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Comparison via Roll-Over Shape of the Kinematic Performance of two Low-Cost Foot Prostheses

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Abstract— **Bench tests are not sufficient to compare the performance of foot prostheses since only the dynamic behavior can be evaluated in the testing machines. This work supplements the bench tests described by several standards with a single patient (below knee amputee) kinematic evaluation using the concept of Roll-Over Shape to compare two low-cost prostheses against the sound limb. The Roll-Over Shape is generated first, by experimentally obtaining the trajectories of the patient's ankle, knee, and center of pressure throughout the stance phase of the gait cycle; and second by mathematically transforming these trajectories into a shank-based coordinate system with the ankle as origin. Unlike previous work that compares the roll-over parameters obtained via the quasi-static method, this paper compares the roll-shape of a trans tibia amputee wearing eather a SACH foot, or a high energy return foot (TEC-LIMBS), and the contralateral sound limb. The outcomes demonstrate a lower difference in the Roll-over radius of the TEC-LIMBS foot with respect to the sound limb (<10%), while the SACH foot presents a greater difference with respect to the sound limb (>40%). The findings of the tests performed in this study indicate that the TEC-LIMBS foot has a better kinematic performance than the SACH type prosthesis, a prosthesis widely used for humanitarian purposes.**

I. INTRODUCTION

The most popular prosthetic foot available for humanitarian purposes is the solid ankle cushion heel (SACH) foot and its various [16], [17], but this design is limited to only providing shock absorption at heel strike. A natural limb, on the contrary not only absorbs energy at heel strike, but also delivers energy to impulse the leg forward prior to the swing phase [14]. Consequently, a high energy-return and ultra-low cost prosthetic foot was developed in our previous work in collaboration with LIMBS International [3]. This prosthetic foot design addresses the functional requirements of a trans-tibial amputee with a moderate daily activity level between K2 and K3 [14]. This work tests the TEC-LIMBS prosthetic foot using the Roll-Over Shape model (ROS) and compares it with the ROS of both a SACH foot and the contralateral sound limb. Table I lists three foot prostheses available for humanitarian purposes as well as listing the main advantages and drawbacks of each product including cost, capability to return energy, durability, and local manufacture.

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Table I shows that while, on the one hand, the Niagara foot meets the desired performance requirements, it is not cheap, on the other hand, both the Jaipur and the EB1 foot prostheses are inexpensive, but are not durable. Thus, there is an evident necessity of an inexpensive prosthetic foot that provides the high-energy return and the low-price requirements of emerging markets and without compromising durability and simple manufacture. The TEC-LIMBS promises to fulfill these requirements, thereby meeting the needs of humanitarian organizations

This work assesses the dynamic and kinematic behavior of the TEC-LIMBS prosthetic foot. This assessment encompasses two tests: a mechanical bench test and a patient-based motion capture test. The American Orthotic Prosthetic Association (AOPA) standard evaluates the dynamic behavior of the prosthetic foot designs using the data acquired from a universal test machine with a fixture designed according to the test specifications. The AOPA standard categorizes the dynamic behavior of both the forefoot and the heel [2]. It assigns the code L5976 to prostheses where both of its components, keel and heel, have a dynamic response. Table II lists nine foot prostheses available in the industrialized world that have the same L-code designation. Unfortunately, due to their cost (all above 500 USD), these are not viable humanitarian solutions to the prosthetic requirements. Furthermore the prostheses designed and manufactured in industrialized countries rarely meet the requirements of low-income amputees [15], such as waterproof, sun exposure, abrasion, and tear resistance [16]. The TEC-LIMBS foot tested in this work meets the AOPA L5976 designation, and addresses the prostheses requirements of humanitarian applications.

