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Control of support limb muscles in recovery after tripping in young and older subjects

Received: 17 February 2004 / Accepted: 11 May 2004 / Published online: 21 August 2004
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Abstract Older people fall more often after tripping than young people due to a slower development of mechanical responses. This might be due to age-related changes in muscle properties, but also to changes in motor control. The purpose of the present study was to determine whether (a) timing and sequencing of muscle activation and (b) the magnitude and rate of development of muscle activation in recovery after a trip differs between young and older subjects. We focused on the support limb, as it contributes to recovery after tripping by counteracting the forward angular momentum. Ten young (25 years) and seven older (68 years) men and women walked over a platform and were tripped several times at different points in the gait cycle. Kinematics and EMG of the support limb muscles were measured. After tripping, rapid EMG responses (60–80 ms) were observed in hamstring and triceps surae muscles in both young and older subjects. A slightly increased delay (11 ms) was found only in the soleus muscle of the older subjects. The muscle activity patterns (timing and sequencing) were similar in young and older subjects, but the magnitude and rate of development of muscle activity were significantly lower in older subjects. Especially the lower rate of development of muscle activation in the support limb of older subjects is likely to reduce the rate of force generation, which can contribute to inadequate recovery responses and falls.

Keywords Aging · EMG · Stumble · Balance recovery

Introduction

Tripping over an obstacle is a balance threat that results in a fall when recovery reactions are inadequate. Indeed, tripping is found to be one of the main causes for falls and fall-related injuries, especially in the elderly population (Nevitt et al. 1991; Berg et al. 1997). Investigation of the recovery responses after tripping over an obstacle might help to identify causes of falls, particularly in elderly people with a high risk of falling.

In a previous study (Pijnappels et al. 2004c), it was shown that older subjects (in particular fallers) were less successful in their recovery than young subjects. This was attributed to a slower generation of joint moments and a lower peak ankle moment in the support limb of the older subjects. Similarly, elderly subjects were shown to be less able to recover after a sudden release from a leaning angle due to a slower development of mechanical responses (Thelen et al. 1997). A loss of muscle fibers, predominantly of type II fibers, with ageing has been demonstrated (Porter et al. 1995; Tideiksaar 1997; Kirkendall and Garrett 1998) and tendon compliance was shown to increase (Reeves et al. 2003). These changes in muscle properties would cause muscles to become slower and less strong and thus might underlie the observed age effect on the recovery from tripping. However, changes in motor control might also contribute.

Two strategies for recovery after tripping have been described, the occurrence of which depends on the time of trip initiation in the swing phase (Eng et al. 1994). An elevating strategy is observed after a perturbation in early swing and consists of an elevation of the obstructed (ipsilateral) swing limb to overtake the obstacle. A lowering strategy is seen during late swing and consists of an immediate placement of the obstructed foot on the ground, followed by a step of the contralateral limb to overtake the obstacle. The strategies are defined on the basis of the obstructed swing limb, but a strategy-dependency was found in the support limb as well (Dietz et al. 1986). Thus, dependent on the context, appropriate muscle responses need to be selected for

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recovery after a trip. It is conceivable that age-related changes in functioning of the basal ganglia negatively affect such response selection (Bloem et al. 1995; Dimitrova et al. 2004). Furthermore, studies on spinal reflexes associated with voluntary movements revealed that the delay in these reflexes increased with age (Burke and Kamen 1996; Leonard et al. 1997). Changes in latencies and sequencing of responses to postural perturbations with age that were described in literature (Woollacott et al. 1986; Stelmach et al. 1989) may be the result of these age effects on the functioning of the nervous system.

In addition, the level of muscle activation may differ between young and old subjects within the same strategy. Motor neuron excitability appears reduced in the elderly, as evidenced by lower H-reflex amplitudes as compared to young adults (Scaglioni et al. 2002). Pavol et al. (2001) ascribed falls after tripping in a group of elderly subjects to a slower execution of the recovery strategy. In slipping, older subjects show the same phase-dependent strategies and onset latencies as young subjects, but lower levels of muscle activation during the response (Tang and Woollacott 1999).

