Influence of an unexpected perturbation on adaptive gait behavior

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Abstract:

During locomotion over uneven terrain, gait must be adapted to avoid a trip. In the event of a foot-obstacle contact, the body reactively responds to the perturbation. However, it is unknown if any proactive adjustments are made in subsequent strides to reduce the likelihood of another contact, and how long any proactive adaptations persist. This study examined gait behavior while stepping over a 10 cm obstacle placed in the middle of an 8 m walkway. The four obstacle crossings that preceded a spontaneous obstacle contact were compared to the eight obstacle crossings subsequent to the contact. Foot position before the obstacle was not modified following the obstacle contact. However, toe clearance and peak toe elevation increased in the limb that was tripped; the unperturbed limb showed no differences. These findings demonstrate that the sensory information of the perturbed limb proactively influenced the ipsilateral but not the contralateral limb, supporting the idea that the lead and trail limb are controlled independently during obstacle crossing. The proactive adaptation lasted for at least eight trials, suggesting that an unexpected perturbation influences the control of adaptive gait well after obstacle contact.

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1. Introduction

Functional mobility requires that gait is adapted to accommodate or avoid obstacles in the environment. When stepping over an obstacle, maladaptation to the obstacle's height could cause a trip and potentially a fall. Falls can have a tremendous financial cost and lead to decreased activity levels due to a lack of confidence or the inability to perform locomotor tasks [1] and [2]. To gain insight into the manner in which a trip is avoided, researchers have reported lower limb kinematics when approaching and clearing an obstacle [3] and [4]. Occasionally, obstacle contact spontaneously occurs [e.g., 5]. If enough contacts are observed, further insight into adaptive locomotor control can be gained. It is conceivable that obstacle contact may proactively change the behavior used to clear the obstacle in subsequent trials. For example, a subject may modify the position of the foot placement in front of the obstacle (termed 'horizontal distance') and/or raise their toe higher (termed 'toe clearance' and 'peak toe elevation') when stepping over the obstacle in subsequent trials to proactively reduce the likelihood of future obstacle contacts. Horizontal distance and toe clearance are correlated in non-perturbed adaptive gait [6], but it is unknown if they are both modulated following an unexpected perturbation. Furthermore, if gait is proactively modulated following obstacle contact, the magnitude and persistence of the modulation is unknown. Additionally, if the control of each limb is independent, as has been suggested [7], [8] and [9], the changes should be limited to the perturbed limb.

This study examined changes in gait behavior after a spontaneous obstacle contact. Two hypotheses were tested. First, a larger horizontal distance, toe clearance and peak toe elevation would be observed in the trials immediately following a trip, but these measures would decrease in subsequent trials. Second, the effect of the trip would only be observed in perturbed limb (i.e., limb independence would be observed).

2. Methods

Data were examined from two previously reported studies in which at least one obstacle contact was observed [10] and [11]. Study protocol and written informed consent was approved by the local IRB. Participants stepped over an obstacle for either 40 [10] or 100 [11] consecutive trials with either unobstructed or partially obstructed vision. The obstacle was 10 cm by 78 cm by 0.5 cm (height by width by depth) and was held upright by L-brackets attached to the bottom. Vision was partially obstructed by goggles that blocked the lower visual field information up to approximately two steps ahead of the participants. Of the 15 participants from the previous studies, seven contacted the obstacle once and one contacted the obstacle twice. A total of nine contacts were observed in 1140 trials (0.8%) and all contacts were with the second limb that crossed the obstacle (termed 'trail limb'). Six contacts occurred during partially obstructed vision, three with unobstructed vision. Six of the nine contacts had at least four trials before and eight trials after the trip to allow for comparison between pre- and post-contact. Five of those contacts were with partially obstructed vision, one was with unobstructed vision. This study focused on the five contacts with the trail limb that occurred with partially obstructed vision. Although five contacts is a relatively low number of trials to examine adaptive gait behavior, consistent behavior following the contact would indicate that gait was modulated in a principled manner. Trail limb toe clearance decreases as the number of consecutive trials increases [10], potentially due to learning or fatigue. However, the contacts examined for this paper occurred

