of-mass (CoM) (Mickelborough et al., 2004; Polcyn et al., 1998). In addition, older adults show less frequent MGLU activation of the swing leg prior to the foot-off than that observed in young adults, leading to a less effective lateral shift of the CoP (Mickelborough et al., 2004). With regard to step or gait termination, no research has been performed to investigate the age-related changes in muscle activation patterns. However, using kinetic analysis, Tirosh and Sparrow (2004) found that older adults produced smaller braking forces with the leading leg and modulated the propulsive forces of the trailing leg less effectively than young adults did. Consequently, older adults more frequently used two-step terminations and a longer stopping time than young adults did when they were asked to suddenly stop walking.

Given the limited information regarding the neuromuscular control of dynamic balance in middle-aged individuals, we conducted this study to investigate the muscle activation characteristics during the initiation, single-leg-support, and termination phases of fast single forward volitional stepping in both healthy young adults and middle-aged adults. We aimed to describe the activation patterns of the trunk as well as the activation patterns in the distal and proximal lower extremity muscles during the initiation, single-leg-support, and termination phases of fast forward stepping in healthy young adults. In addition, we compared the characteristics of these muscle activations between health young and middle-aged adults.

2. Methods

2.1. Participants

Nine healthy young adults (6 male, 3 female, mean [SD] age = 22.1 [2.6] years, mean [SD] height = 167.7 [9.2] cm, mean [SD] weight = 64.3 [9.0] kg) and nine healthy middle-aged adults (6 male, 3 female, mean [SD] age = 52.3 [8.3] years, mean [SD] height = 163.5 [9.9] cm, mean [SD] weight = 63.0 [7.8] kg) were recruited from the university campus and surrounding communities to participate in this study. All recruited individuals signed the informed consent approved by the Institutional Review Board. The two groups exhibited no differences in their collective gender distribution, body height, and body weight ($P > 0.05$). Moreover, all participants completed a self-reported basic demographics, health status, and leisure-time physical activity questionnaire in addition to undergoing the Berg Balance Scale (BBS) examination to assess their balance ability (Berg et al., 1992). All participants met the inclusion criteria of having no falls within the previous year, no neurological, musculoskeletal, cardio-pulmonary, or cognitive disorders, and were characterized with good balance ability as determined by a score greater than 54 in the BBS. With the exception of one middle-aged and one young participant, all of the participants were engaged in leisure-time physical activities for at least 60 min weekly (range = 60 min to 6 h for both groups). The physical activities involved mostly competitive sports, martial arts, or jogging among the young participants and walking or Tai-Chi exercises among the middle-aged participants.

2.2. Equipment

The stimulus box of the Reaction/Movement Time Device (Model 63017, Lafayette Instrument, Lafayette, IN, USA) was used to provide warning and stimulus light signals during the stepping experiment. Two foot-switches (MA-153, Motion Lab System, Inc., Baton Rouge, LA, USA) were used to determine the time of foot-off and foot-contact. Surface electromyography (EMG, Delsys Inc., Boston, MA, USA) was recorded and processed for the bilateral TA, medial GA, rectus femoris (RF), BF, MGLU, and ES muscles. Two force plates (AMTI OR6-7, Advanced Mechanical Technology, Inc., Watertown, MA, USA), which measures 50.9 cm in length and 46.4 cm in width, were used to record the ground reaction forces underneath the legs. The plates were placed side by side with the 46.4 cm-long side of each plate being positioned right next to each other. A piece of thin, light weight, and non-glossy paper covered both plates so that the investigators could mark the footprints for later calculation of the step length.

Data collected from the stimulus light, foot-switches, force plates, and EMG were synchronously sampled at 1024 Hz and then converted into digital data using the DataPac 2000 Acquisition and Analysis System (DataPac 2000, Run Technologies, Mission Viejo, CA, USA).

2.3. Protocol

The stimulus box was placed 1 m in front of the participant at eye level. The two foot-switches were placed underneath the first metatarsal head and mid-heel of the swing leg. Initially, the participant stood barefoot on the center of one force plate (plate 1) and faced the other force plate (plate 2). Each participant was instructed to stand with his or her feet shoulder-width apart and ankle joints aligned with the mediolateral axis of the plate 1, Each participant was then asked to bear weight equally on both feet, and this was ensured by visual inspection to verify that no lateral shearing force and rotational torque was detected on the online computer scope of DataPac 2000.

Using a simple reaction-time paradigm, a block of six trials was tested for stepping with each leg for all participants. The testing order of the legs was randomized among the participants. In each trial, a warning light was initially presented to alert the participant to keep his or her eyes focused on the stimulus box. After a varied foreperiod interval (1–6 s), which prevented participants from anticipating the onset of the stimulus light, the stimulus light was activated. Upon seeing the light, the participant had to perform a fast, safe, forward, and comfortable-length single-stepping movement toward the plate 2. The participants were asked to keep the stance leg in contact with the floor and to apply approximately 50% of their body weight on each leg after landing and to maintain the landing posture for approximately 2 s in order to allow the investigators to mark the landing footprints. The force and EMG data were collected for 5 s for each stepping trial, beginning 1 s prior to onset of the stimulus light.

2.4. Data processing and analysis

The overall course of stepping was divided into three subphases, specifically the step-initiation, the single-leg-support, and the landing phases, based on the foot-switch signals. The step-initiation phase began at the onset of the stimulus light and ended at the foot-off (both switches off) of the swing leg. The single-leg-support phase occurred from the foot-off to the initial foot-contact (one switch on) of the swing leg. The landing phase began upon initial foot-contact and ended at the whole foot-contact (both switches on) of the swing leg.

We calculated the step velocity in order to indicate the behavioral performance of the participants. First, the step length was measured as the anteroposterior displacement of the midpoint heel mark of the swing leg from the initial to the final landing position on the paper. A high intra-rater agreement (>95%) of this step length measure was ensured prior to conducting the measurement. The step velocity was then calculated by dividing the step length by the duration of the single-leg-support phase (Thelen et al., 1997, 2000; Wojcik et al., 1999).

In order to understand whether or not the participants placed sufficient load on the swing leg after landing, we calculated the relative vertical forces loaded onto each leg during the 500 ms time window after complete foot landing, in other words after the landing phase, for both groups. The landing phase was not included in this after-landing weight distribution in order to eliminate the influence of the impact force immediately after landing. The maximum backward horizontal ground reaction force after landing ($F_{Y\_Max\ Backward}$) was also calculated and normalized by body weight to indicate the braking force after landing (Crenna et al., 2001).

