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The Effects of Cognitive Load and Optical Flow on Antagonist Leg Muscle Coactivation during Walking for Young and Older Adults

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Abstract

The purpose of this study was to compare how healthy aging interacts with environments that challenge cognitive load and optical flow to affect antagonist leg muscle coactivation during walking. We measured leg muscle activity in sixteen older adults (70.4 ± 4.2 years) and twelve young adults (23.6 ± 3.9 years) walking on a treadmill at their preferred speed while watching a speed-matched virtual hallway. Cognitive load was challenged using a dual-task to interfere with available attentional resources. Optical flow was challenged using perturbations designed to create a perception of lateral imbalance. We found antagonist coactivation increased with aging, independent of condition. We also found that, compared to unperturbed walking, only in the presence of optical flow perturbations did the older adults increase their antagonist coactivation. Antagonist coactivation in the young adults was not affected by ei t her condition. Our findings provide evidence that antagonist leg muscle coactivation in healthy older adults is more sensitive to walking environments that challenge optical flow than environments that challenge cognitive load. As increased antagonist coactivation may indicate compromised balance, these findings may be relevant in the design of living environments to reduce falls risk.

Keywords

Aging; Gait; EMG; Muscle Coactivation; Visual Feedback; Dual Task

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Conflicts of Interest: None to disclose.

Introduction

Aging brings a progressive decline of balance and mobility. As age advances, it is important that older adults walk efficiently and safely to maintain their independence and reduce their risk of falling, a major cause of injury and death among older adults (Stevens et al., 2006). Studies with older adults have identified many intrinsic risk factors contributing to falls that emerge through the natural process of aging (Ambrose et al., 2013; Rubenstein, 2006), including changes in gait, muscle strength and quality, cognition, and vision. Accordingly, the risk of falling can increase when walking in environments that challenge those effects of aging (Lord et al., 2006; Talbot et al., 2005). However, the relative contributions of the various environmental factors that interact with aging to increase falls risk are comp lex and poorly understood. As a result, fall reduction interventions that modify living areas to reduce environmental hazards typically only identify hazards closely related to physical causes of falling (e.g. slippery floors, uneven surfaces, unlit surfaces) (Shroyer, 1994). Insight into how other environmental factors interact with aging to decrease walking balance in older adults may enhance the effectiveness of these interventions (Feldman and Chaudhury, 2008).

Older adults may reveal the relative priority they place on environmental factors to falls risk through subtle reactions in their control of balance when walking. One potential indicator of compromised balance when walking is the increased coactivation of agonist and antagonist leg muscles. By simultaneously activating groups of muscles with opposing joint actions, both young and older adults can increase stiffness in their leg joints, which may mitigate the effect of unexpected balance disturbances when walking (Hallal et al., 2013a; Stokes et al., 2017). Antagonist coactivation increases with age, and it is thought that older adults naturally adopt this feedforward strategy to enhance their balance and compensate for the effects of aging (Hortobágyi et al., 2009; Nagai et al., 2011; Peterson and Martin, 2010; Schmitz et al., 2009). While some walking environments cause similar increases in antagonist coactivation for both young and older adults (e.g. walking up and down hills) (Franz and Kram, 2013), there may be environments that influence the reliance on antagonist coactivation more for older adults than young adults (e.g. climbing stairs) (Larsen et al., 2008). Thus, disproportionate changes in antagonist coactivation when walking may reflect important interactions between age and specific environmental factors that place older adults at a higher risk for falls.

Two environmental factors that can influence walking balance in older adults are cognitive load and optical flow. For example, introducing a cognitive task during walking, such as counting backwards by sevens, can interfere with the cognitive resources needed for locomotion and subsequently increase gait variability (Al-Yahya et al., 2011; Beurskens and Bock, 2012). This particular cognitive dual-task has become quite popular due to its ability to discriminate between older fallers and non-fallers (Springer et al., 2006). Perturbations to optical flow create a visual sensation of motion and this also has a large impact on gait variability in older adults—possibly more so than the cognitive dual-task (Francis et al., 2015). For example, mediolateral perturbations of optical flow can manipulate visual feedback to create the perception of lateral imbalance, thus increasing trunk sway and disrupting lateral step placement (Francis et al., 2015; Franz et al., 2017, 2015). Although environments that increase cognitive load or alter optical flow challenge the maintenance of balance very differently, increased antagonist coactivation may be a common strategy that older adults use to counteract these disturbances, as there is growing evidence that antagonist coactivation is elevated when walking in these environments (Hallal et al., 2013b; Lo et al., 2017; Stokes et al., 2017). However, the relative influence of these walking environments to interact with aging and increase antagonist coactivation is not well understood. Investigating how antagonist coactivation is used by older adults in these environments may provide insight into which environmental factor is a more prominent contributor to increased falls risk.

