RESEARCH ARTICLE

The influence of carrying an anterior load on attention demand and obstacle clearance before, during, and after obstacle crossing

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Abstract
Carrying an anterior load during obstacle negotiation increases attention demand, which may differ at various crossing stages. Less is known on the impact of lower visual field obstruction and the weight of the anterior load on obstacle negotiation and attention demand. The objectives of this study were to: (1) determine if carrying a weighted anterior load, lower visual field occlusion, or both, modify obstacle clearance and/or reaction time (RT); and (2) examine whether RT is modulated across obstacle crossing phases as measured by a probe RT protocol. Sixteen young adults crossed an obstacle while carrying no load, a clear 5 kg load, and an opaque 5 kg load, while performing a simple RT task. Auditory stimuli were presented at five locations: (1) two steps before the obstacle; (2) one step before the obstacle; (3) as the leading limb crossed the obstacle; (4) as the lead limb touched down after the obstacle; and (5) as the trail limb crossed the obstacle. The toe clearance height of the leading limb was greatest for the weighted opaque box load type followed by the weighted clear box type compared to the no box load type. Carrying an anterior load during obstacle crossing did not influence RT. RTs were longer at the pre-crossing and beginning of the crossing phases compared to after-crossing phases. Results suggest that carrying a weighted anterior load and lower visual field occlusion increase the risk for tripping. Attention demands differ across obstacle crossing phases during dual-tasking and should be considered in fall-risk assessments.

Introduction

Carrying an anterior load and obstacle avoidance are often performed together (Rietdyk et al. 2005). Avoiding an obstacle while carrying an anterior load may increase cognitive as well as physical demands, which may restrict the control of gait and lead to an increased risk of tripping (Harley et al. 2009; Overstall et al. 1977). Greater opaque load sizes may further obstruct the view of the ground immediately in front of the path. Therefore, the physical demand of the anterior load in combination with the occlusion of vision of

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the obstacles may increase attentional requirements of successfully navigating and clearing obstacles (Hawkins et al. 2011).

Attention has been proposed to have a limited capacity as a deterioration in performance of one or more tasks has been observed during dual-tasking (Woollacott and Shumway-Cook 2002). Carrying an object in front of the body while negotiating an obstacle has been shown to increase attention demand, as measured by a probe reaction time (RT) technique that presented stimuli at specific locations in the navigation path (Hawkins et al. 2011). Previous work has shown longer RT when carrying 5 kg and 10 kg anterior load types relative to the 2 kg load type, suggesting that RTs are longer with greater postural demand (Hawkins et al. 2011). Lower visual field occlusion is ecologically valid, such as walking in some dim lighting situations or even carrying a large but light opaque load. Although toe clearance during obstacle crossing has been modulated by the partial visual occlusion (Rietdyk and Rhea 2006), this study (Hawkins et al. 2011) did not consider whether the partially occluded vision of the path caused by carrying the opaque load directly in front of the body would impact obstacle negotiation or attention demand.

Stepping over an obstacle can be divided into three stages (Worden et al. 2016). Pre-crossing involves approaching the obstacle; obstacle crossing consists of stepping over the obstacle; and after-crossing occurs once the trail limb has cleared the obstacle. Sparrow et al. (2002) outlined that obstacle crossing preparation demands attention. Preparing for obstacle crossing imposes alterations to the gait pattern that serves to decrease walking velocity as early as two steps prior to the obstacle (Chen et al. 1991). Additionally, foot placement must be adjusted prior to obstacle crossing relative to the obstacle parameters to maintain trunk stability during crossing (Muir et al. 2019). Other work has exhibited increased cognitive demand as observed by longer simple RT in the pre-crossing phase compared to the crossing phase (Brown et al. 2005). This suggests that information processing demands may be higher pre-obstacle crossing due to the increased feedforward information used in planning.

