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Effects of Balance Status and Age on Muscle Activation While Walking Under Divided Attention

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We examined the role of attention during different phases of the gait cycle by using a dual-task paradigm. Younger and older adults performed a self-paced treadmill walking task, a semantic judgment task, and both tasks simultaneously. We recorded vocal reaction time for the judgment task, and we recorded muscle activity by the use of electromyography. We derived dual-task costs from difference scores (single vs dual task). Our analysis of the judgment task showed that both groups responded more quickly during dual-task conditions than during single-task conditions. In five of eight muscle groups, stance-phase muscle activity decreased significantly from dual to single task. For older adults, individuals with poor balance increased their muscle activity during dual-task performance. These results suggest that, during moderately demanding walking and cognitive performance, poor balancers can compensate successfully for their motoric vulnerability.

WALKING and talking are two everyday activities often performed simultaneously. In a situation with minimal attentional demands (e.g., a quiet shopping mall with level surfaces), older adults may have no difficulties walking and talking, but when walking on uneven terrain or navigating stairs (Hamel, Okita, Bus, & Cavanaugh, 2005), older adults may be more vulnerable to falls if their attention is divided (Sparrow, Bradshaw, Lamoureux, & Tirosh, 2002). A growing literature indicates that cognitive and sensory or sensorimotor abilities become increasingly correlated in healthy aging (Baltes & Lindenberger, 1997; Li & Lindenberger, 2002; Schneider & Pichora-Fuller, 2000). Researchers have examined this relationship experimentally by using dual-task methodology (Li, Krampe, & Bondar, 2005; McDowd, Vercruyssen, & Birren, 1991) in the related domains of gait and balance research (Woollacott & Shumway-Cook, 2002). In a dual-task paradigm, participants perform two tasks simultaneously or alone. The computation of dual-task costs (DTCs), that is, single-task minus dual-task performance, controls for individual and age differences in baseline functioning (e.g., muscle strength, response speed). A comparison of DTCs across task domains gives an indication of task priority (e.g., the absence of DTCs in Task A coupled with substantial costs in Task B suggests that Task A was prioritized).

Dual-task methods have been successfully applied to the domain of gait and postural control (Brown, Shumway-Cook, & Woollacott, 1999; Ebersbach, Dimitrijevic, & Poewe, 1995; Lajoie, Teasdale, Bard, & Fleury, 1993; McIlroy, Norrie, & Brooke, 1999; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997; Teasdale, Bard, LaRue, & Fleury, 1993; Weerdesteyn, Schillings, van Galen, & Duysens, 2003; Yardley, Gardner, & Lavie, 1999). In the majority of such studies, the simultaneous performance of a cognitive task and a motor task results in age-related increases in cognitive DTCs, motor DTCs, or both. Researchers have attributed variations in the locus and magnitude of DTCs to factors such as task complexity and postural threat (Woollacott & Shumway-Cook, 2002).

In studies of walking, researchers have observed age-related increases in DTCs when obstacles appear suddenly in the participants' walking path (Chen, Schultz, Ashton-Miller, Giordani, et al., 1996), and when the participants are under challenging dual-task conditions such as walking while memorizing (Lindenberger, Marsiske, & Baltes, 2000). Li, Lindenberger, Freund, and Baltes (2001) found a marked asymmetry of DTCs such that age equivalence was observed in walking-related DTCs but age-related increases were observed in memory-related DTCs (older adults showed greater memory-related DTCs than younger adults did). These researchers interpreted the results as showing the prioritization of walking, in keeping with the "posture-first" principle (Woollacott & Shumway-Cook, 2002). With more lenient self-paced walking experiments, other researchers have observed age equivalence in walking-speed DTCs (Kemper, Herman, & Lian, 2003) but age-related increases in stride-variability DTCs (Beauchet et al., 2003).

Overall, this literature suggests an age-related increase in attentional involvement during walking. What is less clear is why the locus of these aging effects varies across studies. Variation in task familiarity is one consideration: Studies that include extensive training on one task (e.g., Lindenberger et al., 2000; Weerdesteyn et al., 2003) or both tasks (Li et al., 2001) are in the minority, and even fewer studies involve dual-task practice prior to testing (c.f. Pellecchia, 2005). A second consideration concerns difficulty level: Most dual-task walking experiments involve challenging conditions designed to test performance limits. Fewer studies mimic everyday walking situations in which individuals freely choose their pace and task priority (c.f. Beauchet et al., 2003; Kemper et al., 2003; Lajoie et al., 1993).

