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The effect of perturbation onset timing and length on tripping recovery strategies

Camila Shirota, Ann M. Simon, Elliott J. Rouse, *Student Member, IEEE*, and Todd A. Kuiken, *Member, IEEE*

***Abstract*—In control subjects, trips during the early and late swing phase of walking elicit elevating and lowering strategies, respectively. However, the transition between these recovery strategies during mid-swing is unclear. A better understanding of this transition would provide insight into what factors cause individuals to choose one strategy over another. Three control subjects walked on a treadmill while attached to a custom-made tripping device. Perturbations of various lengths (ranging from 50 ms to 350 ms) were applied throughout the swing phase of gait. The results suggest that as perturbation length increased, the transition from elevating to lowering strategies occurred at earlier perturbation onsets. The transition period varied linearly with perturbation length. Perturbation lengths of 150 ms to 250 ms more closely replicated strategy selection in trips induced by real obstacles. Perturbations that are longer in duration force the transition from an elevating to a lowering strategy to occur at an earlier percentage of swing. These results show that perturbation length affects recovery strategy selection in response to trips.**

I. INTRODUCTION

TRIPPING has been used as a model of gait disturbance in various studies ranging from investigating the neural circuits involved in locomotor control [1], [2] to falls in elderly populations [3], [4]. In adults [3], [5], recovery from a trip follows two main strategies: elevating and lowering. These strategies are categorized based on lower limb kinematics and depend on when the perturbation occurs within the swing phase of gait [6], [7]. Subjects employ an elevating strategy in response to trips that occur in early swing (5%–25% of swing phase). The affected foot is elevated to clear the obstacle, and then is placed on the ground on the other side of the obstacle. Subjects employ a lowering strategy in response to trips that occur in late swing (55%–75% of swing phase). The affected foot is quickly lowered to the ground and the contralateral foot is the first to clear the obstacle.

If individuals are tripped during mid-swing, it is difficult to predict which strategy they will use. There is not a clearly defined transition between using an elevating or a lowering recovery strategy [7]. This poorly defined transition might indicate flexibility in choosing a recovery strategy, or the dependency on additional factors that have not been previously researched. One possible factor is perturbation length. Previous studies have reported cases where the initial recovery reaction is insufficient to overcome an obstacle, e.g., the foot remains caught behind the object [7]. In this situation, the subject must change from an elevating to a lowering strategy, known as a delayed lowering strategy, to avoid a fall. This situation indicates that perturbation length influences the choice of a recovery strategy.

Few studies have observed perturbation length; in those studies, subjects were tripped by interrupting the forward swing of their leg with a cord attached to the ankle. Perturbation length was controlled by changing the amount of time the leg was interrupted. One of the early tripping studies in human subjects [1] investigated changes in muscle activity in response to perturbations of length 20 ms, 40 ms, 80 ms, and 160 ms. Larger electromyographic responses were observed following perturbations in late swing. Forner Cordero *et al.* [8] studied the kinematics of recovery steps following short (250 ms) and long (450 ms) perturbations. They reported that the lowering strategy was used following short perturbations in mid and late swing and long perturbations in early swing. Elevating and delayed lowering strategies were also used following a short perturbation that occurred during early swing. However, they did not analyze how strategies varied with perturbation length. Thus, it remains unclear how perturbation length affects the choice of recovery strategy.

In this paper, we investigated the effects of perturbation lengths and onset timing on recovery strategy. We hypothesized that longer lengths would force the use of lowering strategies, anticipating the transition from the elevating strategy to earlier in swing phase.

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C. Shirota is with the Department of Biomedical Engineering, Northwestern University, Evanston, IL 60208 USA and the Center for Bionic Medicine, Rehabilitation Institute of Chicago, Chicago, IL 60611 USA (phone: 312-238-6821; fax: 312-238-2081; e-mail: camila.shirota@u.northwestern.edu).

A. M. Simon is with the Center for Bionic Medicine, Rehabilitation Institute of Chicago, Chicago, IL 60611 USA (e-mail: annie-simon@northwestern.edu).

E. J. Rouse is with the Department of Biomedical Engineering, Northwestern University, Evanston, IL 60208 USA and the Center for Bionic Medicine, Rehabilitation Institute of Chicago, Chicago, IL 60611 USA (e-mail: e-rouse@u.northwestern.edu).

T. A. Kuiken is with the Departments of Physical Medicine and Rehabilitation and Biomedical Engineering, Northwestern University, Evanston, IL 60208 USA and the Center for Bionic Medicine, Rehabilitation Institute of Chicago, Chicago, IL 60611 USA (e-mail: tkuiken@northwestern.edu).

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II. METHODS

A. Tripping device

A custom-made tripping device was built to impede forward motion of the swing leg during walking (Fig. 1). A sock was placed over the subject's shoe. An elastic band secured each sock in place. Straps attached to the sock ran posteriorly to a retractable cord. The retractable cord maintained a low level of tension in order to avoid becoming slack and unintentionally disturbing gait. Subjects reported that they did not feel any interference while walking due to the tripping device.