throughout the previously reported studies (i.e., some in early trials and some in late trials), thus we are confident that the gait behavior observed after obstacle contact was not due to fatigue or learning. Trials were divided into three groups: Pre included the four trials preceding the contact, Post A included trials 1–4 after the contact and Post B included trials 5–8 after the contact, resulting in 12 data points for each participant for each dependent variable. Dependent variables for the lead and trail limbs included horizontal distance of the toe from the obstacle in the final approach step, toe clearance (vertical distance of the toe when directly above the obstacle) and peak toe elevation (maximum vertical distance of the toe from the ground when stepping over the obstacle) (Fig. 1). A repeated measures ANOVA was used to examine the effect of trial group (Pre, Post A or Post B) on each dependent variable for each limb and Duncan grouping was employed as a post hoc test (both $p \leq 0.05$).
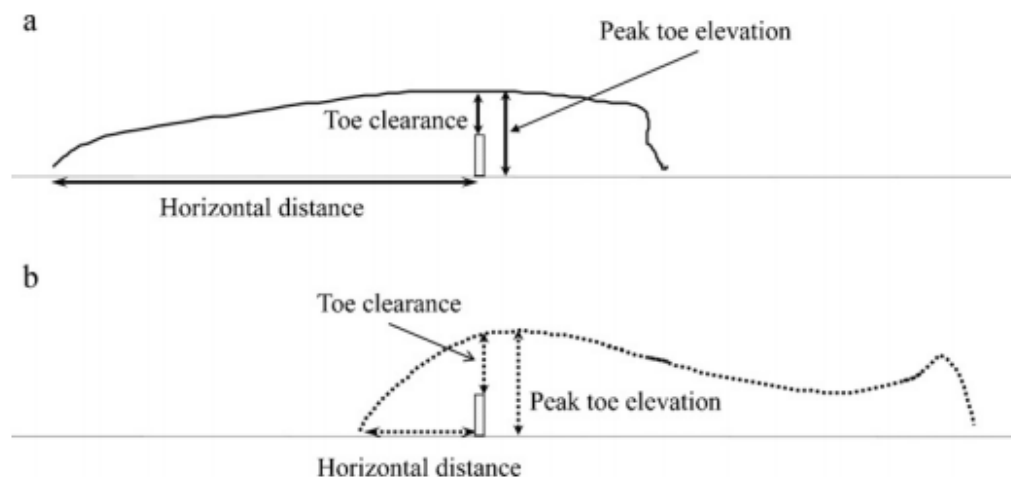

Fig. 1. Sagittal view of the toe trajectory of the lead limb (a) and trail limb (b) and the corresponding dependent variables.

