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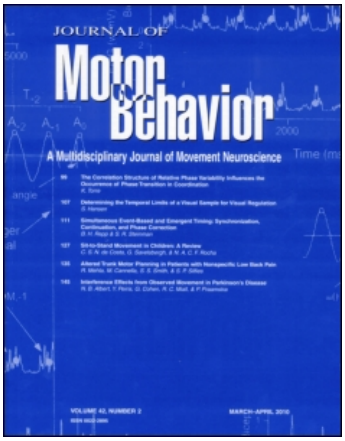

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RESEARCH ARTICLE

Attentional Demands Associated With Obstacle Crossing While Carrying a Load

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ABSTRACT. The extent to which different locomotor tasks require cognitive control is not well characterized. In this article, the authors consider the potential increase in attentional demands associated with carrying an anterior load while clearing an obstacle. Nine healthy male volunteers participated in 80 walking trials, 20 in each of 4 conditions: 1 no load condition (NL) and 3 carrying conditions (2KG, 5KG, and 10KG). Of the 20 trials in each condition, 12 included a probe reaction time (PRT) test during lead limb obstacle crossing, which was used to measure cognitive load. A load-dependent increase in PRT was observed, with PRT in the 2KG condition being significantly greater than in the NL condition, and PRT in the 5KG and 10KG conditions being significantly greater than in the 2KG condition. These results suggested that cognitive load was increased when: (a) the obstacle was occluded from vision by the load, and (b) the magnitude of load was increased.

Keywords: attention, carrying, gait, obstacle clearance

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Both obstacle avoidance and load carriage are essential, common aspects of normal function and many activities of daily living; indeed these two motor tasks are often performed simultaneously in the context of functional human locomotion. Obstacle avoidance and carrying, independent of one another, increase the physical and cognitive demands associated with the control of gait, and therefore increase the risk of falling, especially in the elderly. For example, tripping over obstacles and instability have been reported as two of the most common causes of falls in older adults (Blake et al., 1988; Campbell et al., 1990; Chou, Kaufman, Brey, & Draganich, 2001; Overstall, Exton-Smith, Imms, & Johnson, 1977; Tinetti & Speechley, 1989), and increasing the cognitive demands during an obstacle clearance task has been associated with increased risk of tripping (Harley, Wilkie, & Wann, 2009; Weerdesteyn, Schillings, van Galen, & Duysens, 2003). When considered together as simultaneous acts within the context of gait, the effects of obstacle avoidance and carrying, in terms of the cognitive demands placed on the control system, are unknown. The demands associated with obstacle avoidance and carrying during gait may be enhanced by not only the potential need to stabilize and avoid dropping the load, but also by the potential for visual occlusion of the obstacle by the load being carried, for example when carrying a laundry basket and simultaneously navigating a cluttered environment. Many falls occur during locomotion, and tripping related to obstacles in the travel path is a contributor to these falls (Ashley, Gryfe, & Annies, 1977; Overstall et al., 1977). Although the extent to which carrying alone contributes to falling is presently unclear, better understanding of the interaction between obstacle avoidance and carrying, in terms of the cognitive demands required to control locomotion, may provide insight into the fall risk associated with performing multiple motor tasks at the same time.

