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Obstacle crossing during locomotion: Visual exproprioceptive information is used in an online mode to update foot placement before the obstacle but not swing trajectory over it

Highlights

► We determine when exproprioceptive information is typically utilised to control gait over obstacles. ► The lower visual field (lvf) was unpredictably occluded during the final approach and/or period of crossing. ► When available, online lvf exproprioceptive input was used to control/update final foot-placement. ► Lvf occlusion during just the period of crossing had no effect on toe-clearance. ► Thus increases in toe-clearance seen in obstacle negotiation are due to uncertainties regarding final foot placement..

Abstract

Although gaze during adaptive gait involving obstacle crossing is typically directed two or more steps ahead, visual information of the swinging lower-limb and its relative position in the environment (termed visual exproprioception) is available in the lower visual field (lvf). This study determined exactly when lvf exproprioceptive information is utilised to control/update lead-limb swing trajectory during obstacle negotiation. 12 young participants negotiated an obstacle wearing smart-glass goggles which unpredictably occluded the lvf for certain periods during obstacle approach and crossing. Trials were also completed with lvf occluded for the entirety of the trial. When lvf was occluded throughout, foot-placement distance and toe-clearance became significantly increased; which is consistent with previous work that likewise used continuous lvf occlusion. Both variables were similarly affected by lvf occlusion from instant of penultimate-step contact, but both were unaffected when lvf was occluded from instant of final-step contact. These findings suggest that lvf (exproprioceptive) input is typically used in an online manner to control/update final foot-placement, and that without such control, uncertainty regarding foot placement causes toe-clearance to be increased. Also that lvf input is not normally exploited in an online manner to update toe-clearance during crossing: which is contrary to what previous research has suggested.

Introduction

Although gaze during obstacle negotiation is typically directed two or more steps ahead[1], visual information of the swinging lower-limb and its relative position in the environment (visual exproprioception) is available in the lower visual field (lvf). It has previously been suggested that lead-limb trajectory over an obstacle is updated using concurrent lvf information[2-4]. However, we recently demonstrated that this is not necessarily the case; at least not for adaptive gait involving descending a kerb[5]. By unpredictably occluding lvf during the approach to the kerb-edge, we showed that lvf information acquired prior to final-foot placement, rather than concurrent lvf input, was used to control/update foot-clearance and key pre-landing kinematic parameters. In the studies that suggested concurrent lvf information is used to update toe-clearance during obstacle crossing, participants wore goggles that occluded the lvf for the entirety of the trial. Thus the differing findings between our recent study and previous studies, is likely attributable to the means of lvf occlusion; though this requires confirmation. Such confirmation was the purpose of the present study.

Methods

From either 4 or 5 walking-steps away twelve healthy adults (4/8 male/female, age 25±6.3 years, height 169.3±9.2 cm and mass 69.1±28.1 kg) negotiated an obstacle (6 or 10 cm high) under various lvf occlusion conditions. Kinematic data were collected (100Hz) using a 6-camera system (Vicon 460, Oxford) and the set-up/design we used previously[5]. The tenets of the Declaration of Helsinki were observed and the study met with bioethics-committee approval. Participant's vision was assessed[6] to be within the limits of healthy eyes[6].

Force sensitive resistors (FSR, Delysis, Boston) were attached to each shoe-sole, 1 cm lateral of heel midpoint, and another 1 cm anterior to this (right shoe-sole only). Signals from the FSRs switched smart-glass goggles (see[5]) from transparent to translucent (occluding the lvf) at either heel contact of penultimate (right) or final (left) step before the obstacle, and back to transparent at right foot contact following crossing (figure 1). Lvf occlusion trials were presented with a 1:4 ratio, which avoided participants planning for 'worst case scenario'[7] and increasing weighting of central visual cues/feedforward mechanisms[8]. Trials were repeated 3 times (each height) giving 12 perturbed and 48 unperturbed. Trial order was completely randomised. Participants then completed 6 trials (3 at each height) with the lvf occluded for the entirety of the trial.

Head-flexion was assessed (see[5]) to check whether participants attempted to receive visual exproprioceptive information in their upper field when lvf was occluded. Head-flexion was unaffected by visual condition ($p>0.05$), indicating there were no significant differences in the amount of head-flexion across the visual conditions. The following variables were analysed; trail-foot placement distance, lead toe-clearance, and lead-foot placement distance after obstacle[2, 9 – see footnote table 1].

Data were analysed using repeated measures ANOVA, with vision condition (x4) and step height (x2), as repeated factors. Level of significance was $p < 0.05$, and Tukey's HSD was used for post-hoc analyses.