The purpose of the present study was to determine whether control of the support limb muscles after tripping differs between young and older subjects. We questioned whether (a) timing and sequencing of muscle activation and (b) the magnitude and rate of development of muscle activation in recovery after a trip is changed with age. It was hypothesized that in older adults, muscle response time would be delayed, activation sequence would be altered, and magnitude and rate of development of muscle activation would be decreased. For this investigation, we had young and older subjects walk over a platform, and tripped them several times over an obstacle at different points of the gait cycle to elicit elevating as well as lowering strategies. Muscle activation patterns of the support limb muscles were measured, and onsets, amplitudes, and rise times (time from response onset to response peak) were compared between the young and older subjects.

Materials and methods

Subjects

Participants in this study were ten young subjects (five female, 25.2±4.2 years) and seven older subjects (five female, 68.3±3.0 years). All subjects were fit and healthy and screened for having no orthopedic, neuromuscular, cardiac, or visual problems. Subjects were informed about the research procedures before they gave consent in accordance with the ethical standards of the Declaration of Helsinki. Protocol and data collection were described previously (Pijnappels et al. 2004b)

Experimental setup and protocol

Subjects were instructed to walk at a self-selected speed over a 12×2.5-m platform and instructed by feedback to maintain this walking velocity. In the platform, 21 aluminum obstacles (15 cm height) were hidden over a total distance of 1.5 m. During several walking trials one of these obstacles appeared from the ground unexpectedly to catch the subject's swing limb. The obstacles appeared about 100 ms before impact, which minimized an effect of sound and sight of the appearing obstacle. Young subjects were tripped in about 15 out of 60 walking trials. Older subjects were tripped in about 7 out of 40 walking trials, as the experiment was more strenuous for these subjects. At the start of each trial, subjects did not know whether or where an obstacle would appear. Online kinematic data of toe markers were used to calculate the subject's step length and velocity. Based on these variables, the computer calculated when and where relative to the stance limb an obstacle had to appear to initiate a trip in a specific phase of the stride cycle (i.e., early or late swing). A full-body safety harness, attached to a ceiling-mounted rail, prevented subjects from falling. The safety ropes provided enough slack for free motion, and a spring in series with the ropes ensured smooth catching in case of an imminent fall. A trial was classified as a fall when the vertical force in the ropes, measured by a force transducer (AMTI M3-1000), exceeded 200 N.

Data collection and analysis

Gait kinematics were recorded using four arrays of three cameras (Optotrak, Northern Digital). Motions of 12 infrared light-emitting markers, bilaterally placed on joints, were tracked at a sample frequency of 100 Hz. Furthermore, electromyograms (EMGs) were recorded from the main muscles of the support limb: biceps femoris (BF), m. semitendinosus (ST), m. rectus femoris (RF), m. vastus lateralis (VL), m. tibialis anterior (TA), m. gastrocnemius medialis (GM), and m. soleus (SO). Bipolar Ag/AgCl (Medicotest A/S) surface electrodes were attached after cleaning and gentle abrasion of the skin. Electrodes were placed over the mid-muscle belly, in line with the direction of the fibers. The center-to-center electrode distance was 2.5 cm. The EMG signals were amplified 20 times (Porti-17; Twente Medical Systems), high-pass filtered (5 Hz), and stored on disk at a sample frequency of 1,000 Hz with a 22-bit resolution. Next, the signals were whitened (fifth-order) (Clancy et al. 2002) to reduce the influence of tissue filtering and movement artifacts, Hilbert transformed, rectified, and finally low-pass filtered (fifth-order Savitzky-Golay filter). This filtering method preserves sudden activity onset without producing a phase-lag.

