Journal of Biomechanics 47 (2014) 2679–2684

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Trip recovery strategies following perturbations of variable duration

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ARTICLE INFO

Article history:
Accepted 12 May 2014

Keywords:
Trip
Recovery strategy
Perturbation duration
Perturbation onset
Limb dominance

ABSTRACT

Appropriately responding to mechanical perturbations during gait is critical to maintain balance and avoid falls. Tripping perturbation onset during swing phase is strongly related to the use of different recovery strategies; however, it is insufficient to fully explain how strategies are chosen. The dynamic interactions between the foot and the obstacle may further explain observed recovery strategies but the relationship between such contextual elements and strategy selection has not been explored. In this study, we investigated whether perturbation onset, duration and side could explain strategy selection for all of swing phase. We hypothesized that perturbations of longer duration would elicit lowering and delayed-lowering strategies earlier in swing phase than shorter perturbations. We developed a custom device to trip subjects multiple times while they walked on a treadmill. Seven young, healthy subjects were tripped on the left or right side at 10% to 80% of swing phase for 150 ms, 250 ms or 350 ms. Strategies were characterized by foot motion post-perturbation and identified by an automated algorithm. A multinomial logistic model was used to investigate the effect of perturbation onset, side, and the interaction between duration and onset on recovery strategy selection. Side perturbed did not affect strategy selection. Perturbation duration interacted with onset, limiting the use of elevating strategies to earlier in swing phase with longer perturbations. The choice between delayed-lowering and lowering strategies was not affected by perturbation duration. Although these variables did not fully explain strategy selection, they improved the prediction of strategy used in response to tripping perturbations throughout swing phase.

1. Introduction

The ability to safely navigate the environment greatly affects an individual's independence and quality of life. Falls can not only lead to debilitating injuries, but also affect a person's confidence while walking, thus negatively affecting their ambulation. Recovery from sudden, unbalancing perturbations elicits stereotypical kinematic patterns to recover balance and avoid falls (Eng et al., 1994; Moyer et al., 2009). However, the selection of a recovery strategy following a trip is not well understood. When tripped, able-bodied individuals usually employ three recovery strategies to maintain balance, clear the obstacle that caused the trip and continue walking (Eng et al., 1994; Schillings et al., 2000). Recovery strategy selection is strongly related to trip onset during swing phase (Schillings et al., 2000). In early swing, individuals use an elevating strategy—the tripped foot is elevated to clear the obstacle. In late swing, a lowering strategy is used—the tripped foot is quickly lowered to the ground and the contralateral foot is the first to cross the obstacle. A delayed-lowering strategy also occurs early in swing phase (Schillings et al., 2000; Forner-Cordero et al., 2003) and often results when the tripped foot remains caught behind the obstacle. This strategy begins similarly to the elevating strategy in that the tripped foot is elevated, but if unable to clear the obstacle it is lowered to the ground and the contralateral foot is the first to cross the obstacle (Schillings et al., 2000).

Trips that occur during mid-swing phase show an overlap in recovery strategies (Schillings et al., 2000; Pavol et al., 2001; Roos et al., 2008) indicating that there may be factors other than perturbation onset that influence strategy selection. Muscle activations and kinematics of mid-swing recovery strategies are similar following impact with obstacles but quickly diverge (Schillings et al., 2000), indicating that any differences that affect strategy selection occur within a short time of impact. Previous studies investigating strategy selection in elderly subjects focused on subject characteristics, such as preferred walking speed, limb strength and reaction times, to explain the altered use of strategies

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http://dx.doi.org/10.1016/j.jbiomech.2014.05.009
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in comparison to young individuals (Pavol et al., 2001; Pijnappels et al., 2008; Roos et al., 2010). However, this cannot explain why strategy overlap occurs within a subject. Another factor that could influence this divergence in strategies is the interaction between the foot and the obstacle, as this is directly related to the perturbation and can influence the execution and effectiveness of recovery strategies. The amount of time that the foot is in contact with the obstacle is one way to characterize this interaction. In early swing phase, long perturbations (400–550 ms) have been associated with delayed-lowering strategies, while shorter (200–300 ms) perturbations elicited elevating and delayed-lowering strategies (Forner-Cordero et al., 2003). In mid-swing, elevating strategies have been associated with shorter (115 ms) perturbations (Pijnappels et al., 2004), while lowering strategies followed longer (150–300 ms) perturbations (Forner-Cordero et al., 2003). These data suggest that perturbation duration interacts with perturbation onset, affecting strategy selection. For example, if perturbation duration surpasses pre-determined amounts, delayed-lowering or lowering strategies would be used instead of elevating strategies in early and mid-swing, respectively. However, this possible added effect of duration has not been investigated.