An extensive body of research has demonstrated that gait and postural control draw on attentional resources, and are not as automated as was previously thought (for a review, see Woollacott & Shumway-Cook, 2002; Yogev-Seligmann, Hausdorff, & Giladi, 2008). *Attention*, in this context, is defined as an individual's information processing capacity, which is assumed to be limited (Neumann, 1984). The assumption of limited capacity is based on the observation that in dual-task situations, performance on either one or both tasks deteriorates. In the context of postural control studies, many researchers have adopted dual-task or probe reaction time (PRT) paradigms to investigate the degree to which successful performance of various postural tasks depends on cognitive resources (see supplementary Tables 1 and 2, Yogev-Seligmann et al.). Some studies have reported on the motor errors that occur when multiple motor tasks are performed simultaneously (e.g., Bloem, Valkenburg, Slabbekoorn, & Willemsen, 2001; Coppin et al., 2006). Others have reported on the combined motor and cognitive decrements that occur when a complex cognitive task is performed in concert with a postural task (e.g., Schrodt, Mercer, Giuliani, & Hartman, 2004; Weerdesteyn et al., 2003), and last, many have reported on increases in PRT during postural tasks of varying complexity (e.g., Abernethy, Hanna, & Plooy, 2002; Gage, Sleik, Polych, McKenzie, & Brown, 2003; Lajoie, Teasdale, Bard, & Fleury, 1993, 1996; Regnaux, Roberston, Smail, Daniel, & Bussel, 2006; Sparrow, Bradshaw, Lamoureux, & Tirosh, 2002). The degree to which these various paradigms are accepted as valid methods to assess the attentional demands associated with postural control is a topic of debate (Woollacott & Shumway-Cook, 2002). Some researchers believe that the only way to clarify the attentional costs of a postural task is to adopt the PRT approach in an effort to evaluate the cognitive demands associated with the postural task exclusively (Ebersbach, Dimitrijevic, & Poewe, 1995; Teasdale,

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Bard, LaRue, & Fleury, 1993). Unlike the dual-task paradigm, which may result in divided attention between the cognitive and motor tasks, using a PRT test allows attentional demands to be objectively measured while the postural task remains unaffected. It is for this reason that we chose a simple auditory PRT test to assess the attentional demands associated with carrying a load while clearing an obstacle in the present study. Although many researchers have explored the attentional demands associated with various postural tasks, no studies have addressed the ecologically important influence of load carriage on attentional demands during obstacle clearance.

Previous research suggests that carrying while navigating an obstacle in the travel path may increase attentional demands due to the requirement to regulate upper body inertia while concurrently controlling lower limb coordination in order to avoid the obstacle (Huang, Hodges, & Thorstensson, 2001; Rietdyk, McGlothlin, Williams, & Baria, 2005). Furthermore, evidence that cortical resources are required for successful obstacle clearance has been provided by visuomotor processing experiments (Drew, Andujar, Lajoie, & Yakovenko, 2008; Graci, Elliott, & Buckley, 2010; Marigold & Patla, 2007; Marigold, Weerdesteyn, Patla, & Duysens, 2007; Mohagheghi, Moraes, & Patla, 2004; Patla, 1998; Patla & Vickers, 1997, 2003). These studies suggest that precise visually guided foot placement in the approach phase (Patla & Greig, 2006), as well as peripheral vision for online fine tuning during the obstacle crossing phase (Graci et al., 2010), are critical factors in determining whether the obstacle is cleared successfully. The purpose of the present study was to investigate the attentional demands associated with obstacle clearance while performing an anterior carrying task. The complexity of the task was altered by increasing the load, as well as by visual occlusion of the obstacle by the load. A PRT test was used to measure the attentional demands associated with the lead-limb-crossing phase of obstacle clearance. The decision to focus on the lead limb at the point in time of obstacle crossing was due to this being the first opportunity for obstacle collision during the movement and therefore opportunity for tripping and falling (Eng, Winter, & Patla, 1994; Pavol, Owings, Foley, & Grabiner, 2001; Pijnappels, Bobbert, & van Dieën, 2004); furthermore, this choice of timing defined that the individual would be in single-limb support during the carrying and obstacle-crossing task. It was hypothesized that attentional demands associated with the obstacle clearance task would increase (a) in the carrying conditions (compared with the single noncarrying condition) due to interference with online visuomotor integration (Drew et al., 2008) and (b) as a function of increasing the weight of the load due to increased attentional demands required to control equilibrium while carrying and stepping over an obstacle (Huang et al., 2001; Lajoie et al., 1993; Siu, Catena, Chou, van Donkelaar, & Woollacott, 2008).

