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EVALUATION OF ANGULAR KINEMATICS OF LOWER LIMB AMPUTEES USING QUANTITATIVE FLUOROSCOPIC IMAGING

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Abstract. *In the design of a functional prosthetic socket for lower limb amputees it is desirable to mimic the actions of a healthy limb as close as possible. While limiting the degree of freedom to which the residual limb is able to move in the prosthetic socket during ambulation (walking) is a prerequisite for an adequate fitting, with inadequate understanding of the specific anatomy of the patient including residuum changes after amputation, an overly tight socket fit can lead to pain, pressure ulcers and infections. Furthermore, changes in the initial alignment between the residual limb and socket have been shown to affect the pressure distribution within the socket.*

The purpose of this study was to measure and report the angular kinematic data/variables of lower limb amputees under protocols designed to infer the kinematics within the socket during walking and static weight hold on the artificial limb. The study details the angular motion kinematics of the tibia within the residuum with and without the addition of a 5kg mass used to replicate forces applied to the residual limb while undergoing the swing phase of slow and fast walking. Using quantitative fluoroscopic imaging techniques, continuous frame by frame tracking of tibia and prosthesis have been recorded and measures of residual limb/tibia angular kinematic have been performed. The understanding of the angular motion of the tibia within the residuum conveys a new insight in socket design (comfort and performance considerations) and furnishes a straightforward view into the effects of surgical amputation and prosthetic fit techniques.

1 INTRODUCTION

Clinical studies showing that a majority of people with lower-limb amputation experience socket instability, discomfort, or residual limb pain [8,9,13] indicate the need of a better design for a functional and stable prosthetic to enable individuals to maximize their quality of life by better engaging in a day by day physical activities.

Recent biomechanical studies [1] have determined that in walking and running the socket absorbs the impacts [12,21] and behaves as a variable stiffness device which store and release energy. Moreover, for the below-knee amputee running, relatively shorter aerial and swing times (-35%), and longer ground contact times (15%), which increase reaction forces in the socket have been observed. These biomechanical findings suggest that the dynamics of the stump inside the socket can lead to undesirable side effects [8].

While reflective markers placed at specific locations convey a good understanding of the joints and (prosthetic foot) kinematics [17,18] it gives few indication of the stump motion inside the socket [2,3]. Since the weight distribution insight the socket is playing an important role in socket design, a better understanding of the angular kinematics between the residual tibia and the prosthetic is absolutely essential [16]. To answer the need, the Quantitative Fluoroscopy (QF) technology developed at the Institute for Musculoskeletal Research and Clinical Implementation at the Anglo-European College of Chiropractic (AECC), which can perform semi-automated continuous motion analysis of multiple images of the osseous linkages [6,7], have been used for the analysis of angular kinematics between the residual bone and the socket.

Using a new coronal plane QF imaging protocol the angular kinematics of the residual limb (residuum) within the socket have been assessed during walking and static weight hold using the participant's prosthesis. The study details the residual limb angular kinematics with and without the addition of a 5kg mass used to replicate slow and fast walking. The understanding of the angular motion of the tibia within the residuum conveys a new insight in socket design (comfort and performance considerations) and furnishes a straightforward view into the effects of surgical amputation and prosthetic fit techniques.

2 METHODS

A protocol to measure the angular motion of the tibia while simulating the swing phase of gait was designed based on some studies reported in literature in [3,10,11]. The protocol using QF was approved in November 2012 by the National Research Ethics Service (REC reference: 13/SW/0248) due to the need for 'Approval for research involving ionizing radiation' [15], however, the effective dose received by any individual was minimal, with a maximum dose of received by any participant across the cohort was 5x10-6 mSv (in addition to the UK average annual background radiation dose of 2.7mSv). To simulate angular kinematics under slow walking, fast walking and static weight hold on the artificial limb gait the protocol requires the participants to apply load as a weight transfer from foot to foot, that is, rocking from one foot to another. A platform with handrails (Figure 1) has been used to level the participant(s) to the fluoroscope height where the angular kinematics images of the limb-prosthesis interface are recorded (Figure 2). The image intensifier was positioned as close as possible to the participant's amputated limb ensuring that magnification/distortion effects were minimal and the base of the prosthetic socket would not leave the image field at any time.