Another potential factor in strategy selection is the one in which leg is tripped. Many previous studies only perturbed the left (Eng et al., 1994; Schillings et al., 2000; Forner-Cordero et al., 2003), right (Dietz et al., 1986) or dominant (Smeesters et al., 2001) sides. In these setups, subjects can anticipate which leg will be disturbed, which could affect their reactions. While other studies allowed variations on tripped side (Pijnappels et al., 2004; Roos et al., 2010), potential differences caused by laterality (the preference to manipulate with one side, and stabilize with the other) and functional asymmetry (the left leg provides more support, while the right leg provides more propulsion) of the lower limbs were not considered (Sadeghi et al., 2000; Seeley et al., 2008). Although the roles of the two legs are less obvious than the asymmetry in upper limbs, data should not be pooled until the potential effects of these differences on recovery strategy selection is investigated.

Carefully examining the effects of perturbation characteristics on strategy selection would enhance our understanding of dynamic balance recovery and aid in designing proper interventions to improve outcomes in impaired or fall-prone populations. The purpose of this study was to investigate the extent to which perturbation onset, duration and side of the trip affect recovery strategy selection throughout swing phase. We used a custom tripping device (Shirota et al., 2011) to systematically arrest the swing foot for various durations during early, mid, or late swing phase. Altering perturbation duration emulates different lengths of foot contact with an obstacle, either during initial impact or when the foot gets caught and cannot overcome the obstacle. We hypothesized that lengthening perturbation duration would gradually anticipate the transition from elevating to delayed-lowering and lowering strategies to earlier in swing phase. In addition, we hypothesized that recovery would be different on the right and left sides. Finally, we expected that perturbation duration would have minimal effects in late swing and that only lowering strategies would be observed.

2. Methods

2.1. Tripping device

We created a device to induce trip-like perturbations to the swing leg during treadmill walking. A retractable tether was attached to the subject's foot (Fig. 1a) and routed to the back of the treadmill, where it passed through the custom-made braking device (Fig. 1b). The tether ran between two grooved surfaces that were clamped together by a solenoid to interrupt the forward motion of the swing foot, thus perturbing gait. Two such devices were used so each foot could be independently tripped. Uniaxial load cells (LC703-50, Omegadyne, Sunbury, OH) measured tension on the tethers. Forces on the freely moving cords were less than 12 N and did not obstruct gait.

The device was controlled in real-time with xPC Target (The Mathworks, Natick, MA). Data from force plates embedded in the treadmill were used to identify swing phase. Perturbation timing, duration, and side were varied by the controller.

2.2. Protocol

Seven right-leg dominant subjects (24.3 ± 2.3 years old, 1.74 ± .11 m, 71.3 ± 12.5 kg) gave informed consent and participated in this study, which was approved by the Institutional Review Board. Leg dominance was determined by asking subjects with which leg they kick a ball. Subjects walked at the average overground speed of 1.4 m/s (Perry and Burnfield, 2010) on a split-belt force treadmill (ADAL 3D-F/COP/Mz, Medical Developpement, Andrézieux-Bouthéon, France). Subjects wore an overhead harness with approximately 15 cm of slack before providing support during falls.

Motion capture data were obtained from the pelvis and lower limbs (Cruz et al., 2009). Tether loads, solenoid control signals, and force plate and motion data were acquired simultaneously by EVaRT (Motion Analysis, Santa Rosa, CA). Video data were sampled at 100 Hz and analog data at 1 kHz.