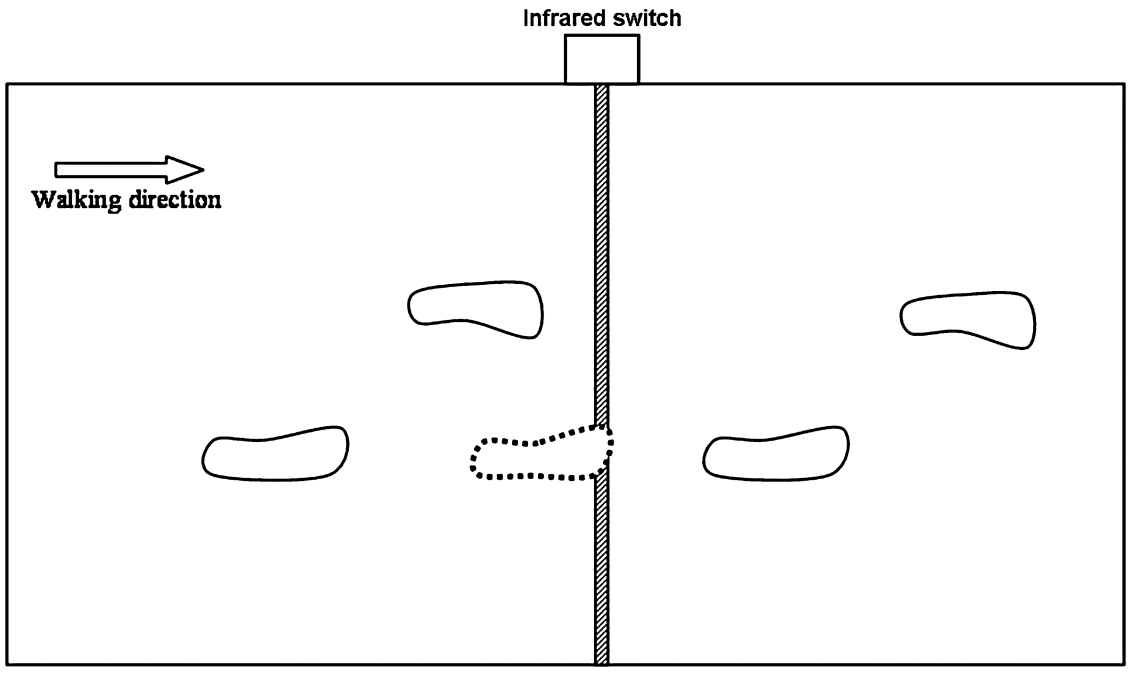

FIGURE 1. Starting position along a 7-m walkway. A starting position was determined for each participant based on preferred stride length, ensuring that the right foot was always the lead limb during obstacle crossing. An infrared switch was used to trigger the auditory signal during PRT trials. Dashed outline foot represents the right foot as the lead limb crossing the obstacle.

Method

Participants

Nine healthy men volunteered to participate in this study and provided informed consent. Participants were recruited from among the student body. Approval for the study was granted by the local Institutional Research Ethics Board. Exclusion criteria included low back injury, pain, or discomfort in the past six months, and any upper body or lower body musculoskeletal or neurological injury or impairment that might affect balance or gait. The average age of the participants was 23 years $\pm$ 1.3 years and the average height was 176 $\pm$ 5.0 cm.

Equipment and Participant Preparation

A collapsible wooden obstacle (20 cm high, 110 cm wide, and 2 cm deep) was placed in the middle of a 7 m long walkway. A starting position along the walking path was determined for each participant based on preferred stride length. The starting position was determined such that each participant had no difficulty planting his left foot prior to the obstacle and clearing the obstacle with his right foot as the lead limb. An infrared switch was used in the probe reaction time condition to trigger an audible signal (beep) during lead-limb obstacle crossing; the auditory stimulus was delivered through a loud speaker attached directly to a computer. The infrared switch was activated by breaking a beam spanning the width of the obstacle along its top edge (Figure 1). A seven-camera motion capture system was used to capture kinematic data (MX40, Vicon, Denver, Colorado, USA). Infrared reflective markers were placed on the first metatarsal and heel of the right foot, the first metatarsal of the left foot, and the superior aspect of the obstacle to calculate lead-limb obstacle-crossing kinematics (Figure 2). In the loaded conditions, participants carried a plastic box with handles at either end (Rubbermaid; 34 cm width $\times$ 50 cm length $\times$ 22 cm height; see *Protocol* section for further detail). Markers were also placed on the superior and distal aspects of the load to monitor its position, and measure the distance at which the load occluded vision of the obstacle (Figure 2).

