Control of adaptive locomotion: effect of visual obstruction and visual cues in the environment

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Abstract:

Visual information regarding obstacle position and size is used for planning and controlling adaptive gait. However, the manner in which visual cues in the environment are used in the control of gait is not fully known. This research examined the effect of obstacle position cues on the lead and trail limb trajectories during obstacle avoidance with and without visual information of the lower limbs and obstacle (termed visual exproprioception). Eight subjects stepped over obstacles under four visual conditions: full vision without obstacle position cues, full vision with position cues, goggles without position cues and goggles with position cues. Goggles obstructed visual exproprioception of the lower limbs and the obstacle. Position cues (2 m tall) were placed beside the obstacle to provide visual cues regarding obstacle position. Obstacle heights were 2, 10, 20 and 30 cm. When wearing goggles and without position cues, a majority of the dependent measures (horizontal distance, toe clearance and lead stride length) increased for the 10, 20 and 30 cm obstacles. Therefore lower limb–obstacle visual exproprioception was important for the control of both limbs, even though with normal vision the trail limb was not visible during obstacle clearance. When wearing goggles, the presence of position cues, which provided on-line visual exproprioception of the self relative to the obstacle position in the anterior–posterior direction, returned lead and trail foot placements to full vision values. Lead toe clearance was not affected by the position cues, trail clearance decreased but was greater than values observed during full vision. Therefore, visual exproprioception of obstacle location, provided by visual cues in the environment, was more relevant than visual exproprioception of the lower limbs for controlling lead and trail foot placement.

Keywords: Gait adaptations, Stabilit, Vision, Locomotion

Article:

Introduction

In order to coordinate movement within the environment, visual information is needed for planning and ongoing control. Understanding the manner in which visual cues from the environment are used is critical to our understanding of visual control of human locomotion. During obstacle crossing, Patla (1998) found that direct visual information of the lower limb and the limb's position in the environment (termed visual exproprioception) was important for the control of the swing limb trajectory, as visual obstruction of the lower limb resulted in placing the foot farther away from the obstacle, biased the swing limb upwards and decreased precision control of the swing limb. In contrast, during stepping up to a platform with visual obstruction, the lead and trail limb trajectories were not affected, indicating that while lower limb–obstacle visual exproprioception was sufficient, it was not necessary to maintain the swing limb trajectory (Rietdyk et al. 2005). The latter paper proposed that visual cues available from the platform, which were not available from the obstacle, could have been used to control the swing limb trajectory. For example, the visual obstruction prevented the subject from seeing the leading edge of the platform as the subject came within two steps, but the remainder of the platform was visible and could have provided cues regarding location and height of the platform. This proposal is consistent with the observation that visual structure surrounding a target facilitated memory-guided reaching (e.g., Krigolson and Heath 2004).

A logical progression of these studies would be to examine if visual cues in the environment are used in the control of adaptive locomotion. Obstacle crossing is a well-studied paradigm which provides useful information regarding the control of adaptive gait (e.g., Chen et al. 1991; Patla and Rietdyk 1993; Patla 1998; Vallis and McFadyen 2005). In this study, visual structure during obstacle crossing was increased with cues regarding obstacle position: vertical references (2 m high) were placed on each side of the obstacle to enhance visual information regarding obstacle position. Goggles obstructed visual exproprioceptive information of the lower limbs and the environment immediately in front of the subject. Adding position cues provided visual exproprioception of the eyes/head relative to the obstacle position. This paper specifically examines if visual cues, in the absence of lower limb exproprioception, influence the lower limb trajectories during obstacle avoidance.

Key measures to examine the control of lower limb trajectories are the position of the foot relative to the obstacle at foot placement (horizontal distance), stride length and the vertical distance between the toe and the obstacle during the swing phase (toe clearance). These measures are affected by visual information (Mohagheghi et al. 2004; Patla 1998) and obstacle properties (Patla and Rietdyk 1993; Patla et al. 1996). In addition, correlations between horizontal distance and toe clearance reflect the association between visual and kinesthetic inputs (Mohagheghi et al. 2004). Multiple obstacle heights (from 2 to 30 cm) were examined as repeated exposures to the same obstacle resulted in decreased clearance (Rhea and Rietdyk 2005).