For each young subject, 10 trials of normal walking and 10–15 left-leg tripping trials were selected from all trials with complete kinematic, dynamic, and EMG data. For the older subjects, who had fewer trials with complete data

available, 5 walking trials and 3–7 tripping trials could be selected. The recovery attempts of the tripping trials were classified and grouped as elevating or lowering strategies, based on kinematics of elevation or immediate placement of the obstructed swing limb, respectively. Heel strike, toe-off, and obstacle-foot contact were detected, based on kinematic data (Pijnappels et al. 2004a).

For analysis of the EMG patterns, the time series of filtered and rectified EMGs (in millivolts) of the undisturbed walking trials of each subject were averaged and subtracted from the EMG time series of the individual tripping trials. For comparison of muscle activity (timing and sequencing) among subjects and strategies, the resulting data of the responses of each muscle were normalized with respect to the maximum EMG activity during the walking trials. Onsets of the muscle responses were determined on the resulting signals by means of a dynamic process model in combination with statistically optimal change detection, described by Staude and Wolf (1999). This method searches for changes in the EMG sequence by use of the likelihood ratios over small time windows, over the first 200 ms after trip initiation. The rise times of the muscle responses were calculated as the time from onset of the response to 90% of the response peak. Furthermore, for a period of 300 ms following trip

initiation, the mean amplitudes of the responses were determined over windows of 20 ms.

For statistical analysis of differences in EMG responses between young and older subjects, within-subjects averaged (across trials) parameters were tested in a multivariate analysis of variance (MANOVA) for repeated measures. For each muscle, differences in onset, rise times, and amplitudes were tested and comparisons were made between both age groups. Differences in response amplitudes were tested over time windows for significance between strategies using *post hoc* paired *t*-tests. The level of significance was set at $P=0.05$.

Results

All subjects walked at a constant velocity between walking and tripping trials. Walking velocity was not significantly different between young and older subjects [1.59 (SD 0.23) and 1.41 (SD 0.22) m/s, respectively], nor were EMG amplitudes significantly different between age groups across different muscles. None of the young subjects fell during the experiments, but all of the older subjects fell in one or two tripping trials. Figure 1 presents the typical time series of the EMG responses of the

