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A combined kinematic and kinetic analysis at the residuum/socket interface of a knee-disarticulation amputee

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ABSTRACT

The bespoke interface between a lower limb residuum and a prosthetic socket is critical for an amputee's comfort and overall rehabilitation outcomes. Analysis of interface kinematics and kinetics is important to gain full understanding of the interface biomechanics, which could aid clinical socket fit, rehabilitation and amputee care. This pilot study aims to investigate the dynamic correlation between kinematic movement and kinetic stresses at the interface during walking tests on different terrains.

One male, knee disarticulation amputee participated in the study. He was asked to walk on both a level surface and a 5° ramped surface. The movement between the residuum and the socket was evaluated by the angular and axial couplings, based on the outputs from a 3D motion capture system. The corresponding kinetic stresses at anterior-proximal (AP), posterior-proximal (PP) and anterior-distal (AD) locations of the residuum were measured, using individual stress sensors.

Approximately 8° of angular coupling and up to 32 mm of axial coupling were measured when walking on different terrains. The direction of the angular coupling shows strong correlation with the pressure difference between the PP and AP sensors. Higher pressure was obtained at the PP location than the AP location during stance phase, associated with the direction of the angular coupling. A strong correlation between axial coupling length, L, and longitudinal shear was also evident at the PP and AD locations i.e. the shortening of L corresponds to the increase of shear in the proximal direction. Although different terrains did not affect these correlations in principle, interface kinematic and kinetic values suggested that gait changes can induce modifications to the interface biomechanics.

It is envisaged that the reported techniques could be potentially used to provide combined kinematics and kinetics for the understanding of biomechanics at the residuum/socket interface, which may play an important role in the clinical assessment of prosthetic component settings, including socket fit quality.

1. Introduction

A prosthetic socket is an essential part of any lower limb prosthesis, which is custom-made and provides attachment between the rest of the prosthesis and the residuum of a lower limb amputee. The critical interface, formed by the residuum and the socket, is well recognised to play an important role in amputee comfort, residuum tissue health and overall rehabilitation outcomes [1,2]. Consequently, the biomechanical understanding of this interface has attracted significant interest [3]. In the past 60 years, a number of studies have sought to assess the kinematics and kinetics at this interface. For example, in order to evaluate the real-time interface kinematics, various imaging techniques involving X-ray [4–6], Dynamic Roentgen Stereogrammetric Analysis (DRSA) [7], ultrasound technology [8] and non-contact sensors [9], have been exploited and these have reported up to 57 mm of axial coupling [10] and 10° of angular coupling [8] in a gait cycle (GC). Equally, in order to evaluate the real-time interface kinetics, interface stress sensors such as strain gauge-based sensors [11–13] and magneto-resistive sensors [14], have been inserted at

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the residuum/socket interface and up to 350 kPa pressure (i.e. stress acting normal to skin) and 80 kPa shear (i.e. stress acting parallel to the skin) have been reported during amputee walking tests [14,15].

Despite all these studies, imaging-based technologies for kinematic evaluation are either not widely available, expensive or can expose the patients to radiation. This limits their accessibility in a prosthetic clinical setting. To address this challenge, we have recently developed a new and clinically accessible method to characterise the 3D dynamic kinematic coupling at the residuum/socket interface using a 3D motion capture dataset [16]. Preliminary results obtained from walking tests of a trans-femoral amputee suggested up to 11° of angular coupling in the sagittal plane and 35 mm of axial coupling, aligning well with the findings of other studies [8,17]. For the interface kinetic studies reported to date, most stress sensors reported were only able to measure pressure, including a few commercial systems e.g. Tekscan F-Socket system and Novel. The few reported combined pressure and shear sensors were either too bulky, required socket modifications to insert at the interface [14], or were built on rigid substrates [18,19], all of which precluded their use at the interface of a tight fitting socket. We have recently developed a unique thin and flexible sensor, which can be directly applied at residuum/socket interface to provide combined pressure and shear measurement during ambulation [20,21].

It is well known in the field of lower limb biomechanics that, in the case of trans-femoral amputees, the relative kinematic movement between the femur and the socket determines the forces or stress profiles that the socket exerts on the residuum, as a function of GC [3,22]. For example, it has been suggested [3,22] that the distal femur moves posteriorly for knee stabilisation and results in higher pressures in the posterior-distal region of the residuum in early stance phase. In late stance phase, in order to initiate knee flexion, the distal femur presses anteriorly causing higher pressure at the anterior-distal location. Sanders, et al. [9] also highlighted the importance of correlating the dynamic residuum axial displacement in the socket with the corresponding interface pressure and shear stresses in order to provide a combined assessment, which is critical for clinical outcome measures.

