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The effects of anterior load carriage on lower limb gait parameters during obstacle clearance

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ABSTRACT

The purpose of this study was to assess the effect of anterior load carriage on obstacle-crossing behaviour, with a focus on lower limb gait parameters. Nine male participants (age 23 ± 1.8 years, height 176 ± 5.0 cm) volunteered. Participants either walked without a load (No Load), or carried a load (2KG (empty box), 5KG, 10KG), and stepped over a 20 cm obstacle. Vision of the obstacle was obscured 1.0 m to 1.3 m prior to the obstacle. Significant correlations were found between trail limb toe distance and lead limb toe clearance, in the 2KG, 5KG, and 10KG conditions. Toe clearance increased with load (No Load, 147.3 ± 13.9 mm; 2KG, 162.5 ± 15.6 mm; 5KG, 167.6 ± 17.6 mm; 10KG, 173.9 ± 17.5 mm; $p < 0.0001$). Trail limb toe distance, trail limb toe distance variability, lead heel distance variability, and lead limb toe clearance variability were greater in the 2KG, 5KG, and 10KG conditions, compared with the No Load condition. Participants adopted a conservative gait pattern during obstacle crossing when carrying a load, evidenced by increasing toe clearance, which may have been influenced by availability of visual information regarding obstacle position. In contrast with previous literature, increased lead limb toe clearance may have been associated with absence of relative surface height difference pre- and post-obstacle crossing.

1. Introduction

Obstacle avoidance during gait is a common challenge and an essential component of successful locomotion. Navigation around, or over obstacles results in a change in the gait patterns from those observed in level walking, and potentially increases both the physical [1,2] and cognitive demands on the system [3]. Changes in system center of mass, and visual occlusion of the obstacle during anterior load carriage may add complexity to an obstacle-crossing task, resulting in adaptive gait patterns during the task, possibly to increase a margin of safety (clearance of the obstacle) to avoid obstacle contact [4–7]. The purpose of this study was to assess the influence of increasing loads carried anteriorly on lower limb gait parameters during obstacle crossing.

Previous research has demonstrated that perceptible characteristics of obstacles in the walking path influence obstacle-crossing behaviour. Generally, toe clearance values of the leading limb increase and crossing speed of the foot decreases as obstacle height increases or obstacle width increases, possibly to mitigate risk of contacting the obstacle. Distance between the heel and obstacle at heel contact after obstacle crossing increases with obstacle height [8–11]. As well, Patla et al. demonstrated that toe clearance was increased if the obstacle was perceived as being fragile in nature [12]. Availability of visual information related to the location and nature of the obstacle (e.g., obstacle height and width) has been shown to influence obstacle-crossing behaviour. Removal of visual information during the approach phase toward an obstacle resulted in a 50% failure rate during crossing, associated with incorrect placement of the trail limb foot, not incorrect lead limb elevation [13]. Periodic absence of vision during the approach phase resulted in both increased lead limb peak toe elevation and toe clearance, and increased toe-to-obstacle distance for both the leading and trail limbs [14]. Similarly, Rietdyk and Rhea [15] showed that when wearing goggles that obstructed the view of the lower limbs and the obstacle, toe clearance, horizontal distance and lead stride length all increased during obstacle crossing; when position cues were provided, lead and trail foot placement returned to full vision values, though lead toe clearance remained elevated. Patla [6], and later Rhea and Rietdyk [16] showed that visual exproprioceptive information, or visual information relating positioning of the body to the environment, not exteroceptive information, visual information of the environment, provides online guidance of foot trajectory during obstacle crossing. Increased toe clearance during obstacle crossing, in the

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absence of vision of the obstacle, likely represents a conservative adaptive response to decrease the likelihood of obstacle contact and risk of tripping.