All data were collected with the tethers attached, since the presence of a tether does not significantly affect gait (Forner-Cordero et al., 2003). An initial 5 min of walking was used to estimate swing phase duration, which was input to the device controller. Trips were programmed at 5 to 7 points separated by increments of 10% of swing phase. Over the following 60 min, the tether was braked on the right or left side, throughout swing phase, for 150, 250, or 350 ms. For each subject, 30 to

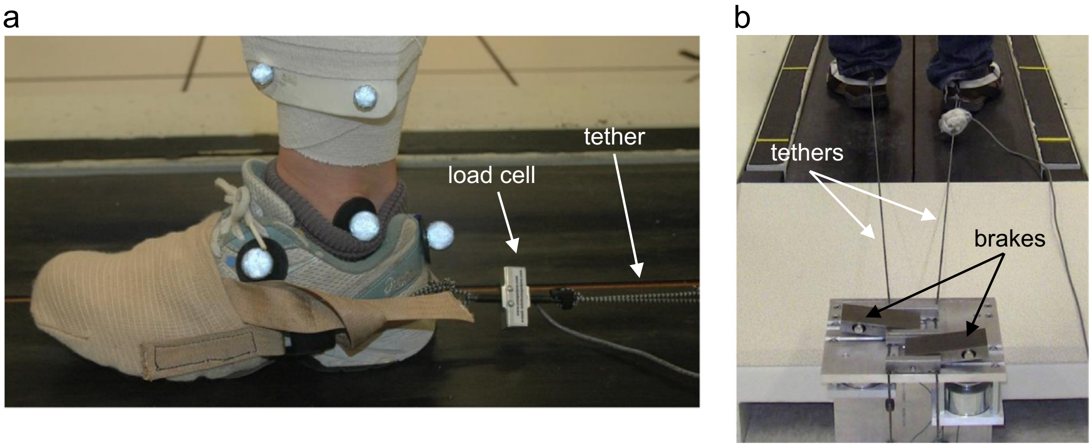

Fig. 1. The tripping device included (a) a tether and a uniaxial load cell attached to each of the subjects' feet and (b) two solenoid-driven brakes mounted on the back of the treadmill that could independently arrest the movement of each tether.