The CoP trajectories in the anteroposterior and mediolateral direction were calculated based on the force plate data in order to understand the dynamics of the participant's stepping movement. We calculated the maximum CoP displacement in the posterior (CoP_{AP}) and lateral (toward the swing leg) (CoP_{ML}) directions between the light onset and complete foot-off events. In step-initiation, the CoP_{AP} indicates the ability to generate the forward momentum and the CoP_{ML} indicates the ability to shift the CoP towards the stepping leg (Mann et al., 1979). The time to CoP_{AP} and CoP_{ML} was also calculated.

The EMG data were demeaned, band pass filtered (20–450 Hz), and the full-wave was rectified using the DataPac 2000 Acquisition and Analysis System (DataPac 2000, Run Technologies, Mission Viejo, CA, USA). We first identified bursts of activation for each muscle during the stepping movement. A time window of 700–200 ms prior to onset of the stimulus light was used in order to calculate the baseline EMG activity of each muscle investigated. The onset and termination of a muscle burst were defined as the time at which the EMG amplitude of the muscle rose above and fell below the baseline EMG activity by two standard deviations, respectively (Henriksson and Hirschfeld, 2005). For clarity, a muscle burst is denoted herein as the abbreviation of muscle name, leg, and burst number. For instance, the burst "ES_{sw_1}" indicates the first ES burst of the swing leg, while "$MGLU_{st\_2}$" indicates the second MGLU burst of the stance leg.

Subsequently, the occurrence rate, onset latency, and burst duration for each muscle burst, and the normalized co-contraction duration of the investigated muscles were analyzed. The occurrence rate of the muscle bursts represented the percentage of trials in which a muscle demonstrated a burst among all tested trials in a participant. The muscle onset latency was defined as the duration from the onset of the stimulus light to the onset of a muscle burst. The burst duration was defined as the time between the onset and termination of each burst. The normalized co-contraction durations of the TA/GA pairs during the step-initiation and the single-leg-support phases were defined as the intervals in which both the TA and GA were activated divided by the duration of the step-initiation and single-leg-support phases, respectively. Similarly, the normalized co-contraction durations of the RF/BF pairs in the step-initiation and single-leg-support phases were calculated using the same algorithm. The co-contraction duration was not calculated for the landing phase because this phase was typically very short (approximately 50–90 ms).

2.5. Statistical analysis

We first used the Shapiro–Wilk and Levene's tests to examine the normality and homogeneity of all dependent variables, respectively, and found no violations. Thus, the paired *t*-test was performed for the left- and right-leg stepping trial comparisons. Since no significant differences were observed in any of these variables between the two types of stepping trials, the average values of these variables from the left- and right-leg stepping trials were used for later analyses.

In order to compare the age group differences with regard to muscle activation characteristics, one-way multivariate analyses of variance (MANOV) procedures were used to control for type I error. An á-priori alpha level of 0.05 was set for all statistical tests (Portney and Watkins, 2009). The Mahalanobis' distance for multivariate normality and outliers were verified ($P < 0.01$), and no violation of the multivariate normality was found. Follow-up tests using separate univariate ANOVAs with Bonferroni adjustments were conducted if the MANOVA procedures demonstrated statistical significance (Schutz and Gessaroli, 1987). Due to our relatively small sample size and the large number of muscles and muscle bursts, we performed five separate MANOVA procedures for each dependent variable. For example, in order to test for group differences in muscle occurrence rate, the first MANOVA procedure was performed to test group differences when all of the first bursts of the stance leg muscles were considered simultaneously. The second MANOVA procedure was performed to test group differences when all of the second bursts of the stance leg muscles were considered simultaneously. Similarly, the 3rd, 4th, and 5th MANOVA procedures were performed in order to test age group differences in a dependent variable across the 1st, 2nd, and 3rd bursts of the swing leg muscles, respectively. The independent *t*-test was used to compare the group differences in force and four CoP variables.

All statistical analyses were performed using SPSS 15.0 for Windows (SPSS Inc.). The effect size of the group differences was also calculated for all dependent variables. The effect size values between 0.2 and 0.49, between 0.50 and 0.79, and for 0.80 and above indicated small, moderate, and large differences, respectively (Cohen, 1988).

3. Results

Analyses of the vertical ground reaction forces showed no significant group differences with regard to normalized weight bearing on the stepping (Y: 47.3 ± 12.9%; M: 40.6 ± 18.0% total weight bearing on both legs) or stance (Y: 52.7% ± 12.9% M: 59.4 ± 18.0%) legs after landing ($P > 0.05$). This result suggests that the participants were able to meet the task requirement and assume approximately equal weight bearing on both feet after landing.

3.1. Step velocity, step length, phase duration, $F_{Y\_Max\ Backward}$, and CoP variables

The young and middle-aged groups were not significantly different in step velocity, step length, and duration of any of the three sub-phases ($P > 0.05$, Table 1). There were also no significant group differences in $F_{Y\_Max\ Backward}$, CoP_{AP} and CoP_{ML}, and the time to CoP_{AP} and CoP_{ML} ($P > 0.05$, Table 1).

3.2. Sequence of essential muscle activations during the step-initiation, single-leg-support, and landing phases of young and middle-aged adults

The majority of the investigated muscles showed two activation bursts during the course of stepping, with an occurrence rate greater than 50% (Tables 2 and 3). One exception was the RF_{st}, which displayed only a single long burst throughout the stepping course (Fig. 1). Other exceptions were the TA_{sw} and RF_{sw}, which at times demonstrated three bursts (Fig. 1 and Table 3).

Fig. 1 (top) shows the sequence of the essential muscle activations (filled bars) during stepping in young adults. We defined the essential muscle activation as having an occurrence rate of 90% or greater. In the step-initiation phase, the stance leg demonstrated TA_{st_1} activation, followed by RF_{st_1} and then $MGLU_{st\_1}$ activation. In addition, the swing leg showed TA_{sw_1} and $MGLU_{sw\_1}$ activation, followed by GA_{sw_1} activation. In the single-leg-support phase, the RF_{st_1} burst was sustained and TA_{sw_2} and RF_{sw_2} activations were observed. Prior to landing, the stance leg did not demonstrate any essential burst, except for the sustained RF_{st_1}. The $MGLU_{sw\_2}$ and GA_{sw_2} started just before landing and continued for a period of time after landing.