Subjects stepped over obstacles both with and without goggles and with and without position cues. Based on previous research, we hypothesized that wearing goggles without position cues in place would result in increased horizontal distance, toe clearance and stride length for all obstacle heights. With full vision, we hypothesized that the position cues would not alter the dependent measures, as we did not expect that position cues would provide more information than available with full vision. We hypothesized that with obstructed vision due to wearing goggles, the position cues would reduce the horizontal distance to values similar to full vision. The position cues provided no information regarding obstacle height, and we did not expect that the position cues would directly reduce limb elevation. However, decreased horizontal distance is associated with lower toe clearance (Mohagheghi et al. 2004). Therefore, we also hypothesized that foot clearance would be reduced as a function of the position cues while wearing goggles.

Methods

Procedures of this study were approved by the Institutional Review Board of Purdue University. Eight subjects participated with informed consent. Subjects included five females and three males (age 22.9 ± 3.6 years (mean ± standard deviation); mass 63.3 ± 9.4 kg; height 1.70 ± 0.10m). All participants were free from any known neurological or orthopedic disorders or any impediments to normal locomotion, as verified by self-report. Subjects had normal or corrected to normal vision. Four infra-red emitting diodes were placed on the lateral aspect of the right toe and heel and medial aspect of the left toe and heel of their shoes. Two diodes were placed on the head (on the goggles) and one diode was placed on the top of the obstacle. Position data were recorded at 60 Hz with two Optotrak 3020 sensors (NDI, Waterloo, ON, Canada).

The independent variables were goggles, position cues and obstacle height. The two goggle conditions were full vision (no goggles) and goggles, the position cues were either present or not and five obstacle heights were examined (2, 10, 20, 30 cm and a no obstacle condition). A full factorial design was implemented, resulting in 20 conditions (2 goggles by 2 position cues by 5 obstacle heights). Cartoon drawings of the goggle and position cue conditions are provided in Fig. 1. The goggles were horizontal blinders that obstructed vision of the lower limbs and ground immediately in front of the subject (approximately 1.2 m; represented as shaded area in Fig. 1b, d). Position cues were constructed of PVC tubing (6 cm diameter, 2 m in height) and painted black to increase contrast relative to the visual background. The position cues were placed beside the obstacle, 96 cm apart (similar to the width of a typical doorway). The position cues were visible when wearing the goggles and provided information regarding obstacle position even when the obstacle was not visible due to the goggles (Fig. 1d). Obstacles (90 cm wide and 0.5 cm deep) were manufactured from masonite, painted black and designed to tip if contacted, reducing the possibility of a fall. One hundred and sixty completely randomized trials were completed by each subject (eight trials of each condition). Subjects walked at a self-selected pace down an 8 m walkway. The start position was determined during initial trials without the obstacle in place, such that the subject would not step directly on the obstacle if they did not modify their strides during approach.

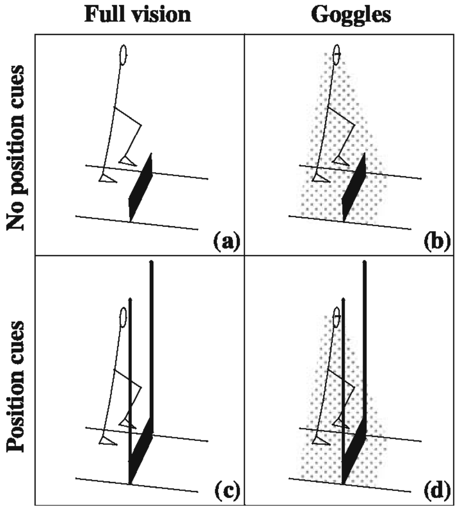

Fig. 1 Cartoon diagram of the four visual conditions. Full vision (no goggles) without position cues (**a**), goggles without position cues (**b**), full vision with position cues (**c**), goggles with position cues (**d**). The *shaded areas* in (**b**) and (**d**) represent the area of visual obstruction due to the goggles

