Inversion-Eversion Stiffness of Ankle-Foot Prosthesis Affects Amputee's Balance-Related Effort during Walking

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1 Introduction

Lack of stability is one of the major challenges for individuals with below-knee amputation, and they experience more falls and have less confidence in balance [1]. Specifically, in the medial-lateral direction, below-knee amputees have more variable foot placement and reduced abilities to quickly respond to foot placement errors [2, 3], which may be related to the increased incidence of falling.

If we model human medial-lateral dynamics as an inverted pendulum in the frontal plane, the torque on the hinge joint (which is the inversion-eversion torque) plays an important role in the stabilization. One simple and reasonable model to describe this torque is a spring-like model with a certain stiffness. Some amount of positive stiffness may be beneficial for level ground walking, but too much stiffness may not be as good in uneven ground because it turns ground height disturbances within the foot contact area into significant torque disturbances on the leg.

The purpose of this study is to alter the inversion-eversion stiffness from negative (destabilizing) to positive (stabilizing) values to identify the cost of human active stabilization. From the experiment we observed that this stiffness has a significant influence on the stability and balance-related effort of amputee walking.

2 Methods

A. Hardware Platform
We recently developed the two degree-of-freedom ankle-foot prosthesis emulator with active control in both plantar-dorsiflexion and inversion-eversion torque [4]. This prosthesis emulator has torque and angle sensing in both directions, and can provide high magnitude and high bandwidth torque control. Other biomechanical data were collected using indirect respirometry (Oxycon Mobile, San Diego, CA, USA), motion capture (Vicon, Oxford, UK) and the instrumented treadmill (Bertec, Columbus, OH, USA).

B. Prosthesis Control Strategy
The prosthesis was controlled by a double-layer controller. Impedance control in both plantarflexion and inversion-eversion was incorporated in the high-level controller, which took in the pre-set template parameters (including the inversion-eversion stiffness) and the measured plantarflexion and inversion-eversion angles to generate the torque references for both toes. The low-level controller for each toe was a feedback loop to track the reference using proportional-derivative control with additional iterative learning compensation.

C. Experimental Methods
Thus far, we have collected data for one amputee subject. Six conditions were completed in this collection, the first five of which were conditions using the prosthesis emulator with five different inversion-eversion stiffnesses, and the last one of which was the baseline condition using the subject's prescribed prosthesis. In the first five conditions, we tested inversion-eversion stiffnesses of -175Nm/rad, -100Nm/rad, 0Nm/rad, +100Nm/rad and +175Nm/rad in a random order, where the negative values correspond to destabilizing springs and positive ones correspond to stabilizing springs.

The amputee subject walked for six minutes in each condition and took three minutes rest in between. Data from all the devices described above were recorded in the each conditions.

D. Measure of Balance-Related Effort
(i) Metabolic Cost
Net metabolic cost is a good indicator for active stabilization effort. The rates of oxygen consumption and carbon dioxide production were recorded for quiet standing and then for all walking trials. Then the metabolic power was calculated based on the averaged data over the steady-state period.
(ii) Step Width Variability
Step width variability could indicate active control of foot placement for balance. Step locations were measured by both the motion capture and the instrumented treadmill when the foot was on the ground. The standard deviation of step widths was used to quantify the variation of lateral foot placement.
(iii) Average Step Width
Amputees tend to take wider steps to compensate instability [2]. In addition to the standard deviation described above, the average of step widths was also used to measure the lateral stability.

3 Preliminary Results

Here we present the results for a single pilot subject with amputation. The stabilizing conditions with positive inversion-eversion stiffness tended to reduce Metabolic Cost (Figure 1 (a)), Step Width Variability (Figure 1 (b)) and Average Step Width (Figure 1 (c)), while the destabilizing conditions tended to increase them. Metabolic Cost, Step Width Variability and Average Step Width were 19.2%, 26.4%, and 20.0% lower, respectively, with the most stabilizing virtual spring than with the most destabilizing virtual spring. In this figure, the trend in Step Width Variability (b) was not as clear as Metabolic Rate (a) and Average Step Width (c), which may be because the subject consciously used different stepping strategies in some conditions to compensate instability. In all, these indicators suggested that stabilizing stiffness could improve balance and reduce balance-related effort during walking.

4 Summary and Future Work

This pilot data suggested that the inversion-eversion stiffness had a significant impact on the stability indicators, and positive stiffness tended to decrease balance-related effort while negative stiffness tended to increase it. We could infer that ankle inversion-eversion stiffness plays a key role in the lateral balance.

We plan to finish the data collection for six subjects using the protocol described above. After that, we plan to try the same experiment in the presence of random ground height disturbances. From the results of even and uneven ground experiments, we may be able to identify the optimal inversion-eversion stiffness, which may be beneficial for the design of commercial ankle-foot prostheses.

References

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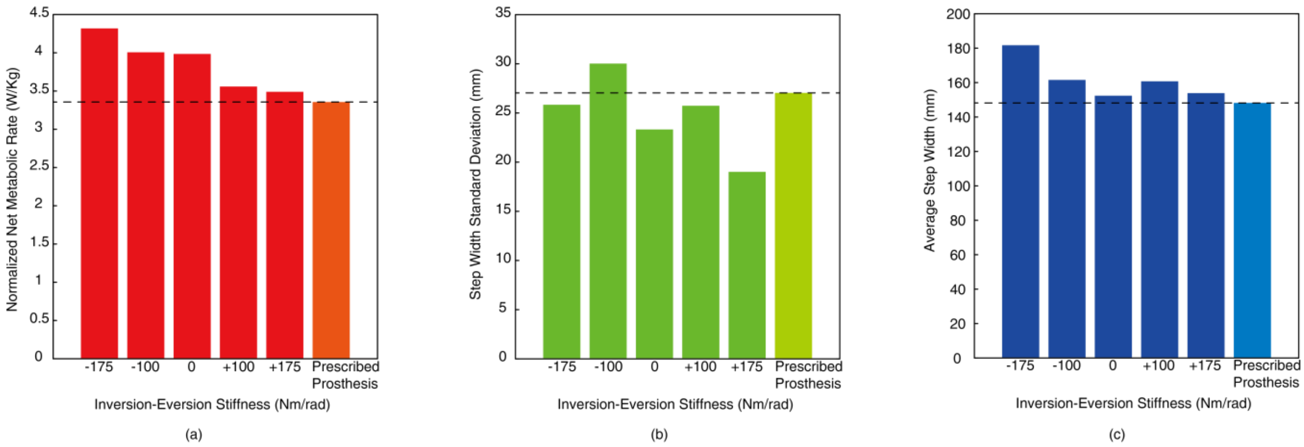

Figure 1: Influences of inversion-eversion stiffness on (a) Metabolic Cost, (b) Step Width Variability, and (c) Average Step Width for one subject with unilateral transtibial amputation.