The overall essential muscle activation pattern for the middle-aged adults was slightly different from that observed in young adults. In particular, some additional essential muscle activations were observed in the middle-aged adults (Fig. 1 bottom), including BF_{st_1} and BF_{sw_1} activations during the step-initiation phase and TA_{st_2}, ES_{st_2}, and BF_{sw_2} activations, which occurred immediately before landing and ended at a time after landing. In addition, $MGLU_{sw\_1}$ and $MGLU_{sw\_2}$ were shown to be non-essential bursts among the middle-aged participants.

Table 1
Step velocity, step length, the duration of the three sub-phases, horizontal ground reaction force and CoP displacement during stepping for the young (Y) and middle-aged (M) groups.

Behavioral performance	Y	M	Effect size of group difference
Step velocity (cm/s)	135.7 (30.8)	119.9 (23.0)	0.6
Step length (cm)	33.5 (9.4)	31.6 (7.3)	0.2
Duration of the three sub-phases			
Step-initiation (ms)	503.7 (61.4)	459.5 (87.7)	0.6
Single-leg-support support (ms)	251.2 (53.0)	283.9 (130.8)	0.3
Landing (ms)	53.6 (29.3)	92.0 (94.0)	0.6
Horizontal ground reaction force (% of body weight)			
$F_{Y\_Max\ Backward}$	8.5 (1.7)	7.6 (5.5)	0.2
CoP variables			
CoP_{AP} (cm)	4.5 (1.7)	3.3 (1.6)	0.7
CoP_{ML} (cm)	7.4 (2.4)	7.6 (2.5)	0.1
Time to CoP_{AP} (ms)	386.3 (49.1)	351.6 (74.8)	0.5
Time to CoP_{ML} (ms)	430.8 (64.0)	394.0 (66.2)	0.6

Data are presented as mean (SD). $F_{Y\_Max\ Backward}$: the maximum backward horizontal ground reaction force after landing normalized by body weight. CoP_{AP}, CoP_{ML}: the maximum CoP displacement in the posterior and lateral (toward the swing leg) directions, respectively, between the light onset and complete foot-off events.

3.3. Quantitative analysis of muscle activation differences between the two age groups

The occurrence rate, onset latency, and burst duration of all muscle bursts that occurred during the course of stepping were compared between the two groups, and the results are presented below.

3.3.1. Occurrence rates

A significant group effect (Hottelling's $T^2 = 3.9$, $F(5, 12) = 9.3$, $P = 0.001$) was found in the occurrence rate of the 1st burst of the swing leg. Follow-up univariate tests showed that the middle-aged adults had a lower occurrence rate of $MGLU_{sw\_1}$ ($P < 0.05$, effect size = 1.2) and a higher occurrence rate of ES_{sw_1} ($P < 0.01$, effect size = 1.8) than that observed in the young adults (Table 3). No significant differences were noted for the other muscle activations.

3.3.2. Onset latency

No significant differences were observed between the groups in onset latency for any muscle activations.

3.3.3. Burst duration

A significant group effect (Hottelling's $T^2 = 5.1$, $F(6, 11) = 9.4$, $P = 0.001$) was detected in the burst duration of the 2nd burst of the swing leg. Follow-up univariate tests showed that the middle-aged group had a longer burst duration for GA_{sw_2} ($P < 0.01$, effect size = 1.4) and BF_{sw_2} than those observed in the young adults ($P < 0.001$, effect size = 2.9) (Table 3). No significant differences were observed for the other muscle activations.

3.3.4. Normalized co-contraction duration

The MANOVA procedures also showed a significant difference between the young and middle-aged adults for the normalized co-contraction duration of the stance leg in the single-leg-support phase (Hottelling's $T^2 = 0.826$, $F(2, 14) = 5.8$, $P < 0.05$). Subsequent univariate tests showed that the middle-aged group had a longer normalized co-contraction duration for RF_{st}/BF_{st} during single-leg-support phase ($P < 0.01$, effect size = 1.7) (Table 4).

4. Discussion

4.1. Sequence of essential muscle activation

During the step-initiation phase in the young adults, most but not all of our findings for muscle activation were similar to those reported previously. The present findings that were consistent with previous studies on gait initiation included the sequential TA_{st_1}, RF_{st_1}, and $MGLU_{st\_1}$ activation and the sequential TA_{sw_1},

Table 2
The occurrence rate, onset latency, and burst duration of muscle bursts on the stance leg side during stepping in the young (Y) and middle-aged (M) groups.

Muscle burst	Occurrence rate (%)		Onset latency (ms)		Burst duration (ms)	
	Y	M	Y	M	Y	M
ES_{st_1}	52.8 (28.9)	75.0 (35.6)	355.4 (84.9)	320.1 (139.5)	98.7 (35.0)	117.6 (40.9)
$MGLU_{st\_1}$	94.4 (16.7)	93.5 (16.6)	375.5 (57.7)	371.1 (91.9)	208.0 (35.6)	199.6 (63.2)
BF_{st_1}	53.7 (28.6)	90.7 (20.2)	383.9 (86.6)	316.5 (112.4)	148.4 (72.4)	286.9 (230.9)
RF_{st_1}	100.0 (0.0)	100.0 (0.0)	329.0 (77.5)	329.2 (161.0)	528.6 (152.5)	778.6 (293.0)
GA_{st_1}	58.3 (27.0)	77.8 (22.8)	608.5 (53.5)	511.6 (150.5)	116.1 (34.2)	245.5 (131.3)
TA_{st_1}	100.0 (0.0)	100.0 (0.0)	212.8 (28.5)	215.5 (48.7)	395.3 (80.7)	376.4 (65.6)
ES_{st_2}	71.3 (31.2)	93.5 (9.1)	735.4 (120.2)	673.9 (186.0)	208.9 (102.8)	288.3 (110.3)
$MGLU_{st\_2}$	68.5 (38.4)	79.6 (34.4)	652.3 (88.5)	624.4 (154.2)	212.7 (80.5)	239.8 (119.6)
BF_{st_2}	46.3 (34.4)	84.3 (25.8)	721.1 (135.9)	694.9 (169.2)	135.8 (59.8)	335.2 (151.6)
GA_{st_2}	64.8 (22.4)	75.9 (30.2)	934.8 (130.8)	1028.9 (222.4)	179.3 (55.0)	245.6 (140.4)
TA_{st_2}	71.3 (34.9)	97.2 (8.3)	724.2 (120.3)	704.9 (164.3)	248.6 (137.2)	359.6 (237.7)

Data are presented as mean (SD). ES, erector spinae; MGLU, gluteus medius; BF, biceps femoris; RF, rectus femoris; GA, medial gastocnemius; TA, tibialis anterior; $_{st\_1}$, 1st burst of the stance leg; $_{st\_2}$, 2nd burst of the stance leg.