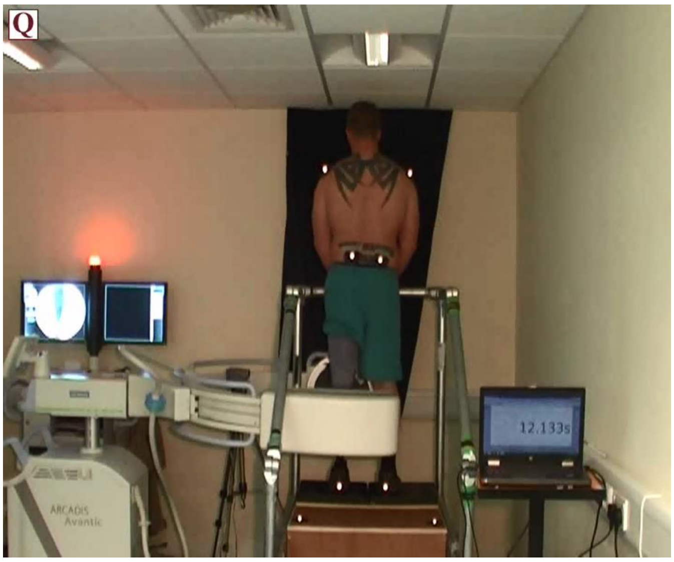


Figure 1: Depicting the stance of a unilateral trans-tibial amputee volunteer during residual limb fluoroscopy imaging procedure with and without the addition of a 5kg mass used to replicate slow and fast walking.

Residual limb image acquisition, which quantifies tibial motion within the socket while accounting for magnification effects [5], has been performed for 3 test configurations named:

i) Rocking from Foot to Foot (RFF): a gait cycle duration of 2 seconds was determined to be of optimal duration. This was designed to be as close as possible to the natural gait cycle and avoid image blur across the image sequence allowing accurate image tracking of the tibia. During this simulated gait cycle the participants were been asked to move their full weight from rock from foot to foot (using a metronome for guidance) during which 10 seconds of fluoroscopic imaging took place. The fluoroscopic recording acquired in the anterior-posterior (AP) view of the limb/prosthesis interface started once the participants confirmed their comfort with the motion. This allowed a recording of consecutive 5 gait cycles.

ii) Rocking with 5 kg mass on Prosthetic Limb (R5kgPL): The RFF procedure was repeated with the addition of a 5 kg mass to simulate the force applied during a slightly faster walking swing phase [14]. All participants mentioned that they are comfortable with the addition of the 5 kg mass which was attached to the base of the prosthetic limb.

iii) Static Weight-Bearing Hold (SWBH): carrying no additional mass weight the participants have been asked to slowly put their weight on their prosthetic limb and held it there for a short period of time (about 10 seconds).

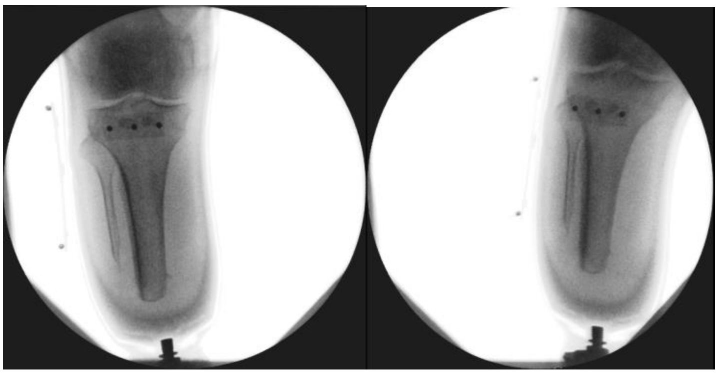


Figure 2: Example of successful tracking of tibial rotation during image acquisition

Two force plates placed on the platform were used to measure the body weight distribution during these testing protocols.

3 DATA ANALYSIS

In order to perform the data analysis, all the recorded images have been transferred from the fluoroscope to a dedicated computer for enhancement and analysis. Each fluoroscopic image sequence typically contained up to 150 individual DICOM images and was 350 megabytes in size. Individual image frames (Figure 3) were extracted from the sequence into '.jpg' format files using a JPEG compression performed in the Matlab environment.

Following enhancement of the images, templates have been manually placed around the tibia and metallic base of the prosthetic socket. These templates, called the 'reference templates', are used the verification process as well as a simplified representation of the tibia. The tracking algorithm makes note of the grayscale pixel information contained within each tracking template, as well as its location in the image. This information is then compared to the pixel data for the same location in the next frame. The template is then automatically moved both laterally and in rotation by small increments into locations near to its previous location and the process is repeated.

Via cross-correlation methods, each image in each position is compared to that of the previous image. This process is then repeated for each subsequent image and tracking template for that image sequence [6,7].

