STIFFNESS COMPARISON OF RUNNING PROSTHETIC FEET OF DIFFERENT CATEGORIES AFTER BENCH TESTING

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The purpose of the work is the comparison of stiffness properties of Running Prosthetic Feet (RPF) for transtibial amputee athletes after the introduction of test methods to collect and analyse their Load-deflection curves. The study explores the effect of the orientation of the socket (ϑ_G) with respect to ground during a load cycle.
The three Ossur feet Cheetah Xtreme Category 4th, 5th ,6th underwent extensive testing on a multi-component test bench. Results show that the unit interval between categories does not matches with the interval in terms of equivalent stiffness Keq introduced as synthetic stiffness parameter.

KEYWORDS: running prosthetic feet, ground reaction forces, stiffness characterization, categories

INTRODUCTION: The creation of specific carbon-fibre running prostheses allowed people with lower extremity amputation to reach incredible results. This phenomenon has raised many debates in sport and scientific communities about the potential advantages or disadvantages of using running specific prostheses (RSP) and in particular running prosthetic feet (RPF) when amputee athletes participate in able-bodied competitions (Hobara, 2014).
Carbon-fibre prostheses have a very high stiffness to weight ratio if compared to monolithic materials, high strength and high energy storage capabilities. However, manufacturers don't share quantitative information about mechanical properties such as stiffness or damping of RPF that are however classified by category. Each category is supposed to be associated to athlete's mass, the higher the mass, the higher the category. RPF that belongs to a higher category show typically thicker blades but the definition of stiffness is unknown. Indeed, despite some attempts in the recent past (Beck at al, 2016),(Rigneya S.M at al, 2017) there is a lack of standard classification protocol expressing objective parameters such as stiffness of RPF, as well as a unified fatigue and impact testing procedure to guarantee athletes safety. Test methods shall take into account the correct load components acting on the RPF during the full cycle of the stance (Petrone, N. et al. ,2020) a single load component and a fixed ground orientation are not sufficient for a complete stiffness characterization that require multi-component load test benches (Petrone, N. et al., 2020 *Proceedings 2020*, 49(1), 75)
The introduction of a specific definition of stiffness can be the first step for a scientific, objective and representative characterization of running prosthetic feet and prostheses.

METHODS:
The Reference systems adopted for force and moments expression are reported in Figure 1 and 2. Focusing on the sagittal plane, a Ground reference frame (X_G,Y_G) and a Socket reference frame (X_S,Y_S) were associated to in-vivo data collections for TT amputees: data available from field load collection (Petrone, N. et al. ,2020) allowed to collect and express loads both in the Ground and in the Socket reference frame.
To determine the load deflection curves of a set of RPF, a multi-component test bench (named "Colossus") was used as sketched in Figure 2. Given an absolute laboratory reference frame (X_L, Y_L,), the socket was substituted by a multiaxial load cell to which a reference frame (X_C, Y_C) was associated. The 6-axis load cell measures forces (FX_C, FY_C, FZ_C) and moments (MX_C, MY_C, MZ_C) in the bench Load Cell reference system, corresponding in-vivo to the TT Socket reference frame. A triaxial load cell collocated under the contact plate measures the ground reaction forces (FX_G, FY_G, FZ_G) in the Ground reference system that can be oriented at an

angle ϑ_G with respect to the Socket-Cell axis (Fig.2). The test bench allows the possibility to set angle ϑ_G between the ground and the Socket-Cell axis at prefixed angles values (-15°, -7.5° 0°, 7.5°,15°), Negative values of ϑ_G are referred to the first braking phase of a running step, while positive angles are connected to the final propulsive phase of a step. ϑ_G is also the in-vivo variable angle between the TT Socket axis Y_S and the vertical direction Y_G normal to the ground. In the bench, sandpaper was applied to the rigid aluminium surface simulating the ground and RPF were tested without spikes.

Three different J-shaped RPF for trans tibial amputee were tested in the Colossus bench: Ossur Cheetah Xtreme Category 4th, 5th and 6th. Category is related to athlete body mass and the following abbreviation were used: 4th=Cat 4 (69-77 kg); 5th=Cat 5 (78-88 kg); 6th=Cat 6 (89-100 kg). Feet were connected to the load cell by means of an adaptor allowing to align the feet following indications suggested by the manufacturers: foot tilt Angle 7° and foot Tip Anterior Position (TAP) equal to 63 mm (Migliore G. et al. ,2020)

A known vertical force F1 was applied at 30 N/s with the first servo hydraulic actuator and the corresponding reaction force F_{YC} was measured at the 6-axis load cell. The displacement of the vertical cylinder dYC was zeroed at the undeformed configuration corresponding to the foot is touching the ground. The second servo hydraulic actuator allows to control the force F2 and displacement S2 applied to the RPF at the ground contact point in the X_C direction. The ratio between F_{XC} and F_{YC} (evaluated with respect the socket/cell reference frame) define the parameter $\rho = F_{XC} / F_{YC}$. During the tests, the values of $\rho=0$ was maintained fixed for each investigated angle ϑ_G. The test bench can perform tests with positives and negatives values of load ratio ρ.

