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Technical note

Characterisation of dynamic couplings at lower limb residuum/socket interface using 3D motion capture

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ABSTRACT

Design and fitting of artificial limbs to lower limb amputees are largely based on the subjective judgement of the prosthetist. Understanding the science of three-dimensional (3D) dynamic coupling at the residuum/socket interface could potentially aid the design and fitting of the socket.

A new method has been developed to characterise the 3D dynamic coupling at the residuum/socket interface using 3D motion capture based on a single case study of a trans-femoral amputee. The new model incorporated a Virtual Residuum Segment (VRS) and a Socket Segment (SS) which combined to form the residuum/socket interface. Angular and axial couplings between the two segments were subsequently determined. Results indicated a non-rigid angular coupling in excess of 10° in the quasi-sagittal plane and an axial coupling of between 21 and 35 mm. The corresponding angular couplings of less than 4° and 2° were estimated in the quasi-coronal and quasi-transverse plane, respectively.

We propose that the combined experimental and analytical approach adopted in this case study could aid the iterative socket fitting process and could potentially lead to a new socket design.

1. Introduction

The functionality of lower-limb prostheses and the comfort at the residuum/socket interface are critical elements in determining the successful rehabilitation of an amputee. Indeed, the socket has long been established as the key to maintaining limb stability during various activities [1]. An optimal socket fitting ensures both a bespoke load transfer profile to the residuum and limb control stability, in dynamic settings. Currently, the socket fitting and manufacturing processes are most often based on the accumulated experience of the prosthetist [2] to match the complex shape of each individual residuum [3, 4]. There are limited objective criteria to assess the relative motion between the residual limb and the prosthesis.

The importance of the relative motion between the residual limb and the socket has long been recognised by Radcliffe [5] over 35 years ago. Indeed he conceptualised the development of a quadrilateral socket based on the 'anticipated' movement of the femur within the soft tissues. However, this approach lacked empirical evidence at the time. More recently, radiological imaging techniques [6–14] have been employed in order to quantitatively characterise the residuum/socket interface coupling, which has been defined by a range of terms involving bone/tissue [6], bone/socket [7] and tissue/socket [9] interactions. As an example, Papaioannou and colleagues [8], using Dynamic Roentgen Stereogrammetric Analysis (DRSA) based on 10 trans-femoral amputees, highlighted that the slippage between the residuum and socket reached a maximum of 15 mm in the anterior–posterior (AP) direction and 10–30 mm in the axial direction. The use of other equipment like X-ray [10–12] or spiral X-ray computed tomography (SXCT) [14] also showed the bony position relative to residuum tissue and the socket, respectively.

A non-contact photoelectric sensor [15] was also used to measure the distal position of the residual limb relative to the socket during walking. An ultrasound-based study conducted by Convery and Murray [16] determined the motion of the residual femur relative to the lateral wall of socket. In the stance phase, a femoral extension of 7° and abduction of 9° were observed. The femoral extension was restored during the swing phase, while the abduction was restored during the mid-stance phase and the swing phase. Other researches incorporated an instrumented prosthesis to measure the socket internal/external rotation about the pelvis [17,18]. Despite all these studies implying the relative motion at the residuum/socket interface, the exact nature of the dynamic coupling is still not fully understood. Most

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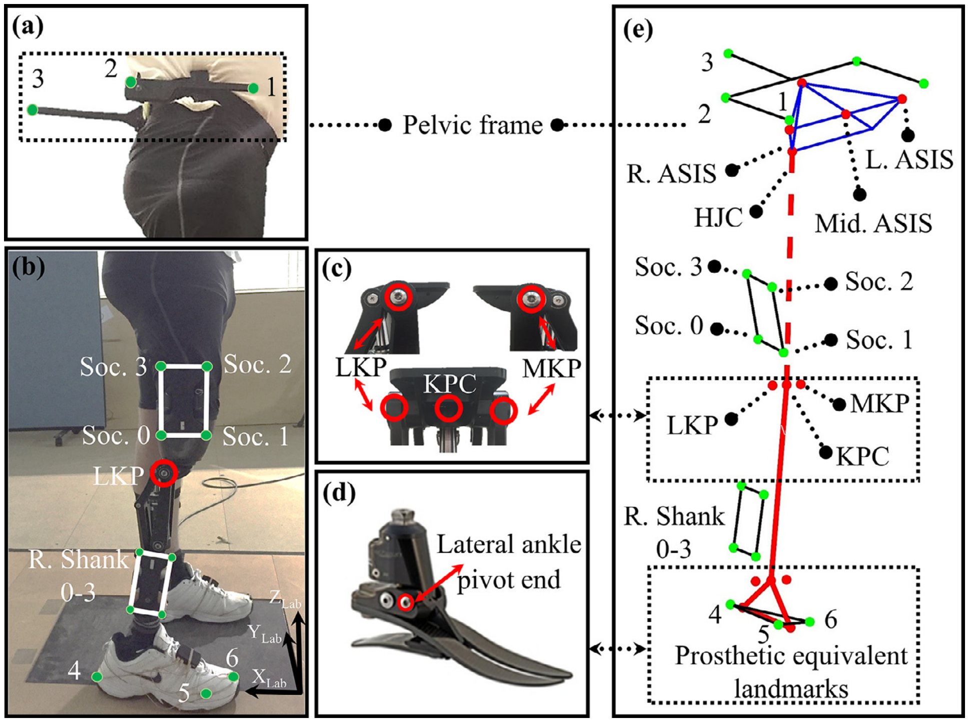