Results

Obstacle height had no effect on any variable and there were no significant height-by-vision interactions ($p>0.27$). Trail-foot placement ($p=0.013$) and lead toe-clearance ($p<0.001$) were affected by vision condition. Trail foot placement distance was greater when lvf was occluded throughout compared to full-field vision ($p=0.015$) and final-step lvf occluded condition ($p=0.03$), but there were no differences between penultimate- or final- step lvf occluded conditions and full-field vision ($p>0.47$). Clearance was greater in penultimate-step lvf occluded ($p=0.03$) and lvf occluded throughout ($p=0.0003$) conditions compared to full-field vision, and was greater when lvf was occluded throughout compared to final-step lvf occluded condition ($p=0.03$, figure 2). There was no difference in clearance between final-step lvf occluded condition and full-field vision ($p=0.26$). Lead-foot placement after crossing was unaffected by vision condition ($p>0.05$).

Discussion

The foot-placement distances and toe-clearance values observed (across conditions) are comparable with those found previously[2-4, 10]. Both measures were unaffected by obstacle height, which is consistent with previous studies[3, 4, 10].

When lvf was occluded throughout, trail foot-placement distance and toe-clearance were both significantly increased in comparison to that found under full-field vision. These increases indicate participants were uncertain about the exact location of the obstacle during crossing and increased safety margins accordingly. This finding is consistent with previous work that likewise used continuous lvf occlusion[2-4]. When lvf was occluded from instant of penultimate-step contact, a non-significant increase in foot-placement distance was observed (table 1) and toe-clearance became significantly increased. In contrast, when lvf was occluded from instant of final-step contact neither variable was affected. In both unpredictably occurring occluded conditions the lvf remained occluded during lead-limb crossing. The key difference between these conditions is that participants gained visual information regarding final foot-placement when lvf was occluded from instant of final-step contact (due to information gained prior to occlusion), but did not obtain such information when lvf was occluded from instant of penultimate-step contact. Thus the fact that toe-clearance was increased following lvf occlusion from instant of penultimate-step contact but was unaffected when lvf was occluded from final-step contact, suggests that visual exproprioceptive information regarding final foot-placement is paramount in determining toe-clearance margins.

Notably, trail foot-placement distance (and toe-clearance) when lvf was occluded from penultimate-step contact, was not statistically different to that observed when lvf was occluded throughout. This indicates that occlusion of lvf from instant of penultimate-step contact did cause a meaningful increase in foot-placement distance, despite the increases observed not being significantly greater than those under full-field vision. This suggests that lvf exproprioceptive input is used in an online manner to control/update final foot-placement, and without such control, uncertainty regarding foot placement causes toe-clearance to be increased, and/or is used to update obstacle position information during the penultimate step, and without such updating margins of safety (foot-placement and toe-clearance) are increased. Furthermore, the finding that toe-clearance was unaffected by lvf occlusion from instant of final-step contact, highlights that concurrent lvf input is not normally exploited to update toe-clearance: which is contrary to what has previously been suggested[2-4].

Findings are consistent with our recent study investigating how lvf information is used when descending a kerb[5]. These converging results suggest that adaptive gait typically utilises online lvf (exproprioceptive) input to control/update final-step placement (before obstacle/kerb-edge), but not swing trajectory during crossing.

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Figure 1. Illustration of the different visual conditions i) full-field vision, ii) penultimate-step lvf occlusion, iii) final-step lvf occlusion, and v) lvf occlusion throughout - not shown in figure. Laboratory ambience illuminance (measured at eye level) was 531 lux.

Figure 2. Group mean (±SE) lead toe-clearance for the different visual conditions.

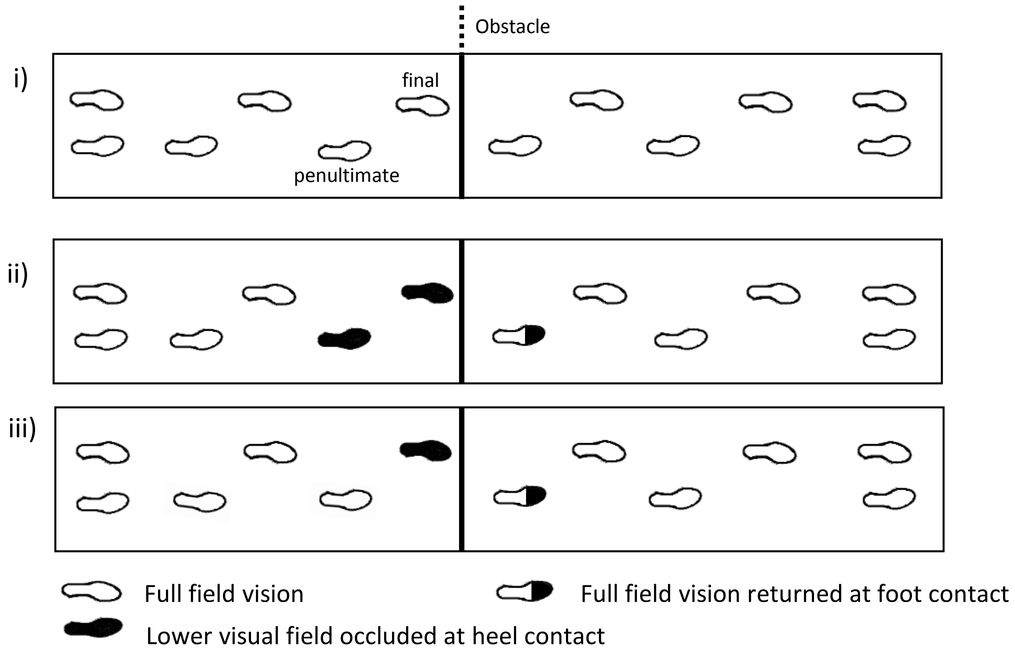
Obstacle
i)
final
penultimate
ii)
iii)
Full field vision
Full field vision returned at foot contact
Lower visual field occluded at heel contact