Subjects self-selected which foot, right or left, would cross the obstacle first (lead foot), but they were required to maintain that foot as the lead foot throughout all trials. No practice trials with the obstacles or goggles were given. If a subject felt their balance was compromised by the goggles, they could immediately flex their neck to view the obstacle. However, we did not want subjects to flex the neck during crossing unless necessary, therefore, subjects were instructed to look ahead and step over the obstacle as they would while walking normally. This instruction is consistent with natural behavior, as subjects fixate on the obstacle during approach but not during crossing (Patla and Vickers 1997). Although a no obstacle condition was observed, only the obstacle trials are examined in this paper.

The position data was filtered at 6 Hz with a fourth-order zero-phase-shift low-pass Butterworth digital filter (Winter 1990). Dependent variables included lead and trail foot horizontal distance (horizontal distance of the toe to the obstacle in the steps immediately preceding the obstacle), lead stride length (see icons in Fig. 2), and lead and trail toe clearances (vertical difference between the toe and obstacle as the toe cleared the obstacle) (see icons in Fig. 3). Trail stride length could not be determined as the trail foot was out of view at trail foot contact following obstacle clearance for about half the trials. The absolute head angle in the sagittal plane (pitch) was determined relative to horizontal. Head pitch range of motion (the range from maximum to minimum) was determined for one stride (from lead heel contact before the obstacle to lead heel contact after the obstacle).

Before we could determine if position cues compensated for lack of visual exproprioception from the lower limbs, we needed to confirm that wearing goggles without position cues in place affected the dependent measures similarly for all obstacle heights. Therefore, we compared the conditions without position cues with a two-factor analysis of variance (goggles by obstacle height). The effect of goggles differed between obstacle heights for lead horizontal distance, lead stride length, lead and trail toe clearances ($P \leq 0.037$) but not for trail horizontal distance ($P = 0.22$). Post hoc analyses revealed that for the 2 cm obstacle, wearing goggles significantly increased lead toe clearance and trail horizontal distance, but decreased trail toe clearance, lead horizontal distance and lead stride length, although the decreases were not significant. For the 10, 20 and 30 cm obstacles, all measures increased, with one exception for the 10 cm obstacle (decreased lead stride length, not significant). These findings generally support our first hypothesis for the larger obstacles, but not the 2 cm obstacle. Therefore, we excluded the 2 cm obstacle from further analyses as the effect of wearing goggles was different relative to the 10, 20 and 30 cm obstacles.

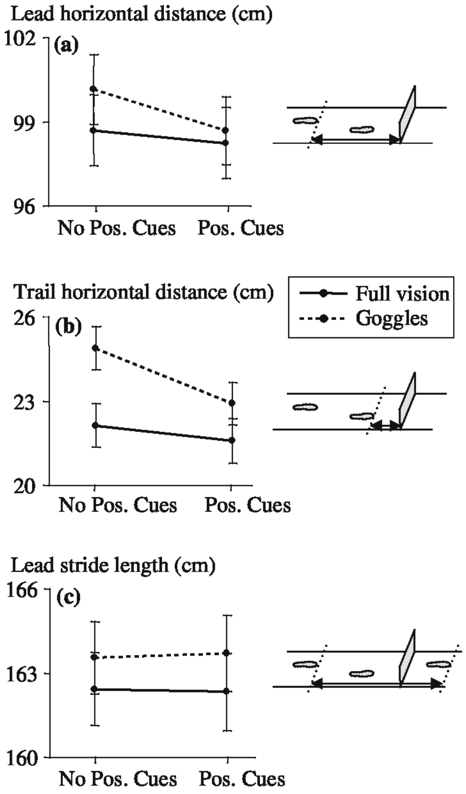

Fig. 2 Lead horizontal distance (**a**), trail horizontal distance (**b**) and lead stride length (**c**) as a function of position cues (*Pos. Cues*) and goggles (full vision: *solid line*; goggles: *dotted line*). *Error bars* represent standard error. *Icons* on right side of figure provide a representation of the dependent measure