The purpose of this study was to compare how healthy aging interacts with environments that challenge cognitive load and optical flow to affect lower limb antagonist coactivation during walking. As such, we collected electromyographic (EMG) signals for healthy young and older adults walking on a treadmill in a virtual reality environment while performing a cognitive dual-task, walking with mediolateral optical flow perturbations, and walking unperturbed. We first hypothesized that antagonist coactivation during walking would increase with aging independent of condition. We also hypothesized that the between-group differences we would observe during unperturbed walking would increase when performing a cognitive dual-task and when walking with optical flow perturbations, with optical flow perturbations eliciting a greater increase than the cognitive dual-task.

Methods

Participants

Sixteen healthy older adults (mean ± standard deviation; age: 70.4 ± 4.2 yrs, height: 1.65 ± 0.05 m, mass: 68.2 ± 11.6 kg, 15 female) and twelve healthy young adults (age: 23.6 ± 3.9 yrs, height: 1.69 ± 0.25 m, mass: 70.7 ± 11.3 kg, 7 female) participated in the study. All participants walked without the aid of an assistive device, were free of orthopedic injuries in the prior six months, had no neurological injury or pathology, and met the American College of Sports Medicine cardiovascular guidelines for exercise. Subjects were excluded if they had experienced an unanticipated fall in the previous six months, or scored outside the normal range on the Dynamic Gait Index (DGI) (Herman et al., 2009), an eight-task battery (score: 0–24) that scores an individual’s ability to walk normally, navigate obstacles, and turn. DGI scores ≤19 have been associated with fall risk in older adults (Shumway-Cook et al., 1997). The older adults in this study scored an average of 22.9 ± 2.5 on the DGI, and the young adults all scored the maximum 24. All subjects were assessed for cognitive decline with the Trail Making Test Part B (TMT-B), which measures the time taken to draw lines sequentially on a sheet of paper connecting 25 labeled targets in an ascending order that alternates between numbers and letters (Kortte et al., 2002). The TMT-B is highly sensitive to the presence of cognitive impairment, and subjects were excluded from the study if their time to completion was >1 S.D. above the mean time required for their age, based on normative data (Tombaugh, 2004). The experimental protocol was approved by the University of Wisconsin–Madison Health Sciences Institutional Review Board, and all subjects provided written informed consent before participating in the study.

Experimental Protocol

We determined each subject's preferred overground walking speed by instructing subjects to walk two times down a 10-m walkway at a normal, comfortable pace. Speed was calculated from the average time to cross the middle 6 m of the walkway (young: 1.36 ± 0.12 m/s, older: 1.25 ± 0.13 m/s, $p = 0.025$). Subjects then completed all experimental conditions while walking at their preferred overground speed on a split-belt instrumented treadmill (Bertec, Columbus, OH). A speed-matched virtual reality hallway was rear-projected onto a semi-circular screen surrounding the front of the treadmill (height = 2.7 m, radius = 1.0 m), as described in previous publications (Francis et al., 2015; Franz et al., 2015). For all conditions, subjects were simply instructed to look forward as if walking down an actual hallway. All older adults wore a safety harness that could prevent a full fall, but it was adjusted to neither constrain nor assist their movement on the treadmill. Four older adults were uncomfortable walking at their preferred overground speed. For these subjects, we slowed the treadmill speed by 10% to enable completion of the study protocol (i.e. older adults mean treadmill speed became 1.22 ± 0.12 m/s). Anticipating this possibility, we also examined the effect of walking speed by inviting the young subjects to repeat all test conditions at 80% of their preferred walking speed.