Protocol

Participants wore a tight-fitting sleeveless shirt and shorts, and were barefoot throughout testing. Each participant completed a total of 80 walking trials; in 60 of these trials, participants were asked to carry a box bimanually positioned in front of their body. Participants were instructed to proceed walking along the pathway, and to step over the obstacle with their right foot. They were instructed to visually fixate on a mark on the wall ahead, and, for carrying trials, to hold the

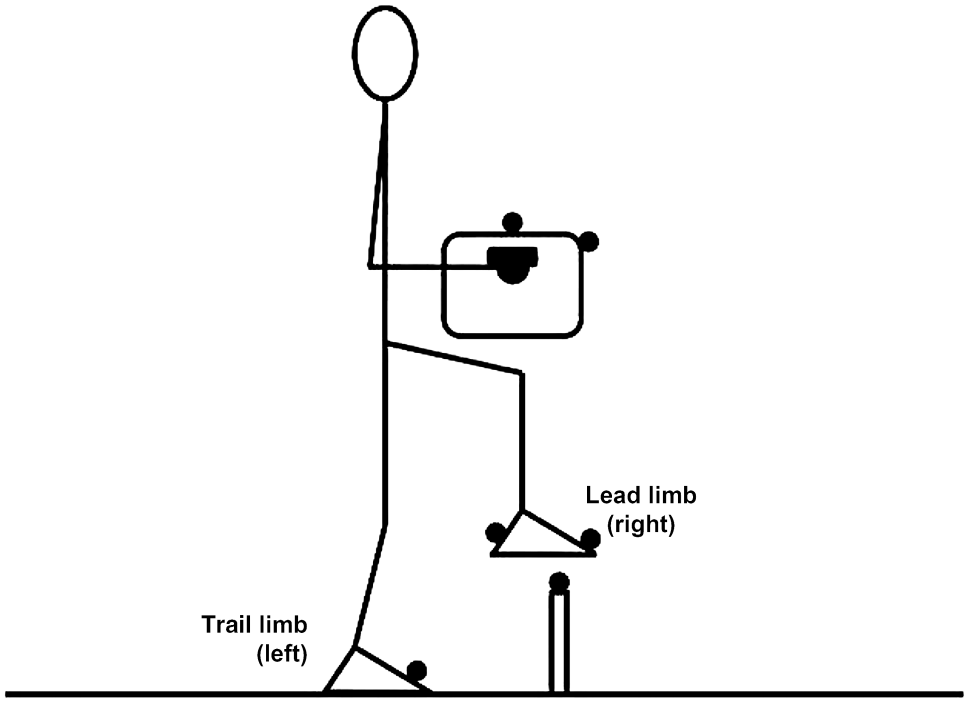

FIGURE 2. Placement of infrared reflective markers on the individual and the obstacle. Infrared reflective markers were placed at the first metatarsal and heel of the right foot, the first metatarsal of the left foot, and the superior aspect of the obstacle. Markers were also placed on the load to monitor its positioning against the abdomen.

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box against their abdomen with their elbows kept at 90°. The dimensions of the box were chosen to ensure that all participants were able to elevate the lead limb to clear the obstacle without elevating the box and without hitting the box with their knee. The anterior carrying position occluded vision of the obstacle from 1 to 1.3 m prior to obstacle clearance, approximately one full stride, in all participants. Twenty trials were completed in each of four load conditions: no load (NL), empty box weighing 2 kg (2KG), 5 kg (5KG), and 10 kg (10KG). The load was altered by using three identical boxes with differing amounts of weight inside. Of the 20 trials in each condition, 12 trials included a PRT test. In the PRT condition, an auditory tone signaled participants to provide a response; participants were instructed to respond verbally in the event that they heard the auditory stimulus, by saying the word "butter," which begins in a hard consonant that can be detected easily by the microphone used to collect the verbal response. The microphone was attached by a headpiece, and was placed directly adjacent to the mouth. The order of the trials with respect to the LOAD and PRT conditions was completely randomized. Participants were familiarized with the equipment and the protocol prior to the beginning of the experiment, which allowed the experimenters to ensure that the microphone was positioned to detect the verbal response, and that the individual participant's starting position along the walkway was appropriate to allow a normal approach to the obstacle and obstacle crossing with the right foot.