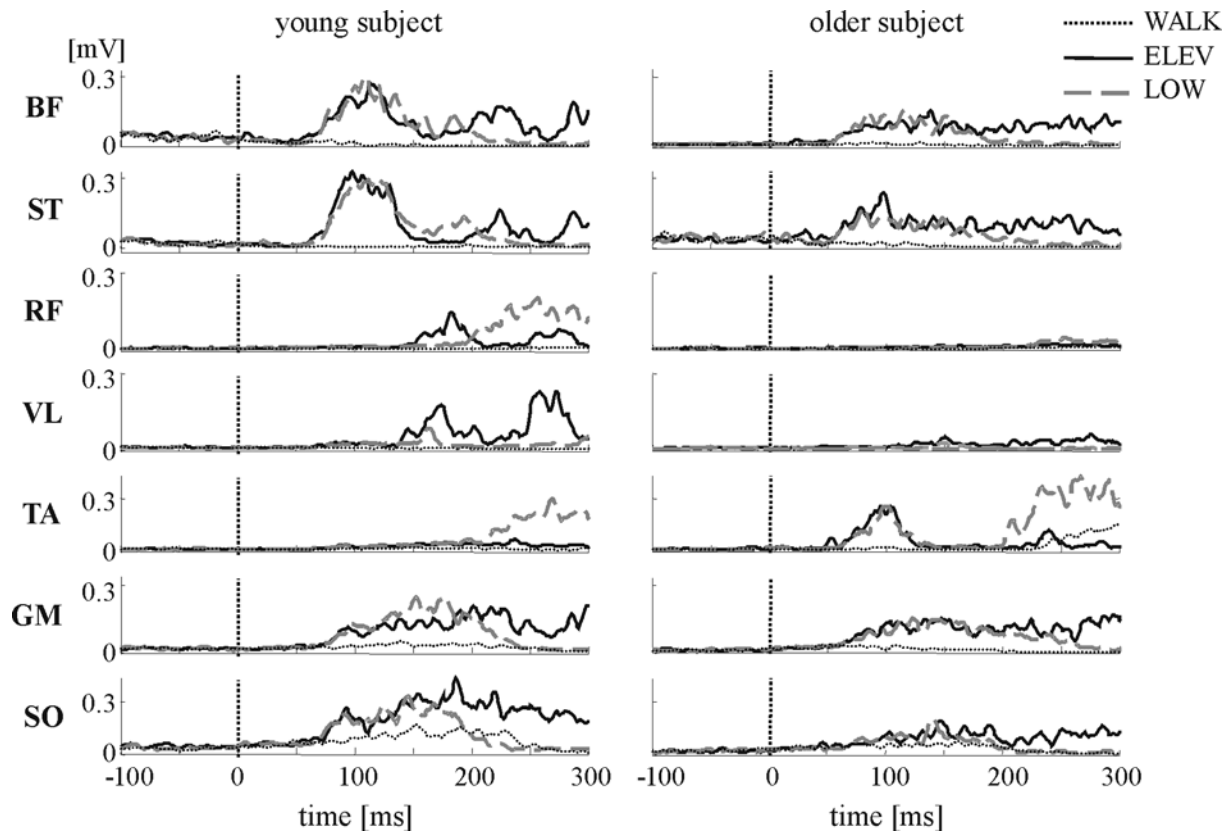


Fig. 1 Averaged support limb muscle activity of a young subject and an older subject for normal walking (dotted black line), for elevating strategies (solid black lines), and for lowering (dashed gray lines) strategies. Muscles are biceps femoris (BF), semitendinosus (ST), rectus femoris (RF), vastus lateralis (VL), tibialis anterior (TA), gastrocnemius medialis (GM), and soleus (SO). Although the

older subject presented here shows clear responses in the TA muscle, generally the TA responses were very small. Time series are part of the stance phase and synchronized to the averaged time of trip initiation in the stance phase. The dotted lines at $t=0$ ms indicate trip initiation (early stance in the elevating strategy and late stance in the lowering strategy)

support limb muscles for a young and older subject for walking and for both the elevating and lowering strategies. A clear difference in responses between the two strategies becomes apparent after about 200 ms, both in the young subjects and in the older subjects.

Timing and sequencing of muscle activation

Figure 2A shows a bar graph of the response latencies for both strategies for the young as well as for the older subjects. In both age groups, rapid responses (after about 60–80 ms) were seen in the hamstrings (BF and ST) and triceps surae muscles (GM and SO), followed by responses (after about 90–130 ms) in the quadriceps muscles (RF and VL). The responses in the TA were generally very small. Between-subjects testing revealed that a significantly increased muscle latency (11 ms) occurred only in the SO muscle of the older subjects compared to the SO latencies of young subjects. Onset times of the responses in the support limb muscles were independent of strategy and there was no significant interaction between strategy and age.

With similar onsets of the muscle activities between young and older adults, the sequencing of muscle activation appeared to be unaltered with age. Figure 3 depicts the mean EMG amplitudes over time of selected support limb muscles. Graphs of ST and SO were similar to those of BF and GM, respectively, and are, therefore, not represented. A significant interaction between strategies and time was found, indicating that indeed support

limb responses are strategy dependent. The average time of divergence of amplitudes, as revealed by *post hoc t*-tests (Fig. 3), was not different between age groups: 203 (SD 41) ms in young subjects and 209 (SD 47) ms in older subjects. In the elevating strategy, the hamstrings and triceps surae muscles stayed activated, leading to a prolongation of the push-off while the obstructed swing limb was placed forward, and the VL muscle was activated which resulted in knee extension. In the lowering strategy, the hamstrings and triceps surae muscles were deactivated and the RF muscle was activated, resulting in knee extension. Furthermore, a late TA activity was seen in the lowering strategy.