Fig. 1. (a) An illustration of Coda pelvic frame with three markers on the prosthetic side. (b) The location of eleven real markers (shown in green dots) on the prosthetic side of the subject. The lab coordinate system is also shown with the origin at the front left corner of the force plate. The *x*-axis (X_{Lab}) was positive in the direction of walking, the *y* axis (Y_{Lab}) was positive from left to right and the *z*-axis (Z_{Lab}) was positive vertically. All 3D coordinates of physical and virtual markers were expressed relative to this origin. (c) The location of the digitised points (shown in red circles) – Lateral Knee Pivot (LKP) and Medial Knee Pivot (MKP) – on the KX06 knee. (d) The location of lateral ankle pivot end on the Echelon foot. The medial equivalent was also digitised but cannot be seen in this photo. (e) The equivalent segment model with virtual and real markers shown in red and green dots respectively. Prosthetic side of the limb, pelvic segment model and pelvic frame are shown as red, blue and black lines, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the existing techniques are either not widely available, expensive or can expose the patients to radiation. This limits their accessibility in a prosthetic clinical setting.

3D motion capture and analysis systems have been widely accepted and used to study amputees' gait [19–21]. However, in most cases, a rigid segment at the residuum/socket interface is assumed on a linked segment model for amputees, in a similar manner to that assigned in able-bodied gait analysis [22]. This approach assumes no relative movement between the residuum and the socket, while in reality, the residuum/socket interface should be treated more like hydrostatic fluid containment [23]. The presence of relative movement at this interface contradicts the rigid linked segment assumption and hence suggests the previous results should be viewed with caution [24]. Gholizadeh et al. [25] measured the vertical displacement between the liner and socket using 3D motion capture system, however only static results were reported.

In this paper, we report a novel model incorporating separated segments for the prosthetic socket and the residuum, respectively, with a view to characterise the dynamic non-rigid coupling at the residuum/socket interface. A case study using a 3D kinematic motion capturing system was conducted to validate the established model.

2. Method

2.1. Subject

A male right trans-femoral subject, who had an amputation below his knee soon after he was born and then above the knee in his teens, was recruited to the study (28 years old, body mass 79 kg, and height 177 cm). The subject had a stable residual limb volume, free from infection and inflammation, and was capable of repeated, unassisted walking trials. The subject was fitted with a supracondylar suspension socket, KX06 polycentric knee and Echelon Foot with an axial/torsional shock absorber VT unit (Chas A Blatchford & Sons Ltd.). He had used this system every day for a period in excess of one year. An experienced, accredited & Certified Prosthetist/Orthotist (CPO) verified the alignment of the prosthetic components and the fit of the socket prior to testing.

2.2. 3D kinematic motion capture

2.2.1. Real marker placement

The configuration of marker placement on the subject, during the motion capture process, was based on a six degree-of-freedom (6-DoF) model as shown in Fig. 1. This incorporated a total of 28 real markers, including a marker wand and a pelvic frame.

A frame consisting of six markers was worn around the pelvis with the sides lying in the plane of the anterior superior iliac spine (ASIS) and the posterior superior iliac spine (PSIS) landmarks (Fig. 1a). On the prosthetic side, a cluster of four markers was fitted to the lateral socket wall (Fig. 1b). These markers were numbered sequentially, starting with Soc. 0 at the distal-posterior corner, and continuing anti-clockwise to Soc. 3 at the proximal-posterior corner. A strap was tightened around the cluster to ensure stability. Similarly, on the shank segment, a cluster of four markers was mounted on the lateral-distal region of the prosthetic knee, as shown in Fig. 1b. Three markers were placed on the shoe at equivalent positions to the heel, the 5th metatarsal and the hallux, using double-sided tape (marked as 4, 5 and 6 in Fig. 1b).

2.2.2. Virtual marker digitisation and estimation

The motion of the pelvis was tracked using a pelvic frame (ODIN User Guide, 2013). The hip joint centres (HJCs) were defined in relation to a pelvic reference system [26] using Roentgen