Subjects walked while viewing the virtual hallway during three experimental conditions, presented in fully randomized order and each lasting three minutes. In the first condition, subjects walked unperturbed (i.e. the control condition). In the second condition, subjects performed a cognitive dual-task: walking while verbally counting backwards by sevens from a random three-digit number. We chose this cognitive dual-task because it does not include a confounding visual or auditory component and there is evidence it disrupts balance in older adults (Jamet et al., 2004; LaRoche et al., 2014). In the third condition, subjects walked in the presence of optical flow perturbations, which create a visual perception of lateral imbalance (Thompson and Franz, 2017). Here, the foreground of the virtual hallway swayed mediolaterally as the sum of two sinusoids (0.135 and 0.442 Hz, with amplitudes of 0.175 m) while the projected end of the hallway remained stationary (i.e. challenging balance but not the direction of travel). Mediolateral optical flow perturbations at these frequencies are difficult for subjects to anticipate and have shown to increase gait variability, particularly in older adults (Francis et al., 2015; Franz et al., 2015). Before collecting data, we provided time for each subject to familiarize themselves with each walking condition.

Measurement and Data Analysis

We recorded surface electromyography (EMG) bilaterally from the medial hamstrings (MH), vastus lateralis (VL), medial gastrocnemius (MG), soleus (SL), and tibialis anterior (TA) muscles using a Trigno™ Wireless EMG system (Delsys Inc., Boston, MA) sampling at 2 kHz. After shaving the skin and cleansing with isopropyl alcohol, we placed electrodes (Trigno single differential, 10 mm inter-electrode distance) over the muscle bellies in line with fiber orientation, following SENIAM recommendations (Hermens et al., 2000). We also recorded the 3D positions of markers placed on the sacrum and both heels using an eight-camera motion capture system at 100 Hz (Motion Analysis, Santa Rosa, CA). We th en processed all data using a custom MATLAB script (MathWorks Inc., Natick, MA). First, we low-pass filtered marker trajectories (8 Hz, 4th order Butterworth filter) and identified heel strikes from peaks in the fore-aft heel positions relative to the sacral marker (Zeni et al., 2008). Second, we band-pass filtered (10–350 Hz) and full-wave rectified the EMG data before low-pass filtering (10 Hz) to obtain linear envelopes of muscle activation. We divided the EMG data into strides and normalized by time (1000 points per stride) and amplitude (root-mean-square values during unperturbed walking). We then ensemble averaged these normalized EMG data across consecutive steps (300+ steps/trial), providing muscle activation profiles across the gait cycle. Finally, these ensemble activation profiles were averaged bilaterally across right and left legs.

We calculated coactivation across the gait cycle for three agonist-antagonist muscle pairs: MH/VL, MG/TA, and SL/TA. The coactivation indices (CI) were calculated as (Schmitt and Rudolph, 2008):

$$CI_{i=1}^{1000} = \frac{lowEMG_i}{highEMG_i} \times \left(highEMG_i + lowEMG_i\right)$$

where $lowEMG_i$ is the ensemble EMG signal of the less active muscle, and $highEMG_i$ is the EMG signal of the more active muscle at each instant of the gait cycle.

Statistical Analysis

A mixed two-way factorial ANOVA tested for main effects of and interactions between age groups (young, older) and across all walking conditions (unperturbed, cognitive dual-task, optical flow perturbations) on mean stride antagonist coactivation index in the MH/VL, MG/TA, and SL/TA muscle pairs. Shapiro-Wilk and Levene's tests confirmed assumptions of normality and homogeneity of variance, and we used a Greenhouse-Geisser correction if the assumption of sphericity was violated. When we found age × condition interactions, we tested for simple effects of condition on each age group, and simple effects of age at each condition, all using one-way ANOVAs with post-hoc f-tests. Within significant simple effects, we also investigated when the effects occurred during the gait cycle and which muscles contributed to the effects by evaluating the mean coactivation index and mean EMG activity for phases of the gait cycle (Perry et al., 1992): loading response (0–10%), mid-stance (10–30%), terminal stance (30–50%), pre-swing (50–60%), initial swing (60–73%), mid-swing (73–87%) and terminal swing (87–100%).

An independent samples t-test compared preferred treadmill speed between age groups, both with and without normalization to leg length (Hof, 1996). To determine if group differences in stride antagonist coactivation could be explained by differences in walking speed, a two-way repeated measures ANOVA tested for main effects of walking condition and speed (80%, 100% preferred) in the young subjects.

We performed all the statistical analyses using SPSS (version 24, SAS Institute), and defined significance when $p < 0.05$.

Results

The two-way mixed ANOVA revealed significant interactions and main effects between age and walking condition on mean stride antagonist coactivation index (Table 1). The older adults generally walked with significantly greater antagonist coactivation than the young adults (Fig. 1), and antagonist coactivation significantly increased only for older adults walking with optical flow perturbations.