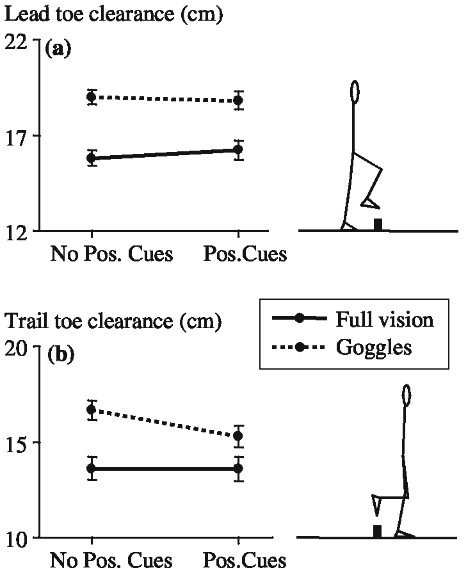

Fig. 3 Lead toe clearance (**a**) and trail toe clearance (**b**) as a function of position cues (*Pos. Cues*) and goggles (full vision: *solid line*; goggles: *dotted line*). *Error bars* represent standard error. *Icons* on right side of figure provide a representation of the dependent measure

A three factor (goggles by position cue by obstacle height) within-subject repeated measures analysis of variance was conducted for each dependent variable. Duncan's multiple range tests were used to determine significant relationships among variables. The significance level was set to $P \leq 0.05$. For each of the four conditions (Fig. 1), a Pearson correlation analysis was conducted to determine the association between horizontal distance and toe clearance for the lead and trail limbs. Before correlations were conducted, horizontal distance and toe clearance were normalized to body height.

Results

All subjects contacted the obstacle one or two times (total of 12 contacts or 1.2% of all trials). All contacts were with the trail foot. Half of the contacts were with full vision, half were with goggles. When collapsed across obstacle height, five contacts (41.7%) occurred during full vision without position cues, one contact (8.3%) occurred during full vision with position cues, one contact (8.3%) occurred in the goggles without position cues condition and five contacts (41.7%) occurred in the goggles with position cues condition. When collapsed across visual conditions, nine contacts (75%) occurred with the 30 cm obstacle, two contacts (16.7%) with the 20 cm obstacle, one contact (8.3%) with the 10 cm obstacle and zero contacts with the 2 cm obstacle. No change in head pitch range of motion was observed between goggles and no goggles ($P = 0.64$).

No significant three-way interactions (goggles by position cue by obstacle height) were observed ($P > 0.12$). Therefore, we examined the two-way interaction, goggles by position cue, to determine if the position cues had an effect on the dependent variables, and if that effect was dependent on wearing goggles.

Foot placement before the obstacle

The effect of position cues on horizontal distance was dependent on goggles ($P = 0.026$ and $P = 0.019$, for lead and trail horizontal distance, respectively; Fig. 2a, b). Post hoc analyses revealed that with full vision, these measures were not affected by the position cues. When wearing goggles (without position cues), both feet were placed at a greater distance from the obstacle. With goggles and position cues, horizontal distances for both feet were not different from full vision without position cues.

Lead stride length

A significant goggle by position cue interaction was not observed for lead stride length ($P = 0.40$; Fig. 2c). Lead stride length increased while wearing goggles (main effect of goggles, $P < 0.000\ 1$), and was not affected by the position cues (main effect of position cue, $P = 0.94$).