Data Processing

Kinematic data were sampled at 64 Hz; dependent measures included lead-limb toe clearance, vertical crossing velocity, horizontal crossing velocity, lead-heel obstacle distance, and trail-limb toe distance, which were calculated offline using custom software (Matlab, Mathworks, Natick, Massachusetts, USA). Lead-limb toe clearance was determined as the vertical distance between the first metatarsal marker and the obstacle marker, at the time of toe crossing over the obstacle. Lead-limb horizontal and vertical toe-crossing velocity were determined as the velocity of the first metatarsal marker in both the horizontal and vertical directions at the time of toe crossing; velocity was calculated as the first derivative of the position of the first metatarsal marker. Lead-limb heel distance was determined as the horizontal distance between the obstacle marker and the right-foot heel marker at floor contact, after obstacle crossing. Trail-limb toe distance was determined as the distance between the position of the left-toe marker and the obstacle at the point of lead-limb toe crossing. These data were used to confirm that gait patterns during obstacle crossing were not affected by performing the PRT test. The probe reaction time stimulus signal and the verbal response signal were sampled at 2880 Hz. All data were recorded using the Vicon Nexus (Version 1.3) software, and stored on a dedicated desktop computer for later processing. The latency between the stimulus onset and the participant verbal response was calculated as the reaction time, which was used to describe changes in cognitive demands associated with performing the obstacle clearance task and carrying.

Statistical Analysis

All statistical analyses were completed using SAS (SAS Institute, Cary, North Carolina, USA). To confirm that obstacle crossing kinematics were not altered as a function of performing the PRT test, a two-factor (LOAD [NL/2KG/5KG/10KG] by PRT [NO-PRT/PRT]) repeated measures analysis of variance (ANOVA) was used to investigate changes in lead-limb toe clearance, vertical and horizontal toe-crossing velocity, lead-limb heel-to-obstacle distance, and trail-limb toe distance. An ANOVA was then used to examine the effects of LOAD (four levels: NL, 2KG, 5KG, 10KG) on probe reaction time. Duncan's post hoc test was used to investigate differences between levels of LOAD.

Results

Kinematics

Performance of the PRT test did not influence gait kinematics during obstacle crossing. This was confirmed by the absence of statistical significance in comparing several obstacle-crossing gait parameters (lead-limb toe clearance, lead-limb horizontal and vertical toe-crossing velocity, lead-limb heel-to-obstacle distance, trail-limb toe distance) between the PRT and No-PRT trials. There were also no interaction effects observed between LOAD and PRT conditions for any kinematic measures, indicating that the gait pattern at each level of LOAD was not affected by performance of the PRT test. There was a significant main effect of LOAD on lead-limb toe clearance ($p = .0038$) and trail-limb toe distance ($p = .0146$). LOAD main effects are discussed in detail elsewhere (Perry et al., 2010). All kinematic results are summarized in Table 1.

PRT

PRT was affected by LOAD during obstacle clearance, $F(3, 20) = 4.1$, $p = .0203$. PRT ($M \pm SEM$) at each LOAD level was: NL, 0.261 ± 0.010 s; 2KG, 0.277 ± 0.009 s; 5KG, 0.283 ± 0.012 s; and 10KG, 0.281 ± 0.010 s. Post hoc analysis revealed that PRT in the 2KG condition was significantly greater than in the NL condition, and that PRT in both the 5KG and 10KG conditions were significantly greater than in the 2KG condition but not different from one another (Figure 3).

