Experimental Validation of the Lower Leg Trajectory Error, an Optimization Metric for Prosthetic Feet

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SUMMARY

We have created a novel optimization metric for prosthetic foot design called Lower Leg Trajectory Error (LLTE). It 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 and selecting values of design variables to minimize the error between this trajectory and target physiological lower leg kinematics.

To validate the LLTE as a design objective for prosthetic feet, clinical testing with a prosthetic foot prototype with varying rotational ankle stiffness was performed. The results of the clinical studies and the design of the fully-characterized prosthetic foot prototype enabling varying rotational ankle stiffness are presented and discussed in this work.

INTRODUCTION

The LLTE metric was developed in previous work [1] to provide a quantitative understanding of how a passive prosthetic foot design can be optimized for able-bodied kinematics. The LLTE is calculated by applying ground reaction forces (GRFs) between an able-bodied foot and the ground to a model of a prosthetic foot through the stance phase of gait. The resulting prosthetic foot deflection, and thus the trajectory of the lower leg segment, is computed during a step. The error between the modeled trajectory of the lower leg segment and target physiological lower leg kinematics is then evaluated using a root mean squared error (RMSE) function to produce the LLTE. A foot that minimizes the LLTE value is desired, as it means the prosthetic leg will follow an able-bodied kinematic trajectory under able-bodied loading.

To validate the LLTE as a design objective for prosthetic feet, clinical testing with prosthetic feet prototypes must be performed in order to ensure that (i) the model accurately predicts the lower leg kinematics of a subject using a fully characterized prosthetic foot and (ii) that feet with stiffness and geometry that produced a predicted sub-optimal LLTE value perform worse than feet with near optimal LLTE values.

A prosthetic foot prototype suitable for gait analysis study testing the clinical viability of LLTE must be built such that it is:

(i) Light enough that the weight of the foot does not affect the gait kinematics over the duration of the test.

(ii) Fully mechanically characterized such that the deformation of the foot under a given load can be calculated, thereby allowing evaluation of the LLTE value for the foot.

(iii) Modular so that at least one design variable can be altered during testing in order to compare gait kinematics across a range of values of that design variable e.g. ankle stiffness or forefoot bending stiffness.

A modular prosthetic foot that consists of a rotational ankle joint with interchangeable springs to vary the rotational ankle stiffness and a cantilever beam was designed and built [2]. The design variables of the architecture – the rotational stiffness of the ankle and the bending stiffness of the forefoot – were chosen according to the LLTE optimization results of the foot architecture [3].

A clinical study will be run in the spring of 2017 using five variations of this the prosthetic prototype with different ankle stiffnesses. Four will have LLTE sub-optimal ankle stiffnesses of 1.5, 3.1, 5.0 and 16 Nm/deg, and one will have the predicted LLTE optimal ankle stiffness of 3.7 Nm/deg. The results of the clinical study and the design of the fully-characterized prosthetic foot prototype will be presented in this poster.

PROTOTYPE CONCEPT AND MECHANICAL DESIGN

The conceptual architecture consists of a rotational ankle joint with constant stiffness k_{ank} and a cantilever beam forefoot with a bending stiffness k_{met} (Fig. 1). The geometry (h and d_{rigid}) of the rotational ankle, beam forefoot foot were selected to replicate the articulation of the physiological foot-ankle complex from a set of published gait data [4]. The design variables, k_{ank}, and k_{met}, were previously optimized using our LLTE-based design method [3]. For this study, Winter's gait data for a subject of body mass 56.7 kg [4] were used as inputs into the LLTE model. The set of design variables yielding the lowest value for LLTE was taken to be the optimal design. The minimum LLTE value, 0.222, was calculated for k_{ank}= 3.7 Nm/deg and k_{met} = 16.0 Nm². Through a sensitivity analysis on the ankle stiffness and forefoot stiffness, it was noted that the LLTE values were much more sensitive to ankle stiffness than forefoot stiffness [2]. The clinical study that will be conducted for this work was thus focused on varying the ankle stiffness to see its effect on gait compared to the range of LLTE values calculated. The range of rotational stiffness that will be tested spans a similar range as ankle quasi-stiffness data from normal walking, which have been estimated as roughly 1.5-6.3 Nm/deg [5], 3.5–17.3 Nm/deg [6] or 3.5–24.4 Nm/deg [7] during different phases of gait.