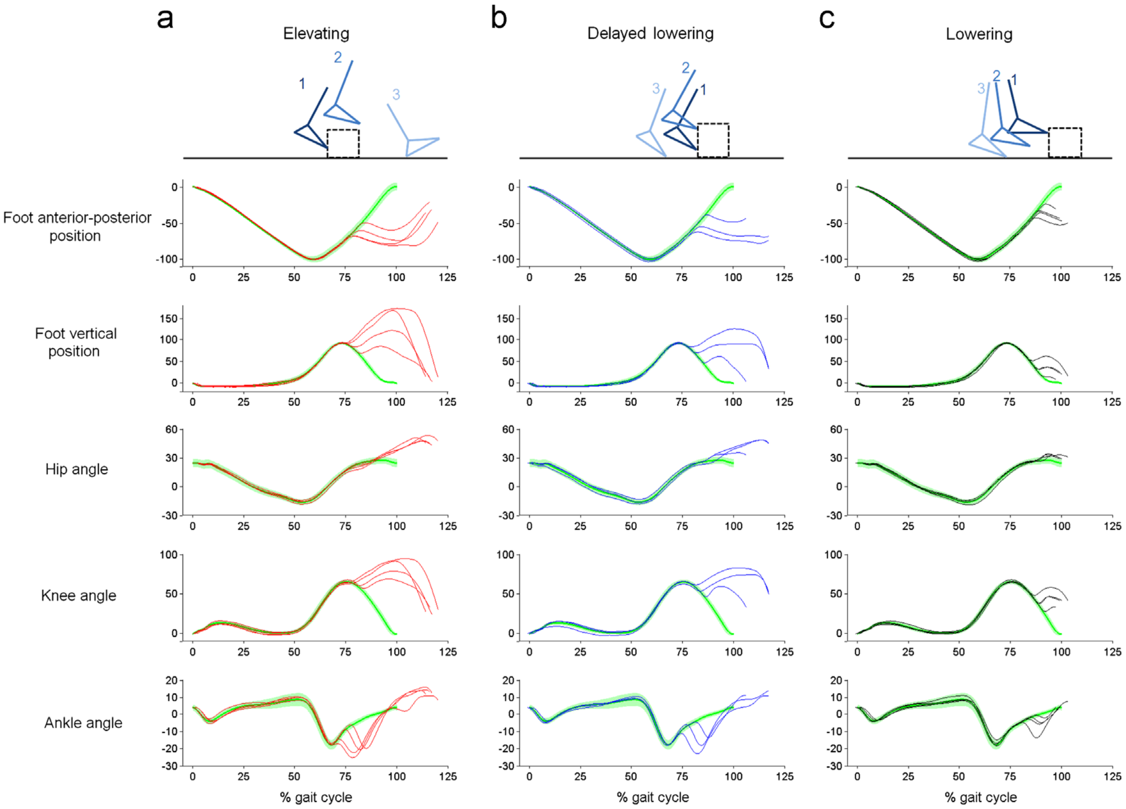

Fig. 2. Kinematic data of tripped strides for one subject using (a) elevating, (b) delayed-lowering, and (c) lowering strategies. From top to bottom: foot position in the anterior–posterior and vertical directions (normalized to average walking amplitude and relative to position at foot strike), and hip, knee and ankle angles (in degrees relative to standing; flexion is positive). Individual trial data (thin lines) are plotted over the average and standard deviation (shaded region) of baseline walking. Data are aligned in time at toe-off.

42 perturbed trials and five undisturbed walking trials were collected in random order. Each trial was 10 s long, with at least one minute between trials.

Subjects were instructed to attempt recovery after perturbations, continue walking, and only use treadmill handrails if necessary. To distract subjects and reduce possible anticipatory reactions, they were engaged in conversation with an experimenter.

2.3. *Analysis*

Data were analyzed in Visual3D (C-Motion, Germantown, MD) and Matlab (The Mathworks, Natick, MA). After discarding trials with incomplete data (missing motion markers), we analyzed 28 to 40 trips per subject. Ground reaction forces were used to identify foot-strike and toe-off. The unperturbed trials recorded among the tripping trials were used to obtain baseline kinematic data, including a new estimate of swing phase duration. Due to hardware failure, no tether load data were available for one subject, and load for only one side was recorded for 4 subjects. In order to report the most accurate perturbation onset times, we improved the estimate of onset by using the tether load when available or the solenoid control signal added to the average device activation delay (41 ± 9 ms). Perturbation onset was normalized to a percentage of the new estimate of swing phase duration. These improvements modified onset times so they did not necessarily align across subjects. However, within a subject, trials corresponding to the same programmed onset were within 5% of the average for that group. Perturbation duration was defined as the duration of activation of the tripping device.[1]

Only data from the perturbed side were analyzed. Recovery strategies were automatically identified by a novel analytic technique. Previous studies have identified recovery strategies by observing placement of the tripped foot relative to the physical obstacle (Eng et al., 1994; Schillings et al., 2000). Since we did not have a physical obstacle, we used foot trajectory to differentiate between strategies (Fig. 2). Trials where the foot trajectory in the anterior–posterior and vertical directions were within 2 standard deviations of the average walking profile were considered to not have elicited a recovery reaction and were not further analyzed. All discarded trials were beyond 60% of swing phase, where only lowering strategies are expected, so their effect on results is minimal. In the remaining trials (26 to 31 per subject), we used the position data to identify strategies as either

- elevating—the foot was elevated and placed ahead of the perturbed position (Fig. 2a);
- delayed-lowering—the foot was elevated and placed at or behind the perturbed position (Fig. 2b); or
- lowering—the foot was not elevated and was placed at or behind the perturbed position (Fig. 2c).

A value higher than 10% above baseline (undisturbed walking) vertical amplitude was required to indicate foot elevation. If the foot did not follow any of these patterns (i.e., was not elevated and was placed ahead of the perturbed location) it was an incomplete arrest—the forward motion of the foot was not completely stopped, similar to kicking the obstacle out of the way. However, because this was a valid kinematic pattern to recover from perturbations in this experiment, it was treated as an additional recovery strategy.

A multinomial logistic regression (Agresti, 2002), which is an extension of logistic regression to multiple outcome categories, was used to test the effect of different predictors on strategy selection. The parameters of this model convey the odds ratio of choosing an outcome category (e.g., elevating, delayed-lowering, or incomplete arrest) relative to a reference category (e.g., lowering), when the corresponding predictor increases. The remaining comparisons between classes are obtained by dividing the coefficients of the corresponding classes (Agresti, 2002). Perturbation onset and tripped side were independent predictors. The effect of duration was examined by an onset-duration interaction term in the model since we were interested in the modulation of the effect of onset by duration. Perturbation duration was included as a predictor with 3 ordinal levels, centered around the programmed durations: between 100 ms and 200 ms (142 ± 13 ms; mean ± standard deviation), between 200 ms and 300 ms (251 ± 5 ms), and 300 ms or longer (350 ± 1 ms). We also included subject as an independent factor to account for possible differences across subjects. The adequate application of the multinomial model was verified by calculating the ratio between the total number of samples (206)