When navigating over an obstacle, the increased physical and cognitive demands result in observed changes in gait pattern relative to steady state walking, and therefore may not be automatically controlled (Chen et al. 1991). Anterior load carriage during obstacle negotiation is thought to increase attention demand as a function of the added load coupled with controlling the limbs, all while planning to cross the obstacle (Rietdyk et al. 2005). Carrying an anterior load creates a shift in the center of mass upwards and anteriorly and occludes vision. Increasing the weight of an anterior load can also elevate toe clearance during crossing (Perry et al. 2010). This may be attributed to the lack of vision of the obstacle and to altered stepping patterns, which results in a more conservative and adaptive response as well

as reduction in the likelihood of obstacle contact. Therefore, carrying an anterior load will likely increase toe clearance during an obstacle crossing; however, it remains unclear whether this is due to visual occlusion or to the load itself.

The overarching purpose of this study was to extend previous work (Hawkins et al. 2011; Perry et al. 2010) to examine attention demand during an obstacle crossing task while anteriorly carrying no load, a clear 5 kg load, or an opaque 5 kg load. The specific objective was to determine if the added load, the partial occlusion of the lower visual field from carrying an opaque box, or both would increase attention demand and/or obstacle clearance. The study also aimed to examine whether RT would be modulated across the three obstacle crossing phases (i.e., pre-crossing, crossing, or after-crossing) as measured by a probe RT protocol. It was hypothesized that the opaque box would result in longer RT and/or greater obstacle clearance parameters than the clear box and no box load types, as dual-tasking can lead to interference in either or both tasks. It was also believed that the clear box load type would display longer RT and/or greater obstacle clearance parameters compared to the no box load type due to the added load. Lastly, it was also hypothesized that the pre-crossing phase would exhibit greater attention demand than the crossing and after-crossing phases due to the increased information processing during obstacle crossing preparation (Brown et al. 2005).

Method

Participants

Sixteen healthy young adults participated in the experiment, with an average age of 22.1 ± 1.9 years, seven of which were males. Fourteen participants were right leg dominant and crossed the obstacle with their right leg first. The remaining two were left leg dominant and crossed the obstacle with their left leg first. This study was approved by the local Institutional Research Ethics Board. All participants signed an informed consent form and completed a health questionnaire determining past injury or condition that may have affected their static or dynamic balance. Based on these criteria, no one was excluded from participating in the study.

Equipment and participant preparation

The walking task involved obstacle crossing and was performed in a large room (18×9 m). The walking course was 8 m in length with one wooden obstacle (20 cm high, 110 cm wide, and 2 cm deep) placed 4 m away from the starting line. The start and end of the course were marked with black tape. The photoelectric cell overtop of the obstacle was triggered by breaking a beam of light that extended the width of the

room. The three-foot switches were moved according to participants' step length, two of which were placed one and two steps before the obstacle, while the other was placed one step after the obstacle. The sensors were hidden under the 4-m brown walking path covering to deter the participants from allocating attention to them and/or altering their gait pattern. The photoelectric cell and the foot switches were used to trigger a loud audible beep during the walking task. Participants were asked to verbally respond to this beep as quickly as possible with the word 'top'. The auditory signal was administered at a fixed frequency of 2850 Hz for approximately 100 ms. The word 'top' was used as a response because it begins with a hard consonant, which made the identification of the start of the response more apparent in the auditory recordings. An mp3 player was attached to the upper arm and recorded the audible stimuli as well as the response to the stimuli such that RT could be measured. A probe RT protocol was used to provide information on cognitive load at critical periods of interest (Jehu et al. 2018).

A Vicon512™ three-dimensional motion analysis system (Oxford Metrics, Tustin, CA, USA) with eight infrared high-resolution cameras was used to capture kinematic data. Fourteen reflective markers were placed on participants' left and right first metatarsal, lateral malleolus, calcaneus, lateral epicondyle, anterior and posterior superior iliac spine, and acromion. Two markers were also placed on the top corners of the obstacle and were used to calculate step clearance.

A plastic Rubbermaid™ tote was used for the opaque box load type. It was 34 cm wide, 50 cm long and 22 cm high. The 5-kg weight was placed on the side closest to the participant. The clear box consisted of a wooden shell of a box making it transparent to facilitate full vision of the travel path. The clear box was 40 cm wide, 57 cm long, and 22 cm high, with 5 kg ankle weights strapped to the bottom side of the box closest to the participant. The empty opaque box and clear box were of similar weights.