TABLE I: Comparison of foot prostheses available for humanitarian purposes

Prosthetic Foot	Energy Return	Local Mfg	Ultra-Low Cost	Durability
Jaipur Foot	No	Yes	Yes (<10 USD)	Fails fatigue test ISO-22675
EB1 Foot	No	Yes	Yes (<8 USD)	Fails fatigue test ISO-22675
Niagara Foot	Yes	No	No (>50 USD)	Passes fatigue test ISO-22675

TABLE II: Other High-Cost foot prostheses classified with the same L5976 code according to the AOPA standard.

Prosthetic Foot	Manufacturer
OB 1D10 Dynamic Foot	Otto Bock
Senator (VS1)	Freedom Innovations
Elation	Ossur
Sure Flex	Ossur
Impulse	Ohio Willow Wood
Magnum	Ohio Willow Wood
CC2	Ohio Willow Wood
CCHP	Ohio Willow Wood
Seattle Lightfoot	Trulife

In contrast to the dynamic behavior assessment via the bench test, the kinematic behavior evaluation uses patient joint marker and center of pressure trajectories, acquired over time in a motion capture laboratory (MoCap), to generate the ROS. The ROS is a rocker-based inverted pendulum model employed to assess and compare the performance of human walking during the stance phase of the gait cycle [6], [12]. This model is generated after transforming the joint position data into a shank-based coordinate system. In recent years, many experiments have been conducted to evaluate the kinematic performance of low-cost prostheses, but there is an evident lack of uniformity in the procedures followed. Thus, the outcomes obtained can not be compared [15]. The strength of the ROS model is not only that it can be applied to rigid and multi-joint systems, but also that it presents a high repeatability in the resutls obtained [4].

A wide range of tests using the ROS are reported in the literature, yet most of them obtain the markers trajectories using quasi-static experiments [5], [8], [4]. Unlike the patient-based method used in this work, the ground reaction forces exerted on the prosthetic foot in the quasi-static method differs significantly from the shape and range of forces that the prosthesis will experience when worn by an amputee[4]. Furthermore, Hansen et al. demonstrated that ROS is invariant to changes in walking speed [10], heel height [12] or load carried [9]. Similarly, the effects of the arc length in the ROS are reported and characterized according to its influence in the gait cycle performance [11].

Experiments using the ROS have been conducted on low-cost prostheses available for humanitarian purposes. Eaton, et al. compare the kinematic behavior of seven different prostheses through their ROS obtained via the quasi-static method [17], while Sam, et al. not only obtained the ROS via the quasi-static method, but also determined the prosthesis non-damped frequency and damping ratio, from the response to a displacement step [15]. Table III lists the ROS radii and the average arc length reported by Eaton, et al. These parameters correspond to a SACH type Jaipur foot, a high-energy return Niagara foot, a SACH foot, and a SACH type ICRC foot respectively. The ROS parameters of the low-cost prostheses listed in Table III can be compared only with the outcomes of experiments conducted via the quasi-static method.

TABLE III: Roll-Over Shape (ROS) parameters of the four most descriptive foot prostheses tested by Eaton et al. [5].

Prosthetic Foot	Average Arc Length	Radii
Jaipur	129 mm	151 mm
Niagara	204 mm	300 mm
SACH	181 mm	350 mm
ICRC	178 mm	420 mm

This paper is organized as follows: First, we describe the experimental methods used to obtain the required data. Second, the experimental results are presented, analyzed and discussed. Finally, conclusions are generated based on the experimental results presented.

II. METHODS

The ankle-foot Roll-Over Shape (ROS) requires finding the trajectory of the foot's Center Of Pressure (COP) during the stance phase of the gait cycle as well as the ankle (lateral malleolus) and the knee (lateral femoral condyle) position trajectories in a room-based coordinate system (Fig. 1); afterwards, the markers and COP trajectories are translated and rotated from a room-based coordinate system into a shank-based coordinate system with the ankle as origin [7]. This transformation results in a smooth curvy progression of the COP from the heel strike to the toe off, the arch resulting of this transformation is the ankle-foot ROS, and reflects the overall motion of the system during the stance phase of gait [12]. The translation and rotation of the coordinate system is performed via the rotation the translation matrix in homogeneous coordinates for each point acquired over time. Since the sagittal plane corresponds to the YZ plane on the room coordinate system and the rotation is about the X axis, the translation and rotation matrices have the structure shown in Table IV. The Y and Z parameters represent the distance from the point to be transformed (knee or COP) to the new origin (ankle), likewise θ represents the angle between the ankle and the knee with respect to the Z axis.