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[1] This corresponds to the maximum perturbation duration, as it is the amount of time the device can impede forward movement of the swing foot. The effective perturbation duration depends on the reaction of the subject – see tether load analysis and discussion section.

and predictor variables (4), which is beyond the minimum recommended value of 10 (Peduzzi et al., 1996). Model parameters were considered significant at the .05 level. All statistics were performed in R (R Core Team, 2012).

Tether loads were used to characterize the force interaction at the foot as a function of strategy and perturbation duration. For each subject, trials from a single side were analyzed (4 right and 2 left legs). We measured the amount of time during which the force was 3 standard deviations above baseline. This interaction time was normalized by the average swing phase duration of the corresponding subject. Average load duration values across subjects were compared. The Kruskal–Wallis test was applied to test the effect of perturbation duration on load duration for each strategy.

3. Results

Our tripping device elicited elevating, lowering, and delayed-lowering strategies. Lower limb kinematics showed similar trajectories within each of the recovery strategies across all perturbation durations (Fig. 2). Elevating and delayed-lowering strategies were used in early to mid-swing and lowering strategies were used in mid- to late swing, where incomplete arrests also occurred (Fig. 3).

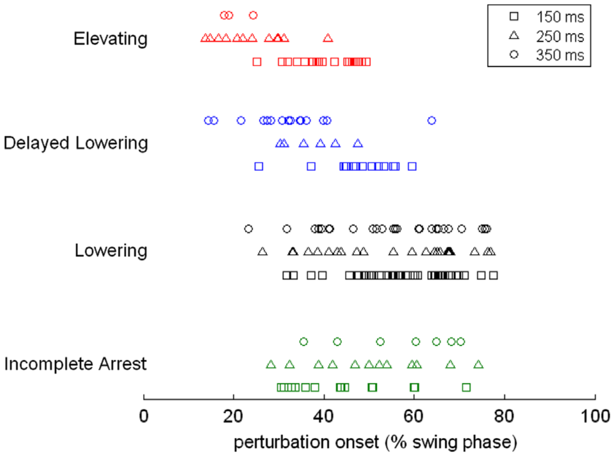

Fig. 3. Perturbation onset for each trial, grouped by recovery strategy and perturbation duration. For each recovery strategy, perturbation durations were separated between three groups: 100–200 ms (bottom), 200–300 ms (middle) or more than 300 ms (top).

Perturbation onset by itself significantly improved the prediction between elevating and lowering, and lowering and delayed-lowering strategies (Fig. 4). The odds ratios indicated that as perturbation onset increased, delayed-lowering and lowering strategies were more likely to occur than elevating strategies. Lowering strategies were more likely to occur than delayed-lowering strategies with increasing onset. Adding the onset-duration interaction significantly improved the fit of the multinomial model ($\chi^2(3)=22.9$, $p<.001$). The interaction term improved the prediction between elevating and lowering strategies, and elevating and delayed-lowering strategies. The addition of tripped side also improved the fit of the multinomial model ($\chi^2(3)=12.38$, $p<.01$). Side was a significant predictor only when comparing the odds of incomplete arrests versus any other strategy. Incomplete arrests were not significantly different from lowering strategies. Adding subject as a predictor further improved the fit of the multinomial model ($\chi^2(6)=135.16$, $p<.001$).

Tether load durations varied across strategies for a given perturbation duration (Table 1). Loads tended to be shorter for lowering strategies. For each strategy, load duration tended to increase with perturbation duration, although these effects were not significant ($p=.08$ for elevating, $p=.16$ for delayed-lowering and $p=.66$ for lowering strategies).

4. Discussion

Recovery from trips follows three different strategies but how strategies are chosen is not fully understood. Although the use of elevating and lowering strategies is strongly related to perturbation onset during swing phase, onset alone does not explain how subjects determine which recovery strategy to use

Table 1
Mean tether load durations across subjects, normalized to % swing phase. Data are grouped by strategy and perturbation duration. Number of subjects per group are in parentheses.