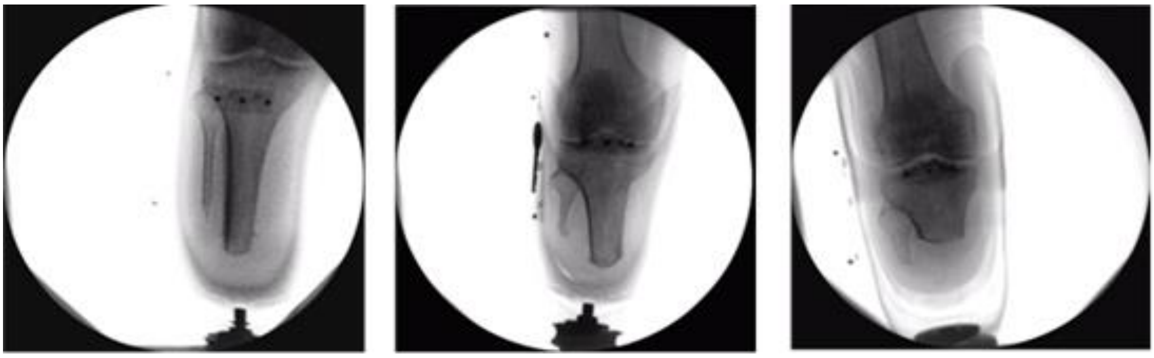


Figure 3: Individual image frames - examples of the variation in the residual tibia length and shape

The benefit of this process is its ability to quantify the location of the residual limb within the socket and to provide standardization of the measurements. However, there were some complications within this quantification process. While identification of the tibial outline and anatomical landmarks were found to be satisfactory, tracking of the tibia often failed as it moved though the image field at speed (i.e. shifting weight).

In the full loading and full traction positions, where the limb is momentarily motionless, the tibia was readily identifiable. However, between these two positions, when the tibia is moving at speed, motion blur reduces the likelihood of successful image tracking. To account for these difficulties, manual or discrete identification of tibia positions were necessary at extremes of motion. To achieve this, the original templates have been manually replaced in a corrected position before continuing automated tracking. This allowed the relative sizes and shapes of the reference templates to be maintained and to give consistent results.

Additional quality assurance procedures included inspection for image distortion, magnification and out of plane rotation of the prosthesis. Image distortions such as pin cushion effect were not observed, since this is automatically corrected by the image interface of the Siemens fluoroscope used (Siemens Arcadis Avantic – Siemens GMBH, Germany). To account for magnification errors in the fluoroscopic images of the prosthesis limb an imaging protocol for measuring the proximo-distal motion of the residual tibia within the soft tissues of the residual limb and estimating errors which may arise in these measurements have been considered [7].

Although the literature does not elaborate on tibial angulation in the coronal plane, previously conducted studies using sagittal or oblique imaging views have required adaptations to overcome the angular alignment change between the prosthesis and tibia as the tibia as it descends into the socket and soft tissue [3, 14,19,20]. In the course of this investigation it became apparent that such a method was needed and that it must be applicable across a range of tibia shapes and socket/suspension style combinations.

4 RESULTS

To standardize the results and to account for coronal plane rotation variations in the alignment of the residual limb and socket, a method for measuring the proximo-distal motion of the tibia was derived from similar radiographic techniques which imaged the residual limb in the sagittal plane [14,19]. The method considered the proximo-distal direction defined in the coronal plane passing through the center of the tibia, and represented by a line running from the center of the tibial plateau, perpendicular to it and extended to the bottom of the prosthetic socket (Figure 4). This compensate for asymmetries at the distal end of the tibia due to the surgical techniques used or to post-surgical bone growth.