TABLE IV: Translation (a) and Rotation Matrices (b) employed to convert the position trajectories from a room-based coordinate system into a shank-based coordinate system.

(a)

0
Y
Z

(b)

1	0	0
0	$\cos\theta$	$\sin\theta$
0	-$\cos\theta$	-$\sin\theta$

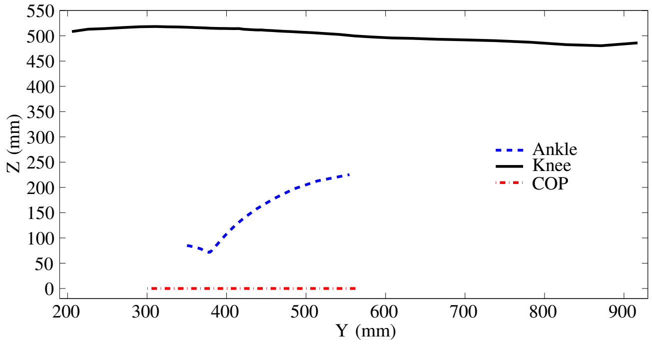

Fig. 1: Room-based marker trajectories and COP acquired over time in a motion capture laboratory

The equipment employed to capture the trajectory data and COP is firs; a Vicon Motion Capture system with 7 infrared cameras sampling at a rate of 100 frames per second, and second, a TekScan pressure mapping system sampling at a rate of 50 Hz. A subject with a left leg trans-tibial amputation was selected for the test described below. The patient had been wearing a SACH foot for 13 months, since a car accident caused his amputation. The walking speed was set to the most comfortable and self-selected by the patient. Three trials were captured for each of the three foot samples studied. Table V lists the clinical characteristics of the subject employed for this experiment.

The first prosthetic foot tested was the SACH foot since the patient was wearing this prosthesis upon arrival at the testing site. For each of the two prostheses the markers were placed according to the Helen Hayes lower body marker set [13], the patient had 30 minutes to walk and make any adjustment in the dynamic alignment of the prosthetic foot. As soon as the patient felt comfortable with the current alignment the tests started; The capture system recorded three trials for each foot: the SACH foot, the contralateral sound limb, and the TEC-LIMBS foot.

TABLE V: Clinical and physiological characteristics of the tested subject in the patient-based measurements.

Parameter	Value
Weight	67 Kgs
Gender	Male
Foot Size	11 (US)
Age	23
Amputation Level	Unilateral Trans-Tibial
Actual Prosthesis	SACH Foot
Height	173 cm
Leg Length (Hip to Ankle)	930 mm
Experience wearing the Prosthesis	13 months

Alignment procedures were conducted by a professional prosthetist. Testing of each foot took around 45 minutes; Once the SACH foot was assessed, the prosthetist continued by fitting the TEC-LIMBS foot height according to the patient height. Afterwards, the static and dynamic alignment was performed. The patient re-acquired a normal gait in less than 15 minutes once the TEC-LIMBS foot was properly aligned on the patient. Nevertheless, he was asked to walk 30 minutes more, in order to get used to the dynamic response of the TEC-LIMBS foot.

The data corresponding to each trial is extracted from the MOCAP system, and from the Tekscan platform to subsequently analyze the information employing Matlab. The transformation of the trajectories from the room-based into the shank-based coordinate system is performed using a function in Matlab. Perfectly circular arcs are fitted to the ankle-foot ROS to characterize its radius of curvature, and a mean square error (MSE) is calculated between the proposed perfect arc and the real profile described by the ROS. The ROS characterization method uses geometric parameters of the ROS profile in order to find the arc that best fits the ROS.