Simple Effects of Condition

The walking conditions impacted young and older adults differently. Compared to unperturbed walking, neither the cognitive dual-task nor optical flow perturbation conditions significantly affected mean stride antagonist coactivation in young adults for any muscle pair. The cognitive dual-task also did not significantly affect mean antagonist coactivation in older adults. However, optical flow perturbations significantly increased mean stride antagonist coactivation in older adults (MH/VL: +27%, $p = 0.006$; MG/TA: +29%, $p = 0.001$; SL/TA: +31%, $p < 0.001$). Further, these significant increases in coactivation appeared during every phase of the gait cycle for the MG/TA and SL/TA muscle pairs, and during mid-stance and terminal swing for the MH/VL pair (Fig. 2). This coincided with significant increases in the activation of all leg muscles throughout the gait cycle (Fig. 3).

Simple Effects of Age

Older adults had significantly greater mean stride antagonist coactivation than young adults during every condition (Fig. 1). This coincided with significantly greater activation over the stride for MH and VL muscles than young adults (e.g. during unperturbed walking, MH: +13%, $p = 0.011$; VL: +13%, $p = 0.002$). During mid-stance for every condition, older adults exhibited significantly greater MG/TA and SL/TA coactivation than young adults (+60% and +76% on average, p's < 0.008), driven by greater TA activation (+71% on average, p's < 0.010). Similarly, during mid-swing for every condition, the older adults had significantly greater MG/TA coactivation than young adults (+106% on average, p's < 0.025), driven by greater MG activation (+93% on average, p's < 0.017).

Effect of Speed

Although the older adults walked on the treadmill 10% slower (1.22 ± 0.12 m/s) than the young adults (1.36 ± 0.12 m/s), normalized preferred walking speed on the treadmill did not differ significantly between the young (0.48 ± 0.05) and older (0.45 ± 0.04) subjects. Further, when comparing the young adults walking at their preferred speed to 80% preferred speed (1.07 m/s or 0.38 ± 0.03), we observed no significant main effects of speed or condition on mean stride antagonist coactivation for any muscle pair.

Discussion

In this study, we provide evidence that lower limb antagonist coactivation in healthy older adults is more sensitive to walking environments that challenge optical flow than environments that challenge cognitive load. We measured antagonist coactivation in healthy young and older adults walking unperturbed, walking while performing a cognitive dual-task, and walking with optical flow perturbations. As we first hypothesized, antagonist coactivation during walking increased with age, independent of condition. We also hypothesized that the between-group differences we would observe during unperturbed walking would increase when performing a cognitive dual-task and when walking with optical flow perturbations. In partial support of this second hypothesis, between-group differences in antagonist coactivation significantly increased only when walking with optical flow perturbations. This supports our last hypothesis that optical flow perturbations would elicit larger between-group differences than the cognitive dual task. As increased antagonist coactivation may indicate compromised balance, these findings may be particularly relevant when designing environments and interventions to reduce falls risk in older adults.

Our finding that antagonist coactivation during walking increased with aging is consistent with previous studies (Franz and Kram, 2013; Mian et al., 2006; Oliveira et al., 2017; Schmitz et al., 2009). This supports the common interpretation that older adults instinctively adopt a coactivation strategy when walking to increase leg joint stiffness and potentially mitigate the effects of balance disturbances (Hortobágyi and DeVita, 2006). As Peterson and Martin (2010) observed, the age differences in antagonist coactivation were driven by significantly greater activation of upper leg muscles (i.e. MH, VL) over the stride. We also observed significant age differences in antagonist coactivation of muscles spanning at the ankle joint. For example, MG/TA and SL/TA coactivation for the older adults was significantly higher than young adults during mid-stance, and this likely reflects actively increased ankle joint stiffness to maintain balance as the body progresses forward over the tibia. In addition, we interpret the significantly greater MG/TA coactivation we observed in the older adults during mid-swing as increased joint stiffness to stabilize the ankle in preparation for limb loading.