Discussion

Consistent with previous work, we found that the PRT test did not significantly affect any of the obstacle-crossing kinematics measured in the present study (Abernethy et al., 2002; Gage et al., 2003; Lajoie et al., 1993, 1996; Regnaux

TABLE 1. Summary of the Obstacle-Crossing Kinematics (*M*, *SE*); Performance of the Probe Reaction Time (PRT) Task Did Not Influence Gait Parameters During Obstacle Crossing

	No PRT	PRT	PRT Main effect (*F*-test, *p*-value)	LOAD Main effect (*F*-test, *p*-value)	LOAD x PRT interaction effect (*F*-test, *p*-value)
Toe clearance (mm)	164 (5)	161 (5)	$F(1,8)=0.79$ $p=0.3994$	$F(3,24)=13.67$ $p<0.0001$	$F(3,24)=0.88$ $p=0.4669$
Horizontal crossing velocity (mm/s)	122 (29)	130 (25)	$F(1,8)=1.04$ $p=0.3374$	$F(3,24)=0.84$ $p=0.4855$	$F(3,24)=0.83$ $p=0.4906$
Vertical crossing velocity (mm/s)	2878 (32)	2875 (34)	$F(1,8)=0.57$ $p=0.4723$	$F(3,24)=0.83$ $p=0.4908$	$F(3,24)=0.93$ $p=0.4434$
Lead limb heel-to-obstacle distance (mm)	305 (4)	303 (4)	$F(1,8)=0.02$ $p=0.8875$	$F(3,24)=0.29$ $p=0.8290$	$F(3,24)=1.89$ $p=0.1587$
Trail limb toe distance (mm)	171 (2)	170 (2)	$F(1,8)=0.05$ $p=0.8297$	$F(3,24)=4.29$ $p=0.0146$	$F(3,24)=0.25$ $p=0.8597$

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et al., 2006; Sparrow et al., 2002). The implication of this finding is that changes in PRT can be interpreted as an indication that the information-processing demands of the obstacle clearance task were altered (Ebersback et al., 1995; Teasdale et al., 1993). In other words, the PRT test is not a secondary cognitive task in itself and thus provides a useful measure of change in attentional demands associated with carrying in the present study. We also observed similar PRTs to previous studies using a comparable auditory reaction time test (Gage et al., 2003; Lajoie et al.), with mean PRTs ranging from 261 to 283 ms during walking trials in the present study and mean PRTs ranging from 257 ms during standing to 303 ms during walking in Lajoie et al.'s study. Furthermore, the mean PRT during sitting (baseline) recorded by Lajoie et al. was 235 ms, which is faster than our walking PRTs.

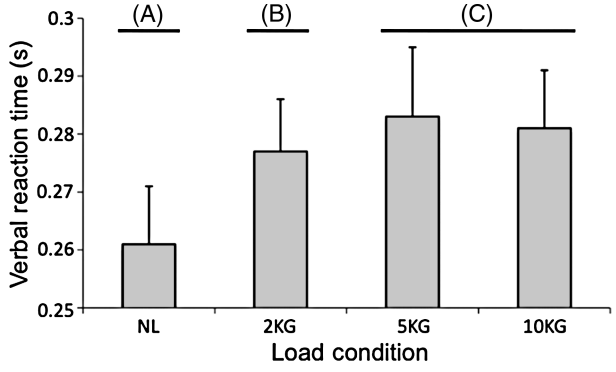

FIGURE 3. Probe reaction time (*M*, *SE*) increased significantly between the (**A**) no load (NL) and (**B**) 2KG conditions, and as the load increased to the (**C**) 5KG and 10KG conditions ($p < .05$).

The largest change in PRT observed in the present study was that between the carrying conditions (i.e., 2KG, 5KG and 10KG), during which vision was occluded while stepping over the obstacle, and the noncarrying condition (NL). This finding supports our first hypothesis (i.e., that interference with visuomotor integration during the carrying conditions increases attentional demands), suggesting that increased information-processing capacity may be required when online visual feedback is unavailable. If we consider obstacle clearance as a lower limb aiming movement, in that precise foot placement is required in order to avoid hitting the obstacle (Patla & Greig, 2006), then this movement can be divided into two phases: (a) the initial impulse phase, consisting of the primary movement of the limb toward the target; and (b) the online control phase, consisting of the use of visual feedback to correct the limb trajectory (Desmurget & Grafton, 2000; Woodworth, 1899). In the present study, we measured PRT during the second phase of the aiming movement (i.e., the phase during which limb trajectory adjustments are made using visual feedback). Because visual feedback was not available during the online control phase in the carrying conditions, participants had to rely on proprioception and visual representations (i.e., memory stores) to guide their behavior (Drew et al., 2008; Lajoie, Andujar, Pearson, & Drew, 2010; Rieser & Pick, 2002), which may be more cognitively demanding than using real-time visual feedback.