Fig. 1. Tripping device attachment to foot.

Movement of the retractable cord was interrupted by a solenoid-driven brake. When activated, the solenoid clamped the cord between two grooved surfaces. A control signal to the solenoid was generated in real-time using xPC Target (The Mathworks, Natick, MA). To maintain symmetry and contribute to the unexpected nature of the perturbations, a separate device was made and independently controlled for each foot.

B. Protocol

Three male able-bodied subjects participated in this experiment (height 1.77 ± 0.08 m; weight 79.4 ± 10.4 kg; age 24.7 ± 2.9 years) (mean ± standard deviation). All subjects reported being right-side dominant. Informed consent was given according to the protocol approved by the Northwestern University Institutional Review Board (STU00017666).

Subjects walked on an instrumented split-belt force treadmill (ADAL 3D-F/COP/Mz, Medical Developpement, Andrézieux Bouthéon, France) at 5 km/h (1.4 m/s). They wore a harness attached to an overhead system that provided support in case they were unable to recover from an induced trip, and were instructed to not use the treadmill handrails unless necessary. To avoid anticipatory responses, subjects were not informed when a trip would occur or which side would be perturbed. To further replicate the unexpected nature of trips and divert subjects' attention away from the tripping device, subjects engaged in conversations with a researcher during the experimental session.

Subjects walked on the treadmill and were not tripped during the first 10 min of the experiment. During this familiarization period, custom software estimated swing phase duration for the real-time tripping device controller. The experiment consisted of at least 40 tripping trials and 5 walking trials. Trials lasted 10 s and were spaced at least 1 min apart. Walking trials were randomly distributed among the tripping trials to reduce subjects' expectation of an upcoming trip, and to provide unbiased estimates of walking patterns for post-processing. Tripping trials were evenly split between the right and left sides. Tripping onset was varied from approximately 10% to 80% of swing phase. Perturbation lengths of 50 ms, 150 ms, 250 ms and 350 ms were tested. Combinations of tripping side, onset, and length were randomly applied.

We used an eight camera system (Motion Analysis, Santa Rosa, CA) and reflective markers were placed on the pelvis and lower limbs. Camera data were captured at 100 Hz. Force plate data and solenoid control signals were acquired at 1 kHz. All data were synchronously collected using Evart (Motion Analysis, Santa Rosa, CA).

C. Data analysis

Force plate and solenoid control data were exported to Matlab (The Mathworks, Natick, MA) for post-processing. Force plate data were low-pass filtered at 10 Hz using a 2^{nd} order Butterworth filter. Heel strike and toe off events were identified from these data. Perturbation length was determined from the solenoid control signal and adjusted to account for 50 ms delays in activation and deactivation of the tripping device. Perturbation onset was the time interval between toe off and activation of the tripping device. Onset times were normalized to the swing phase duration calculated from the randomly distributed walking trials. Recovery strategies were visually identified from the kinematic marker data. Strategies were classified as 1) elevating, 2) lowering, or 3) neither. A strategy was classified as elevating when the foot was initially lifted, and touched the ground ahead of where it was perturbed. Lowering strategies were identified by the lowering of the foot at or behind the perturbation location, relative to the subjects' body. Remaining trials, where gait was perturbed but responses did not follow either of the described strategies, or there were no apparent reactions, were classified as neither. The strategy ultimately used to avoid a fall was selected, i.e., a delayed lowering strategy was labeled as a lowering strategy.

A support vector machine (SVM) classifier was used to determine the border between the elevating and lowering strategy classes. Perturbation onset and length were the input features to the classifier. Trials with neither strategy were excluded from this analysis.

III. RESULTS

The tripping method used in this study was able to elicit both elevating and lowering recovery strategies in able-bodied control subjects. Subjects reported that perturbations felt like trips, as opposed to walking through thick grass or other types of gait perturbations. Fig. 2 illustrates that the strategy subjects chose was dependent upon both perturbation onset timing and length. Trials involving the shortest perturbation length of 50 ms were excluded due to a configuration problem with the tripping device. Offline analysis revealed that these perturbations were not 50 ms in length but either much shorter in duration or effectively zero.