Researchers have interpreted the majority of walking dual-task findings by using a simple resource competition model (Kahneman, 1973; cf. Wickens, 2002) in which significant DTCs imply that simultaneous performance results in overlapping resource demands. However, this approach to studying dual-task performance does not account well for fluctuations or asymmetries in task emphasis. We presently take a more ecological approach (Li et al., 2001, 2005), which considers factors such as task priority, motivation, and individual differences in ability. Based on Baltes and Baltes' (1990) Lifespan Developmental Model of Selection, Optimization, and Compensation, our approach focuses on relative age differences in task priority, as reflected in the DTCs observed in each task domain. This approach also allows for the case of moderate, everyday dual-task situations in which capacity limits are not exceeded, but age and individual differences in motivation or task priority may nevertheless lead to variation in the locus of DTCs (elective selection; see Baltes & Baltes). Under more challenging conditions, in which task demands may approach or exceed capacity limits, evidence for compensatory task trade-offs would be expected (loss-based selection; see Baltes & Baltes), especially for older individuals who should prioritize the avoidance of falls (e.g., Li et al., 2001). Whereas the latter case has been examined in this literature (Bondar, 2002; Li et al., 2001; Rapp, Krampe, & Baltes, 2006), the former has not.

On the basis of the foregoing review, we designed the present study to address several issues: First, we aimed to examine age differences in DTCs during a moderately demanding dual-task situation: self-paced treadmill walking while making semantic judgments. Second, we attempted to control more fully for differences in task familiarity and improve the interpretability of any observed age differences in task prioritization by building in a full session of single- and dual-task training. We also included supplementary measures of balance status, cognitive status, and subjective ratings of dual-task performance to examine the influence of these individual differences factors on DTCs and task prioritization.

Our third aim was to gain more detailed information about age differences in the temporal dynamics of attentional involvement during the gait cycle. In young adults only, Lajoie and colleagues (1993) evaluated the attentional demands of single- and double-support (one foot vs two contacting the ground, respectively) walking on participants who were simultaneously performing a probe reaction-time task. Cognitive-task reaction times were longer during the single- than the double-support phase, suggesting that attentional requirements fluctuate systematically during the gait cycle. We collected surface electromyographic (EMG) data to detect subtle attention-related changes that may not be captured by more global measures of walking. With this method, we segmented the gait cycle into two main phases: (a) preparatory phases and (b) stance phases. We define the preparatory period as 150 ms prior to heel strike (DeMont, Lephart, Giraldo, Swanik, & Fu, 1999), and we define the stance phase as heel strike to toe-off (c.f. Lajoie et al.).

For both phases, we selected leg muscles for their roles in joint stability. The quadriceps (vastus medialis oblique and vastus lateralis) and hamstrings (lateral and medial) provide stability in the knee; the medial and lateral gastrocnemius contribute to knee stability and cross the ankle to provide propulsion during foot push-off; and the tibialis anterior and peroneal longus provide stability to the ankle (Morey-Klapsing, Arampatzis, & Brueggeman, 2005). Although it is well known that these muscles activate differently during different phases of the gait cycle and each muscle may increase and decrease in activity with differing magnitudes (Winter & Yack, 1987), our major goal was to examine possible age differences in DTCs as a function of phase.

Our interest in the preparatory phase of gait comes from research on gait and athletic injury (DeMont et al., 1999), in which young women with knee injuries showed less preparatory leg muscle activity than control subjects did. Muscle activity just prior to heel strike has been associated with motor planning (Dietz, 1992). Assuming that postinjury walking is analogous to a more cautious gait in late life, our older participants should show less preparatory muscle activity than younger adults do. To our knowledge, this preparatory phase has yet to be investigated for age or divided attention effects. In the absence of such research, we made the simple prediction that under dual-task conditions, activity in all leg muscles should decrease, particularly in older adults.

Leg muscle activity in the stance phase serves to stabilize and propel the body (McMahon, 1984). The research on EMG measures of dual-task stance and aging is, to our knowledge, nonexistent. Extrapolating from research on aging and dual-task balance recovery (Rankin, Woollacott, Shumway-Cook, & Brown, 2000), we again made very general predictions: For all muscle groups, we expected older adults to be more vulnerable to attentional distraction and to show greater stance-phase DTCs than younger adults did.