Most research that has examined the influence of load carriage on gait parameters and obstacle avoidance has examined only posterior carriage; that is, when the load is carried on the back, such as when using a backpack [17–21]. More conservative gait patterns are demonstrated during posterior carriage, characterized by decreased stride length and by decreased single limb support time during obstacle crossing. Holbein and Redfern [4] examined anterior carrying and reported changes in whole-body center of mass displacement during gait during one-handed carrying; bilateral, hands at the side carrying; and bilateral hand at the waist carrying. Only one study has investigated the effects of anterior load carriage on lower limb gait parameters during an obstacle crossing-like task; Rietdyk et al. [22] reported that the only gait parameter affected by load during crossing of the leading edge of the step to a new level height was step width, which was increased with load. Vision of the elevated surface continuing beyond the carried load may have cued the position of the leading edge of the change in surface height (the step) and informed toe clearance requirements. No studies have examined the effect of increasing magnitude of the carried load on obstacle-crossing behaviour when stepping over an obstacle. In such a situation, the obstacle may be obscured by the carried load [6], and visual cues to inform position, height, or width of the obstacle may be absent. We anticipated that increasing load would elicit adaptive responses in the gait pattern consistent with a more conservative movement, associated with increased toe clearance of the obstacle, and reduced toe crossing speed.

The purpose of the current study was to assess the influence of increasing loads carried anteriorly on lower limb gait parameters during obstacle crossing. Vision of the obstacle was occluded by the carried load between 1.0 and 1.3 m, approximately one full stride, prior to obstacle crossing. It was hypothesized that with increasing load, evidence of increasingly conservative gait would be observed, characterized by increased lead limb toe clearance and reduced toe crossing speed.

2. Methods

2.1. Participants

Nine healthy males (age, 23 ± 1.8 years; height, 176 ± 5.0 cm) volunteered to participate, and provided informed consent. Study approval was provided by the local institutional Research Ethics Board. Exclusion criteria included: a history of low back or lower limb injury or pain within the past 6 months, and any musculoskeletal or neurological concern that might affect balance or gait.

2.2. Equipment and protocol

A seven camera motion capture system was used to record movement (Vicon, CO, USA). Infrared reflective markers were placed at the right and left 1st metatarsal and right heel, and the superior aspect of the obstacle (Fig. 1). Marker positions were sampled at 64 Hz. All data were recorded using the Vicon Nexus (version 1.3) software, and stored on a dedicated desktop computer for later processing.

Participants wore a tight fitting sleeveless shirt and shorts, and were barefoot. Participants were instructed to walk along the pathway, and to step over the obstacle with their right foot. A marker, placed on the ground three full strides from the first force plate, indicated where the participant was to start each trial. Participants completed a total of 80 walking trials, with 20 trials in each of 4 LOAD conditions; No Load (no carried load), 2KG (carrying an empty box), 5KG, and 10KG. In the 5KG and 10KG conditions, weight was added to the empty box; the load was altered by adding or removing weight prior to each trial. The dimensions of the box were 23 cm high, 60 cm wide, and 40 cm deep. The order of the trials was completely randomized. Participants were instructed to fixate their eyes ahead, at a point on the wall, and to hold the box against their abdomen with their elbows at 90°. The handholds on the box were located on the sides of the box, just inferior to the top edge of the box. In this posture, the obstacle was occluded from view between 1.0 and 1.3 m prior to obstacle crossing. All participants were able to elevate the lead limb to clear the obstacle without elevating the box. Four practice trials, one in each of the four conditions, were performed prior to data collection. The time of toe crossing at the obstacle was determined as the moment when the difference in the spatial locations of the right foot 5th metatarsal marker and obstacle marker within the plane-of-progression was minimized.

