Measured Forefoot Stiffness Across Prosthetic Foot Stiffness Categories

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INTRODUCTION

Prosthetic feet are an essential component of restoring mobility in people with lower limb amputations (LLA).

When deciding which stiffness category of a prosthetic foot to prescribe for individuals with lower limb amputation, clinicians often rely on foot manufacturer recommendations that are based on patient weight and activity level.

However, there is no objective data available to guide the selection of the optimal stiffness category that will match each patient's abilities, goals, and the type of environmental terrains that they typically encounter.

Knowledge of mechanical properties such as linear stiffness would likely be useful in the prosthetic foot prescription process, as it could enable clinicians to select prosthetic feet with the stiffness for which their patients are best suited.

While prior studies have begun to quantify compressive linear stiffness forefoot properties,[1-4] limited data exists measuring stiffness across prosthetic foot stiffness categories or foot sizes.[3]

PURPOSE

To compare measured forefoot stiffness of several commonly prescribed prosthetic feet across manufacturer stiffness categories. Further, to examine whether foot size affects the relationship between category and stiffness.

METHODS

STUDY DESIGN

- Five commercially-available prosthetic foot types were mechanically tested, representing a range of low- to high-activity feet (Figure 1)

Figure 1: (left to right) Walk-tek, Seattle Lightfoot2, Vari-flex, Rush HiPro, All-Pro

METHODS

APPARATUS

- Three sizes of feet (i.e., 27-29 cm) were evaluated for each type. A range of stiffness categories (for users between 130-250 lbs) were tested for each foot type and size.
- Each foot was shod with a standardized shoe and aligned neutrally in all planes
  - Mikrolar R2000, 6-DOF robot was used to apply vertical loads at 20mm/s at a discrete +20º pylon progression angle to isolate the forefoot[2-4]
  - Vicon 8-camera motion capture system collected linear displacement data and AMTI 6-axis load cell was configured in line with the pylon to collect simultaneous force data at 200Hz

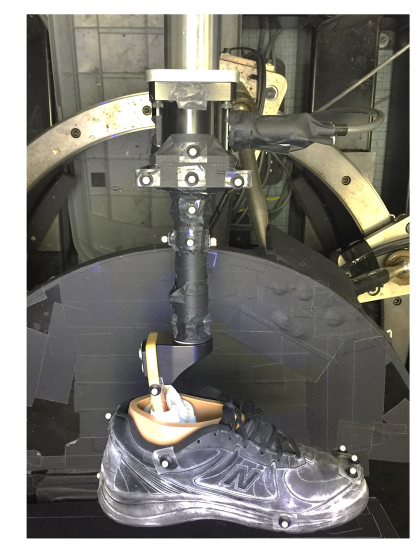

Figure 2: Example of test set up with prosthetic foot

PROCEDURES

- Using displacement control, the R2000 loaded each forefoot for six consecutive cycles
- Minimum vertical load of 50N was maintained throughout testing[2,4]
- Load target threshold for each forefoot was determined as the maximum user body weight indicated for the tested foot stiffness category
- Force-displacement data from the final three cycles were averaged since the first three cycles were considered to be preconditioning

ANALYSIS

- Measured stiffness was calculated by linear regression models fit to force-displacement data from zero load to mean user body weight load for the tested stiffness category
- Linear mixed effects regression was used to assess the association between measured stiffness and stiffness category (fixed effect) with foot size as a covariate
  - Prosthetic foot type and a foot type by stiffness category interaction were modeled as random effects

RESULTS

All feet demonstrated nonlinear behavior during loading. Average measured stiffness across foot types, sizes, and stiffness categories ranged from 17.3 - 44.4 N/mm. Measured stiffness was significantly associated with stiffness category (R^2 =0.54, p<.001) and the slopes of change varied significantly by commercial foot type (foot type by stiffness category interaction p<.01).

On average across foot sizes and all foot types, for a one unit increase in scaled foot stiffness category (i.e., 1-5 from minimum category to maximum category), there was a 3.7 ± 0.7 N/mm (CI: 2.2, 5.1) estimated increase in measured forefoot stiffness. There was no evidence that slopes differed by size for forefoot stiffness (stiffness category by size interaction p=.80).