Table 1. Descriptive Statistics of the Sample

Sample Characteristic	Younger Adults		Older Adults	
	M	*SD*	*M*	*SD*
Age (years)	21	2	71	5
Digit symbol value	67	13	42	9
MoCA value	29	1.4	27	2.6
Trails B-A (s)	26	17	46	41
Treadmill speed (mph)	2.32	0.32	1.68	0.50
Balance status (s)	52	18	25	21

Notes: Digit symbol value = number of symbols correctly identified in 2 minutes; MoCA value = score on the Montreal Cognitive Assessment out of 30; Trails B-A = Version B − Version A completion time on the Trail Making Test; Treadmill speed = self-selected pace; Balance status = Sharpened Romberg Test. For younger adults, $n = 18$; for older adults, $n = 23$; *SD* = standard deviation.

Methods

Participants

We recruited 18 younger adults (18–30 years of age) and 23 older adults (62–80 years of age) by means of campus announcements or advertisements in local newspapers. We screened participants for medical conditions (i.e., stroke, arthritis, hearing loss, or leg injury) that might affect sensory, motor, and cognitive functioning and jeopardize their performance during the experiment. Sample characteristics are shown in Table 1. All procedures met Concordia University ethical guidelines. Older adults were paid an honorarium for their participation.

Materials and Apparatus

Walking task.—We used a Biodex treadmill together with a Biodex body harness during all walking trials. We manipulated postural threat by contrasting level versus downhill walking (0° vs –15°). We chose a downhill slope to avoid confounding postural threat with physical exertion. We measured surface EMG activity by using 17 Medi-Trace Mini-133 electrodes (Kendall-LTP, Chicopee, MA), placed on the point of maximum muscle density for eight muscles of each participant's dominant leg: vastus medialis oblique (VMO), vastus lateralis (VL), medial hamstring (MH: semitendinosus and semimembranosus), lateral hamstring (LH: biceps femoris), medial gastrocnemius (MG), lateral gastrocnemius (LG), tibialis anterior (TA), and peroneal longus (PL). We had a reference electrode placed over the tibia. We sampled the EMG signals for each muscle group at 1000 Hz; we amplified (gain 1000) and transferred them by means of fiber-optic cable to a MyoPac 16-channel receiver (RunTech Inc., Mission Viejo, CA); and we delivered them to the computer board's analog-to-digital converter for input to the DataPac software (RunTech). We had footswitches placed in the shoe of each participant's dominant leg to record heel-strike and toe-off times. We registered footswitch and EMG data by using the DataPac software.

Semantic judgment task.—The experimenter presented words auditorially at 10 different interstimulus intervals (750–3,000 ms), and participants judged whether each word signified a living thing (yes or no). All participants received the same pseudorandom order of words. We varied the interstimulus intervals to ensure that words would occur at different phases of the gait cycle under dual-task conditions. The digitized words were spoken in a female voice and consisted of two-syllable high-frequency concrete nouns (written frequency >1 word per million: Kuçera & Francis, 1967). We presented the word stimuli by using SuperLab Pro 1.74 (Cedrus Corp., San Pedro, CA) on a Power Macintosh G4 computer (Apple, Cupertino, CA). Participants received two 30-word practice lists and four 62-word test lists. Each list contained an equal number of living and nonliving items. We had all test words presented twice with a minimum separation of two lists. We used a Plantronics (Santa Cruz, CA) DSP-300 headset for stimulus presentation and collection of vocal reaction times. The experimenter noted the participants' responses.

Supplementary measures.—We included additional measures to examine the impact of individual differences in cognitive status, subjective dual-task strategy, and sensorimotor status on dual-task performance. We administered three cognitive tests, that is, the Wechsler Adult Intelligence Scale Digit Symbol Substitution Test (Wechsler, 1981), the Montreal Cognitive Assessment (Nasreddine, Chertkow, Phillips, Bergman, Whitehead, & Collin, 2003), and the Trail Making Test (Spreen & Strauss, 1998), to assess processing speed, general cognitive status, and task switching, respectively. At the end of each dual-task condition, participants were to rate perceived task priority, safety, and stability. We assessed balance status with the Sharpened Romberg Test (SRT; Brigg, Gossman, Birch, Drews, & Shaddeau, 1989), which measures how long one can maintain tandem stance (one foot in front, heel to toe), eyes closed and arms placed at the sides of the torso, without moving (maximum of 60 s). We assessed hearing with a Maico-MA 39 audiometer (Maico Diagnostics, Eden Prairie, MN), and we also administered an immediate word repetition baseline, using the same listening conditions as in the cognitive task. We excluded participants if they scored below 90% on the word repetition baseline.