We were surprised to find that between group differences in antagonist coactivation were unaffected by the cognitive dual-task. Walking while performing a second task is common (e.g. talking on the phone) and generally does not constitute a risk for falling, provided walking is mostly automatic and requires little cognitive resources. However, with advanced age, walking requires greater cognitive effort and a larger allocation of attentional resources (Al-Yahya et al., 2011; Szturm et al., 2013). Consequently, many studies have shown that the addition of a second task can interfere with the attentional resources available to older adults and thereby disrupt walking performance (Beurskens and Bock, 2012). We had anticipated that in response to a disruptive dual-task we would observe older adults to increase antagonist coactivation to mitigate this balance threat. We used backwards counting as our additional task, as there is some evidence that such a task may affect antagonist coactivation in older adults (Lo et al., 2017). However, we saw no significant age-related increases in antagonist coactivation from unperturbed walking during the cognitive dual-task condition. One interpretation of our finding is that the older adults utilized all their available attentional resources during the dual-task and thus did not have the capacity to actively increase their antagonist coactivation when their balance was challenged. We find this highly unlikely, as this would be accompanied by noticeable differences in gait kinematics, which we did not observe during our previous study with older adults under this task (Francis et al., 2015). The most likely interpretation of our finding is that the overall attentional demands did not exceed processing capacities to cause interference with gait and therefore the older adults did not increase their antagonist coactivation in response. If there was indeed a change in antagonist coactivation during this cognitive dual-task, it was too small to be detected with our methods. Of course, we cannot exclude the possibility that we may have seen more prominent interactions between cognitive load and aging had we selected a more complex dual task (Boisgontier et al., 2013).

We found between-group differences in antagonist coactivation to disproportionately increase when walking with optical flow perturbations. These perturbations elicit a visual perception of lateral imbalance, which challenges the integration of sensory information when walking to potentially disrupt motor planning and correction (Thompson and Franz, 2017). Prior studies have shown that older adults are particularly susceptible to these perturbations, presumably driven by an age-related dependence on visual feedback during motor tasks (Franz et al., 2015). Indeed, compared to young adults walking with these perturbations, older adults exhibit increased step width variability (Francis et al., 2015), larger joint kinematic variability (Qiao et al., 2018), and increased mediolateral sway (Franz et al., 2015). In response to the optical flow perturbations in this study, older adults significantly increased their mean stride antagonist coactivation for every muscle pair recorded, while the young adults exhibited no significant changes from unperturbed walking. Taken together, this likely indicates that in the presence of optical flow perturbations, older adults have a greater reliance than young adults on antagonist coactivation strategies to maintain their balance. Further, antagonist coactivation at the ankle joint (i.e. MG/TA, SL/TA pairs) significantly increased in the older adults for every phase of the gait cycle, with the greatest changes seen during mid-stance. This finding is consistent with previous studies using optical flow perturbations, showing that changes in antagonist coactivation occur primarily at the ankle joint during early stance (Stokes et al., 2017). However, we also observed that older adults significantly increased MH/VL coactivation during mid-stance and terminal swing in response to these perturbations, which may reflect an additional need for increased knee joint stiffness.

In support of our last hypothesis, the optical flow perturbations elicited greater between-group differences in antagonist coactivation than the cognitive dual-task. We interpret this finding to suggest that antagonist coactivation in healthy older adults is more sensitive to walking environments that challeng e optical flow than environments that challenge cognitive load. To our knowledge, direct comparisons of these environmental factors on antagonist coactivation for young and older adults walking have not been done before. We acknowledge that we used only one type of optical flow perturbation and cognitive dual-task, and our findings may be specific to comparisons between only these specific optical flow perturbations and backwards counting tasks. For example, the effect of aging during optical flow perturbations may depend on the perturbation amplitude (Stokes et al., 2017). Additionally, we recognize that subjects had the ability to prioritize walking over the arithmetic task, whereas the perturbations to optical flow could not be ignored. Indeed, this may contribute to why antagonist coactivation in older adults significantly increased with optical flow perturbations but did not significantly increase during the cognitive dual-task. However, this distinction does not explain why antagonist coactivation in the young adults was unaffected by both conditions. We also acknowledge that the effects of visual and cognitive demands on antagonist coactivation may be more complex (Jamet et al., 2004;

Krishnan et al., 2017), and are often presented concurrently in a variety of common walking tasks (e.g. following a map, looking at a phone). However, our findings do provide evidence that age-related differences in antagonist coactivation are affected differently by these two environments. This also suggests that environments that challenge optical flow might contribute to other age-related differences associated with increased antagonist coactivation, such as increased metabolic cost (Hortobágyi et al., 2011).

If increased antagonist coactivation functions as a feedforward protective mechanism to mitigate balance disturbances, increased antagonist coactivation may indicate when older adults perceive a greater risk of falling (Hallal et al., 2013a; Nagai et al., 2012b). Thus, our findings suggest that healthy older adults perceive a greater risk of falling when optical flow is challenged than when cognitive load is challenged. This is aligned with previous reports that visual impairment brings a relatively higher risk of falls than cognitive impairment (Rubenstein and Josephson, 2006). As balance confidence is predictive of falls risk (Lajoie and Gallagher, 2004; Shumway-Cook et al., 1997), this comparison might be helpful to the design of living environments to reduce falls risk (Lord et al., 2006).