Magnitude and rate of development of muscle activation

A significant interaction effect of strategy and age on EMG amplitudes was found. No interaction effect of strategy, time, and age was found, indicating that the difference between strategies in amplitudes over time was the same for young and older subjects. From Fig. 3 it can be deduced that the difference in strategies between young and older subjects was primarily due to a difference in the (relative) magnitude of the EMG amplitudes in most time intervals. This, in turn, appeared to be due to a slower increase in activity in the older subjects. The rise times of the EMG amplitudes were significantly longer for older subjects in the BF, GM, and SO muscles (Fig. 2B). Note a trend toward an increased rise time in the other muscles, except for the small and variable responses in TA. Rise times of the responses in the support limb muscles were independent of strategy and there was no significant interaction between strategy and age.

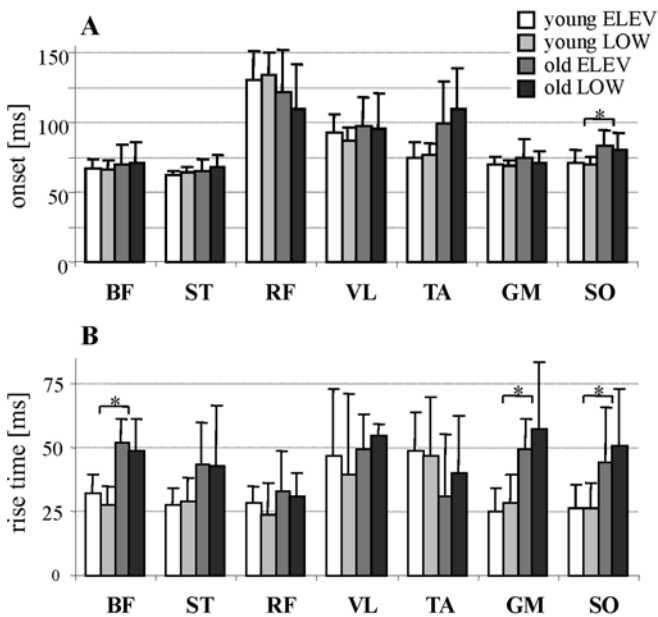
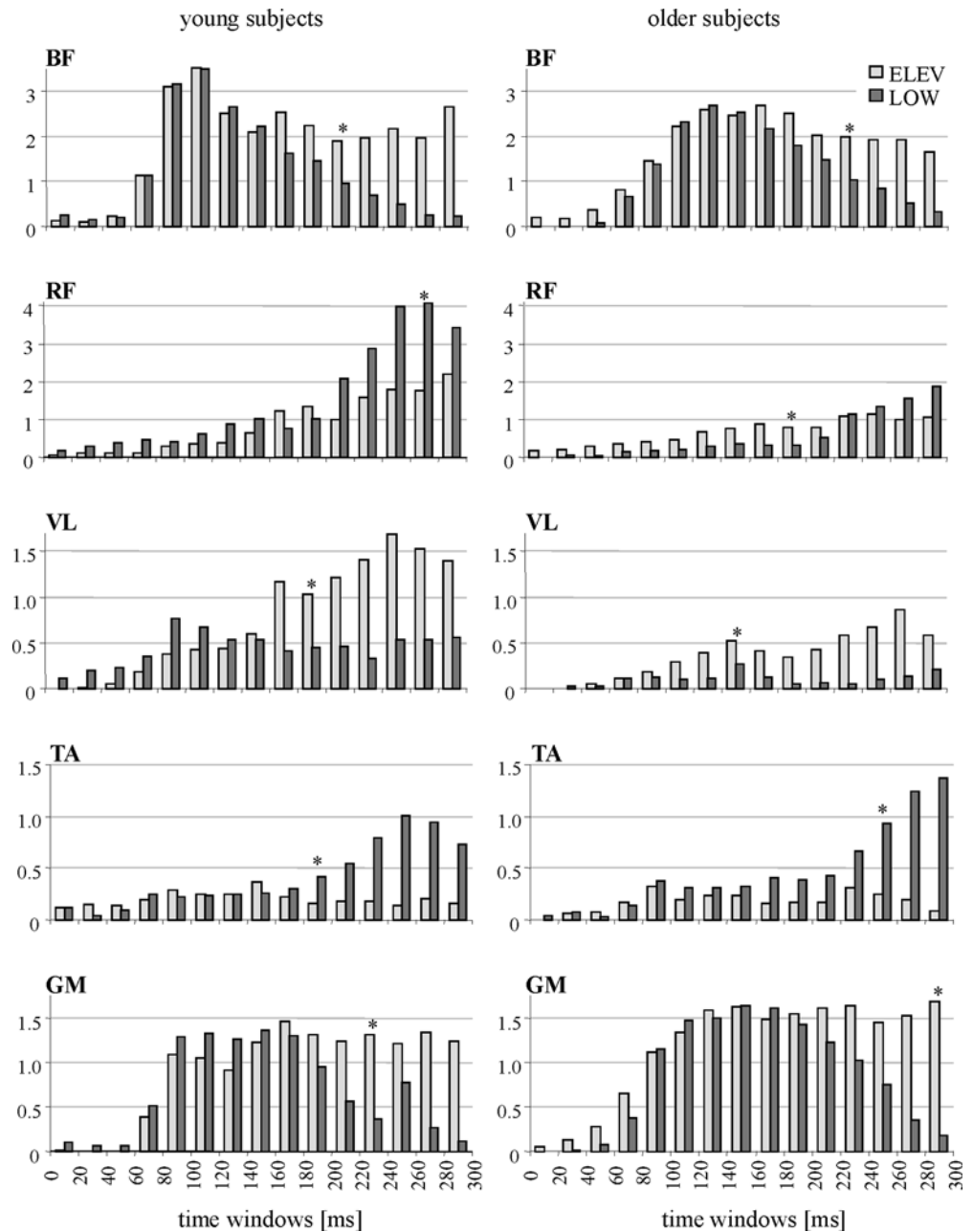