Table 3
The occurrence rate, onset latency, and burst duration of muscle bursts on the swing leg side during stepping in the young (Y) and middle-aged (M) groups.

Muscle burst	Occurrence rate (%)		Onset latency (ms)		Burst duration (ms)	
	Y	M	Y	M	Y	M
ES_{sw_1}	25.0 (21.7)	68.5 (27.3)**	399.6 (128.1)	440.5 (137.8)	109.7 (46.8)	125.1 (82.6)
$MGLU_{sw\_1}$	99.1 (2.8)	75.9 (26.1)*	254.4 (73.7)	273.0 (106.0)	243.0 (102.3)	183.3 (73.1)
BF_{sw_1}	67.6 (31.6)	90.7 (14.1)	329.8 (54.9)	330.2 (120.6)	136.4 (46.3)	115.1 (26.8)
RF_{sw_1}	43.5 (35.5)	52.7 (28.9)	226.6 (46.0)	311.3 (209.6)	126.8 (51.1)	93.8 (39.7)
GA_{sw_1}	92.6 (16.9)	100.0 (0.0)	341.7 (80.0)	336.8 (125.7)	125.9 (18.0)	142.8 (33.2)
TA_{sw_1}	100.0 (0.0)	100.0 (0.0)	226.6 (40.0)	248.5 (89.6)	211.0 (128.1)	151.4 (53.1)
ES_{sw_2}	58.3 (35.1)	83.3 (26.4)	776.7 (167.8)	718.2 (188.9)	214.0 (111.0)	345.4 (177.7)
$MGLU_{sw\_2}$	98.1 (3.7)	86.1 (18.6)	683.5 (121.6)	601.3 (170.5)	216.2 (62.6)	264.6 (76.3)
BF_{sw_2}	82.4 (24.5)	99.1 (2.8)	645.2 (92.7)	634.9 (246.6)	148.9 (60.3)	475.5 (150.3)***
RF_{sw_2}	100.0 (0.0)	92.6 (16.9)	486.1 (63.4)	493.8 (162.3)	115.0 (37.5)	110.1 (18.0)
GA_{sw_2}	96.3 (11.1)	100.0 (0.0)	710.5 (118.0)	622.4 (167.6)	302.4 (87.7)	564.8 (247.4)**
TA_{sw_2}	100.0 (0.0)	100.0 (0.0)	488.6 (120.5)	463.2 (124.4)	121.2 (44.5)	136.7 (29.2)
RF_{sw_3}	55.6 (40.2)	75.9 (21.0)	666.8 (176.2)	630.9 (186.6)	157.5 (46.7)	189.3 (75.1)
TA_{sw_3}	57.4 (34.5)	75.0 (37.0)	575.0 (151.9)	560.7 (225.6)	172.5 (111.5)	290.0 (141.3)

Data are presented as mean (SD). ES, erector spinae; MGLU, gluteus medius; BF, biceps femoris; RF, rectus femoris; GA, medial gastocnemius; TA, tibialis anterior; $_{sw\_1}$, 1st burst of the swing leg; $_{sw\_2}$, 2nd burst of the swing leg, $_{sw\_3}$, 3rd burst of the swing leg.
* Significantly different from the young group ($P < 0.05$).
** Significantly different from the young group ($P < 0.001$).
*** Significantly different from the young group ($P < 0.01$).