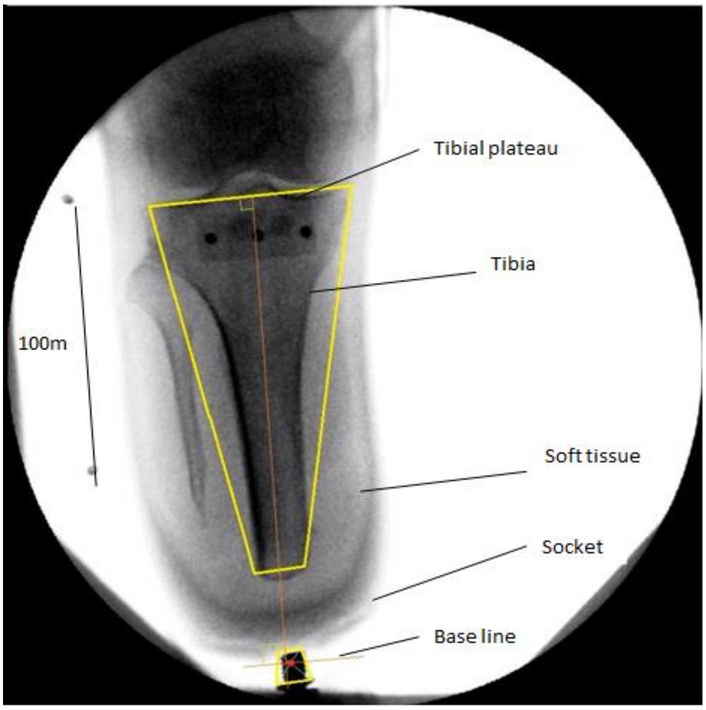
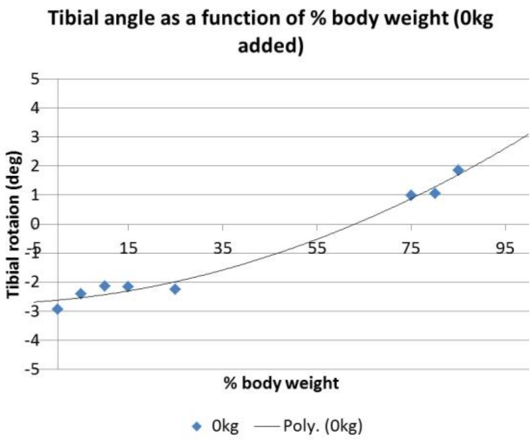
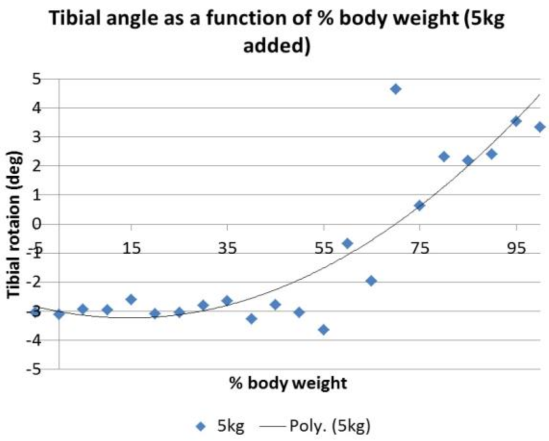


Figure 4: Tibia angular kinematics - a method to measure the angular changes

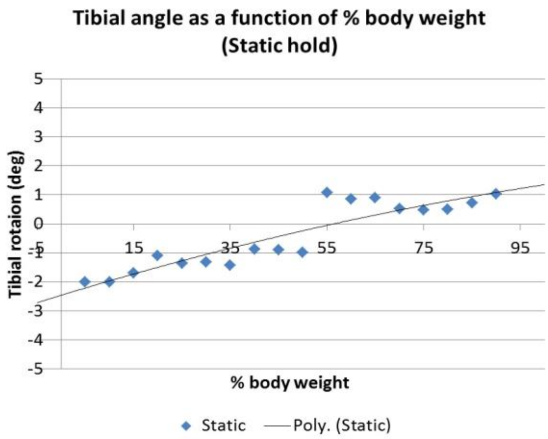
To account for angular changes, the socket base was identified as a line, perpendicular to the proximo-distal direction and passing through the center of the prosthesis base marker. The tibia angular kinematics as a function of body weight and static hold is shown in Figure 5. It can be seen that the addition of a 5 kg mass shown in Figure 5.b which is used to replicate forces applied to the residual limb while undergoing the swing phase of fast walking, affect the angular kinematics in Figure 5.a by an increase from 4.8 to 8.3 degrees. From Figure 5.c it can be also observed that the angular kinematics is minimal when a static hold is performed.



(a)



(b)



(c)

Figure 5: Angular kinematics of the prosthetic foot/tibia for (a) no weight attached, i.e., slow walking (b) 5 kg weight attached, i.e., fast walking, and (c) full body weight is slowly applied to residual limb, i.e., static hold

It was also observed (but not presented here) that the variation in the residual tibia length and shape shown in Figure 3 can affect both the initial angle of the tibia with respect to the base of the socket as well as the angular kinematics of the tibia inside the socket.

5 CONCLUSIONS

In this study the angular kinematics of lower limb amputees have been assessed for walking and static weight hold on the artificial limb using Quantitative Fluoroscopic imaging techniques. The study details the angular motion kinematics (maximal angular amplitude) of the tibia within the residuum with and without the addition of a 5kg mass used to replicate forces applied to the residual limb while undergoing the swing phase of slow and fast walking. The study, which provides a better understanding of the pressure distribution within the socket through its angular kinematics, conveys a new insight into socket design for comfort, performance and amputation techniques.

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