Procedure

Session 1.—We tested participants on 2 days, with a maximum of 1 day between tests. First, we determined leg dominance by recording the foot used most often to initiate a step in three separate trials. To determine walking speed, we had the experimenter show the participants the Borg Rating of Perceived Exertion scale (Borg, 1982) and ask them to set their walking pace to a score of 12 (range = 6–19), defined as not underexerting or overexerting. The experimenter forewarned the participants that the speed would be used for both level and downhill walking. Participants walked for 2 minutes, familiarizing themselves with the treadmill, and their set pace. Walking speed was set during level walking and reevaluated during downhill walking. All participants found their initial pace acceptable for downhill walking; thus, no adjustments were made.

Once walking pace was set, six blocks of two trials each (trial duration = 2.5 minutes) were performed for single- and dual-task practice. We used the same block order for all participants: single-task cognition (COG-level), single-task walking (WALK-level), dual-task (DUAL-level), COG-down, WALK-down, and DUAL-down. We opted to give two COG blocks to equate the temporal proximity between COG and corresponding DUAL blocks. During DUAL blocks, the experimenter informed the participants that both tasks were equally important.

Session 2.—After our assessment of balance status (SRT), we had the experimenter apply the EMG electrodes to each participant's dominant leg. We assessed EMG activity during maximum voluntary contraction for each muscle group to establish baseline levels. The experimenter then gave one DUAL-level trial as a warm-up and equipment check. To reduce order and practice effects, we had participants perform one of six counterbalanced orders of the six test blocks (e.g., WALK-level, DUAL-level, COG-level, WALK-down, DUAL-down, and COG-down).

Statistical Analyses

For both the cognitive and muscle activity data, we calculated difference scores (DTCs) to evaluate the effects of age group and walking difficulty.

Cognitive data.—Overall accuracy was very high ($\geq 94\%$), so we used mean correct reaction times trimmed at $\pm$ 3 *SD* to analyze cognitive performance. This resulted in the removal of 0.008% of all relevant data points. There were no significant age differences in the number of outliers discarded, $p = .86$ (younger adults, $M = 1.94$, $SD = 1.77$; older adults, $M = 2.04$, $SD = 1.67$). All correlations between reaction time and accuracy were negative and nonsignificant ($ps > .15$), suggesting the absence of speed–accuracy trade-offs. We subjected the DTCs (RT dual – RT single) to an Age Group (younger, older) $\times$ Walking Difficulty (level, downhill) mixed-factorial analysis of variance (ANOVA).

Muscle activity data.—We processed the EMG signals by means of full-wave rectification and we bandpass filtered them (Butterworth) below 50 Hz and above 300 Hz. We manually

Table 2. Cognitive Mean Reaction Times for Single and Dual Tasks and DTCs for Younger and Older Adults

Task or Cost	*M* Younger	*M* Older	*SD* Younger	*SD* Older
Level slope				
Single	648	725	94	106
Dual	605	656	105	113
DTCs	−43	−69	95	92
Downhill slope				
Single	671	724	82	103
Dual	603	670	119	119
DTCs	−68	−54	99	86

Notes: DTCs = Dual task costs (dual – single); *SD* = standard deviation. All reaction times are in milliseconds. Participants performed the cognitive single task while they were in a standing position (beside the treadmill); they performed the cognitive dual task while they were walking on the treadmill. The sample size was $n = 18$ for younger adults and $n = 23$ for older adults.

identified the preactivation and stance phases by inserting markers that coincided with the heel-strike and toe-off signals. For each of the eight muscle groups, we compiled the data into integrated electromyographic (IEMG) activity. Integrated electromyography provides an area measure of the muscle activity to be used in comparisons. For simplicity, we use the terms *IEMG* and *EMG* interchangeably in this article.

For the preactivation data, we normalized IEMG activity to the mean amplitude of each muscle group and analyzed it for area and mean amplitude 150 ms prior to heel strike. We reported each preactivation measure as a percentage of the mean. For the stance data, we normalized IEMG activity from heel strike to toe-off to each individual's maximum voluntary contraction, resulting in a percentage maximum voluntary contraction value per muscle group. We followed the conventional method of analyzing each muscle group and phase of gait separately, given that individual muscles may exhibit different types of contractions (e.g., eccentric, concentric, or isometric) within and across phases, and they may differ in the magnitude of activation values. Because we were primarily interested in aging and attentional effects, we focused on examining the effects of age group (younger, older) and walking difficulty (level, downhill) by using DTCs (single – dual) in a series of mixed-factorial ANOVAs.