Figure 1

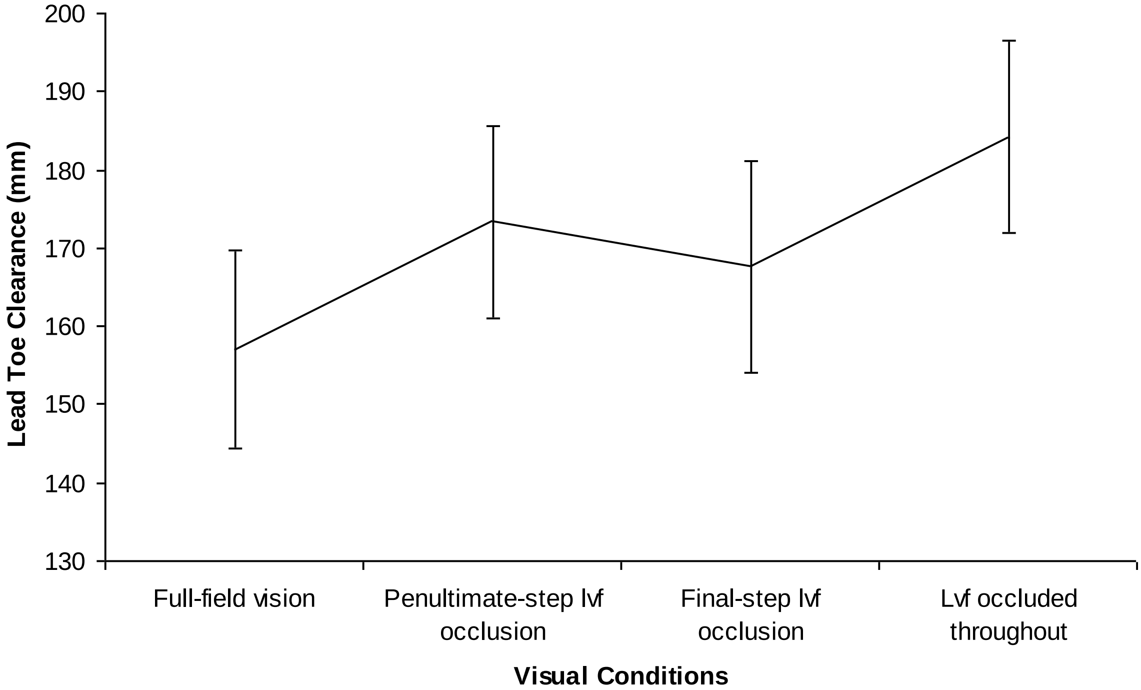
200
190
180
170
160
150
140
130
Lead Toe Clearance (mm)
Full-field vision
Penultimate-step lvf occlusion
Final-step lvf occlusion
Lvf occluded throughout
Visual Conditions

Figure 2

Table 1.Group mean (±SD) trail-foot placement before (a), lead toe-clearance over (b), and lead-foot placement after (c) obstacle (mm).

	1. Full-field	2. Penult lvf occ	3. Final lvf occ	4. Lvf occ throughout
Trail foot placement before	206 (62) [4]	217 (49)	213 (74) [4]	235 (69) [1,3]
Lead toe clearance	157 (44) [2,4]	173 (43) [1]	168 (47) [4]	184 (42) [1,3]
Lead-foot placement after	614 (62)	619 (69)	612 (55)	636 (97)

Superscript indicates the condition(s) that were significantly different to condition presented (see text for p-values). NB. Foot placements and toe clearance were the horizontal and vertical distances between the end of 2nd toe and obstacle during ground contact and point of crossing respectively (2, 9).