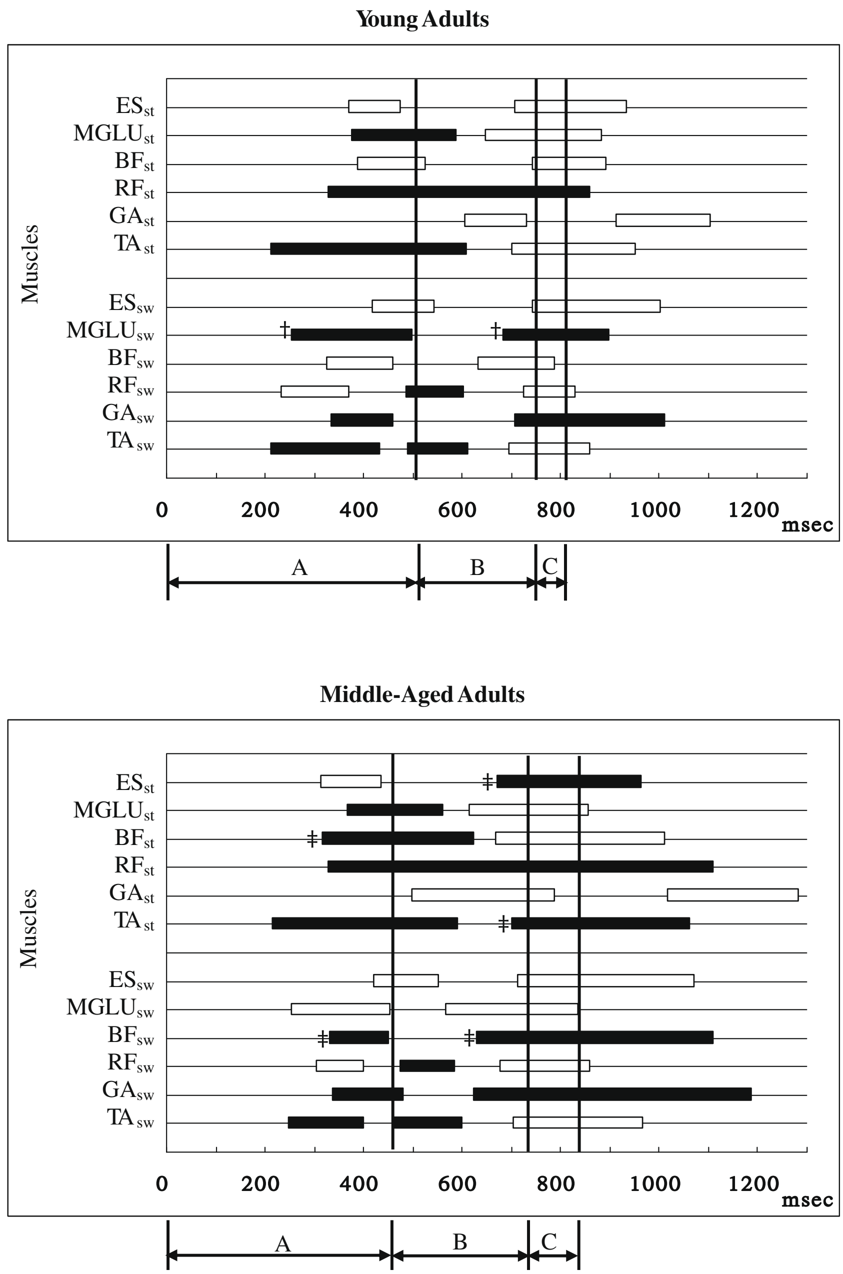

Fig. 1. Muscle activation patterns during stepping in young and middle-aged adults. $_{st}$: stance leg, $_{sw}$: swing leg. The three solid vertical lines indicate complete foot-off, initial foot-contact, and complete foot-contact, respectively. Time zero (0) is the time at which the stimulus light was activated. Phases A–C refer to the step-initiation, single-leg-support, and landing phases, respectively. The filled and empty horizontal bars indicate essential (occurrence rate ⩾90%) and non-essential (occurrence rate <90%) bursts, respectively. The length of the bar indicates the mean group burst duration. The start and end of each bar indicate the onset and offset of muscle activation, respectively. The single cross symbol (†) indicates that the burst was an essential burst in young adults, but not in middle-aged adults. The double cross symbol (‡) indicates that the burst was an essential burst in middle-aged adults, but not in young adults.

$MGLU_{sw\_1}$, and GA_{sw_1} activation. The 1st bilateral TA and $MGLU_{sw\_1}$ bursts were thought to move the CoP backward and laterally to the side of the swing leg, respectively (Fig. 2). Subsequent $MGLU_{st\_1}$ activation may then help shift the CoP laterally from the swing leg to the stance leg (Fig. 2) (Elble et al., 1994; Jian et al., 1993; Mann et al., 1979). The RF_{st_1} activation may help to stabilize the stance leg. In addition, the GA_{sw_1} activation may aid an individual during push-off from the swing leg.

The short $MGLU_{st\_1}$ burst (duration ~200 ms) and the prolonged RF_{st_1} burst (duration 500–800 ms) were unique to the stepping movement. A previous study investigating gait initiation reported a longer $MGLU_{st\_1}$ (about 350 ms) and shorter RF_{st_1} (about 200 ms) (Mann et al., 1979). We speculated that our observation of a short $MGLU_{st\_1}$ burst and a longer RF_{st_1} burst were task-specific. In this study, we asked our participants to step forward as quickly as possible. The participants may achieve this goal by rapid forward movement of the CoM, potentially at the expense of minimizing the lateral shift of the CoM toward the stance leg side. Thus, a long $MGLU_{st}$ burst is not desirable. In contrast, when healthy young adults performed a gait initiation task at a comfortable pace, they shifted the CoM forward and laterally towards the stance leg (Jian et al., 1993). A longer $MGLU_{st}$ burst may be used to achieve that purpose. Furthermore, since our participants did not completely lift off the stance leg and kept approximately 50% of

Table 4
The normalized TA/GA and RF/BF co-contraction duration during the step-initiation and single-leg-support phases in the stance and stepping legs of young (Y) and middle-aged (M) groups.

	Y	M
% of step-initiation phase		
TA_{st}/GA_{st}	0.8 (0.6)	6.2 (7.6)
RF_{st}/BF_{st}	5.6 (6.6)	17.0 (6.7)
TA_{sw}/GA_{sw}	14.3 (4.6)	14.6 (3.0)
RF_{sw}/BF_{sw}	4.0 (5.8)	4.6 (4.2)
% of single-leg-support phase		
TA_{st}/GA_{st}	10.9 (8.0)	29.4 (27.4)
RF_{st}/BF_{st}	12.1 (10.5)	47.0 (27.0)**
TA_{sw}/GA_{sw}	4.4 (7.7)	10.3 (10.3)
RF_{sw}/BF_{sw}	16.4 (16.9)	14.3 (13.6)

Data are presented as mean (SD).
** Significantly different from the young group ($P < 0.01$).

their total weight on the stance leg after landing, the sustained RF_{st} activation throughout the stepping course may have fulfilled this weight bearing function.

In the single-leg-support phase of stepping, in addition to the sustained RF_{st_1} burst, we also detected simultaneous the TA_{sw_2} and RF_{sw_2} bursts that began early and ended in the middle of the phase. As in gait initiation (Mann et al., 1979), the TA_{sw_2} burst may serve to lift off the foot of the swing leg. However, the RF_{sw_2} during this phase may be specific to the stepping task. We hypothesize that the RF_{sw_2} may help flex the hip in order to quickly lift the swing leg off the floor. Kinematic data will be required in future studies to test these hypotheses.

During step termination, none of the muscle activations observed in the stance leg were essential, with the exception of the RF_{st_1}. The prolonged RF_{st_1} may help stabilize the stance leg while the swing leg lands on the floor. The other major muscle activations that occurred during this phase were the sequential $MGLU_{sw\_2}$ and GA_{sw_2} activations. The GA_{sw_2} activation may also contribute to deceleration of the swing leg motion upon landing (Hase and Stein, 1998). Moreover, the $MGLU_{sw\_2}$ may help stabilize the hip and pelvis and move CoP back to the swing leg during landing (Fig. 2).

Overall, our results support previous reports in that the initiation and termination of stepping may share similar motor program to those used in the initiation and termination of gait, respectively (Brunt et al., 1999; Crenna and Frigo, 1991; Hase and Stein, 1998). However, neuromuscular control of the single-leg-support phase of the stepping movement appears to be different from that of gait (Gantchev et al., 1996) due to the differences in task nature.