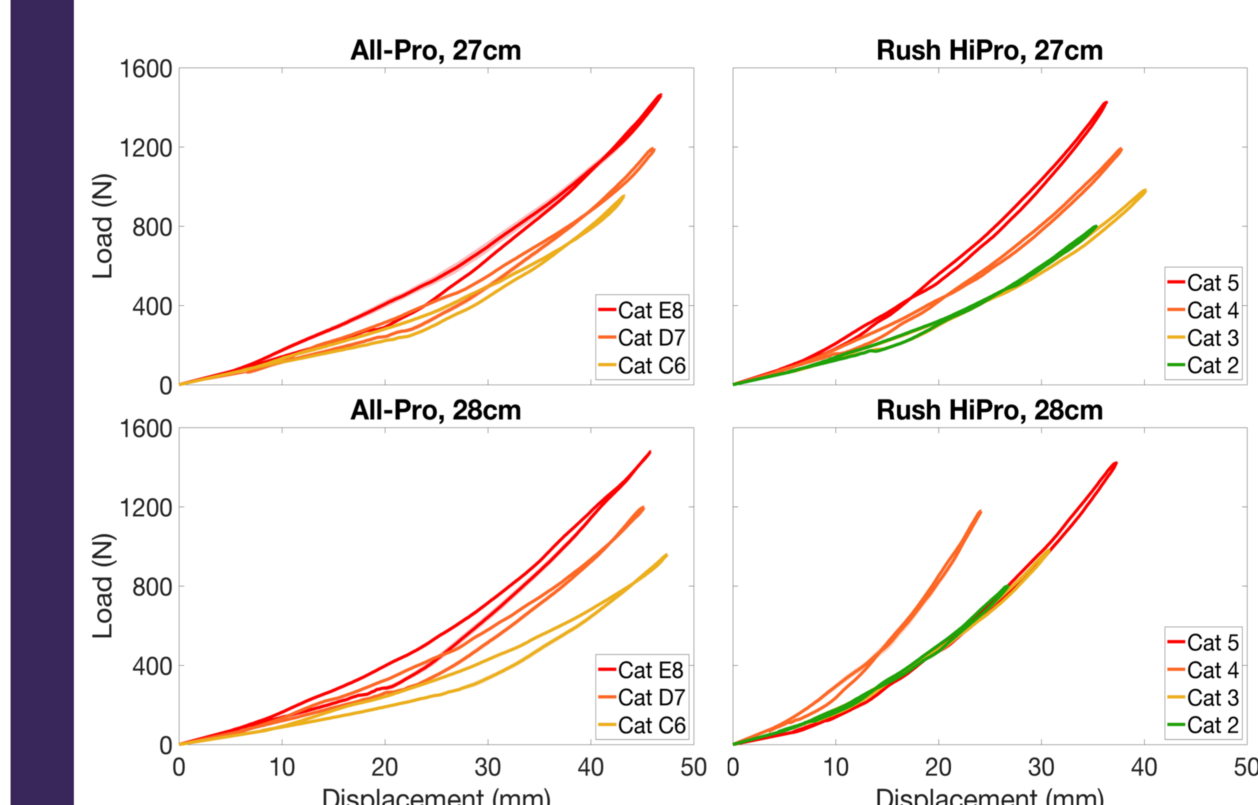

Figure 3: Example force vs displacement data for prosthetic forefeet in two sizes. While the All-Pro data conform to the expected order of increasing stiffness with increasing category, there are inconsistencies in the Rush HiPro data across categories and foot sizes.

Despite the overall correlation between measured stiffness and stiffness category, there were often instances observed in the force-displacement curves in which the expected patterns were not followed within individual foot models and sizes (Figure 3). Of the 15 foot size and model combinations tested, discrepancies were observed in 8/15 groups of forefeet in which higher stiffness category feet were not stiffer than lower stiffness category feet.

DISCUSSION

On average, measured forefoot stiffness was significantly correlated with increasing stiffness category (p<.001).

While this statistical result is generally consistent with clinical intuition that when selecting a higher stiffness category foot one can expect the prosthetic foot to be generally more stiff, we found that over half of the forefeet tested had inconsistencies in the order of force-displacement curves across prosthetic foot stiffness categories (i.e., consecutive categories were not ordered as expected). Furthermore, these findings are based on stiffness slopes, which may not sufficiently capture nonlinear behavior.

Given the lack of published objective prosthetic foot properties, clinicians must rely solely on manufacturer recommendations. Inconsistencies in measured stiffness across foot stiffness categories and foot sizes means that clinical expectation of foot performance may not correspond with measured stiffness in practice, complicating the selection of a prosthetic foot.

SIGNIFICANCE

Prosthetic foot stiffness plays an important role in functional mobility of people with lower limb amputation. These findings suggest variation in measured stiffness across categories and underscore the importance of publishing standardized mechanical testing results for prosthetic feet. This information would be useful for prescribing clinicians to access when selecting an optimal foot for a patient with LLA.

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