III. Results

Fig. 2 shows the Roll-Over Shapes (ROS) obtained from the patient-based experiments performed on the SACH foot, the contralateral sound limb and the TEC-LIMBS foot respectively.

According to the Roll-Over Shape (ROS) shown in Fig. 2 the profile described by the SACH foot is flattened in the mid-stance phase as compared with the profile of the sound limb and the TEC-LIMBS foot. In contrast the ROS of the TEC-LIMBS foot closely follows the sound limb profile. In the late-stance phase of the gait cycle and prior to the opposite heel contact, the foot in support phase is unloaded and the stored energy is released, thus a downward movement appears at the end of the ROS [7]. This movement is only described by the TEC-LIMBS foot and the sound limb, demonstrating that the dynamic response of the TEC-LIMBS foot adequately approximates the natural delivery of energy described by the sound limb.

Table VI lists the radius of curvature fitted to the the SACH foot, the contralateral sound limb and the TEC-LIMBS foot, as well as the average MSE between the ROS profile and a perfect arc for each. Then, both the SACH and the TEC-LIMBS are compared to the sound limb via the radius of curvature and the difference is expressed as a percentage. The MSE represents the variance between the points of the ROS with respect to the points of an estimator. The points of the estimator are obtained evaluating the Y coordinates of the ROS points in an estimation function, which is the parametric equation of a circle solved for Y.

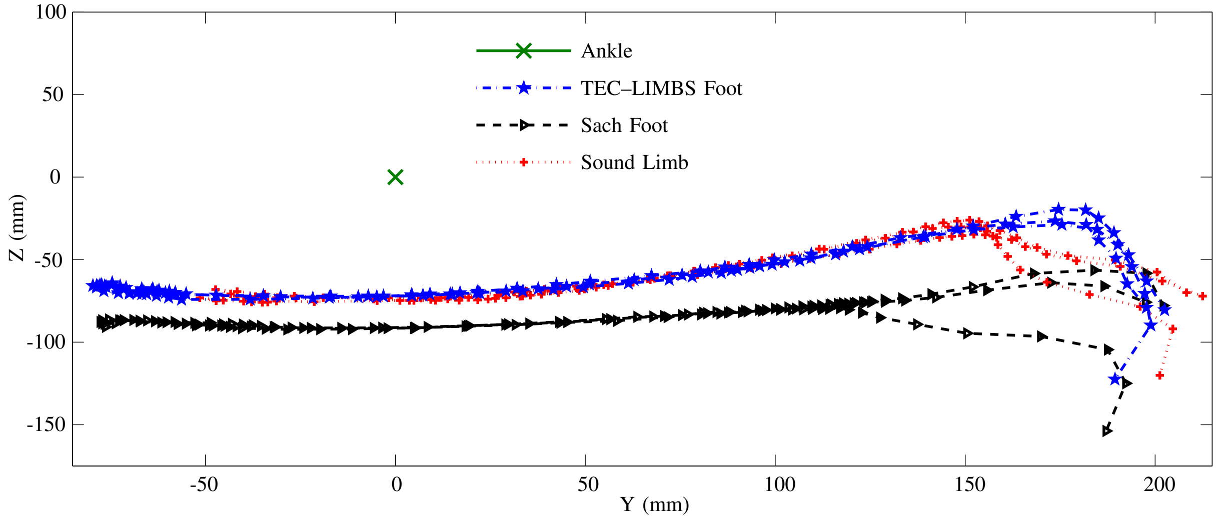

Fig. 2: Roll-Over Shapes (ROS) of the SACH foot, the contralateral sound limb and the TEC-LIMBS foot.