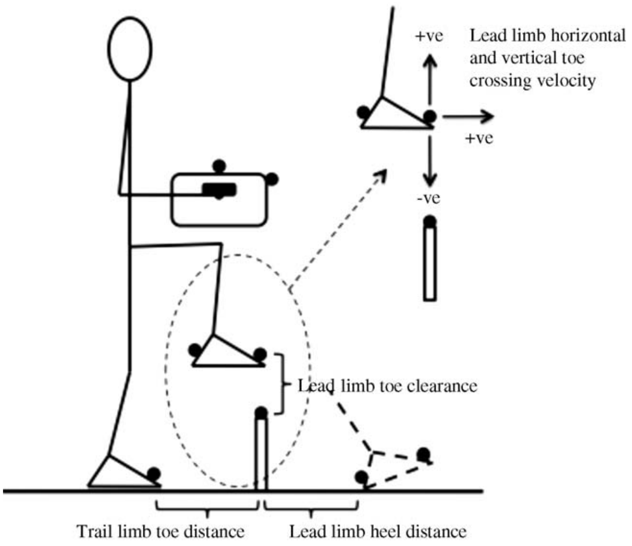

Fig. 1. Schematic diagram of methods and dependent measures. Participants were instructed to walking along the pathway and cross the obstacle with their right foot first, which was considered the "lead limb". The left was considered the "trail limb". Participants held the box against their abdomen with the elbows at 90°.

2.3. Dependent measures

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 of 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 horizontal distance between the obstacle marker and the first metatarsal of the trail limb at the time of lead limb toe crossing. These measures are described in Fig. 1. Within-subject variability was calculated for lead limb toe clearance, trail limb toe distance, and lead limb heal distance, as the standard deviation of each participant's individual performance across trials within each condition.

2.4. Statistical analysis

All statistical analyses were completed using SAS (SAS Institute, NC, USA). Pearson correlation analyses were used to examine the relationships between lead limb toe clearance and trail limb toe distance, and between lead limb toe clearance and lead limb heel distance, for each LOAD condition (No Load, 2KG, 5KG, 10KG). Repeated measures analysis of variance (ANOVA) was used to examine the effects of LOAD on the following dependent measures: lead limb toe clearance, lead limb horizontal and vertical toe crossing velocity, lead limb heel distance, trail limb toe distance, lead limb toe clearance variability, trail limb toe distance variability, and lead limb heel distance variability. In the analyses of lead limb toe clearance variability, trail limb toe distance variability, and lead limb heel distance variability, the standard deviation of each measure, for each participant was entered to the ANOVA. Statistical significance was considered at $p < 0.05$. Duncan's post hoc test was used to explore differences between levels of the LOAD condition.

3. Results

Relationships between trail limb toe distance and lead limb toe clearance, and lead limb heel distance and lead limb toe clearance: Significant correlations were observed between trail limb toe distance and lead limb toe clearance in the 2KG, 5KG, and 10KG conditions; this relationship in the No Load condition was not

Table 1
Correlation between lead limb toe clearance (TC) and trail limb toe distance (TTD) and lead limb heel distance (LHD), for each Load condition (No Load, 2KG, 5KG, and 10KG). The relationship between TC and TTD at each loaded condition (2KG, 5KG, 10KG) was significant. The relationship between TC and LHD was not significant in any condition. Statistically significant relationships are bolded, and *p*-values for each test are included in parentheses.

Load conditions		TTD	LHD
No Load	TC	−0.0352 ($p = 0.6649$)	−0.1503 ($p = 0.0629$)
2KG	TC	**0.2144** ($p = 0.0085$)	−0.0300 ($p = 0.7114$)
5KG	TC	**0.2744** ($p = 0.0006$)	0.1059 ($p = 0.1913$)
10KG	TC	**0.2443** ($p = 0.0024$)	0.1463 ($p = 0.0722$)

significant. The relationship between lead limb heel distance and lead limb toe clearance was not significant in for all LOAD conditions. These data are presented in Table 1.

3.1. *Lead limb toe clearance*

Lead limb toe clearance was significantly affected by LOAD ($p < 0.0001$). Lead limb toe clearance in the No Load condition (147.3 ± 13.9 mm) was smaller than in all other LOAD conditions; the 2KG (162.5 ± 15.6 mm) and 5KG (167.6 ± 17.6 mm) conditions were not different; lead limb toe clearance in the 10KG condition (173.9 ± 17.5 mm) was greater than all other LOAD conditions (Fig. 2).

3.2. *Trail limb toe distance*

Trail limb toe distance was lower in the No Load condition (154.3 ± 7.5 mm) than in any of the other three conditions ($p = 0.0196$; Fig. 3); trail limb toe distance in the 2KG (174.6 ± 9.8 mm), 5KG (175.8 ± 10.2 mm), and 10KG (176.2 ± 11.4 mm) conditions were not different.