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An alternate explanation, however, for the significant increase in PRT observed during the carrying conditions in comparison to the noncarrying condition arises when considering the possibility that the CNS may treat the acts of stepping over an obstacle and maintaining upright posture while carrying as two separate tasks (Woollacott, 1993). In other words, our results support the idea that integrating the postural demands associated with carrying a load, with the voluntary activity of stepping over an obstacle draws more heavily on attentional resources than performing either one of these motor tasks on its own. Evidence for the existence of separate motor control systems for posture and voluntary movement is derived from early studies demonstrating that patients with cerebellar disorders exhibit impaired postural control, while their movement control remains intact, as well as more recent studies demonstrating that posture must be regulated in order to maintain balance during voluntary movement of the trunk and/or limbs (Babinski, 1899; Frank & Earl, 1990). These studies suggest that posture and movement are controlled independently; however, they do not address the attentional demands associated with coordinating posture and movement simultaneously. The present study provides insight into this question by demonstrating that the attentional requirements (PRT) during a voluntary movement (i.e., stepping over an obstacle) increase when the postural demands become more complex (i.e., adding an anterior load). Furthermore, the increase in PRT observed between the lighter load condition (2KG) and the heavier load conditions (5KG and 10KG) suggests that the attentional capacity required may depend on the degree to which posture has been destabilized by the weight of the carried load. This is in line with work by Lajoie et al. (1993) and others (e.g., Armstrong, 1988; Dietz, 1992; Drew, 1988; Patla, Prentice, Robinson, & Neufeld, 1991) who have shown that when the balance requirements of a walking task increase (e.g., single-support phase, stepping over an obstacle, changing speed or direction), response times increase as well, suggesting that supraspinal information processing is necessary to effectively maintain equilibrium. The concurrent increase in lead-limb obstacle clearance associated with the carried load also suggests that this particular aspect of obstacle crossing relies on attentional resources. That is, when the attentional demands of the task increase (e.g., due to carrying a load), lead-limb toe clearance increases as well, perhaps to reduce the risk of tripping as a result of contacting the obstacle (see Perry et al., 2010).

Future research is needed to investigate obstacle clearance while carrying heavier loads (greater than the maximum load in the present study; i.e., 10 kg) in order to determine if a significant load-dependent increase in PRT emerges when loads generating a more dramatic destabilization to the system center of mass are carried; in addition, potentially destabilizing influences of unstable loads (e.g., sloshing water, bags of sand) on balance control should be examined. Researchers should also address the attentional demands associated with anticipatory control during the obstacle approach phase while carrying. A limitation of the present study was the difficulty in separating the effects of increasing load from the effects of decreasing vision on the attentional demands associated with performing the task. However, because only one other study has examined changes in obstacle crossing behavior while carrying a load (Reitdyk et al., 2005), the present study adds to a very small body of literature demonstrating the important influence of carrying on obstacle crossing behavior, and describing directions for further research. To effectively interpret the degree to which occluded vision or load carriage place demands on higher level cognitive systems during obstacle clearance, studies with specific manipulations to address these issues are needed. Future research should use a transparent box or loaded frame, which allows for conditions of both vision and occlusion of the obstacle to parse the different effects of these manipulations. Last, future researchers should also include an arousal measure, such as the galvanic skin response, in order to determine if visual occlusion or load carriage during obstacle clearance is associated with increased arousal. Increased arousal due to perceived postural threat may affect the degree to which attentional resources are diverted towards the motor task and away from the PRT test (Gage et al., 2003).

The results of the present study clearly suggest that visual occlusion and increasing load during carrying while stepping over an obstacle are associated with increased attentional demands during task performance. The implications of these findings include elevated risk of tripping and falling during carrying tasks, whether performed in the home or the workplace. For example, carrying a load is a common task for warehouse workers, as are other simultaneous tasks such as checking inventory locations. The combined effects of carrying while performing an attentionally demanding task may increase fall risk in the workplace, and recognizing the link between these risk factors may represent a future approach for fall-risk reduction.

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