Fig. 2 A Onsets of EMG activity (with SD) in the support limb muscles after trip initiation for both strategies (elevating and lowering) and age groups (young and older subjects). B Rise times (with SD) of the EMG activity (from onset till 90% of the response peak). Muscle names are as in Fig. 1. Statistically significant differences ($P < 0.05$) were only found between age groups (no interactions with strategy) and are indicated with an asterisk

Discussion

The purpose of the present study was to determine whether (a) timing and sequencing of muscle activation or (b) the magnitude and rate of development of muscle activation in recovery after a trip differs between young and older subjects. Both aspects of the control of the responses after a trip could be affected in older subjects, resulting in inadequate recovery after tripping. The rate at which the recovery limb is activated was addressed by other authors (Eng et al. 1994; Schillings et al. 2000). One should bear in mind, however, that the support limb contributes to accelerating the recovery limb relative to the upper body. The support limb provides time and clearance for proper positioning of the recovery limb (Pijnappels et al. 2004a). Furthermore, we focused on the support limb, as this limb contributes to recovery after tripping by counteracting the forward angular momentum during push-off (Pijnappels et al. 2004a). Young subjects achieved an adequate push-off in the support limb by fast and large moment generation through rapid responses in the hamstring and triceps surae muscles (Pijnappels et al. 2004b). Older subjects (in

Fig. 3 Mean amplitudes in muscle activity within 20-ms windows for a total period of 300 ms following trip initiation for the support limb muscles. Muscle names are as in Fig. 1. Note that the magnitude (after subtraction of normal walking activity and normalization for the maximum activity during normal walking) of the responses is larger in BF and RF than in VL, TA, and GM. Time windows where amplitudes start (and continue) to differ significantly between strategies are indicated by an *asterisk*



particular fallers) were less successful in their recovery, mainly because they had lower rates of moment generation in the support limb joints than young subjects (Pijnappels et al. 2004c). Given that the moments generated during tripping are high in the support limb, we focused on the large lower limb muscles. In the recovery reactions of older subjects, multiple steps were observed, as reported in other studies (Luchies et al. 1994; McIlroy and Maki 1996). Multiple steps in the elderly are likely to be an effect of a less effective response early on; an initial (inadequate) recovery step requires further reduction of the remaining angular momentum, for which multiple steps are inevitable.