3.3. *Horizontal and vertical lead toe crossing velocity*

Neither horizontal nor vertical lead toe crossing velocity was affected by LOAD ($p = 0.4855$, and $p = 0.4908$, respectively).

3.4. *Lead limb heel distance*

Lead limb heel distance was not affected by LOAD ($p = 0.8290$).

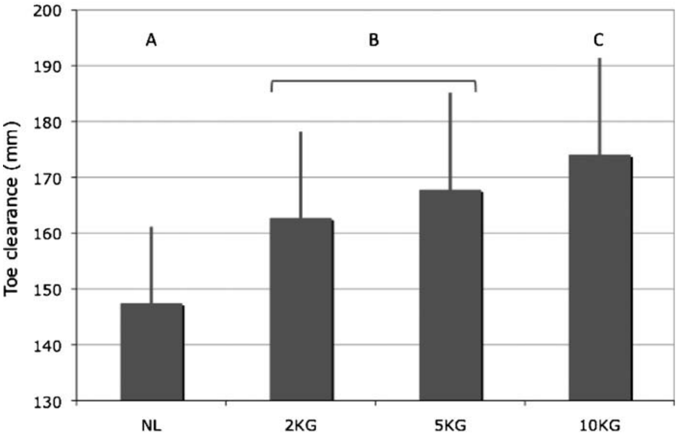

Fig. 2. Lead limb toe clearance, measured as the vertical distance between the position of the lead limb toe marker and the obstacle was significantly greater in 2KG and 5KG (162.5 ± 15.6 mm, and 167.6 ± 17.6 mm, respectively) conditions, which themselves were not different, compared with the No Load condition (147.3 ± 13.9 mm). Lead limb toe clearance in the 10KG condition (173.9 ± 17.5 mm) was significantly greater than the No Load, 2KG, and 5KG conditions. (Conditions: NL = No Load; 2KG = empty box; 5KG = 5 kg load (including weight of box); 10KG = 10 kg load (including weight of box).) Error bars represent SEM.

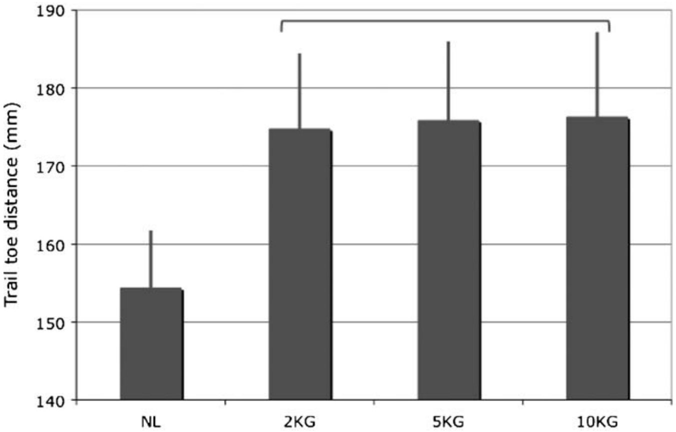

Fig. 3. Trail limb toe distance, defined as the distance between the position of the left toe marker and the obstacle, was significantly greater in 2KG, 5KG, and 10KG conditions, compared with the NL condition; trail limb toe distance was not different between the 2KG, 5KG, and 10KG conditions. (Conditions: NL = No Load; 2KG = empty box; 5KG = 5 kg load (including weight of box); 10KG = 10 kg load (including weight of box).) Error bars represent SEM.

Table 2
Mean within-subject variability, calculated as mean of participants' standard deviations within each LOAD condition, for lead limb toe clearance (TC), trail limb toe distance (TTD), and lead limb heel distance (LHD). For each dependent measure, variability was significantly lower in the No Load condition, compared with the other three conditions, and not different between the 2KG, 5KG, and 10KG conditions. SEM is included in parentheses. The *p*-values for each LOAD main effect are included for each measure below the each column heading.