	150 ms	250 ms	350 ms
Elevating	36% ($N=3$)	67% ($N=3$)	75% ($N=1$)
Delayed-lowering	29% ($N=4$)	44% ($N=3$)	64% ($N=5$)
Lowering	23% ($N=5$)	24% ($N=5$)	22% ($N=5$)

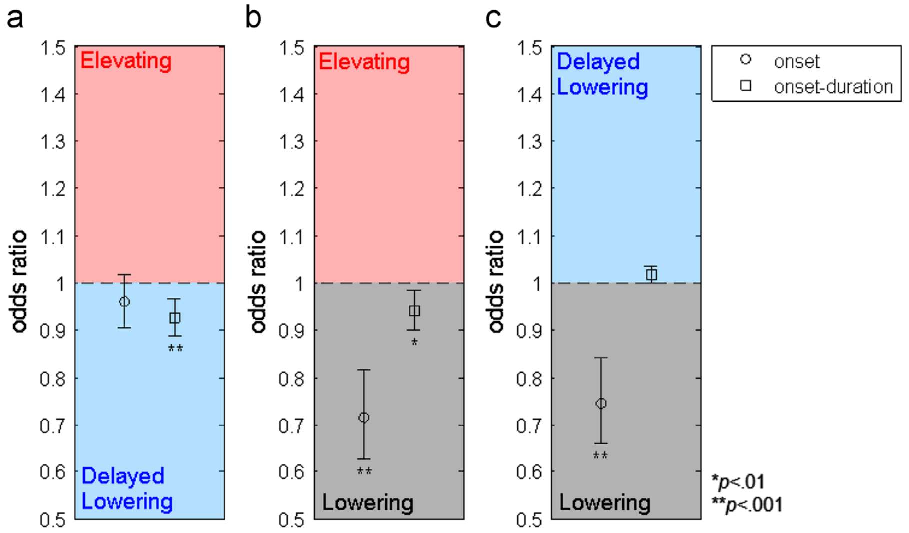

Fig. 4. Outcome of the multinomial model: 95% confidence interval of the odds ratio for the onset and onset-duration interaction predictors. Side was not a significant predictor of recovery strategy. Two by two comparisons between strategies are indicated in each graph; shaded areas indicate the values associated with each strategy. (a) Onset-duration interaction significantly improved the prediction between elevating and delayed-lowering strategies. (b) Onset and onset-duration interaction were significant between elevating and lowering strategies. (c) Onset significantly improved the prediction between delayed-lowering and lowering strategies.

(Schillings et al., 2000; Forner-Cordero et al., 2003; Eng et al., 1994). The purpose of this study was to characterize the effect of perturbation onset, duration and side on recovery strategy selection throughout swing phase. Understanding proper strategy selection is critical to improve interventions in impaired populations. We have established a framework to study the influence of perturbation duration on recovery strategy selection that can be extended to study populations at high risk of falls, such as people with gait impairments and the elderly.

Perturbations from our device elicited recovery strategies that resemble those following trips with physical obstacles, while allowing unexpected, repeated and controlled perturbations. Joint kinematics were similar to data from trips with objects (Schillings et al., 2000; Eng et al., 1994). Specifically, we observed increased hip and knee flexion during lowering strategies, and increased flexion followed by extension of the same joints for elevating and delayed-lowering strategies. Our ankle data for all strategies agree with those of Schillings et al. (2000) with an initial plantarflexion followed by increased dorsiflexion until foot-strike. These joint angle profiles are important to ensure foot clearance to overcome the obstacle and avoid falls.

This agreement in recovery strategy kinematics further validates our strategy identification based on foot trajectories. Previous studies with tether-based perturbations used step duration and length to identify strategies (Forner-Cordero et al., 2003; Krasovsky et al., 2012). However, changes in gait time parameters (e.g., swing duration of the tripped foot) vary not only with strategy but also with perturbation onset. In particular, lowering strategies in mid-swing have similar swing duration to unperturbed gait (Schillings et al., 2000) but were identified from shorter than normal step durations in the tether-based studies. Our proposed method avoids possible confounding effects of perturbation onset on step duration by using foot trajectories post-trip to identify recovery strategies.