IV. Discussion

Comparing the findings reported in this experiment with previous work that correlate the radius of curvature of the ankle-foot Roll-Over Shape (ROS) with metabolic expenses of walking of able-bodied subjects, a radius of curvature around 0.3 leg length was shown to be energetically advantageous [1]. This behavior is observed in both the contralateral sound limb and TEC-LIMBS foot radius of curvature. The radius described by the SACH foot increases 41% with respect to the radius of the sound limb. The high stiffness of the forefoot actually restricts the plantar flexion at the mid stance phase. Thus the ROS described by the SACH foot is flatter than the ROS of the sound limb. The reduced plantar flexion is an inherent characteristic of the SACH foot due to its construction, since it is composed of a wooden keel that is not elastically deformable and thereby does not deliver energy. These findings agree with the previously characterized low-cost prosthetic foot by Sam. et al. [15], which demonstrates a similar flattened area in the mid-stance phase due to the rigidity of the SACH type prostheses. In comparison, the radius described by the TEC-LIMBS foot only decreases 9.6% with respect to the one of the sound limb. This decrement in the radius of the ROS is due to insufficient stiffness at the forefoot, and should be addressed in future work. According to the ROS showed in Figure 2 the TEC-LIMBS foot describes a smoother transition from the heel-strike to toe-off when compared to the SACH foot. These findings are similar to those obtained from industrialized market prosthetic feet characterized by Curtze et al. [4], where they analyzed the kinematic behavior of energy-return prostheses. Additionally, the arc length can be compared qualitatively from Fig. 2 , the SACH foot and the TEC-LIMBS foot show a similar but larger arc-length than the observed in the sound limb, thereby increasing the ground reaction force exerted in the contralateral sound limb at the heel-strike according to the findings reported by Hansen et al. [11]. Yet, comparing the arc-length only as a measure of the time during the stance phase is not sufficient to evaluate its performance since the distribution of the COP along the arc can be completely different for two similar arc-lengths. Information regarding the transition between the different phases of the gait could be obtained by analyzing the COP's distribution along the stance phase.

TABLE VI: Roll-Over Shape radius of curvature, MSE and difference in percentage with respect to the sound limb

Foot	Radius of curvature	MSE (Average)	Difference in percentage
SACH	543 mm	1.3	41.0 ± 3 %
Sound Limb	385 mm	1.9	-
TEC-LIMBS	348 mm	1.8	9.6 ± 3 %

Although Curtze et al. [4] did not report significant variances in the radius of curvature obtained from quasi-static method and patient-based measurements for energy-return foot prostheses, the findings, here reported, show a considerable difference between the radius obtained for the SACH foot and the radius reported by Eaton et al. [5]. We attribute this difference to the kinematic behavior observed with the complex multi-joint dynamics that occur during amputee gait, unlike the emulation body weight used in the quasi-static method. Hence, we propose that patient-based measurements are more robust than the quasi-static method when comparing prosthetic feet versus a sound limb.

V. Conclusions

Comparing quantitatively the Roll-Over Shapes (ROS) via the radius of curvature has been reported previously and reinforced in the current work as a universal and valid methodology to asses the kinematic behavior of foot prostheses. The low MSE reported between the radius of curvature and a perfect radius indicates the good curve fitting and the repeatability achieved among the trials. The ROS model is essential in the design phase of lower limb prostheses since it provides general information about the dynamic and kinematic performance during the stance phase. This type of kinematic analysis should be used iteratively and combined with dynamic analysis obtained from bench tests in order to enhance the functionality of existing prostheses, as well as to create foot prostheses that better mimic a natural limb.

The results of this work shows that the lower radius of curvature observed in the TEC-LIMBS foot with respect to the radius of curvature of the sound limb, evidences the low forefoot stiffness in the pre-swing phase of the gait cycle. In comparison, the SACH foot has a much more rigid forefoot and its radius of curvature is considerably larger and flatter than the radius of curvature of the sound limb. Finally, the current outcomes suggest the need to increase the forefoot stiffness of the TEC-LIMBS foot in order to more closely mimic the behavior of a sound limb.

While this work was designed primarily to compare the TEC-LIMBS with the most available foot for humanitarian purposes (SACH), this work has also suggested that the low-cost prostheses could be successfully compared to more expensive first-world products as those listed in table II, products which have the same dynamic response classification.

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