Beyond Weight-Based Categorization: A Novel Stiffness Framework for the Characterization of Running Prosthetic Feet

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Summary

Running Prosthetic Feet (RPFs) are essential for Paralympic athletes, yet the current approach for stiffness categorization is incomplete and lacks the capacity to account for the complex behavior of RPFs during gait. This study proposes an innovative test method to assess RPF mechanical behavior by the means of three parameters: Spring-equivalent stiffness (K_{eq}), Stiffening Ratio (S) and Bi-axiality Ratio (B). Test setup takes inspiration from midstance loading conditions, imposing a controlled vertical displacement while allowing a free horizontal translation. Tests were conducted on three C-shaped RPFs, varying in curvature and stiffness category. Results highlight differences in stiffness behavior, demonstrating the method's ability to capture different RPF behavior. The approach offers a comprehensive framework for RPF classification beyond weight-based methods.

Introduction

RPF are specialized prosthetic limbs designed for Paralympic running. There are no globally-accepted test for the characterization of RPFs in operating condition, thus, RPFs classification is solely based on a number associated to athlete's weight category. Although in practice from decades, this methodology is incomplete, since it does not account for the complex behavior of RPFs. Some research regarding characterization of RPFs stiffness have been conducted [1,2] but still do not account for vertical-horizontal coupling displacement behavior and COP variation during loading.

This study proposes an innovative approach to characterize C-shaped RPF with a single test by the means of three parameters, similarly to the ISO 16955 with respect to 22675.

Methods

Test setup is inspired to midstance loading condition, defined as the instance of maximum vertical load during gait, associated with a GRF oriented almost vertically [1]. Test machine is composed of a vertical servo-hydraulic actuator moving a stiff sledge carrying a clamp-adapters to secure the RPF; in addition, a sliding base with a tartan layer on top [3] is controlled by a horizontal actuator and is set to translate freely horizontally. Based on in-vivo tests and literature data [1] the foot is aligned with $\theta_{clamp} = 10°$ and a vertical displacement is imposed up to 110 mm. To characterize the RPF, three parameters are used:

$\boldsymbol{K_{eq}}$ $[\boldsymbol{N/mm}]$ **–** Defines global RPF stiffness based on the energy equivalence of a linear spring [4].

Stiffening Ratio S – Describes RPF stiffening during loading, defined as the ratio of the slope of the Load-Deflection curve linear fit in the last (K_{fin}) and first (K_{in}) 20 mm of loading.

Biaxiality Ratio B – Indicates an RPF's tendency to elongate horizontally under vertical compression, defined as the ratio of horizontal to vertical displacement.

Tests were conducted on three different Ottobock RPFs to validate the capacity of the test to capture different stiffness behaviors. Two belong to the same stiffness category but differ in curvature—one featuring an inflection point and the other without—while the third shares the same curvature as one of them but falls into a different stiffness category.

Results and Discussion

Results (Table 1) show the test is able to capture different RPF behavior. RPF category influences stiffness both globally (K_{eq}) and locally (S) more than it does the shape, which has a higher effect on the biaxiality behavior (B). These differences may be perceptible to athletes, highlighting the need for a more comprehensive characterization of RPF stiffness.

Table 1: Summary table and parameters formulae

	Cat 2.5 – Inflection point	Cat 3.5 – Inflection Point	Cat 3.5 – No inflection point
K_{eq}[N/mm]	11.8	14.1	13.6
$S\,[-]$	1.53	1.74	1.68
$B\,[-]$	0.932	0.956	0.906
$K_{eq} = \frac{2Area}{dy_{max}^2}$	$S = \frac{slope_{lin.fit[90\to110]}}{slope_{lin.fit[0\to20]}}$	$B = slope_{lin.fit}\,[d_x = f(d_y)]$	

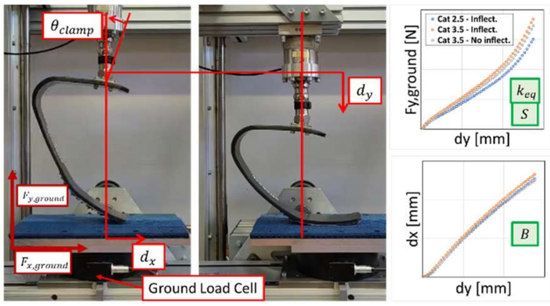

Figure 1: Left: Uncompressed RPF. Center: RPF at maximum compression. Right: data extracted.

Conclusions and future work

Ongoing tests are being conducted on various RPF to study how category, shape and alignment influence stiffness behavior. Additionally, in-vivo tests will be performed to assess whether test metrics provide results comparable to athletes' subjective perception of stiffness and align to in-vivo stiffness models.

References

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