Protocol

Participants wore a tight-fitting shirt, shorts, and shoes. There were 96 trials performed: 9 control and 87 experimental. During the control trials, three consisted of walking over the obstacle with no box, three with the clear box, and three with the opaque box. The 87 experimental trials were broken down into 29 with no box, 29 carrying the clear 5 kg load, and 29 with an opaque 5 kg load. The box was carried in front of the participant with both arms at waist level. Participants walked at a comfortable pace and stepped over the obstacle with their dominant leg. The participants were asked to look straight ahead while walking and holding the box so that their elbows were bent at 90°. During the trials there was the possibility of auditory stimuli occurring at five separate locations along the course that were marked
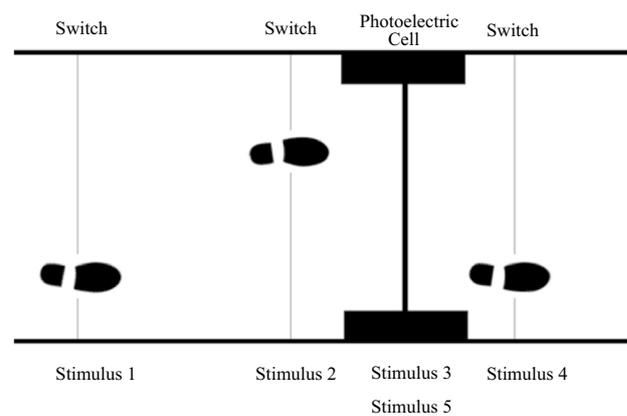
Fig. 1 Overhead view of the obstacle crossing set up. Foot switches were used for stimuli 1, 2 and 4, while a photoelectric cell detected when the lead limb crossed the obstacle (stimuli 3) and when the trail limb crossed the obstacle (stimulus 5)

with the photoelectric cell (i.e., for the leading and trailing toe) and three-foot switches (Fig. 1). The stimuli were randomly presented 1–2 times across the five stimulus locations during each of the 87 trials. In instances where two stimuli were presented within a trial, the second stimulus was not presented within one step of the first stimulus in order to provide adequate time to verbally respond. The control trials contained no auditory stimuli and were included to prevent anticipation. Before data collection, participants walked the course multiple times to familiarize themselves with the task and for the foot switches to be properly spaced. Trials where the obstacle was contacted were discarded and repeated.

Data analysis

Audacity 2.0.5 for Mac was used to calculate RT, which is the time interval between the beginning of the stimulus and the onset of the response. Minimum toe clearance height for the lead and trail limbs was calculated after reconstruction in Workspace and processed through Vicon Bodybuilder (Vicon Motion Systems Ltd. Oxford, Oxfordshire, UK). Minimum toe clearance was determined using the vertical distance between the first metatarsal and the top of the obstacle.

Statistical analysis

All data are expressed as means with standard deviations. The dependent variables of mean and variability of clearance height were analyzed using separate two-way analysis of variance (ANOVA) with repeated measures on Load Type (3 levels: no box, clear box and opaque box) and Limb (2 levels: leading limb and trailing limb). The dependent variable of RT was analyzed using a two-way ANOVA with repeated measures on Load Type (3 levels: no box, clear box

and opaque box) and Stimulus Location (5 levels: two steps before, one step before, leading limb crossing, one step after and trailing limb crossing obstacle). If Mauchly's Test of Sphericity was violated, a Greenhouse–Geisser correction was performed. Statistical significance was set at $p < 0.05$. When necessary, the least significant difference (LSD) post hoc analysis was performed to determine the location of significance. All analyses were performed in SPSS.

Results

Obstacle contacts

Table 1 reports the number of participants who contacted the obstacles and the total number of obstacle contacts across load type conditions.