4.2. Age-related changes in muscle activation characteristics, $F_{Y\_Max\ Backward}$, and CoP variables

In the present study, with the exception of the $MGLU_{sw\_1}$ and $MGLU_{sw\_2}$, most of the essential muscle activations in the young adults were also present in the middle-aged adults. However, the middle-aged adults showed additional essential muscle activations, such as bilateral 1st BF activations during the step-initiation phase as well as TA_{st_2}, BF_{sw_2}, and ES_{st_2} activations during the late single-leg-support and landing phases. The MGLU is the major muscle responsible for the CoP lateral shift during gait initiation (Elble et al., 1994; Jian et al., 1993; Mann et al., 1979). Decreased MGLU activation has been observed in older adults during gait initiation (Mickelborough et al., 2004). Our results revealed that the decrease recruitment of the MGLU activation also occurs in middle-aged adults during stepping movement. However, no group difference was found in CoP_{ML}. According to previous studies, the lateral CoP movement before toe-off is also associated with the

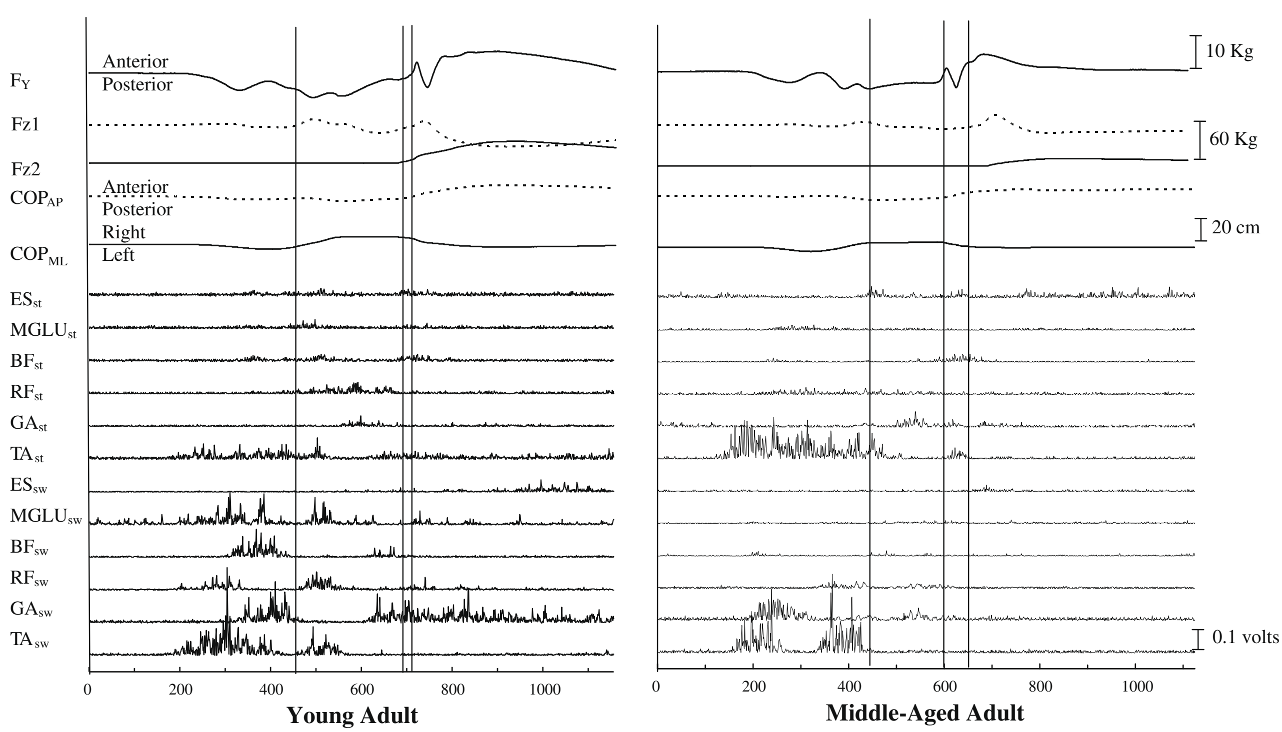

Fig. 2. Representative ground reaction force data from two force plates, CoP trajectories and muscle activation patterns of one young participant and one middle-aged participant during left leg forward stepping. Fz1 and Fz2 represent the vertical force of the initial standing and final landing force plates, respectively. F_Y represents the sum of the horizontal ground reaction force of two force plates. The CoP curve is characterized by a solid line that represents the CoP trajectory in the right–left direction and a dashed line that represents the CoP trajectory in the anterior–posterior direction. The three solid vertical lines indicate complete foot-off, initial foot-contact, and complete foot-contact, respectively. Time zero (0) is the time at which the stimulus light was activated.

activation of the peroneus of the swing leg (Mann et al., 1979) or that of the hip adductors of the stance leg (Kirker et al., 2000). Therefore, we speculated that the middle-aged adults may use muscles other than the $MGLU_{sw}$ to produce the lateral shift of CoP for step-initiation. More research is needed to investigate this issue.

We also found that the CoP_{AP} of the middle-aged adults tended to be smaller than that of young adults (effect size = 0.7), but this difference did not reach a significance level ($P = 0.15$). Since CoP_{AP} is known to be associated with activation of anterior leg muscle, primary the TA (Crenna and Frigo, 1991), we speculated that the smaller CoP_{AP} in the middle-aged adults may be correlated with an increase in their occurrence rate of the posterior muscles, such as the BF and ES, or a decrease in their magnitude of the TA activation. However, since we did not quantify the EMG activation magnitude, the second possibility would need further testing.

The additional BF_{st_1} and BF_{sw_1} activations may help to stabilize the stance leg and lift the swing leg during the step-initiation phase, respectively, for the middle-aged adults. Furthermore, although the ES_{sw_1} was not the essential muscle activation in step-initiation, we found that the middle-aged adults relied more upon the ES_{sw_1} activation (68.5% occurrence rate) than the young adults did (25.0% occurrence rate). This ES activation may indicate that middle-aged adults may require this ES activation to help stabilize the trunk during the step-initiation phase.

The additional BF_{sw_2} activation may help decelerate the swing motion of the stepping leg and control the knee joint during landing. Similarly, the additional TA_{st_2} and ES_{st_2} activations may help to stabilize the ankle of the stance leg, and the trunk, respectively, in the landing phase for the middle-aged adults.

The muscle activations that showed longer burst durations in the middle-aged adults were the GA_{sw_2} and BF_{sw_2} activations. These prolonged burst durations should not arise from age differences in duration of the three sub-phases of stepping because there were no group differences in any of the phase durations (Table 1). Thus, middle-aged adults may use the extended burst duration of these muscles in order to produce sufficient braking force and stabilize the legs after the landing phase.