Our between-group differences in absolute preferred walking speed do not appear to explain the observed differences in antagonist coactivation. First, we observed no differences in normalized preferred walking speed between the age groups. Second, we saw no main effect of speed or condition on antagonist coactivation when the young adults walked slower than preferred. Thus, the age × condition interactions we observed here most likely reflect fundamental age-related differences in walking balance control independent of those in walking speed. This contributes to the growing debate regarding how antagonist coactivation is affected by gait speed (Arias et al., 2012; Hortobágyi et al., 2009; Oliveira et al., 2017). However, as reduced gait speed is a common response to challenging walking environments (Al-Yahya et al., 2011), future studies should investigate the potential interaction of age and gait speed on antagonist coactivation in challenging walking environments.

Our measures of antagonist coactivation do not appear to be influenced by changes in gait parameters during the different conditions. In a prior paper we analyzed gait kinematics for this study (Francis et al., 2015), and we found no significant between-group differences in step width and step length. We did find a short but significant reduction in step length during optical flow perturbations for only the older adults. However, this reduction was relatively modest (6%), and does not fully explain the changes in antagonist coactivation for this condition. Nevertheless, we recognize that some of the underlying kinematic differences across conditions could contribute to the observed differences in muscle activity.

This study has several important limitations to consider when interpreting our results. First, our primary measure of antagonist coactivation was the mean coactivation index across an ensemble averaged stride. We were thus limited to examining persistent changes in overall antagonist coactivation that appeared throughout many strides, and this may not account for important step-by-step differences, as well as smaller phase-dependent differences. Second, antagonist coactivation can also increase in response to learning a new skill or when uncertainty exists (Busse et al., 2005). Consequently, antagonist coactivation in an environment could decrease with training or familiarity (Nagai et al., 2012a). We cannot exclude the possibility that the young subjects learned how to walk in these treadmill environments faster than the older adults, or that all subjects were inherently more familiar with the cognitive dual-task than the optical flow perturbations. However, we did allow time for subjects to familiarize themselves with each walking condition before recording data, and we have no reason to suspect a confounding effect of learning or familiarity. Regardless, our results still highlight important age-related neuromuscular differences in response to these walking environments that might be relevant to walking balance control.

In conclusion, our results provide evidence that lower limb antagonist coactivation in healthy older adults is more sensitive to walking environments that challenge optical flow than environments that challenge cognitive load. As older adults may rely more on antagonist coactivation than young adults to stiffen their leg joints to mitigate balance disturbances, these disproportionate increases in antagonist coactivation likely reflect environments where older adults perceive their balance is more compromised, and thus perceive an increased risk of falls. These findings may be relevant to the design of environments and interventions to reduce falls risk in older adults.

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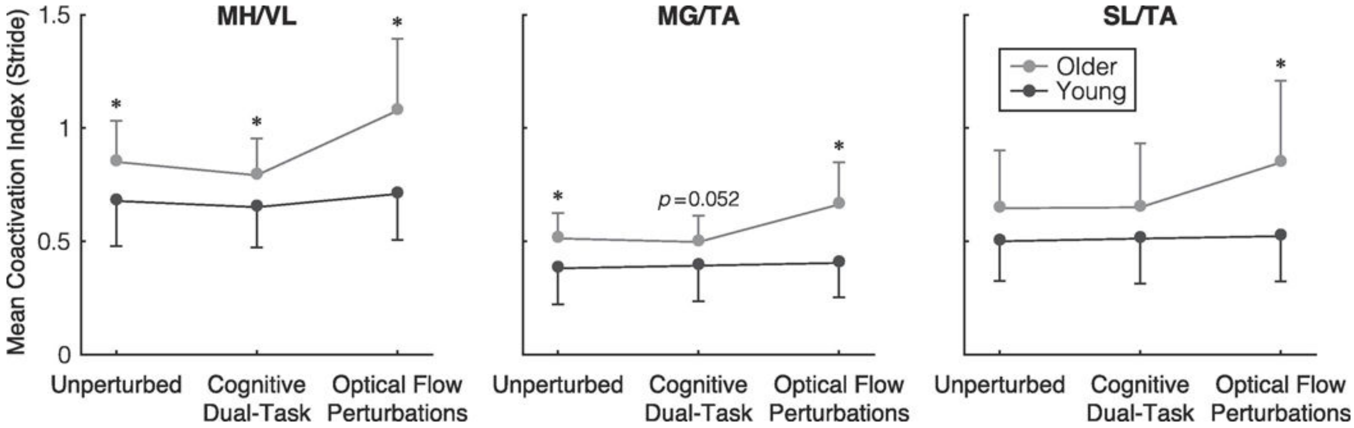

Figure 1.

