Experimental investigation of the lower leg trajectory error metric: implication for the design of ankle-foot prostheses

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***Abstract*— The Lower Leg Trajectory Error (LLTE) provides a quantitative connection between the stiffness and geometry of a prosthetic foot and its biomechanical performance. This metric enables the optimization of prosthetic feet by modeling the trajectory of the lower leg segment throughout a step for a given prosthetic foot. To validate the LLTE as a clinical tool and design objective for prosthetic feet, we conducted a clinical study with five transtibial amputees wearing prototype prosthetic feet with varying stiffnesses. The results of the clinical study and the design of the fully characterized prototype prosthetic feet are presented and discussed in this work.**

Keywords— prostheses, amputee independent prosthesis properties (AIPP), design metric, biomechanics

I. Introduction

While many studies have shown that the mechanical characteristics of prosthetic feet affect a user's gait mechanics [1], there is yet no consensus on *how* to design a passive ankle-foot prosthesis. The Lower Leg Trajectory Error design metric developed in previous work [2], provides a quantitative understanding of how well a passive prosthetic foot design can enable a target motion such as able-bodied gait. Using this metric as a design objective, we created low-cost (~$10s), single part, compliant, plastic prosthetic feet customized for specific transtibial individuals to best replicate natural walking patterns over a full step [3]. Clinical testing over ground with 5 transtibial amputees showed that the LLTE model accurately predicted the lower leg kinematics of the subjects and that these optimized plastic prostheses enable biomechanics similar to high-end carbon fiber feet [cite]. To further validate the LLTE as a design objective for prosthetic feet, we are experimentally investigating the sensitivity of optimized designs to stiffness as well as the connection between Lower Leg Trajectory Error metric and *in-vivo* biomechanics.

II. Experiment Design

Five high-activity level transtibial subjects with weights ranging from 50kg to 90kg were selected for this study. For each subject, the geometry and stiffness of a passive prosthetic foot was optimized using the LLTE to enable close to able-body gait dynamics given the subject's weight, foot size and leg length [3]. From this optimized LLTE design, four additional designs with the same geometry but varying stiffnesses were built. The stiffness increments were chosen based on the incremental changes in stiffness of commercially available prosthetic feet. These prototypes were evaluated using the LLTE metric and were tested on a universal material testing system to characterize their mechanical behavior. Kinetic and kinematic data of each subject using their 5 user-specific prototypes were collected during level-ground walking trials where the foot conditions were presented in a randomized order unknown to the subject.

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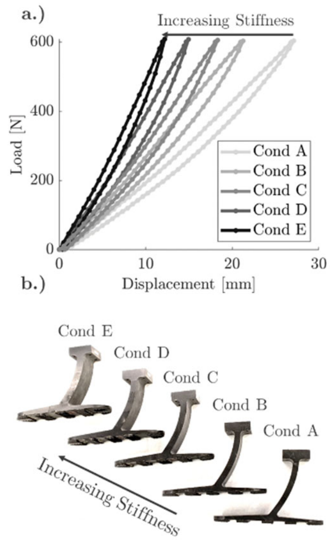

c.)

Subject 1	Stiffness Variation [-]	LLTE Value [-]
Cond A	60%	1.151
Cond B	80%	0.583
Cond C	100%	0.316
Cond D	120%	0.440
Cond E	167%	0.901

d.)

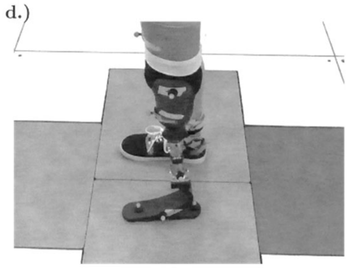

Fig. 1. Prosthetic feet prototypes with varying stiffnesses tested by subject 1. Stiffness profiles (a.) of the 5 prosthetic feet shown here (b) with varying thicknesses but similar geometries. Table (c.) of the LLTE values (lower means better, C being the predicted optimal stiffness) for each condition as well as their relative stiffnesses. Photo of subject 1 wearing foot condition C (d.).

III. Results and Discussion

At the time of the submission, three subjects have participated in the study and two more have been scheduled. The data from the study will be presented at Dynamic Walking. This data will be compared to the theoretical predictions from our LLTE-based analysis. We anticipate the results will confirm that the LLTE-optimized foot does indeed allow a user to walk with closer to able bodied kinematics than the feet with sub-optimal stiffnesses. These results will show the sensitivity of prosthetic foot stiffness to walking kinematics and kinetics, and strengthen the usefulness of LLTE as a design and evaluation tool for prosthetic feet.

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