Different from previous studies that reported longer TA_{st}/GA_{st} co-contraction in healthy older adults as compared to healthy young adults during gait initiation (Polcyn et al., 1998; Halliday et al., 1998), we found longer RF_{st}/BF_{st} co-contraction during the single-leg-support phase in the middle-aged adults as compared to the young adults, which was mainly due to the prolonged BF_{st} burst duration. Researchers have shown that the posterior muscle of the stance leg, such as hamstring, contributes significantly to the braking force of landing during gait termination (Crenna et al., 2001). However, our middle-aged adults had a smaller $F_{Y\_Max\ Backward}$ than the young adults, although the group difference did not reach the significance level (effect size = 0.2, $P = 0.67$). We hypothesized that our middle-aged adults may have greater difficulty with generating a sufficient braking force at landing even though they had attempted to produce a longer burst duration of the BF_{st} in the single-limb-support phase.

In the present study, no group differences were observed regarding onset latency for any investigated muscle. The onset latency of each muscle represents the time required for sensorimotor processing (Schmidt and Lee, 2005). Unlike older adults, who often show longer muscle onset latency than young adults, particularly during gait initiation (Henriksson and Hirschfeld, 2005), our middle-aged adults did not exhibit age-related degeneration of sensorimotor processing time.

Overall, the altered essential muscle activation patterns, longer muscle burst duration in the swing leg, and longer co-contraction of the muscles of the stance leg observed during stepping in the middle-aged adults suggest that they may use different motor programs to execute stepping movements as compared to the young adults. More biomechanical studies are needed to verify our speculation of the function of these altered muscle contraction and possible compensatory strategies in the middle-aged adults. Moreover, it is worth noting that although our healthy middle-aged adults were not characterized by a poorer score on the clinical balance measure, BBS, or a slower onset latency of muscle activations associated with volitional stepping compared to young adults, their muscle activation characteristics did show significant and clinically meaningful age-related variations, as revealed by the large effect sizes of the group differences in numerous muscle activation characteristics. These findings may suggest that decreases in balance ability in middle-aged adults may not be readily observable using conventional clinical balance scales due to their limited sensitivity in detecting subclinical changes in the neuromuscular control of middle-aged adults. An analytical approach to neuromuscular control, on the other hand, may help clinicians identify potential balance control-related problems earlier in middle-aged adults.

Furthermore, Henriksson and Hirschfeld (2005) recently reported that older adults with different physical activity levels presented different neuromuscular patterns of gait initiation. Although the amount of time spent in physical activities was comparable between our middle-aged adults and young adults, it remains to be determined as to whether or not the type of physical activities would affect the neuromuscular control patterns in middle-aged individuals.

4.3. Clinical implications

Rogers et al. (2003) and Melzer et al. (2008) demonstrated effectiveness in reducing step-initiation time and/or the single-support-time after repeated practice of a stepping task in older adults. In addition, Pavol et al. (2004b) found that older adults were able to develop better proactive and reactive postural adaptations after repeated exposure to unexpected slips. Although it remains to be determined as to which form of balance training, i.e., reactive or proactive form, would lead to better results for fall prevention and whether one form of balance training would show transfer effects to the other form of balance ability, we propose that both volitional and reactive step training may be started as early as middle age in order to improve the neuromuscular control associated with such tasks.

5. Conclusions

This study demonstrates that the essential muscle activation patterns associated with stepping movement differed slightly from those associated with gait initiation and termination. Healthy middle-aged adults showed significant and meaningful variations in muscle activation patterns and characteristics during different phases of stepping as compared to young adults. Age-related changes in the neuromuscular control of fast volitional stepping are already present in healthy middle-aged adults.

Conflict of interest

None of the authors have any financial and personal relationships with other people or organizations that could inappropriately influence the work.

Role of the funding source

The role of the National Health and Research Institutes and the China Medical University was simply the funding supporters. The

supporters did not have any involvement in the study design, in the collection, analysis and interpretation of data, and in the writing of the manuscript, and in the decision to submit the manuscript for publication.