Effects of carrying an anterior load on obstacle clearance

There was a load type × limb interaction effect for minimum toe clearance ($F_{(2,28)} = 7.62$, $p = 0.002$, $\eta_p^2 = 0.35$; Fig. 2). Post-hoc analyses for the leading toe revealed greater minimum toe clearance for the opaque box compared to no box load types ($t = -3.62$, $p = 0.003$), the clear box compared to the no box load types ($t = -3.02$, $p = 0.009$), and the opaque box compared to clear box load types ($t = -2.59$, $p = 0.02$). No differences in minimum trailing toe clearance emerged across load types ($p > 0.05$).
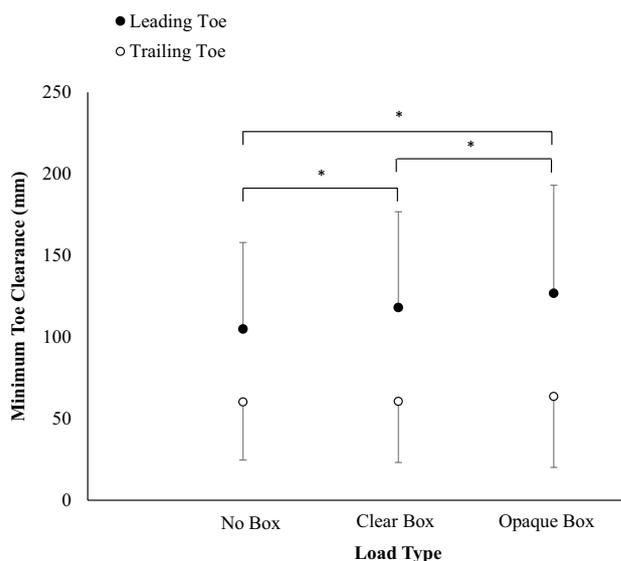
There was a main effect of load type on the minimum clearance height ($F_{(1.28,17.96)} = 4.62$, $p = 0.04$, $\eta_p^2 = 0.25$; Fig. 2). LSD post hoc analysis revealed that the minimum clearance height for the no box load type was less than the minimum clearance for the clear box load type ($p = 0.04$) and opaque box load type ($p = 0.04$). No difference emerged between the clear box and opaque box load types ($p = 0.12$).

The main effect of Limb ($F_{(1,14)} = 13.28$, $p = 0.003$, $\eta_p^2 = 0.49$; Fig. 2) revealed greater minimum toe clearance for the leading toe compared to the trailing toe.

No load type × limb interaction ($F_{(2,28)} = 1.22$, $p = 0.31$), main effect for Load Type ($F_{(2,28)} = 0.98$, $p = 0.39$), or main effect for Limb ($F_{(2,28)} = 1.73$, $p = 0.21$) emerged for the standard deviation of minimum toe clearance (see standard deviation bars in Fig. 2).

Table 1 Total number of obstacle contacts (*n*) and number of participants who contacted the obstacles (*n*) across load types

| Obstacle contacts	No box	Clear box	Opaque box
Total (*n*)	4	3	10
Participants (*n*)	3	2	6

Fig. 2 Minimum leading toe clearance (filled dot; + 1 SD) and trailing toe clearance (unfilled dot; − 1 SD) in mm for the no box, clear box and opaque box load types (*$p < 0.05$)

Effects of carrying an anterior load on RT

The main effect of Load Type on RT was not statistically significant ($F_{(2,30)} = 0.41$, $p = 0.61$) across the no box (314 ± 61 ms), clear box (311 ± 63 ms), and opaque box (315 ± 65 ms) conditions.

Effects of stimulus location on RT

The main effect of stimulus location on RT was statistically different ($F_{(4,60)} = 5.81$, $p = 0.003$, $\eta_p^2 = 0.28$; Fig. 3). Post-hoc analyses revealed RTs for stimulus locations 1, 2 and 3 were significantly greater than those of stimulus locations 4 ($p < 0.001$, $p = 0.01$, $p = 0.01$, respectively) and 5 ($p = 0.01$, $p = 0.02$, $p = 0.04$, respectively).
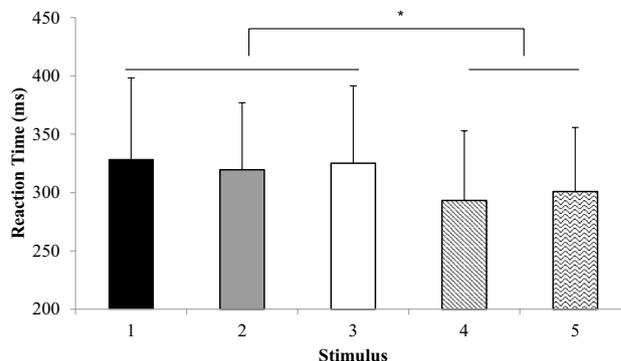
Fig. 3 Mean (+ 1 SD) reaction time (ms) for stimuli 1, 2, 3, 4 and 5 (*$p < 0.01$)

The load type by stimulus location interaction was not statistically significant ($F_{(8,120)} = 1.82$, $p = 0.08$).