Load conditions	Variability (mm)		
	TC ($p = 0.0113$)	TTD ($p = 0.0182$)	LHD ($p = 0.0002$)
No Load	17.1 (0.93)	22.7 (2.13)	30.4 (1.73)
2KG	22.2 (1.94)	31.6 (1.55)	39.7 (2.82)
5KG	21.9 (0.43)	33.4 (1.20)	43.0 (3.06)
10KG	24.2 (1.52)	30.8 (1.58)	39.7 (3.60)

3.5. *Variability of lead limb toe clearance, lead limb heel distance, and trail limb toe distance*

Lead limb toe clearance variability, lead limb heel distance variability, and trail limb toe distance variability ($p = 0.0113$, $p = 0.0182$, and $p = 0.0002$, respectively) were each affected by LOAD (Table 2). For each of these dependent measures, the variability in the No Load condition was lower than in each of the loaded conditions; the three loaded conditions were not different from one another.

4. Discussion

The focus of this study was to determine the effect of carrying a load in an anterior position on lower limb gait parameters during obstacle crossing. Anterior carriage during obstacle crossing is a common challenge, frequently performed in the contexts of, for example, negotiating a cluttered floor while carrying a laundry basket, or moving about in a busy work site. Previous research has clearly demonstrated that toe clearance is adjusted based on a number of factors, including vision of the obstacle, dimensional characteristics of the obstacle, and visual cues related to obstacle location when vision of the obstacle is lost, among others. The main finding of the current study was that increased magnitude of the carried load resulted in increased toe clearance of the obstacle;

lead limb toe clearance increased by 10% between the No Load condition and the lightest (2KG) carrying condition, and again by an additional 7% in the heaviest (10KG) carrying condition. Additionally, the current study confirmed that absence of vision of the obstacle strengthened the relationship between foot placement and toe clearance, as seen in previous research, and increased intra-individual variability in measures of toe clearance, trail limb foot placement, and lead limb foot placement after obstacle crossing. The results of the current study confirm the effect of increasing the carried load on toe clearance during obstacle crossing, and suggest a trade-off between balance control and obstacle avoidance during the obstacle-crossing task, as discussed further, below.

Previous research has demonstrated the strong influence of visual information in determining obstacle-crossing behaviour. Mohagheghi et al. [14] demonstrated the effects of visual sampling during the obstacle approach phase; when vision of the obstacle was not available in the final two steps prior to the obstacle, individuals increased obstacle toe clearance. Coupling between both trail and lead limb placement, and trail and lead limb toe clearance, respectively, was also shown. Rietdyk and Rhea [15] demonstrated similar increases in toe clearance, trail limb horizontal distance, and lead limb stride length in the absence of vision of the obstacle. They reported that provision of visual obstacle position cues, without vision of the obstacle itself, allowed trail limb horizontal distance to return to full vision levels, though lead limb toe clearance remained elevated. In the current study, vision of the obstacle was not available within the final 1.0 to 1.3 meters prior to the obstacle and throughout obstacle crossing, as vision of the obstacle was obstructed by the carried load. Consistent with the previous literature, toe clearance and trail limb foot placement were increased when carrying a load. As well, in absence of vision of the obstacle, participants demonstrated increased intra-individual variability in lead limb toe clearance, and trail limb and lead limb foot placement, further confirming the controlling role of vision, when available, in determining obstacle-crossing behaviour. Not previously reported in the literature, toe clearance of the obstacle increased as the carried load increased. While the influence of vision of the obstacle is clearly a determinant in setting obstacle-crossing behaviour, increased toe clearance with increased load provides new insight into the strategic trade-off between balance control and obstacle avoidance, discussed further, below.