Despite the essential association between the kinematic and kinetic information for the evaluation of interface biomechanics, there is a paucity of studies combining assessments of residuum/socket interface biomechanics. This is largely due to the lack of effective and clinically applicable means for these assessments.

In the present study, we report kinematic and kinetic biomechanical results at the residuum/socket interface based on pilot studies, involving a knee-disarticulation amputee. Various tests were conducted, including walking on level surfaces and ascending and descending ramped surfaces, while 3D motion capture data and interface stress sensors output were collected simultaneously and subsequently analysed. The aim of this pilot study was to demonstrate a new method, which is the first of its kind, for capturing the combined kinematics and kinetics of the residuum/socket interface, and one subject was considered acceptable for demonstration purposes. Furthermore, the results obtained allowed the authors to explore the best way to present the data prior to larger studies.

2. Methods

2.1. The participant

One male, right-sided, knee-disarticulation amputee participated in this study (age 29 years, height 178 cm and mass 81 kg). The participant had a stable residual limb volume, free from infection and inflammation, and was capable of conducting repeated, unassisted walking trials. The participant was fitted with a Pelite liner, a supra-condylar suspension socket, a KX06 polycentric knee and an Elan^{TM} foot (Chas A Blatchford & Sons Ltd., Basingstoke, UK). A senior prosthetist verified the alignment of the prosthetic components and the fit of the socket prior to testing. This study was approved by the institutional Ethics and Research Governance Committee (ID: 12058 and ID: 6008).

2.2. Instrumentation

A gait laboratory was used to acquire the kinematic 3D motion at the residuum/socket interface, as detailed in previous work [16]. It was equipped with a two camera CODA motion analysis system (Charnwood Dynamics Ltd., Leicestershire, UK), an 8 m level walkway and a 5° inclined walkway, also 8 m in length. For both level and inclined walkways, a force plate (Model 9826BA, Kistler Instrument Ltd., Switzerland) was integrated and located approximately at the halfway points of each walkway. The motion analysis system collected the 3D marker data at 200 Hz and three ground reaction force (GRF) components from the force plate at 500 Hz.

In order to collect pressure and shear stress at the residuum/socket interface, a previously reported sensor system was used. Fig. 1a illustrates the sensor system which incorporates three sensor units (SU) and a sensor system controller (SSC). The pressure and shear signals from the SUs are transmitted to the SSC and subsequently sent to a personal computer (PC) wirelessly via Bluetooth at 100 Hz. A PC software was developed to collect, visualise and store the corresponding signals. The positive directions of the pressure (+ve P), circumferential shear (+ve S_C) and longitudinal shear stresses (+ve S_L) are also illustrated in Fig. 1a. Prior to the amputee test, each of the SUs was calibrated as detailed in the authors' previous publication [21].

2.3. Protocols

Upon arrival, the participant was asked to doff the prosthetic socket and change into Lycra shorts. A total of 28 markers (Fig. 2a) were then placed on both the prosthetic leg and the contralateral limb, by the investigator. Three SUs were then attached to the inner surface of the Pelite liner, by a senior prosthetist (Fig. 1b). Subsequently, the amputee donned the socket and he was asked to walk on the level walkway, and then on the 5° descending and a 5° ascending walkway. Cadence was controlled by a metronome set at 100 beats per minute. For the tests carried out on each of the terrains, data were collected from 12 repeated trials with at least seven steps in each of the trials.

2.3.1. Marker placement and digitisation

The real marker placement and virtual marker tracking were based on the conventional six degree-of-freedom model. A frame consisting of six markers (marked as 1–6 in Fig. 2a) was worn around the pelvis, tracking the pelvic movement. On the prosthetic side, a cluster of four markers (marked as Soc.0-Soc.3 in Fig. 2a) was taped to the socket wall and was subsequently used to track the socket movement. Similarly, a cluster of four markers was mounted on the lateral-distal location of the prosthetic knee and was subsequently used to track the shank movement (marked as Shank.0-3 in Fig. 2a). Three markers were attached to the shoe at locations equivalent to the heel, the fifth metatarsal and the hallux.

Virtual markers were digitised (Fig. 2a) and estimated based on the location of the real marker placement. A pelvic model was defined using the digitised Anterior Superior Iliac Spine and Posterior Superior Iliac Spine landmarks and tracked in relation to the pelvic frame, during dynamic motion capture. The hip joint centres (HJC)