Perturbation onset was a significant predictor in the multinomial model, and its interaction with duration further improved the prediction of recovery strategy. As onset increased, subjects were more likely to use lowering strategies. However, onset alone did not help distinguish between elevating and delayed-lowering strategies. Prediction was improved by adding the interaction term – as perturbation duration increased, the overlap between elevating and other strategies was anticipated to earlier in swing phase. However, the interaction term did not help predict between delayed-lowering and lowering strategies. These results agree with the literature – early studies reported two distinct kinematic patterns in recovery from trips (Dietz et al., 1986; Grabiner et al., 1993), but the use of the early-swing strategy (called elevating in subsequent studies) in both early and mid- to late swing prevented a direct association between strategy and perturbation onset (Eng et al., 1994). It has since been shown that both strategies can be used in mid-swing (Schillings et al., 2000; Krasovsky et al., 2012), and EMG responses suggest that factors affecting the selection between strategies occur shortly after the perturbation. Perturbation duration values from previous studies (Pijnappels et al., 2004; Forner-Cordero et al., 2003) suggest that long perturbations could induce lowering instead of elevating strategies in mid-swing though our results do not support this claim. Instead, our data suggest that the selection between elevating and lowering strategies does not relate to perturbation duration. However, perturbation duration does affect the conclusion of a strategy by impeding the necessary forward motion of the foot to overcome the obstacle during elevating strategies, as has been previously suggested (Schillings et al., 2000). Our results further indicate that the switch from an elevating to a delayed-lowering strategy occurs earlier in swing phase with lengthening perturbations. Dietz et al. (1986) showed that perturbation duration was directly related to increases in stance duration when perturbations occurred in early swing, while late swing perturbations shortened stance phase by the same amount regardless of duration. Forner-Cordero et al. (2003) proposed that the decision between carrying out an elevating strategy or modifying it to a delayed-lowering strategy is related to the amount of time needed to recover. Our results suggest that, indeed, delayed-lowering strategies are more likely in response to perturbations that occur later in swing phase when compared to elevating strategies. The trend we observed of increasing tether load duration with perturbation duration for a given strategy is also consistent with these results, although it did not reach significance. A major challenge in our load analysis was that strategies cannot be imposed on subjects, limiting data availability. Responses induced by 150 ms perturbations most closely resembled strategy selection after trips with physical obstacles (Schillings et al., 2000). Future studies could explore the relationship between load duration and strategy by increasing the number of perturbations throughout swing phase.

Including which leg was perturbed improved the fit of the multinomial model. However, it was a significant factor only for predicting incomplete arrests, which are a different type of perturbation – as in scuffing the foot during walking. For perturbations that effectively interrupted the forward movement of the foot, our data suggested no significant differences in recovery strategy use when trips occurred on the right or left sides. This result is consistent with the symmetry in static balance recovery (Smeesters et al., 2001), and also agrees with the lack of lateral differences in trip recovery kinematic parameters reported by Grabiner et al. (1993).

This study has some inherent limitations. The treadmill setup forced subjects to maintain a constant speed, potentially interfering with their ability to slow down during recovery. Although this constraint may have altered subsequent recovery steps, it likely did not affect our results regarding responses to perturbations of various durations. A limitation of our device was the inability to consistently perturb the foot during late swing phase. During swing phase, the tether pulled the foot slightly downward. In late swing, the foot would rapidly strike the treadmill, mandating the end of the perturbed step. However, only lowering strategies were expected in late swing.

5. Conclusion

Understanding trip recovery strategy selection is important to determine the requirements for dynamic balance recovery. Strategies are strongly related to perturbation onset during swing phase. Our data suggested that perturbation duration also affects strategy use by modifying how recovery strategies are completed. Longer perturbations limited the use of elevating strategies to earlier in swing phase. However, perturbation duration did not affect the use of lowering strategies. Strategy selection following perturbations of 150 ms was most similar to that observed following trips with physical obstacles.

Conflict of interest statement

The authors declare that they do not have any financial and/or personal relationships with other people or organizations that could inappropriately influence their work.

Acknowledgments

This work was supported in part by the Rice Foundation, the Brazilian Ministry of Education and the U.S. Department of State through the CAPES/Fulbright scholarship BEX1691/07-4. Sponsors had no input in the study, manuscript writing or decision to submit for publication. The authors would like to thank E.J. Rouse for help in developing the tripping device, N. Fey and A. Melendez-Calderon for discussions, and A. Barlow and A. Adewuyi for editing the text.

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