3. Results

Dependent variables not affected by the trial group were: lead and trail limb horizontal distance, lead limb toe clearance, and lead limb peak toe elevation ($p > 0.09$). Dependent variables which were affected by the trial group were: trail limb toe clearance ($F_{2,57} = 31.3$, $p < 0.01$, $\eta_p^2 = 0.59$, Fig. 2d) and trail limb peak toe elevation ($F_{2,57} = 43.5$, $p < 0.01$, $\eta_p^2 = 0.67$, Fig. 2f). Post hoc analyses revealed that trail limb toe clearance increased 3.9 cm (41.1%) from the pre-trip level in the subsequent four trials following the contact, and remained at the elevated level for at least eight trials following the contact. A similar increase in the magnitude of trail limb peak toe elevation was observed after the contact, 4.0 cm (19.2%) from the pre-contact level, and also remained elevated.
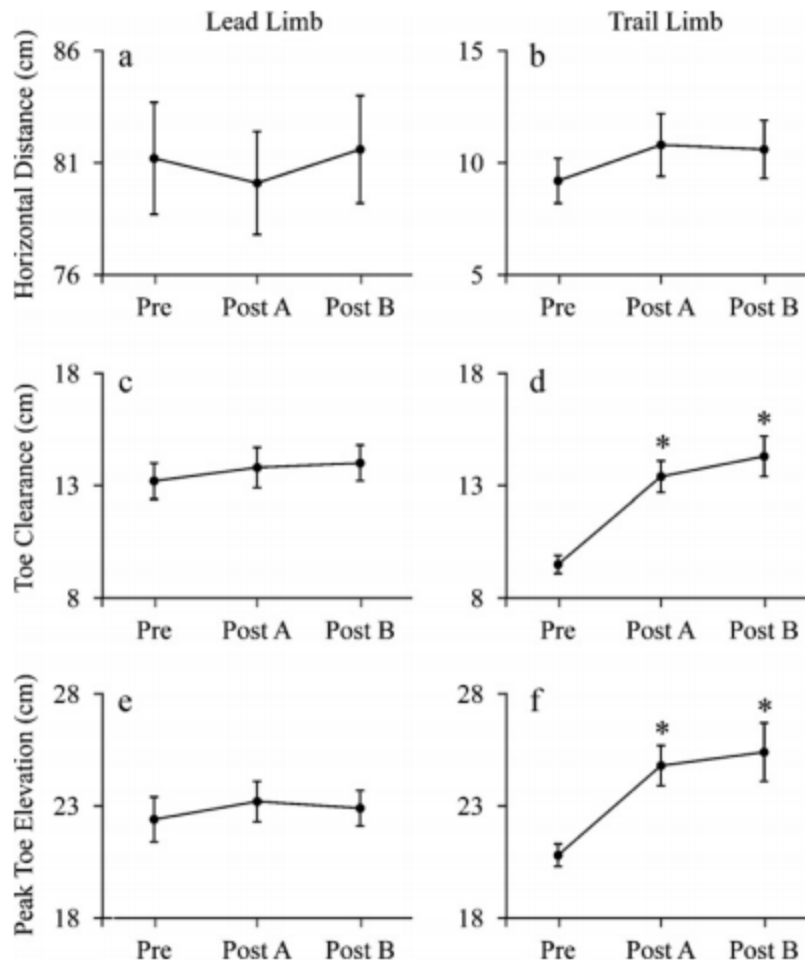
Fig. 2. Horizontal distance, toe clearance and peak toe elevation of the lead (a, c, and e) and trail (b, d, and e) limbs before the trip (Pre), for trials 1–4 after the trip (Post A) and trials 5–8 after the trip (Post B). Significant differences are denoted by asterisks.

4. Discussion

Following obstacle contact, subjects could have proactively adopted a more cautious response by placing the foot farther away from the obstacle and/or stepping higher over the obstacle. However, subjects adopted the same horizontal distance in the eight trials following obstacle contact. This is especially interesting because previous research has shown that foot placement is related to obstacle contact [12] and [13], and there is a significant but weak correlation between the two measures [6], even when vision is partially obstructed [14]. Instead, the subjects adopted an increased trajectory height only, reflected in both the toe clearance and peak toe elevation of the foot when it crossed the obstacle. The obstacle was relatively small (10 cm, less than curb height) and posed no risk to balance if contacted, as the obstacle was designed as a hurdle and simply collapsed when contacted. Despite the low consequence, subjects still modified their behavior in subsequent trials, even though the pre-contact toe clearance was adequate. That is, the somatosensory information and/or the cognitive influence from the obstacle contact appeared to override the somatosensory information from previous successful obstacle crossings, and the limb was elevated higher to prevent a second obstacle contact. The higher elevation highlights the relatively coarse control of the trail limb and could even be described as 'over-

compensation'. Note that observation of a higher number of obstacle contacts would have been ideal. Only a small sample size was available due to the spontaneous nature of these contacts. However, moderately high effect sizes were observed, highlighting the consistent behavior of the participants.

The observation that gait modulation was limited to the perturbed limb is consistent with the suggestion that the lead and trail limb are controlled independently [7], [8] and [9]. That is, the motion and/or feedback of one limb were not used to calibrate/control the movement of the other limb. It could be argued that the limbs are controlled differently due to differences in visual information. That is, under normal visual conditions the lead limb is visible during obstacle crossing while the trail limb is not. However, all trips in this study occurred when the lower visual field was obstructed, so visual feedback was not available from either limb during obstacle crossing. Therefore, the differential across limbs was not due to visual influences. These findings may be relevant for trip training paradigms [15] and [16], where an increase in obstacle height following a trip may be required if multiple trips in successive trials are desired.

Conflict of interest

None.

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