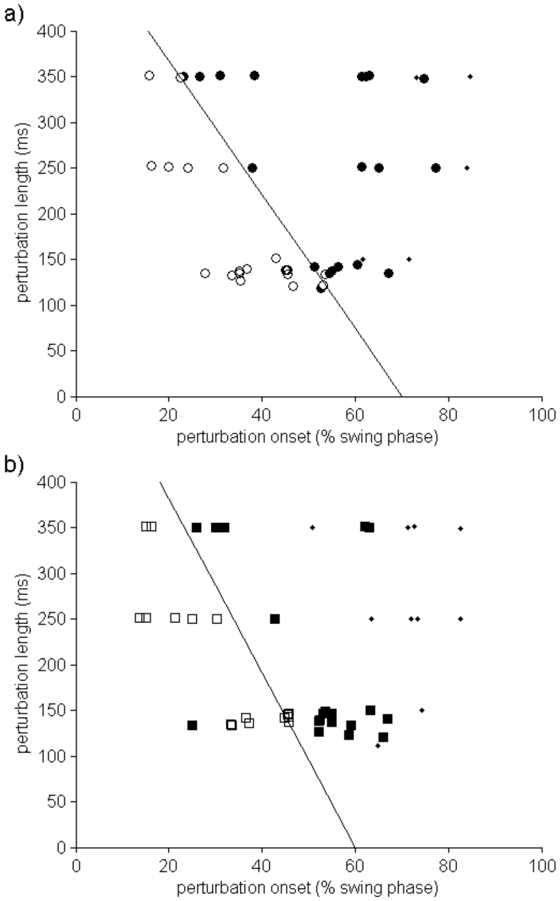

Fig. 2. Perturbation onset and length of trips to the a) right and b) left sides. Subjects recovered from the trip by employing elevating (open symbols) and lowering (filled symbols) strategies. Dots indicate that neither strategy was employed.

There is no noticeable difference between the patterns for the right (Fig. 2a) and left (Fig. 2b) sides. Irrespective of perturbation length, subjects used an elevating strategy in response to perturbations that occur early in swing phase, and a lowering strategy in response to perturbations that occur late in swing phase. The transition between these two strategies depended on perturbation length. The transition region varies linearly with perturbation length. As perturbation length increased, the transition to a lowering strategy occurred early in swing phase. The slope and the y-intercept of the linear boundaries (in ms/% swing phase) were -7.3 and 514, respectively, for the right side and -9.6 and 574 for the left side.

In 15 trials, neither recovery strategy was observed. The majority of these trials occurred late in the swing phase (Fig. 2). In these cases, the foot was directly pulled to the ground by the tripping device, shortening swing phase.

IV. DISCUSSION

While our tripping method did not involve an obstacle, we were able to elicit both recovery strategies in able-bodied control subjects. The strategies observed in this study (i.e., elevating strategy in response to trips in early swing and lowering strategy in response to trips in late swing) are in agreement with previous studies [5]–[7].

As hypothesized, the transition point to the lowering strategy shifted to an early point in swing phase with longer perturbations. Obstructing the swinging foot for longer lengths prevented the forward progression of the leg necessary for an elevating strategy. This forced subjects to resort to a lowering strategy to avoid a fall. Our results indicate that perturbation length on its own is not enough to explain the transition between mid-swing recovery strategies. There is an overlap between strategies for perturbations of 150 ms. This is in agreement with what has been published previously by Schillings *et al.* [7].

Varying perturbation lengths may be similar to varying delays in overcoming physical obstacles. Different lengths may represent differences in the subject's reaction (e.g., slower or faster lifting of the foot), or obstacles of different heights. The delayed lowering strategy where the foot is caught behind an obstacle used repeatedly, forcing the use of a lowering strategy [7], is an example of the former. It is interesting that in the current study, although subjects were aware that there was no physical obstacle and that visual feedback reinforced the absence of an object, the recovery reactions followed those described for trips with real objects [5], [7]. For the lowering strategy in particular, motion capture and/or video data revealed that the contralateral leg was often elevated to clear the fictitious obstacle in the following step. These results indicate that reactions to trips may not be grossly modified by conscious knowledge of what caused the disturbance.

Offline analysis showed that solenoid control signals of 50 ms actually produced a much shorter perturbation length due to current configuration of the tripping device. These shorter lengths unreliably disturbed the swing leg. Trials either went unnoticed by the subjects (e.g., the tripping device was unable to cause a perturbation) or weren't long enough to elicit a correction where a strategy could be observed (e.g., the foot wasn't effectively arrested before being released, resulting in a step that did not follow either strategy). Therefore, based on the current data, the transition between elevating and lowering strategies remains to be tested for perturbations of 50 ms in length.

The current study had some limitations. Perturbation lengths were calculated from the solenoid control signals. It is possible that low levels of slack in the retractable cord of the tripping device could have shortened these lengths. However, this difference would have affected all trials in a similar manner. An artifact of the tripping method affected perturbations in late swing: the tripping device transferred the pull of the cord through to the front of the foot at the sock attachment (Fig. 1). The perturbation caused a moment about the ankle that pulled the front of the foot down, occasionally and unintentionally initiating stance phase. While not ideal, this artifact is not likely to have affected the results. These perturbations occurred at 55%–85% of the swing phase, where a lowering strategy would have been expected. Finally, the labeling of recovery strategies is a somewhat subjective process. Recorded data from all subjects were carefully reviewed by one researcher and labeled as consistently as possible.

V. CONCLUSION

Our results indicate that perturbation length affected the use of elevating and lowering strategies by anticipating the transition for longer perturbations. While this factor influences strategy selection, perturbation onset and length are still not enough to fully explain the choice of one strategy over the other. A measure of foot impact, such as the load experienced by the foot, could be an additional variable used by the body to select a recovery strategy. Finally, perturbation lengths between 150 ms and 250 ms more closely resemble strategy selection as a function of perturbation onset reported in the literature.

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