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References

Berg, K.O., Wood-Dauphinee, S.L., Williams, J.I., Maki, B., 1992. Measuring balance in the elderly: validation of an instrument. Can. J. Public Health 83, S7–S11.
Brunt, D., Liu, S.M., Trimble, M., Bauer, J., Short, M., 1999. Principles underlying the organization of movement initiation from quiet stance. Gait Posture 10, 121–128.
Cho, B.L., Scarpace, D., Alexander, N.B., 2004. Tests of stepping as indicators of mobility, balance, and fall risk in balance-impaired older adults. J. Am. Geriatr. Soc. 52, 1168–1173.
Cohen, J., 1988. Statistical Power Analysis for the Behavioral Sciences, second ed. Lawrence Erlbaum, Hillsdale.
Crenna, P., Frigo, C., 1991. A motor programme for the initiation of forward-orientated movements in humans. J. Physiol. 437, 635–653.
Crenna, P., Cuong, D.M., Breniere, Y., 2001. Motor programmes for the termination of gait in humans: organization and velocity-dependent adaptation. J. Physiol. 537, 1059–1072.
Dite, W., Temple, V.A., 2002. A clinical test of stepping and change of direction to identify multiple falling older adults. Arch. Phys. Med. Rehabil. 83, 1566–1571.
Elble, R.J., Moody, C., Leffler, K., Sinha, R., 1994. The initiation of normal walking. Mov. Disord. 9, 139–146.
Gantchev, N., Viallet, F., Aurenty, R., Massion, J., 1996. Impairment of posturo-kinetic co-ordination during initiation of forward oriented stepping movement in parkinsonian patients. Electromyogr. Clin. Neurophysiol. 101, 110–120.
Halliday, S.E., Winter, D.A., Frank, J.S., Patla, A.E., Prince, F., 1998. The initiation of gait in young, elderly, and Parkinson's disease subjects. Gait Posture 8, 8–14.
Hase, K., Stein, R.B., 1998. Analysis of rapid stopping during human walking. J. Neurophysiol. 80, 255–261.
Henriksson, M., Hirschfeld, H., 2005. Physically active older adults display alterations in gait initiation. Gait Posture 21, 289–296.
Ito, T., Azuma, T., Yamashita, N., 2003. Anticipatory control in the initiation of a single step under biomechanical constraints in humans. Neurosci. Lett. 352, 207–210.
Jian, Y., Winter, D.A., Ishac, M.G., Gilchrist, L., 1993. Trajectory of the body COG and COP during initiation and termination of gait. Gait Posture 1, 9–22.
Kirker, S.G.B., Simpson, D.S., Jenner, J.R., Wing, A.M., 2000. Stepping before standing: hip muscle function in stepping and standing balance after stroke. J. Neurol. Neurosurg. Psychiat. 68, 458–464.
Li, W., Keegan, T.H., Sternfeld, B., Sidney, S., Quesenberry, C.P.Jr., Kelsey, J.L., 2006. Outdoor falls among middle-aged and older adults: a neglected public health problem. Am. J. Public Health 96, 1192–1200.
Lord, S.R., Fitzpatrick, R.C., 2001. Choice stepping reaction time: a composite measure of falls risk in older people. J. Gerontol. A: Biol. Sci. Med. Sci. 56, M627–M632.
Luchies, C.W., Wallace, D., Pazdur, R., Young, S., De Young, A.J., 1999. Effects of age on balance assessment using voluntary and involuntary step tasks. J. Gerontol. A: Biol. Sci. Med. Sci. 54A, M140–M144.
Lyon, I.N., Day, B.L., 1997. Control of frontal plane body motion in human stepping. Exp. Brain. Res. 115, 345–356.
Maki, B.E., Edmondstone, M.A., McIlroy, W.E., 2000. Age-related differences in laterally directed compensatory stepping behavior. J. Gerontol. A: Biol. Sci. Med. Sci. 55A, M270–M277.
Mann, R.A., Hagy, J.L., White, V., Liddell, D., 1979. The gait initiation. J. Bone Joint: Surg. 61, 232–239.
Medell, J.L., Alexander, N.B., 2000. A clinical measure of maxinal and rapid stepping in older women. J. Gerontol. A: Biol. Sci. Med. Sci. 55A, M429–M433.
Melzer, I., Marx, R., Kurz, I., 2008. Regular exercise in the elderly is effective to preserve the speed of voluntary stepping under single-task condition but not under dual-task condition. A case-control study. Gerontology 55, 49–57.
Mickelborough, J., van der Linden, M.L., Tallis, R.C., Ennos, A.R., 2004. Muscle activity during gait initiation in normal elderly people. Gait Posture 19, 50–57.
Pai, Y.C., Maki, B.E., Iqbal, K., McIlroy, W.E., Perry, S.D., 2000. Thresholds for step initiation induced by support-surface translation: a dynamic center-of-mass model provides much better prediction than a static model. J. Biomech. 33, 387–392.
Patel, K.V., Coppin, A.K., Manini, T.M., Lauretani, F., Bandinelli, S., Ferrucci, L., Guralnik, J.M., 2006. Midlife physical activity and mobility in older age: the InCHIANTI study. Am. J. Prev. Med. 31, 217–224.
Patla, A.E., Frank, J.S., Winter, D.A., Rietdyk, S., Prentice, S., Prasad, S., 1993. Age-related changes in balance control system: initiation of stepping. Clin. Biomech. 8, 179–184.
Pavol, M.J., Runtz, E.F., Pai, Y.C., 2004a. Diminished stepping responses lead to a fall following a novel slip induced during a sit-to-stand. Gait Posture 20, 154–162.
Pavol, M.J., Runtz, E.F., Pai, Y.C., 2004b. Young and older adults exhibit proactive and reactive adaptations to repeated slip exposure. J. Gerontol. A: Biol. Sci. Med. Sci. 59, 494–502.
Polcyn, A.F., Lipsitz, L.A., Kerrigan, D.C., Collins, J.J., 1998. Age-related changes in the initiation of gait: degradation of central mechanisms for momentum generation. Arch. Phys. Med. Rehabil. 79, 1582–1589.
Portney, L.G., Watkins, M.P., 2009. Foundations of Clinical Research: Applications to Practice, third ed. Prentice-Hall, Inc., Upper Saddle River.
Rogers, M.W., Mille, M.L., 2003. Lateral stability and falls in older people. Exerc. Sports Sci. Rev. 31, 182–187.
Rogers, M.W., Johnson, M.E., Martinez, K.M., Mille, M.L., Hedman, L.D., 2003. Step training improves the speed of voluntary step initiation in aging. J. Gerontol. A: Biol. Sci. Med. Sci. 58, 46–51.
Schmidt, R.A., Lee, T.D., 2005. Motor Control and Learning: A Behavioral Emphasis, fourth ed. Human Kinetics, Champaign.
Schulz, B.W., Ashton-Miller, J.A., Alexander, N.B., 2007. A kinematic analysis of the rapid step test in balance-impaired and unimpaired older women. Gait Posture 25, 515–522.
Schutz, R.W., Gessaroli, M.E., 1987. The analysis of repeated measures designs involving multiple dependent variables. Res. Quart. Exerc. Sport 58, 132–149.
Talbot, L.A., Musiol, R.J., Witham, E.K., Metter, E.J., 2005. Falls in young, middle-aged and older community dwelling adults: perceived cause, environmental factors and injury. BMC Public Health 5, 86.
Thelen, D.G., Wojcik, L.A., Schultz, A.B., Ashton-Miller, J.A., Alexander, N.B., 1997. Age differences in using a rapid step to regain balance during a forward fall. J. Gerontol. A: Biol. Sci. Med. Sci. 52A, M8–M13.
Thelen, D.G., Muriuki, M., James, J., Schultz, AB., Ashton-Miller, J.A., Alexander, N.B., 2000. Muscle activities used by young and old adults when stepping to regain balance during a forward fall. J. Electromyogr. Kinesiol. 10, 93–101.
Tirosh, O., Sparrow, W.A., 2004. Gait termination in young and older adults: effects of stopping stimulus probability and stimulus delay. Gait Posture 19, 243–251.
Wang, Y., Zatsiorsky, V.M., Latash, M.L., 2006. Muscle synergies involved in preparation to a step made under the self-paced and reaction time instructions. Clin. Neurophysiol. 117, 41–56.
Wojcik, L.A., Thelen, D.G., Schultz, A.B., Ashton-Miller, J.A., Alexander, N.B., 1999. Age and gender differences in single-step recovery from a forward fall. J. Gerontol. A: Biol. Sci. Med. Sci. 54, M44–M50.