Results

In this study we evaluated the importance of attention in the gait cycle during a moderately demanding dual-task situation. The three primary measures of interest were as follows: (a) cognitive reaction time, (b) stance muscle activity, and (c) preparatory muscle activity. We expected that the cognitive DTCs would increase for older adults only, and that both stance and preparatory muscle activity DTCs would decrease to a greater extent in the older sample than in the younger sample as a result of attentional load.

Cognitive Performance

Mean reaction times per condition and derived DTCs are shown in Table 2. To first confirm that there were no age differences or interactions in response-time performance prior to starting the test blocks, we carried out a Session (1, 2) × Age Group (younger, older) ANOVA, in which we compared the last block of practice data in Session 1 with the corresponding block of test data in Session 2. Results revealed no significant age main effects ($p = .60$) or interactions ($p = .67$), which suggests that both age groups were starting the test blocks with comparable levels of cognitive performance.

Our analysis of cognitive DTCs revealed nonsignificant main effects of age group ($p = .82$) and walking difficulty ($p = .73$), and a nonsignificant interaction ($p = .14$). It is notable that the DTC values for both age groups were negative, indicating dual-task facilitation rather than cost. Overall, 71% of the individuals in our sample showed negative DTCs. For older adults, these DTCs were significantly less than zero for level walking conditions ($p = .002$; negative DTCs in 78% of older adults) and downhill walking conditions ($p = .006$; negative DTCs in 70% of older adults). Younger adults' cognitive DTCs were marginally different from zero during level walking ($p = .069$; negative DTCs in 61% of younger adults) and significantly different from zero during downhill walking ($p = .009$; negative DTCs in 72% of younger adults).

Table 3. Single- and Dual-Task Means, DTCs, and Standard Deviations for Stance-Phase Activations of Younger and Older Adults

Muscle Groups	Single Task YA	Single Task OA	Dual Task YA	Dual Task OA	DTCs YA	DTCs OA
Level slope						
VMO	32 (32)	45 (29)	26 (20)	44 (31)	6 (16)	1 (8)
VL	38 (66)	40 (23)	33 (51)	36 (21)	5 (16)	4 (9)
MH	19 (13)	22 (15)	18 (14)	20 (13)	1 (6)	2 (5)
LH	23 (14)	31 (20)	22 (13)	30 (20)	1 (4)	1 (4)
MG	134 (118)	166 (185)	122 (91)	158 (196)	12 (34)	8 (30)
LG	108 (75)	90 (60)	93 (53)	84 (61)	15 (33)	6 (12)
TA	36 (39)	39 (30)	35 (38)	35 (28)	1 (3)	4 (9)
PL	72 (77)	74 (53)	75 (87)	98 (119)	−3 (11)	−24 (105)
Downhill slope						
VMO	61 (41)	75 (48)	60 (41)	70 (49)	1 (7)	5 (16)
VL	52 (28)	59 (30)	50 (27)	57 (31)	2 (8)	2 (12)
MH	16 (12)	21 (20)	16 (13)	20 (17)	−.002 (3)	1 (6)
LH	27 (16)	31 (19)	26 (15)	30 (22)	1 (5)	1 (9)
MG	80 (56)	148 (184)	79 (66)	141 (181)	1 (15)	7 (20)
LG	84 (57)	89 (65)	78 (41)	81 (61)	6 (24)	8 (24)
TA	31 (18)	41 (41)	32 (19)	39 (40)	−.001 (4)	2 (5)
PL	56 (64)	82 (52)	59 (77)	108 (119)	−3 (14)	−26 (106)

Notes: YA = younger adults; OA = older adults; DTCs = dual task costs (single – dual); VMO = vastus medialus oblique; VL = vastus lateralis; MH = medial hamstrings; LH = lateral hamstrings; MG = medial gastrocnemius; LG = lateral gastrocnemius; TA = tibialis anterior; PL = peroneal longus. Standard deviations are given in parentheses; stance values are normalized to each individual's maximum voluntary contraction.