Foot clearance over the obstacle

A significant goggle by position cue interaction was not observed for lead toe clearance ($P = 0.08$; Fig. 3a). Lead toe clearance increased while wearing goggles (main effect of goggles, $P < 0.000\ 1$), and was not affected by the position cues (main effect of position cue, $P=0.53$). A significant interaction (goggle by position cue) was observed for trail toe clearance ($P=0.018$; Fig. 3b). Post hoc analyses revealed that with full vision, trail toe clearance was not affected by the position cues. When wearing goggles and without position cues, trail toe clearance was larger. Trail toe clearance significantly decreased when position cues were available while wearing goggles, but did not return to full vision values.

Correlation of horizontal distance and toe clearance

In the trail limb, significant correlations were observed between horizontal distance and toe clearance for all four conditions (Table 1). For the lead limb, small but significant correlations were observed for all conditions except full vision with position cues (Table 1). Note that correlations were typically lower for the lead versus the trail limb.

In summary, with full vision, the dependent measures were not modified by the position cues. All variables increased as a function of wearing goggles. When subjects wore goggles and position cues were available, lead and trail horizontal distance returned to full vision values and trail toe clearance decreased; lead toe clearance and lead stride length were not affected.

Discussion

With full vision, subjects have visual on-line information of the lower limbs and the obstacle, which the subject uses to control the lower limbs (Mohagheghi et al. 2004; Patla 1998). However, the control of adaptive gait as a function of visual cues in the environment is not fully known. The discussion first focuses on the modified gait variables due to wearing goggles (i.e., obstruction of lower limb-obstacle visual exproprioception), and then examines the effect of position cues (i.e., visual exproprioception of eyes/head relative to obstacle position).

Table 1 Correlation between horizontal distance (HD) and toe clearance (TC) for leading (L) and trailing (T) limbs in each of the four conditions

	Full vision		Goggles	
	LTC	TTC	LTC	TTC
No position cues				
LHD	0.31**	–	0.28**	–
THD	–	0.40**	–	0.37**
Position cues				
LHD	0.14	–	0.33**	–
THD	–	0.23*	–	0.33**

$^{*}P < 0.01$; $^{**}P < 0.001$

Obstruction of lower limb–obstacle visual exproprioception increased horizontal distance, toe clearance and lead stride length.

With obstructed vision and without the position cues, subjects could estimate the position and height of the obstacle during the approach before the obstacle was obscured by the goggles, but did not receive on-line visual information of the obstacle and lower limbs during placement and clearance. Subjects compensated for reduced visual information by increasing lead horizontal distance and clearance, which appears to be a strategy to reduce the likelihood of contact with the obstacle when obstacle location was uncertain (Patla 1998). The amount the stride length increased (1.1 cm) was similar to the increase in lead foot placement (1.5 cm), therefore the post-crossing placement of the foot was not substantially altered. The increased lead foot placement and toe clearance are consistent with the literature for obstruction of lower limb visual exproprioception with goggles (Patla 1998) and complete removal of vision during the approach phase (four steps before the obstacle) (Mohagheghi et al. 2004).

The increased trail horizontal distance and clearance also reflect a safer response, allowing more time to flex the limb to provide adequate clearance (Patla et al. 1996) and decreased risk of contact (Chou and Draganich 1998). Increased trail toe clearance and horizontal distance are consistent with results when vision was completely removed during the approach phase (Mohagheghi et al. 2004). To our knowledge, trail limb measures have not been examined with goggles. The increased trail toe clearance as a function of goggles is especially interesting as the trail limb and obstacle were not visible during crossing either with or without goggles, that is, the visual information would be the same. However, visual information would be different during placement of the trail foot: the trail limb and obstacle were visible with full vision, but were not visible with goggles. We believe that the increased trail toe clearance was a function of decreased visual information at trail foot placement rather than decreased visual information during obstacle crossing, consistent with observations of Mohagheghi et al. (2004). These researchers manipulated vision during obstacle avoidance: trail toe clearance was not modified with full vision during approach and no vision during crossing, but trail toe clearance increased with no vision during approach and full vision during crossing.

