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TRIP RECOVERY STRATEGY SELECTION IN TRANSFEMORAL AMPUTEES USING MICROPROCESSOR CONTROLLED KNEES

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SUMMARY

Previous studies of trip recovery in transfemoral amputees have been limited to a couple trips per subject at few time points during swing phase. It remains unclear if amputees respond consistently when tripped at the same points in swing phase, or if recovery follows kinematic patterns similar to those used by non-amputees. We induced trip-like perturbations at many points throughout swing phase on either the prosthesis- or sound sides of four transfemoral amputees using microprocessor controlled knees. Results indicate that amputees used similar recovery strategies to non-amputees, with one additional strategy. Strategy selection differed from non-amputees, and depended on whether amputees were tripped on their prosthesis or sound sides. Responses to perturbations at similar points in swing phase were consistent for each amputee. Such data may improve fall prevention mechanisms in transfemoral prostheses.

INTRODUCTION

Recovery of dynamic balance after tripping during gait is challenging, requiring a timely, coordinated reaction to avoid falling. Different recovery strategies used by able-bodied subjects during swing phase are strongly associated with when the trip occurs [1, 2]. In early to mid-swing, the tripped foot is elevated over and placed ahead of the obstacle. In mid- to late swing, the tripped foot is quickly lowered to the ground behind the obstacle, and the contralateral foot crosses the obstacle. The delayed lowering strategy occurs when the tripped foot is unable to clear the object during an elevating strategy. The tripped foot is then placed behind the obstacle and the contralateral foot is the first to cross.

For transfemoral amputees, recovering from trips is even more challenging due to a variety of factors—including altered sensory feedback, limited control of the artificial knee and ankle, and the passive mechanics of prosthetic knees. A previous study, in which transfemoral amputees were tripped while walking overground, showed that they are unable to avoid falling even when using some of the most advanced (microprocessor controlled) prosthetic knees [3]. Better understanding of recovery strategy selection is essential to improve these outcomes. Previous studies provide an incomplete picture of how transfemoral amputees attempt to recover from trips: subjects were typically tripped

only once or twice, and precise control over trip timing during swing phase was lacking. Insight into the consistency of trip responses and recovery strategy selection in amputees is critical for development of appropriate fall prevention mechanisms in transfemoral prostheses. In this study we applied trip-like perturbations to both the prosthesis- and sound sides of unilateral transfemoral amputees using microprocessor controlled knees. We analyzed recovery strategies as a function of perturbation onset timing during swing phase.

METHODS

Four unilateral transfemoral amputees (TF1—TF4, aged 44 ± 17 years old; mean \pm standard deviation) participated in this study. All were community ambulators and used their own prostheses with microprocessor controlled knees (either a C-Leg or Genium, Otto Bock, Duderstadt, Germany).

Subjects walked on a treadmill at a comfortable, self-selected speed (0.76 ± 0.23 m/s). Trips were induced by arresting a cord that was attached to the swing foot [4]. Subjects were tripped between 20% to 80% of swing phase on either their prosthesis- or sound sides, for a total of 106 trials across all subjects. Five non-perturbed (baseline walking) trials were also recorded. All trials were separated by at least 1 min and applied in random order. Subjects were instructed to attempt recovery after a trip and to continue walking. Each subject wore a harness that only provided support in case of a fall and could use treadmill handrails for support if necessary, although this was discouraged.

Ground reaction forces, load on the tripping cord, and motion capture data were recorded. Force plate data were used to detect foot strike and toe off. Load on the tripping cord was used to determine time of perturbation onset, defined as time of increase in force on the cord with respect to toe off of the tripped foot. Onset was normalized to each subject's baseline swing phase duration for comparison across subjects. Recovery strategies were identified by the movement of the tripped foot, represented by the trajectory of the lateral malleolus marker in the sagittal plane. Recovery strategies were defined as follows:

- elevating: the tripped foot was lifted and placed ahead of where it was tripped;
- delayed lowering: the tripped foot was lifted and placed at or behind where it was tripped;

- **lowering**: the tripped foot was quickly lowered and placed at or behind where it was tripped—the contralateral foot cleared the virtual obstacle first;
- **skipping**: the tripped foot was placed at or behind where it was tripped—the contralateral foot remained posterior to the tripped foot, and the tripped foot was the first to clear the virtual obstacle.