Walking Performance

Stance phase.—The stance-phase EMG data are shown in Table 3. Our analysis of the stance-phase DTCs revealed a main effect of age group, $F(1, 39) = 5.47$, $p = .03$, $\eta^2 = .12$, for the TA only, such that on average, older adults ($M = 0.03$, $SE = 0.01$) had higher walking-related DTCs in this muscle than younger adults did ($M = –0.001$, $SE = 0.01$). We contrasted DTCs aggregated across age group with zero in a series of

Table 4. Correlations (r) Between Balance Status and Stance-Phase DTCs in Muscle Activity for Older Adults

Muscle Groups	Unrestricted (n = 19) Level	Unrestricted (n = 19) Downhill	Restricted (n = 14) Level	Restricted (n = 14) Downhill
VMO	.562*	.586*	.595*	.479
VL	.435	.073	.361	.138
MH	.376	.504*	.530	.516
LH	.420	.485*	.668**	.587*
MG	.016	.172	.068	.328
LG	.306	.570*	.356	.671*
TA	.255	.373	.065	.277
PL	−.264	.198	−.180	−.135

Notes: Balance status was measured with the Sharpened Romberg Test. DTCs = DTCs = dual task costs (single − dual); unrestricted sample = SRT outliers removed; restricted sample = SRT outliers removed, as well as information for participants who had never been on a treadmill before and who set lower than average walking speeds (for their age group). VMO = vastus medialus oblique; VL = vastus lateralis; MH = medial hamstrings; LH = lateral hamstrings; MG = medial gastrocnemius; LG = lateral gastrocnemius; TA = tibialis anterior; PL = peroneal longus.

*$p < .05$; **$p < .01$.

planned comparisons, showing significant costs for VL_{Level} ($M = 0.05$, $p = .02$), MH_{Level} ($M = 0.02$, $p = .06$), MG_{Level} ($M = 0.10$, $p = .06$), LG_{Level} ($M = 0.10$, $p < .01$), LG_{Down} ($M = 0.07$, $p = .07$), and TA_{Level} ($M = 0.02$, $p = .04$). When we split the results by age group, DTCs were significantly greater than zero in four muscle groups (VL, MH, LG, and TA; $ps \leq .05$), only for older adults.

To examine if individual differences in balance status predicted walking-related DTCs, we correlated balance (SRT) scores with stance-phase DTCs for level and downhill conditions. We identified 2 younger and 4 older adults as outliers on the SRT, and we dropped their data from this analysis. We found five significant positive correlations for the older adults and one significant negative correlation for the younger adults (see the Unrestricted column in Table 4). For older adults the correlations were larger in the downhill condition, suggesting a link between attentional demand, postural threat, and balance.

Preactivation phase.—Higher muscle preactivation reflects better preparation prior to heel strike. Our analysis of the preactivation-phase DTCs per muscle group revealed nonsignificant effects of age group and walking difficulty, and a nonsignificant interaction ($ps > .05$). In addition, planned contrasts revealed that these DTCs were not different from zero ($ps > .05$).

Task Priority, Safety, and Stability

To examine the perception of dual-task performance, we subjected our three questions concerning task emphasis, stability, and safety to Age Group × Walking Difficulty mixed-factorial ANOVAs. In terms of task emphasis, both groups emphasized listening over walking; $F(1, 39) = 67.33$, $p < .001$, $\eta^2 = .633$ overall. During downhill walking, both groups decreased the amount of emphasis placed on listening and placed more emphasis on walking; $F(1, 39) = 8.33$, $p = .006$, $\eta^2 = .176$. Concerning safety and stability, both groups felt less safe during downhill walking ($M = 1.74$, $SE = 0.11$) than during level walking ($M = 1.36$, $SE = 0.09$), with $F(1, 39) = 14.13$, $p < .001$, $\eta^2 = .266$, and less stable during downhill walking ($M = 1.94$, $SE = 0.11$) than during level walking ($M = 1.47$, $SE = 0.13$), with $F(1, 39) = 15.06$, $p < .001$, $\eta^2 = .279$.

Physical Variables

We also evaluated our physical background variables in relation to the experimental findings. A univariate test of self-selected walking pace revealed a significant age difference, $F(1, 39) = 22.30$, $p < .001$, $\eta^2 = .364$, such that younger adults set a higher speed ($M = 2.32$ mph, $SD = 0.32$) than did older adults ($M = 1.68$ mph, $SD = 0.50$). Similarly, our independent measure of balance status (SRT) showed a significant age group difference, $F(1, 39) = 21.10$, $p < .001$, $\eta^2 = .351$, such that younger adults were able to maintain their balance much longer ($M = 52.26$ s, $SD = 17.64$) than older adults did ($M = 24.61$ s, $SD = 20.19$).