Increases in the dependent measures were observed for the 10, 20 and 30 cm obstacles as a function of goggles, but the 2 cm obstacle did not show similar increases in all variables. The interaction may be related to the relatively low risk of tripping on the 2 cm obstacle, and that only small modifications to the swing trajectory were needed to clear the obstacle. Also, the 2 cm obstacle would have been lost to view earlier during the approach phase than the taller obstacles. Therefore, there may have been less reliance on on-line visual information for the 2 cm obstacle, even with full vision.

Visual cues regarding obstacle position compensated for obstructed lower limb–obstacle visual exproprioception for both lead and trail foot placement.

When position cues were in place, they provided on-line position of the eyes/head relative to the obstacle in the anterior–posterior direction. This visual exproprioceptive information could theoretically be combined with somatosensory information of foot position relative to the head to facilitate foot placement. If this were the case, horizontal distances would not be different from those observed during full vision. We found that lead and trail horizontal distances did, in fact, decrease to full vision values when position cues were present. Since increased horizontal distance was observed both with complete withdrawal of vision (Mohagheghi et al. 2004) and when visual information of the lower limb was obstructed (Patla 1998), Mohagheghi et al. (2004) had suggested that changes in foot placement were most likely due to lack of visual information about lower limb movements and not about the obstacle. However, the findings reported here indicate that visual exproprioceptive information of obstacle location relative to the self compensated for loss of visual information about lower limb movement. It is even possible that with full vision the subjects were using visual exproprioception of the obstacle relative to the head, rather than relative to the feet, or some combination of both, to facilitate foot placement.

When stepping up onto a platform with visual obstruction, the lead and trail limb trajectories were unaffected (Rietdyk et al. 2005). We had proposed in the earlier paper that visual cues from the platform, which were not available from an obstacle, could have been used control to the swing limb trajectory. The results reported in this study, compensation in foot placement as a function of position cues, are consistent with this proposal. The changes in foot placement are parallel to memory-guided reaching tasks where enhanced visual backgrounds facilitated the reaching trajectory (e.g., Krigolson and Heath 2004). In summary, visual exproprioception of the lower limbs was less important for controlling lead and trail foot placement than visual exproprioceptive information of the obstacle location.

Lead toe clearance was not affected by position cues, and appeared to be controlled in a feedforward manner with visual obstruction and position cues

While position cues with visual obstruction did alter horizontal distance, they did not alter the lead toe clearance, which was consistent with the fact that the position cues do not provide information regarding obstacle height. In addition, the stride length did not return to full vision values. That is, while the subject used on-line visual information to place the lead foot closer to the obstacle, the same large trajectory was subsequently observed, such that the post-crossing placement was farther away from the obstacle. The larger response ensured safety, keeping the lead toe and heel from contacting the obstacle. The lack of change in lead toe clearance is consistent with the concept that lead limb elevation is more dependent on on-line visual cues, presumably received from the knee in the peripheral visual field (Patla 1998). Evidence of on-line modification of lead limb elevation based on visual input has been observed in recent research (Mohagheghi et al. 2004; Perry and Patla 2001). The decreased lead horizontal distance, without a parallel decrease in toe clearance, highlights that increased lead limb elevation as a function of visual obstruction was not simply a consequence of increased horizontal distance, despite significant correlations between lead toe clearance and horizontal distance observed in the current study and in previous research (Mohagheghi et al. 2004). In summary, visual exproprioception of the lower limbs (which may include information of lower limb relative to obstacle) appears to be more important for controlling lead toe clearance than exproprioceptive information regarding obstacle position.

Control of trail limb clearance during obstacle crossing is feedforward and dependent on information regarding obstacle position