Group mean coactivation index over the stride (mean ± s.d.) for young and older adults during the three walking conditions. Asterisks indicate significant age effects in post-hoc tests.

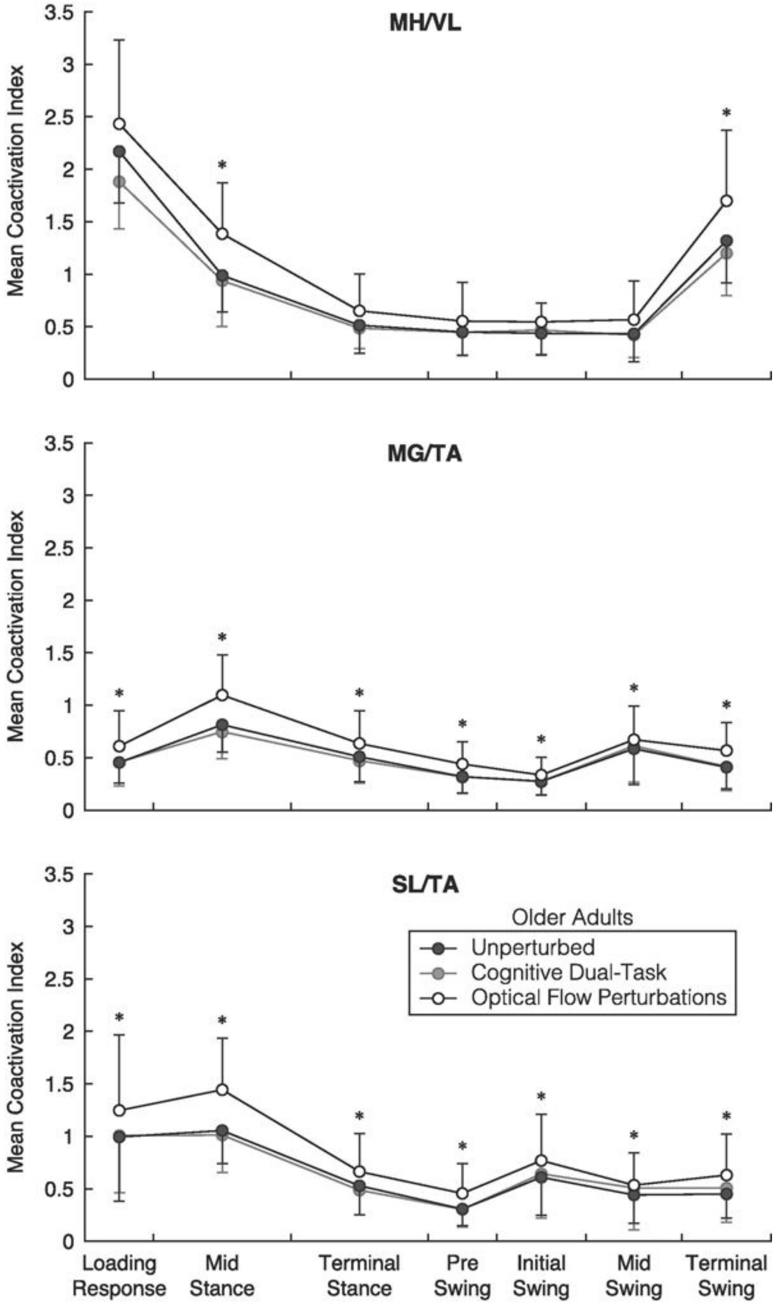

Figure 2.

Mean coactivation index over phases of the gait cycle (mean ± s.d.) for older adults during the three walking conditions. Asterisks indicate significant differences between the optical flow perturbation condition and the unperturbed condition. Coactivation during the cognitive dual-task condition did not differ significantly from the unperturbed condition.