Our physical activity questions revealed that 6 out of 23 older adults had never used a treadmill. Of those 6 participants, 5 had below-average balance scores and also set their walking speeds lower than the average for the older sample (below 1.68 mph). To evaluate whether our correlations between balance status and stance-phase DTCs were driven by this subgroup of novice treadmill users, we excluded the novices and reran the correlations. In doing so, we found that four of the original five correlations remained significant (see the Restricted column of Table 4), suggesting that the relationship between balance status and stance-phase DTCs is reasonably robust even for experienced treadmill users.

To rule out other factors that may have influenced the stance-phase DTCs, we examined correlations between stance-phase DTCs and measures of hearing, cognitive status, walking speed, and weekly exercise. We found no systematic relationships ($ps > .05$). Notably, we also did not find significant correlations between balance status and single-task stance-phase EMG levels, indicating that poor and good balancers had comparable levels of baseline (WALK) muscle activity.

Discussion

The current study extends the findings of Li and colleagues (2001) in several ways. Unlike the study by the Li and colleagues, in which participants pushed their limits with difficult walking and cognitive tasks, the current study involved having participants walk at a steady self-selected pace and perform simple animacy judgments. In addition, the present study involved both single-task *and* dual-task training prior to testing. Under these circumstances, younger and older adults showed similar levels of cognitive facilitation while walking. In addition, individuals in both age groups showed reductions in muscle activity when their attention was divided during the stance phase of the gait cycle, but not in the preparatory phase. Importantly, older adults with poor balance showed smaller stance-phase DTCs than those with good balance, despite showing comparable single-task stance activity.

Cognitive Findings

Our analysis of the semantic judgment DTCs revealed that both age groups were faster during dual-task than during single-task trials. This facilitatory effect parallels recent work by Huxhold, Li, Schmiedek, and Lindenberger (2006) comparing younger and older adults on dual-task cognition and standing balance. These authors reported a U-shaped performance-difficulty function in which balance improved significantly from single-task balance when a simple concurrent cognitive task was added, but was disrupted when cognitive demands increased (see also Siu & Woollacott, 2007). In the present study, our subjective questionnaire and objective performance data provide convergent evidence of cognitive-task priority, which is a significant departure from previous findings (Li et al., 2001). We argue that, for our older adults, the present combination of moderate task demands without threat of falling may have left enough reserve capacity to prioritize and even facilitate cognitive performance. Alternatively, older adults may have deliberately set a conservative walking pace in preparation for the dual-task condition, similar to previous reports in which older adults adopted a simplified speech style in anticipation of dual-task demands (Kemper et al., 2003). In either case, we take the current results as evidence of elective selection and successful dual-task management on the part of the older adults.

Despite the general facilitatory effect, both groups showed sensitivity to our manipulation of walking difficulty, both in terms of the reaction-time data and subjective reports of task emphasis. Nevertheless, our current walking-difficulty effects were very slight, and we do not consider them to constitute a loss-based selection situation in which postural control must be prioritized (cf. Li et al., 2001).

EMG Findings

Across both age groups, five of the eight muscle groups showed significant stance-phase DTCs. Similarly, Rankin and colleagues (2000) found age-equivalent decreases in muscle activity in one muscle group (TA) when participants' attention was divided during a balance-recovery task. The present results join others in demonstrating that even moderate self-paced walking may require higher cognitive control (Hausdorff, Yogev, Springer, Simon, & Gialdi, 2005), and that attentional involvement fluctuates across different phases of gait (Lajoie et al., 1993).

Given the paucity of research on dual-task and aging effects on the gait cycle, we initially hypothesized decreased activity in all muscle groups during dual-task walking as a result of the general competition for resources. We provide here a speculative functional interpretation of the observed pattern of EMG results, framed in terms of the obligatory activation of the muscle groups that did *not* show significant DTCs. In keeping with the posture-first principle of motor prioritization (Woollacott & Shumway-Cook, 2002), we propose that DTCs may only be observed in muscles that can be depleted without significantly compromising postural control while walking. In support of this proposal, all but one attentional effect (nonzero DTC) was observed during level walking, where the control of gait was less demanding and therefore resources could be relinquished to address the cognitive demands. Conversely, during downhill walking, resources were more essential and less easily relinquished to serve cognitive processing. In agreement with the EMG results, the task priority and cognitive data indicate that downhill walking was slightly more demanding than level walking for both age groups.