In this study, when the position cues were available while wearing goggles, trail horizontal distance decreased to full vision values and trail toe clearance also decreased, but not to full vision values. The observation that lead toe clearance did not decrease while trail toe clearance did decrease is consistent with the lower correlations between horizontal distance and toe clearance for the lead limb relative to the trail limb (also observed in Mohagheghi et al. 2004). That is, the control of toe clearance is more dependent on horizontal distance for the trail limb than the lead limb. As noted earlier, the trail foot and position cues were not visible during trail crossing either with or without goggles. However, the position cues would remain visible longer than the obstacle would remain visible, therefore, the information regarding obstacle position would have been stored in memory for a shorter period for the position cues, and may be less prone to error. In other words, the position cues could have provided “short-term” feed-forward control regarding obstacle position. The cumulative effect of these observations supports the concept that control of trail limb elevation during swing is feedforward and dependent on information regarding obstacle position, not just obstacle height. The observation that position cues, in the absence of lower limb visual exproprioception, altered the lead and trail clearances differently supports the argument for independent control of the lead and trail limbs, as proposed by Patla and colleagues (Mohagheghi et al. 2004; Patla et al. 1996).

Is there reduced association between visual and kinesthetic inputs in the enhanced vision condition?

The final point we wish to make is more speculative. It has been suggested that larger correlations reflect larger association between the visual and kinesthetic inputs for control of the limb (Mohagheghi et al. 2004). That is, the proprioceptive feedback associated with limb position and stride length is integrated with visual information from the environment to control the movement. The correlations observed in this study for the full vision condition without position cues were small but significant ($R=0.31$ and $R=0.40$ for lead and trail limb, respectively) and were similar to previous research in a full vision condition ($R = 0.29$ and $R = 0.47$, taken from Table 1 in Mohagheghi et al. 2004). In the enhanced visual condition observed in this study, full vision with position cues, the correlation was not significant for the lead limb and was low for the trail limb, explaining only 5.3% of the variance, less than half of the variance explained by the other three visual conditions.

Therefore, there may be a smaller association between visual and kinesthetic inputs, which could be a consequence of increased weighting placed on the visual information in the enhanced visual environment. In parallel, previous research has found decreased correlations when vision was removed during approach (Mohagheghi et al. 2004), which could be a consequence of increased weighting placed on the kinesthetic information.

It is important to note that our conclusions regarding the effect of visual cues on adaptive gait are limited by several factors. First, subjects were instructed to look straight ahead to prevent them from looking directly down at the obstacle unless necessary. While looking ahead is consistent with normal behavior (Patla and Vickers 1997), we cannot discount that the responses may have been influenced by this instruction. However, subjects participated in all conditions under the same instructions and dependent measures were consistent with the literature: Chou and Draganich 1998 (self-selected trail foot placement measures); Mohagheghi et al. 2004; Patla 1998; Patla and Rietdyk 1993; Patla et al. 1996. Therefore, we would not expect different results if the subjects had not received this instruction. Second, we have assumed that the responses in the full vision condition are the most appropriate, thus when horizontal distance decreased to full vision values with visual cues, this was described as facilitating foot placement. While this seems a reasonable assumption and is consistent with others (Mohagheghi et al. 2004; Patla 1998), we do not know that full vision responses are the most appropriate. While the findings clearly contribute to the growing literature on the significant role of vision in controlling gait adaptations (e.g., Laurent and Thomson 1988; Lee et al. 1982; Patla 1998), it must be kept in mind that in the current study the factors most related to tripping do not appear to be lower limb–obstacle visual exproprioception (goggles) or visual structure (position cues), but rather the limb (100% of the trips were with the trail limb; consistent with Chou and Draganich 1998) and the size of the obstacle (75% of the trips were with the 30 cm obstacle).

Summary

In the current study we found that increased visual structure, which provided cues regarding obstacle position, compensated for obstructed lower limb visual exproprioception for placement of the lead and trail feet before the obstacle. That is, visual exproprioception of obstacle location was more relevant than visual exproprioception of the lower limbs for controlling both lead and trail foot placement. While lead toe clearance was not affected by position cues, trail limb clearance was dependent on visual information regarding obstacle position. In the enhanced vision condition, it appears that there is a reduced association between visual and kinesthetic inputs. Overall, the changes in the trajectories as a result of visual obstruction and visual cues regarding obstacle position further support the significant role of vision in controlling gait adjustments (e.g., Laurent and Thomson 1988; Lee et al. 1982; Patla 1998).

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