During the experiments, subjects were tripped repeatedly at specific times of the gait cycle to elicit elevating as

well as lowering strategies. The number of trips was somewhat higher in the young than in the older subjects because the experiment was more strenuous for the older subjects. Due to repeated tripping, anticipatory changes in walking pattern might have occurred. It has been established earlier that the normal gait kinematics are only minimally affected by anticipation in young subjects (Pijnappels et al. 2001). In addition, although some anticipatory increase in muscle activity could occur in young and older subjects, this effect was only minimal when compared to the magnitude of tripping responses (Pijnappels et al. conditionally accepted). This indicates that our setup allows for ecologically valid experimentation on tripping reactions.

It should be noted that the number of subjects was small and that both males and females participated in this study. Despite the small groups of both sexes, results were significant. Gender differences in balance responses have been reported in older adults (Wojcik et al. 1999) and, in our previous study, we also found older women more likely to fall than older men (Pijnappels et al. 2004c). There is reason to believe that these gender differences are due to differences in muscle strength (Schultz 1995; Lord et al. 2001), rather than to differences in muscle activity.

Timing and sequencing of muscle activation

We found rapid EMG responses after tripping in both age groups, which were qualitatively (in terms of timing and sequencing) similar between young and older subjects. The responses in the support limb muscles of the older subjects were not delayed compared to the young subjects, except for a slightly increased latency in the SO muscle. The patterns of muscle activity became different between strategies at 200 ms after trip initiation in both groups. It can be concluded that the healthy older subjects in our study had no difficulty with rapidly selecting the same responses as young subjects.

The most pronounced early muscle responses were observed in the BF, ST, and GM muscles. These responses (with latencies of 60–80 ms) are non-specific but highly functional as they provide the hip and ankle extension moments and knee flexion moment required for successful recovery (Pijnappels et al. 2004b). The latencies of these responses suggest that they are oligo-synaptic and highly automated, which may account for the relative robustness of their organization to the effects of ageing.

It was found that most elevating strategies were performed after a trip initiated in early swing, whereas most lowering strategies were performed when the trip was initiated in late swing, according to the literature (Eng et al. 1994; Schillings et al. 2000). Still, in young as well as in older subjects, around mid-swing either of these strategies could be elicited. After tripping on a treadmill the transition between strategies was more distinct (Schillings et al. 2000), which might be explained by lower variation of stride length and duration in treadmill walking (Dingwell et al. 2001). However, the occurrence of both strategies in the same part of the gait cycle overground suggests that strategy selection is not heavily constrained, i.e., either one could be adequate. Moreover, the initial responses, which presumably are automated, provide a certain amount of time for the selection of strategy-specific responses (Schillings et al. 2000). Consequently, this strategy selection process may not differentiate the young subjects from the healthy and fit older subjects studied here. It is, however, conceivable that in a more frail population strategy selection is negatively affected by changes in functioning of the basal ganglia (Bloem et al. 1995; Dimitrova et al. 2004).