Similarly, for older individuals with poor balance status, stance-phase activity DTCs were low, suggesting that with internally mediated postural compromise, resources were not as readily relinquished. Conversely, good balancers showed higher stance-phase DTCs. This pattern of positive correlations was even stronger for downhill walking conditions. A simple deficit model would be associated with correlations in the opposite direction (poor balance, high stance-phase DTCs). In contrast, our results favor a compensation model, in line with theories of successful aging (e.g., Baltes & Baltes, 1990). Specifically, in a situation with moderate dual-task demands, older adults who have declining balance abilities may elect to emphasize their neuromuscular output to compensate when their attention is divided. Notably, no relationship was found between single-task stance-phase muscle activity and balance status, suggesting that the addition of a cognitive load is critical for the observed correlations. A further test of this hypothesis could be addressed in future studies involving frail older adults with more severe balance problems.

On a more detailed level, one can consider the three muscle groups for which stance-phase DTCs were *not* observed during level walking (PL, VMO, and LH) in terms of their involvement in joint stabilization. For example, the PL plays an important role in multiple planes of movement. In the nonsagittal (frontal) plane this muscle makes a major contribution to the inversion and eversion (turning inward and outward) of the foot. The additional planes of movement control associated with the PL might necessitate the total available resource. The VMO functions during knee extension and may require full resources in effort to stabilize the patella (kneecap) while the knee is accommodating variations in ground impact during terminal extension. The LH and MH work together to extend the thigh and flex the knee. Additionally, the LH aids in rotation of the tibia (shin), which, like the PL, is a nonsagittal (transverse) plane movement; this added plane of movement at the tibial plateau may necessitate full resources. However, there is a slight inconsistency as the MH has a similar transverse plane function yet did show marginally significant nonzero stance DTCs. We emphasize that this functional analysis is post hoc, and may be limited to the present cognitive and motor test parameters. Future research is needed to explore the boundaries of attentional disruption on the activation of specific muscle groups.

In the preparatory phase, we did not observe significant effects of attentional load, age group, or walking difficulty. Similarly, Maki, Zecevic, Bateni, Kirshenbaum, and McIlroy (2001) found that attention was involved in the stabilization phase of balance recovery, but not in the initial response of the ankle joint; thus our preparatory phase results may indicate a relatively automatic phase of the gait cycle. It is also possible that the moderate demands of both tasks allowed participants to maintain their performance during this phase. Future research is needed to test for changes in preparatory muscle activity with more demanding dual-task conditions. As well, our broad division of the gait cycle into preparatory and stance phases is preliminary, and researchers could expand this division in the future by analyzing the gait cycle with finer resolution (e.g., incorporating single- and double-support phases), or by analyzing muscle activity as a function of the cognitive events (stimulus onset, response onset).

Sample Characteristics

An important caveat to consider is that the individuals tested in this study were highly functioning. The majority of the younger adults were recruited from the Department of Exercise Science and are very familiar with treadmills. The majority of our older adults had been on a treadmill before, and all but one regularly exercised. Research has demonstrated that older adults who have been physically active are faster and more accurate at responding to simple and complex cognitive-motor tasks than those who have not been involved in aerobic activity (Colcombe & Kramer, 2003; Toole, Park, & Al-Ameer, 1993). The present results can therefore be considered conservative estimates of the relationship between aging, attentional load, and muscle activity across the gait cycle. Nevertheless, we have demonstrated a robust pattern of compensatory muscle activation under dual-task conditions that varies as a function of balance status.

Conclusions

Taken together, the current study demonstrates that highly functioning older adults can successfully manage to walk and perform a concurrent cognitive task when task demands are moderate. Given the opportunity to set their own walking pace, the older adults in this study were able to perform like young adults, and they appeared to engage in elective selection (Baltes & Baltes, 1990) and voluntarily prioritize the cognitive task. Dividing the adults' attention reduced stance-phase muscle activity for both age groups to the same degree, underscoring the role of attention in gait and postural control (e.g., Woollacott & Shumway-Cook, 2002). Our findings show that specifically the stance phase of the gait cycle is sensitive to attentional load, and that this sensitivity to attentional disruption is influenced by balance status. Future research is required to determine if a similar pattern can be observed with greater task demands to establish the boundary conditions of successful compensation.

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