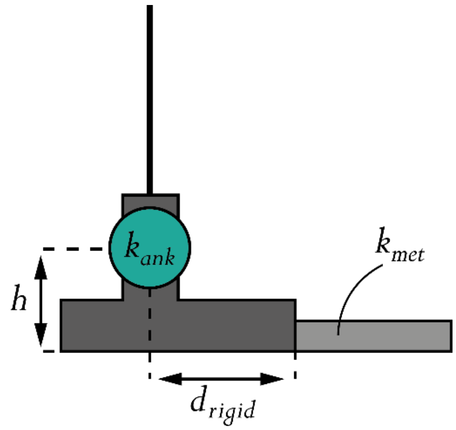

Figure 1: Foot architecture

A prosthetic foot prototype was designed and built to accommodate our specific wide range of ankle stiffnesses with interchangeable springs. A solid model of this prototype is shown in Fig. 2. The stiffness and range of motion requirements for the ankle springs exceeded the possible values for most common springs. Custom machined nylon springs fitted in aluminum mounts were thus designed [2] to provide the required ankle joint rotational stiffnesses. The compliant beam forefoot was made from nylon and was fixed to the rigid acetal resin structure with machine screws fastened directly into tapped holes in the acetal resin. As built, the prototype has a mass of 0.980g.

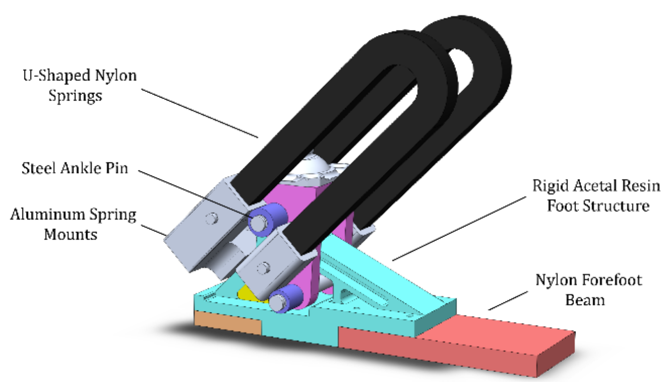

Figure 2: Solid model of the prosthetic foot prototype with a constant rotational stiffness at the ankle of $\boldsymbol{k_{ank}}$ = 3.7 Nm/deg.

CLINICAL STUDY

After thorough mechanical testing and preliminary testing on amputees in India to establish the reliability, comfort, and physical behavior of the prototype, it will be brought to Northwestern University for extensive gait analysis in the spring of 2017. The foot with the five different rotational ankle stiffnesses (1.5, 3.1, 3.7 5.0 and 16 Nm/deg) will be fitted to a female subject of 54.2 kg. The subject will walk on flat ground using the prototype until she feels comfortable. After 10 min using the prototype, the subject will walk at a comfortable speed on a walkway, during which gait kinematic and kinetic data for five steps for each set of ankle springs were collected.

RESULTS AND DISCUSSION

The data from clinical testing will be presented in our poster at Dynamic Walking. These data will be compared to the theoretical predictions from our LLTE-based analysis. We anticipate the results will confirm that the LLTE-optimal foot does indeed allow a user to walk with closer to able bodied kinematics than the feet with sub-optimal ankle stiffnesses. These results will show the sensitivity of ankle stiffness to walking kinematics and kinetics, and strengthen the usefulness of LLTE as a design tool for prosthetic feet.

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