Consistent with previous findings, absence of vision of the obstacle was associated with an increase in the strength of the relationship between toe clearance and trail limb foot placement prior to the obstacle. Patla and Greig [13] reported that failure during obstacle crossing, i.e., foot contact with the obstacle, was associated with incorrect trail limb foot placement, not incorrect lead limb foot elevation, when vision of the obstacle was reduced. Mohagheghi et al. [14], and Rietdyk and Rhea [15] reported significant relationships between lead limb horizontal distance (prior to obstacle crossing) and lead limb toe clearance. Rietdyk and Rhea also suggested an effect of decreased visual information of the trail limb at the time of trail limb foot placement on trail limb obstacle clearance. In the current study, therefore, we examined the relationship between trail limb foot placement, for which vision was absent, and lead limb toe clearance. As Patla and Greig [13] suggested that failure during crossing was due to incorrect trail limb foot placement, we expected a strong relationship between trail limb foot placement and lead limb obstacle clearance, which we observed in each of the load carrying conditions. Not surprisingly, this relationship was not present in the No Load condition when full vision of the obstacle was available; though participants were instructed to fixate on a point straight ahead, peripheral vision is known to be adequate for providing expropprioceptive cues in controlling lower limb movement during obstacle crossing [23,24].

There exists an inherent challenge and potential trade-off between the control of balance, and the avoidance of obstacle contact and tripping during obstacle crossing. During obstacle crossing, elevation of the lead limb and, in the case of the current study, the position of the carried load, both serve to increase the height and anterior position of the system (body + load) center of mass, providing further challenge to balance control. A trade-off between the priorities of balance control and lead limb elevation, as a determinant of obstacle avoidance, is likely. Rietdyk et al. [22] have provided the only analysis to date of this relationship between balance control and obstacle avoidance. They reported that they saw no change in toe clearance during obstacle crossing while carrying a load, but did observe a change in control of balance as indicated by reduced trunk segment roll and increased trunk pitch. Those results suggest prioritization of balance control during obstacle crossing. They also suggested that surface height cues may have been obtained by vision of the continuing, elevated surface. We observed increased toe clearance with increased load, and suggest therefore that participants demonstrated a shift in emphasis toward obstacle avoidance in the current study. The differences in the results of these two studies might reveal a previously unexplored determinant in the control of obstacle crossing; the relative height of the surface after the obstacle. In the paper by Rietdyk et al. [22], participants were asked to step to a new level, similar to stepping over a street curb, and continue walking. The peak height of the foot relative to the new walking surface would have been small, compared with the height of the foot after obstacle crossing in the current study when participants continued walking at the same level, i.e., no relative height difference between the pre- and post-obstacle walking surfaces. Increased foot height after the obstacle in the current study may have been more threatening, because in the event of contact with the obstacle, any balance recovery movement of the lead limb would require more time, as the foot is higher off of the floor. This increased time would be expected to result in larger linear and rotational body segment velocities during balance recovery. Larger forces at foot contact, and larger muscle moments throughout the kinetic chain would be required to effectively arrest body movement to prevent falling, which would be inherently more challenging to the balance control system. Relative surface height differences between the two studies might explain the differences in adaptive gait behaviour during obstacle crossing. In the current study, increased toe clearance with increased load may reflect a shift in emphasis toward obstacle avoidance, predicated on a lack of difference between pre- and post-obstacle walking surface heights.

The focus of the current study was to characterize the effect of increasing carried load on obstacle-crossing behaviour. Whole-body movements were not measured, nor were ground reaction forces. New insights into trade-offs between balance control and obstacle avoidance, predicated on control of the carried load, successful lead limb toe clearance, and avoidance of unplanned, challenging movements and forces in the event of obstacle contact, can be further tested by manipulating relative surface height and further increasing the carried load. As well, use of a very light weight box structure, possibly constructed of cardboard, as a “no load/decreased vision” condition, and use of a weighted, transparent box, as a “loaded/full vision” condition, would help to further elucidate the relationships between availability of vision, and load carriage in the control of adaptive gait during obstacle crossing. Addition of whole-body kinematics and measurement of ground reaction forces prior to and following obstacle clearance will provide insight into the control of movement throughout. The implications of previously published literature, the results of the current study, and such proposed future research include basic understanding of the control of human movement and adaptive movement, and design of the built environment to reduce fall risk and enhance safety.

Conflict of interest

None of the authors have any financial interest in this work, nor any potential conflict of interest or appearance of conflict of interest with regard to this work.

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