Discussion

Main findings

The aim of this study was to examine attention demand and obstacle clearance height during the performance of an obstacle-crossing task while carrying a weighted clear or opaque anterior load. There were three main findings: (1) the mean toe clearance height of the leading limb was greatest when carrying a weighted anterior opaque load, followed by a weighted anterior clear load, compared to no load; (2) carrying an anterior load during obstacle crossing did not influence RT; and (3) RTs were longer for stimuli locations 1, 2 and 3 compared to locations 4 and 5.

Effects of carrying an anterior load during obstacle crossing on obstacle clearance

Carrying a weighted anterior load and the partial occlusion of the lower visual field contributed to participants adopting a cautious obstacle crossing strategy as observed by an increase in minimum toe clearance of the leading limb relative to the no box load type. Multiple factors have been shown to influence obstacle crossing parameters, such as: carrying a weighted anterior load (Hawkins et al. 2011; Perry et al. 2010), visual sampling (Timmis and Buckley 2012; Buckley et al. 2011; Rhea and Rietdyk 2007; Rietdyk and Rhea 2006; Mohagheghi et al. 2004), foot placement regulation (Patla and Greig 2006), obstacle size (Jehu et al. 2018; Chen et al. 1991; Harley et al. 2009; Patla and Rietdyk, 1993), obstacle location (Jehu et al. 2018; Diaz et al. 2018), the number of obstacles in a travel path (Berard and Vallis 2006), and dual-tasking (Jehu et al. 2018; Chen et al. 1996; Siu et al. 2008). This study confirms previous findings that carrying a weighted anterior load alters obstacle clearance parameters, as it shifts the center of mass upwards and anteriorly (Perry et al. 2010), reduces gait velocity (Rietdyk et al. 2005), reduces trunk roll velocity (Rietdyk et al. 2005), and pitches the trunk backwards as a means to increase exteroceptive information (Rietdyk et al. 2005).

Our findings also offer new insights into the visual requirements during obstacle crossing. During walking, people tend to glance at the obstacle and the region in front of it 2–3 steps before the obstacle, then shift their gaze beyond the obstacle, as opposed to looking down at the obstacle during crossing (Marigold and Patla 2007; Patla and Vickers 1997). In fact, previous work has found that continuous visual sampling during obstacle crossing may not be necessary, as individuals are capable of accommodating variations in obstacle height and depth when this information is detected several steps in advance and even as late as one step prior to obstacle negotiation (Diaz et al. 2018; Mohagheghi et al. 2004; Buckley et al. 2011; Timmis and Buckley 2012). Our study extends this work as visual sampling of the obstacle's size and location was available during the approach phase, except for approximately 1–2 steps before the obstacle due to the partial occlusion of the lower visual field caused by the opaque box, and this provoked an increase in toe clearance height.

Previous work has developed a schematic depiction of the spatial cues, computational mechanisms, and spatial representations involved in forming and implementing spatial knowledge to guide navigation (Wolbers and Hegarty 2010). Briefly, spatial cues include both environmental and self-motion cues (Wolbers and Hegarty 2010). In fact, lower visual field occlusion has modified obstacle crossing parameters compared to full vision (Kunimune and Okada 2019), which substantiates our findings as eccentric visual information of the obstacle was attenuated when carrying the opaque box relative to the clear box and no box conditions. Computational mechanisms include both spatial computations and executive processes (Wolbers and Hegarty 2010). Carrying the weighted opaque box may have increased the difficulty in obstacle clearance planning as well as computing the distance to the obstacle due to the partial lower field occlusion. Spatial representations include both online (i.e., during the trials) and offline (i.e., memory of previous trials) representations (Wolbers and Hegarty 2010). The egocentric self-reference representation codes self-to-object spatial relations in body-centered coordinates that are continuously updated as the individual moves through the environment (e.g., Bryant and Tversky 1999; Franklin and Tversky 1990). The allocentric object-to-object representation codes spatial relations among objects in the environment using an orientation-independent reference system (Sholl and Nolin 1997, p. 1497). In both the egocentric and allocentric reference frames, the opaque box condition likely increased complexity of the task by changing how the environment was visually processed due to the partial lower visual field occlusion. Therefore, the variation in spatial cues, computational mechanisms, and spatial representations across conditions may have contributed to modifications in obstacle crossing parameters.