Magnitude and rate of development of muscle activation

Initial, non-specific muscle activity increased more slowly and reached lower normalized amplitudes in the older subjects than in the young subjects. It should be noted that the amplitudes of the EMG signals were normalized with respect to the maximum EMG activity during normal walking. In spite of the lower (but not statistically significant lower) walking velocity in the older subjects, the group averaged absolute EMG amplitudes were not different between young and older subjects. Hence, we felt that it was safe to compare normalized EMG amplitudes between the groups. The rate of development of EMG activity (rise time) is independent of the normalization procedure, and is clearly lower in older subjects than in young subjects (Figs. 2B, 3). The non-specific activity (during the first 200 ms following trip initiation, as found in this study) in the hamstring and triceps surae muscles in the support limb helps to restrain the angular momentum of the body, while providing extension for push-off (Pijnappels et al. 2004b). Both are beneficial to recovery regardless of strategy. Among the older subjects several falls occurred, which are likely due to a limitation in this recovery mechanism, as older fallers showed a slower generation of joint moments and a lower peak ankle moment in the support limb than older non-fallers (Pijnappels et al. 2004c). Probably this is partly due to a deterioration in muscle contraction mechanisms with age (Thelen et al. 1996), which can be the consequence of a range of factors such as loss of type II muscle fibers (Porter et al. 1995; Tideiksaar 1997; Kirkendall and Garrett 1998) or tendon compliance (Reeves et al. 2003). The present data, however, indicate that age-related reductions in the (rate of) muscle activation might contribute to the reduced (rate of) moment generation. It is conceivable that the increased rise time in older adults reflects that the elderly subjects increased muscle activation up to a higher level to compensate for a decreased muscle capacity. If so, the required moment would be reached too late. Moreover, peak normalized and absolute EMG amplitudes are in fact lower in the older adults, strongly suggesting that the muscle activation is reduced and that this contributes to the lack of moment generation. The relative contribution of a decline in muscle activation with age compared to changes in muscle/tendon properties on the (rate of) force generation would require further research, for example by means of model studies.

The strategy-specific responses (after 200 ms following trip initiation, as found in this study) can yield lengthening or shortening of the push-off. In the elevating strategy, a prolonged push-off, brought about by continued hamstrings and triceps surae activity, can help to further restrain the angular momentum; moreover, it can help to accelerate the pelvis upward and forward to gain time and clearance to swing the obstructed limb forward as far as possible (Pijnappels et al. 2004a). In the lowering strategy, a forward acceleration is not beneficial, as this would hamper immediate placement of the obstructed foot. A

shorter push-off with less acceleration is required, which moreover allows making a quick step forward with the support limb for further recovery. Similarly, Dietz et al. (1986) found perturbation dependent prolongations of the stance phase, if the perturbation occurred in early swing. If applied in late swing, the length of the stance phase was independent of the perturbation duration. In our experiments, we also found augmentation of the knee extension in the elevating strategy (Pijnappels et al. 2004a).

Practical implications

The present study showed that especially the rate of increase of muscle activation during recovery reactions after tripping is reduced in older subjects. This will reduce the rate of force generation in recovery after tripping, which in turn could lead to falls. It has been described that strength training can increase muscle strength in older adults (Seguin and Nelson 2003; Reeves et al. 2004). Importantly, these training effects are ascribed in part to neural adaptation (Grabiner and Enoka 1995; Porter et al. 1995; Enoka 1997; Hakkinen et al. 1998). However, Porter et al. (1995) question the generalization of such neural training effects across tasks. In addition, Scaglioni et al. (2002) found increased voluntary activation of the plantar flexors in elderly after strength training but no increase in motor neuron excitability as evidenced by H-reflex amplitudes. It is therefore questionable whether the control of responses can be trained. Positive effects of strength training interventions (Day et al. 2002; Robertson et al. 2002) could be due to effects on muscle properties, which may compensate for a loss in excitability.

Concluding remarks

In the control of muscle responses after tripping, the timing and sequencing of muscle responses seems to be robust to the effects of aging, whereas the magnitude and rate of development of muscle activation declines with age. These findings are in line with conclusions of other perturbation experiments which found that not response delay, but rather differences in levels of muscle activation caused an age-related decline of balance recovery (Tang and Woollacott 1999; Thelen et al. 2000). In particular, in our study the rate of development of muscle activation was found to be lower in the support limb of older subjects. This can contribute to the reduction of the rate of force generation in recovery responses of older adults, providing better insight into why older people fall more frequently after a trip.

Acknowledgements The authors would like to thank Richard Casius for developing the data acquisition software, Leon Schutte for helping with the experiments, and Max Feltham for analyzing the EMG data.

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