RESULTS AND DISCUSSION

The majority of recovery strategies used by amputees resembled those of non-amputees. Across all subjects, elevating, delayed lowering, and lowering strategies were observed, although not all subjects used all strategies (Figure 1). Following trips in mid-swing, two subjects used an additional, skipping-like strategy; TF3 used this following a trip on the prosthesis side and TF1 following trips on the sound side. This additional strategy is different from the hopping strategy reported by Crenshaw et al. [5], where a transfemoral amputee recovered from a trip on the sound side by quickly lowering the tripped foot and subsequently hopping several times on the sound limb to recover balance. This recovery strategy relies on support from only the sound limb over several steps and could have been challenging to use in our setup due to the restricted space of the treadmill.

Choice of recovery strategy was not consistent across all amputee subjects. TF1 (for prosthesis side trips) and TF4 (for all trips) demonstrated similar associations between recovery strategy and perturbation timing as non-amputees (*i.e.*, using elevating strategies in early swing and lowering strategies in late swing). We did not observe this trend in the other subjects, who used the lowering strategy throughout swing phase. After trips on the prosthesis side, amputees would most likely have had difficulty clearing the obstacle with their tripped foot (using elevating strategies) because they do not have voluntary control of the prosthetic knee and ankle. On the sound side, lowering strategies allow the quick placement of the sound foot, potentially providing more reliable support. This difference in recovery strategies between transfemoral amputees and non-amputees indicates the importance of the stance limb during recovery. In non-amputees, kinematics of the stance limb do not change as quickly or drastically as those of the tripped leg, although EMG responses have been shown to occur earlier [6]. Pijnappels et al. hypothesized that the stance limb contributes largely to counteract the moments and accelerations resulting from the perturbation. Future studies are needed investigate how the mechanics of recovery are altered in amputees, and how prostheses should be designed to react to a trip on the contralateral side.

Although transfemoral amputees responded differently from each other and from non-amputees, responses were consistent and repeatable for each individual. While this result needs to be confirmed within a larger population, this trend suggests that fall prevention mechanisms could incorporate an individual's recovery strategy selection preferences during swing phase.

Our study was limited to subjects wearing microprocessor controlled knees (specifically, C-Leg and Genium). These devices have a stumble-recovery mode in which they

provide increased flexion resistance during swing phase. This feature could have provided added support during trip recovery and contributed to subjects' use of lowering strategies. However, previous studies have shown that even these knees cannot prevent falls when flexed beyond 30° at trip [3]. In our data set, the knee was flexed more than 30° from 3% to 60% of swing phase; thus, strategy selection was likely not affected by knee angle at trip. Only subject TF4, who used elevating and delayed lowering strategies when tripped on the sound side, wore the more advanced Genium prosthesis, which may indicate advantages in using this device.

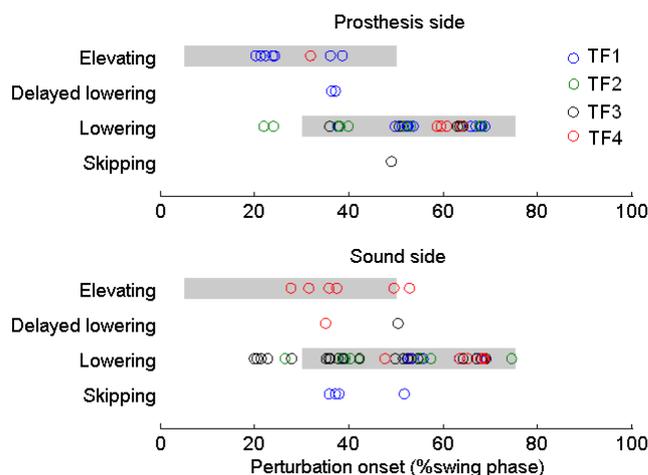


Figure 1: Strategies used by transfemoral amputees to recover from trips on the prosthesis (top) and sound (bottom) sides throughout swing phase. Shaded areas indicate average non-amputee recovery responses [2].

CONCLUSIONS

Transfemoral amputees used elevating, delayed lowering, lowering, and skipping strategies to recover from trips on their prosthesis and sound sides during swing phase. While some subjects used similar strategies to non-amputees, others consistently used a lowering strategy throughout swing phase. However, all responses to trips, on both the prosthesis and sound sides were consistent for each subject.

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