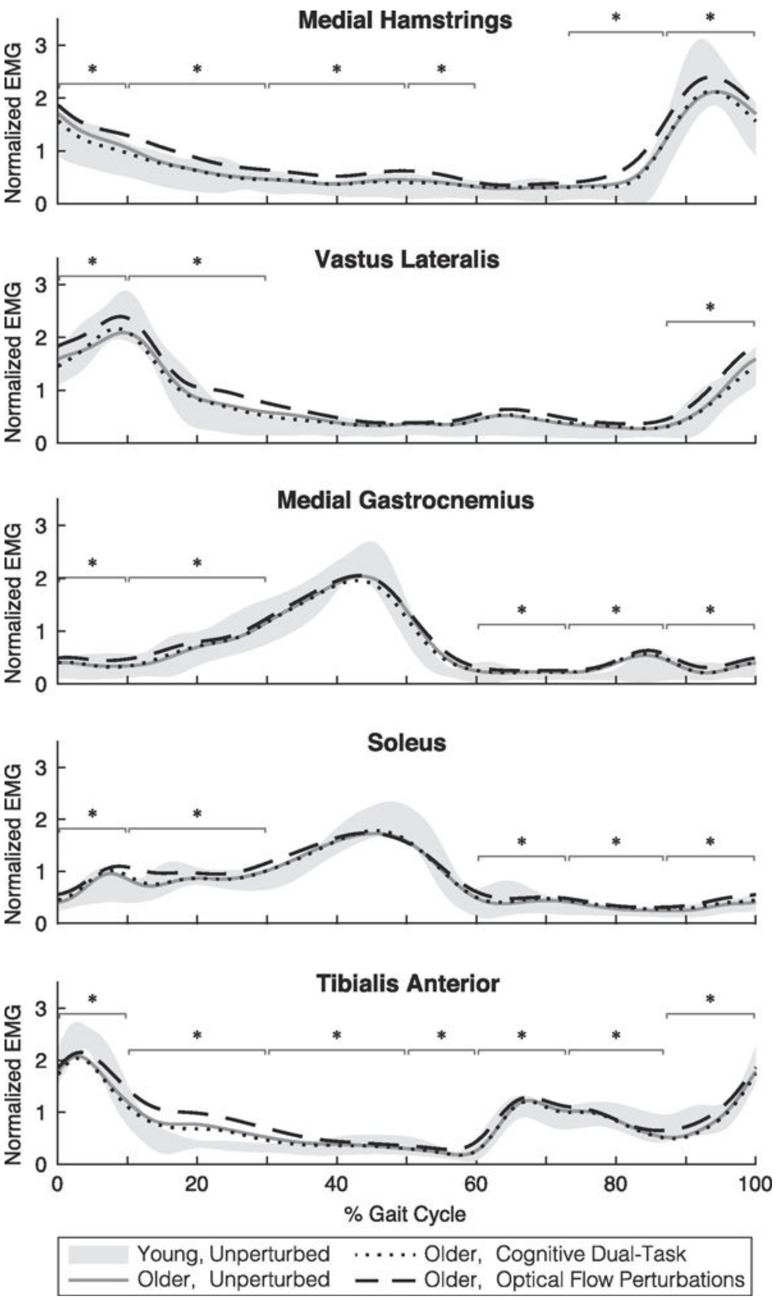

Figure 3.

Mean electromyographic activity over the gait cycle for the young (shaded curve represents mean ± s.d.) and older adults. Each muscle's activity level was normalized to its mean rectified activity during the unperturbed condition. Asterisks indicate phases of the gait cycle for the older adults where mean activity during the optical flow perturbation condition was significantly greater than the unperturbed condition.

Table 1.

A two-way mixed ANOVA tested the influence of age and walking conditions on the mean antagonist coactivation index over the stride.

Antagonist Muscle Pair	**Effect**	***DoF***	***F***	***P***	η_p^2
MH/VL	Age	1.00,26.00	11.23	***0.002***	0.30
	Condition	1.63,42.43	9.48	***0.00l***	0.27
	Age × Condition	1.63,42.43	4.49	***0.023***	0.15
MG/TA	Age	1.00,26.00	9.80	***0.004***	0.27
	Condition	1.33,34.47	16.36	***<0.00l***	0.39
	Age × Condition	1.33,34.47	10.71	***0.00l***	0.29
SL/TA	Age	1.00,26.00	4.39	***0.046***	0.14
	Condition	1.34,34.93	17.65	***<0.00l***	0.40
	Age × Condition	1.34,34.93	12.60	***<0.00l***	0.33