Importantly, this study suggests that carrying a weighted anterior load and occlusion of the lower visual field immediately before obstacle crossing are important risk factors for tripping and should be included in falls-risk assessments. These findings provide a better understanding of the attention requirements involved when carrying an anterior load during obstacle negotiation and have implications for therapeutic interventions fall risk reduction.

Effects of carrying an anterior load during obstacle crossing on RT

Our results revealed no clear pattern for an effect of RT across the no box, clear box, and opaque box load types. The capacity theory assumes that dual-task interference arises from sharing limited attentional resources (Fraizer and Mitra 2008). It suggests that if attention demands exceed processing capacity, then performance on one or both of the tasks will be curtailed (Kahneman 1973). Although Hawkins et al. (2011) observed longer RTs during obstacle negotiation when participants were carrying 5 kg and 10 kg loads relative to not carrying a load, our results suggest that participants prioritized the RT task, resulting in a modification in performance of the obstacle crossing task and no changes in RT. Our results suggest that carrying an anterior load had a greater impact on changing the obstacle negotiation strategy compared to completing a RT task.

Effects of stimulus location on RT

Modulations in attention demand have been observed at various phases of obstacle clearance (Harley et al. 2009; Brown et al. 2005; Austin et al. 1999; Jehu et al. 2018; Worden and Vallis 2016). This study revealed that RTs at the pre-crossing and beginning of the crossing stages (stimuli locations 1, 2 and 3) were significantly longer compared to the end of the crossing and post-crossing stages (stimuli locations 4 and 5; Fig. 3). Pre-crossing RT has been reported to involve greater cognitive resources to develop a motor plan and reorganize the limbs before obstacle crossing (Brown et al. 2005). In contrast to previous work (Brown et al. 2005), we found similar RTs at pre-crossing and the beginning of the crossing stage, which may be attributed to the increased attention demand of carrying an anterior load coupled with negotiating the obstacle in single leg stance, thereby provoking a destabilization effect (Lajoie et al. 1993). Interestingly, faster RTs were revealed at stimulus 5 when the trail limb was crossing the obstacle compared to pre-crossing and beginning of the crossing stages. Previous work has delineated an efference copy to be a movement producing signal generated by the motor system and, together with internal models, can be used to predict the accuracy of future motor output (Jeannerod 2003). Therefore, the faster RT revealed at stimulus location 5 may be explained by the efference copy produced during the lead limb crossing, yielding reduced motor planning (Jeannerod 2003). Naturally, the post obstacle-crossing phase exhibited the fastest RTs as the increased attention demand of motor planning had already been completed. Importantly, obstacle crossing is a goal-directed task requiring continuous information processing to afford appropriate step placement, negotiation of environmental hazards, and strategy selection following unexpected perturbations. This study extends previous work suggesting that obstacle crossing is not an automatic process and requires higher level cognitive functioning (Yogev-Seligmann et al. 2008).

Limitations

This study is only generalizable to healthy young adults. The inherent limitation of the dual-task paradigm implicates the inability to ascertain whether participants prioritized one task over the other. The height of the obstacle was not adjusted according to participants' leg length; thus the level of difficulty of the task may have varied across participants. Although we counterbalanced the trials to control for order effects, it is possible that obstacle crossing strategies may have changed over the course of the experiment, particularly for trials following obstacle contact.

Conclusion

The change in obstacle crossing strategy when carrying weighted clear and opaque boxes suggests that the weight of the load and lower visual field occlusion are important risk factors for tripping. Carrying an anterior load during obstacle crossing did not influence RT, perhaps because the RT task was prioritized by participants and obstacle clearance parameters were impacted instead. Finally, differences in RT across obstacle crossing phases convey that obstacle crossing involves higher level cognitive processing. Modulations in obstacle crossing strategy and attention demand across obstacle crossing phases have important implications for fall-risk assessment.

Compliance with ethical standards

Conflict of interest The authors have no conflict of interest to declare.

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