Peak loads for the different values of ϑ_G were adopted from a reanalysis of GRF collected in the field and compared to the corresponding ϑ_G instantaneous values: larger values were therefore adopted in correspondence to mid stance, while decreasing values were assumed in correspondence of the initial or final instants of the stance. The same peak values were consistently applied to all RPF categories at this stage.

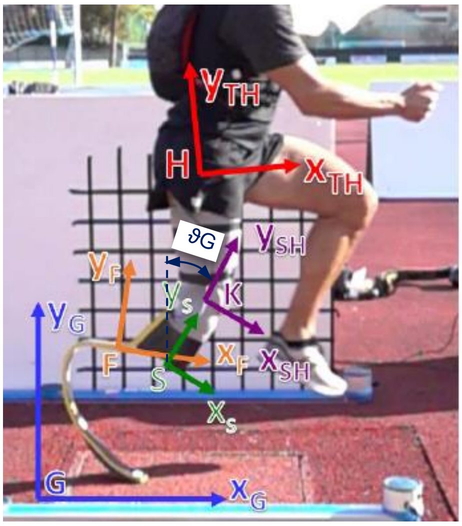

Figure 2: In vivo reference systems and load collection phase (Petrone, N. et al. 2020)

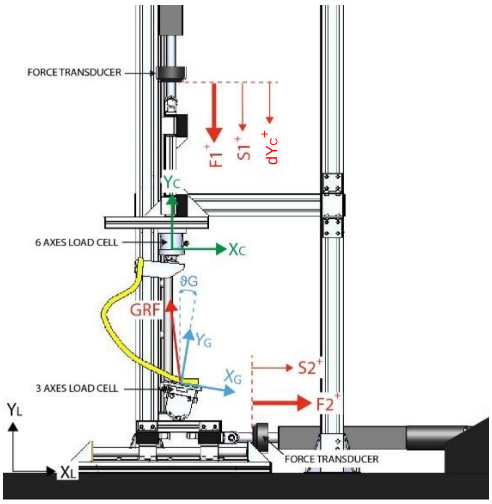

Figure 1: In vitro reference systems and main quantities for the test bench [5]

The stiffness K of an elastic component is typically defined as the ratio between the applied force F and the corresponding displacement d, $K = F/d$, expressed in N/mm: in the case of linear behaviour, the stiffness also relates to the stored elastic energy of the deformed component, $E = \frac{1}{2} K d^2$, corresponding to the area underneath the Load/deflection curve in Figure 4. A precise definition of the stiffness of a RPF is not yet established in literature. This is mainly due to the fact that the Load-displacement curves show typically highly nonlinear trends. Prosthetic feet act like spring component that store energy in the first braking phase of the step (compression phase) and release it in the second propulsive phase (extension phase).

In the present work, in order to express the stiffness with a single value, meaningful also for elastic energy storage considerations, the concept of equivalent stiffness K_{eq} is introduced, based on the area A beneath the load-displacement curves representing the elastic energy stored by the RPF, as shown in Figure 4. $K_{eq}(\rho, \vartheta_G)$ [N/mm] is therefore defined as in (1):

$$\frac{1}{2} \cdot K_{eq} \cdot d_{YC,max}^2 = A \quad (1)$$

where A is the area under the curve and $d_{YC,max}$ the maximum vertical displacement.

RESULTS:
The Load-displacement curves were obtained for all three RPF, in the five ground angles ϑ_G for the fixed load ratio ρ=0.
As an example, the Load(F_{YC})-deflection(dY_C) curves for Ossur Cheetak Xtreme Cat 4 are presented in Figure 3 for the case ρ=0 at various ϑ_G angles. The curves show the bench vertical force Y_C measured in function of the bench vertical displacement dY_C while the horizontal force is consistently maintained to zero.
The results of all tested configuration on the three available RPF are collected in Table 1, in terms of equivalent stiffness parameter K_{eq}.
The direct comparison of curves obtained from the three RPF of same brand & model but different category can be appreciated in Figure 4, where the three RPF were tested for ϑ_G=0 and ρ=0.

