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Investigating the Influence of Shape, Stiffness, and Alignment on Running Prosthetic Feet Behavior

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OBJECTIVE
Running prosthetic feet (RPF) are specialized prosthetic elements designed for running, used by Paralympic athletes for training and in official competitions. They are carbon fibers blades with monolithic structure that store elastic energy by flexing during initial contact with the ground and then release it by extending in the second phase. They can mainly be C-shaped or J-shaped; still, there are a lot of different geometrical variations within each shape group. There are no globally accepted tests for the characterization of RPFs in operating condition, thus, RPFs classification is solely based on a number associated to athlete's weight category, with discrete variation between levels of about 8-10 Kg. Although in practice for decades, this methodology is incomplete, since it does not account for the complex behavior of RPFs, such as its non-linear elastic response. Some research regarding characterization of RPF stiffness has been conducted [1,2] but still do not account for vertical-horizontal coupling displacement behavior and COP variation during loading.
In this work, an innovative approach to characterize C-shaped RPF is proposed to assess how stiffness category, shape and clamp alignment influence RPF mechanical behavior.

METHDOS
The test machine [3] 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 is controlled by a horizontal actuator.
Multiple RPF were considered for this study, all equipped with a spiked sole to replicate how they would be used in-vivo:
Ossur Cheet Xceed: Cat 1, Cat 2, Cat 2.5, Cat 3, Cat 5
Ottobock Runner (Custom RPF):
Curved Geometry, this term means that the distal tip presents an inflection point : Cat 2.5, Cat 3
Even Geometry, distal tip does not present an inflection point: Cat 2.5, Cat 3
Ottobock Runner (commercial RPF): Cat 3, Cat 4
Note that Ossur (Reykjavík, Iceland) and Ottobock (Duderstadt, Germany) classification scales are not equivalent.
RPF classification is derived from a single test, whose setup is inspired by midstance loading conditions, defined as the instance of maximum vertical load during gait, associated with a GRF oriented almost vertically [1]. Based on in-vivo test results and literature data [1] the foot is aligned with \begin{equation} \theta_{clamp}=10\ ° \end{equation}(clockwise) and a vertical compressive displacement is imposed up to 110 mm. The horizontal actuator is set to translate freely to impose a null horizontal load \begin{equation} {(F}_{x,ground}=0\ N) \end{equation} To characterize the RPF, three parameters are used:

Equivalent stiffness K_{eq}\ [N/mm] –Defines global RPF stiffness based on the energy equivalence of a linear spring [4].
\begin{equation}
K_{eq}=2Area/(dy_{max}^2\ )
\end{equation}
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.

\begin{equation}
S=(slope_{lin.fit}[90\rightarrow110]))/(slope_{lin.fit}[0⟶20]))
\end{equation}

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

\begin{equation}
B=slope_{lin.fit}\ \ [d_x=f(d_y\ )]
\end{equation}

Results

Results showed that the category influences stiffness not only globally (K_{eq}) but also locally (S); stiffer RPFs appear to have a higher Stiffening ratio S. Biaxiality does not appear to be influenced by the stiffness category. At equal stiffness category, curved and even geometry behave similarly in terms of stiffness, with just a slightly higher K_{eq} and Stiffening S for the first type of geometry. The main difference lays in the Biaxiality behavior, with curved geometry showing a higher coupling between vertical and horizontal displacements.
Regarding alignment, it was observed that it does not influence the global stiffness, but it has a significant effect on the stiffening and biaxiality ratio. Front-alignment (RPF is more plantarflexed) presents higher stiffening than back-alignments, thus appearing more compliant in the first phase of loading, while getting much stiffer in the last part. Moreover, front-alignment presents a lower biaxiality ratio.

Conclusions

The classification method proposed in this study offers a more comprehensive framework for RPF classification, since experimental results highlighted that the weight-based classification approach is not able to inform on the influence of multiple factors on the overall stiffness behavior of RPF.
It was then used to assess how stiffness category, shape and alignment influence RPF behavior. It appears that the weight category influences stiffness both locally and globally but does not appear to have any effect on biaxiality. Contrarily, shape appears to influence the biaxiality but not the stiffness. Alignment shows a significant influence on the stiffening ratio and biaxiality, but not on the global stiffness behavior.
Ultimately, this approach can be used to provide orthopedic technicians, athletes and coaches with simple and informative data to optimize RPF selection and tuning.

[1] Beck O.B et al. (2016). PLoS ONE, 11(12): 1-16.
[2] Shepherd M.K. et al. (2019) 16th ICORR Proc. 892-898.
[3] Petrone N. et al, (2020) MDPI Proc. 49,75.
[4] Petrone N. et al, (2022), ISBS Proc, 40(1)

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