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Trip recovery strategies following perturbations of variable duration

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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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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

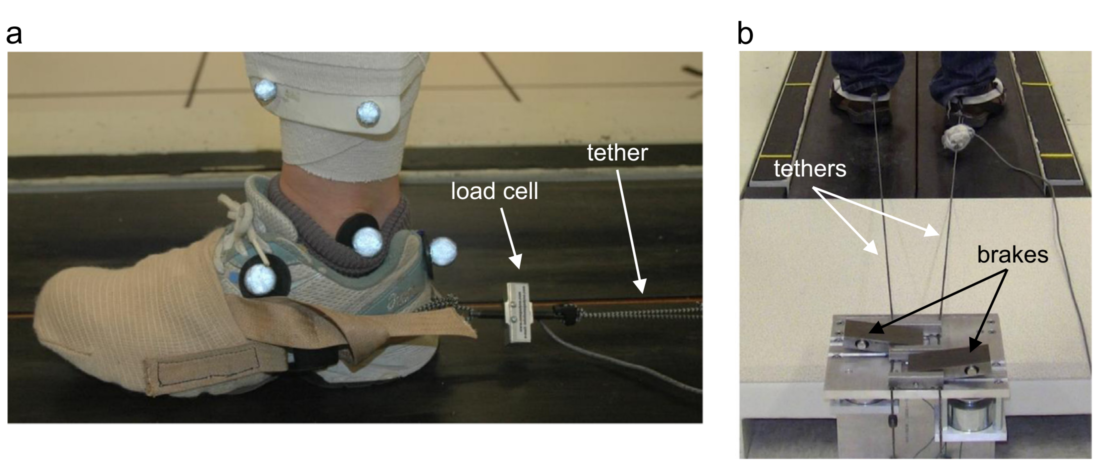

Fig. 1. The tripping device included (a) a tether and a uniaxial load cell attached to each of the subjects' feet and (b) two solenoid-driven brakes mounted on the back of the treadmill that could independently arrest the movement of each tether.

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