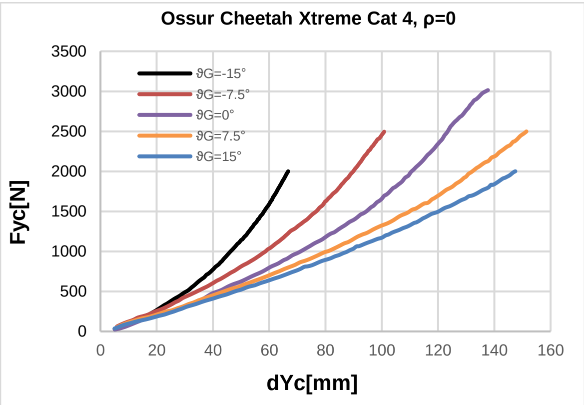

Figure 3: Stiffness curve for Ossur Cat 4 at different ϑ_G

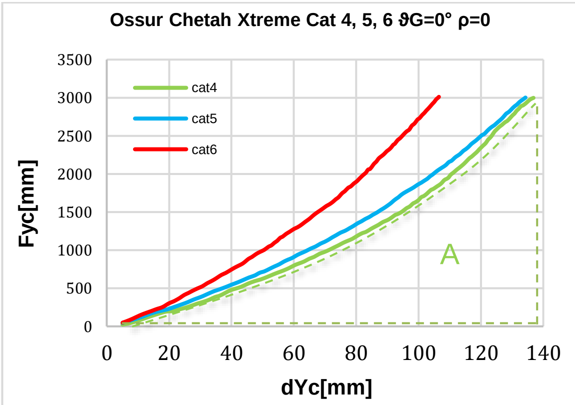

Figure 4: Stiffness curve for Ossur cat 4,5,6 at ϑG=0 and for ρ=0

Table 1: Keq values for each SRPF at different ϑG and for different ρ values

Keq (N/mm)	ρ=0				
	ϑ_G=-15°	ϑ_G=-7,5°	ϑ_G=0°	ϑ_G=7,5°	ϑ_G=15°
CAT 4	21,46	18,96	16,85	13,63	11,86
CAT 5	23,25	23,00	17,95	14,56	12,60
CAT 6	29,53	24,88	22,83	17,90	15,76

DISCUSSION:
The aim of the work was the quantitative comparison of stiffness behaviour of three RPF of the same brand and model but of different Category, to evaluate a possible correspondence between nominal Category and stiffness definition. The equivalent stiffness K_{eq} here proposed has the advantage of being a single value that can be applied to curves of very different shape and extension. On the other hand, the K_{eq} parameter does not express the degree of non-

linearity shown by the RPF in that configuration, as well as it does not reflect the progression of the RPF, for instance its stiffening or softening behaviour. In addition, it may be prone to variations depending on the maximum load applied to the foot during the test, in the case of nonlinear behaviour.
Having stated the possible limitations of the K_{eq} approach, the results give nevertheless interesting insight in the comparative behaviour of the tested RPF.
First of all it is quite clear from Figure 3 how the ground orientation ϑ_G highly affects the shape of the curves, with high stiffening at high negative values and much more linear behaviour at large positive values. Secondly, the comparison of the three categories in the same condition as in Figure 4 allows to appreciate their moderate non linearity, as well as a similar curve shape that gives support to the adoption of the Keq as a quantitative comparative parameter.
What is eventually clear is that the three categories, differing for a unit nominal interval from each other, do not differ correspondingly in the quantitative analysis expressed as Keq. For Cat 4 and Cat 5 with $\vartheta G=0$ and $\rho=0$, values of Keq is respectively 16.85 (N/mm) and 17.95 (N/mm) with a difference equal to 1.10 (N/mm); Keq value for Cat 6 in the same conditions is equal to 22.83 (N/mm). The difference in terms of Keq between Cat 6 and Cat 5 is equal to 4.88 (N/mm), more than four time the difference between Cat 4 and Cat 5.
These results make clear that the inclusion in a specific Category requires a sound quantitative definition of stiffness parameters: this will also influence the association of RPF category and body mass, as present intervals may not be sufficient and exhaustive.
The effort of towards a common terminology, a common test method definition and a clear categorization of RPF has to be encouraged.

CONCLUSIONS: The work introduced a method for a possible characterization for sports running prostheses for athletes with trans tibial amputation based on a quantitative stiffness parameter that can also be extended to other types of running feet and other levels of amputation.
The mechanical characterization according to the proposed method allows a systematic classification of the running prosthetic feet from the point of view of the equivalent stiffness Keq as a starting point.
Three RPF differing of a unit interval in their Category classification did not showed the same intervals in terms of Keq. This raised some enquiries regarding the significance and soundness of RPF categorization for what regards their selection for the different athletes. The proposed approach also provides a basis for the categorization of these components in a regulatory standard.

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