Internal and external prosthesis kinematics assessment using Dynamic Radiography

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Abstract: This study combines the assessment of three-dimensional (3D) total knee prosthesis kinematics with that of amputee socket-stump kinematics/displacement during high-speed strenuous activities (descending stairs-SD, sudden stop-SS) using Biplane Dynamic Roentgen Stereogrammetric Analysis (DRSA) instrumentation. In a case study of a below knee (BK) amputee that had previously undergone knee replacement surgery revealed that deformation between skin-to-socket marker-pairs reached maximum values of almost 22%. Excessive telescoping motion of the residual bone structures with respect to the socket was also observed (Max for SD trials: 29.16 mm). Relative skin strain and relative engineering shear (γ) calculated from skin-marker pairs for step-down and fast-stop trials reached values that ranged between 0.01-0.1 and 81.5 to 129 degrees respectively. This in-vivo, patient-specific, unobtrusive dynamic information is highly-accurate and can significantly impact the iterative cycle of socket fitting and evaluation.

Methods: A sixty-five year old female BK amputee (Fig.1) wearing a patellar tendon-bearing (PTB) socket with silicon liner was selected for this study approved by our institutional IRB. We rigidly fixed several 4mm tantalum markers on the external surface of the socket according to a recognizable pattern for easier tracking. Stripes of tantalum pigment paint in the shape of orthogonal meshes were placed on the skin and liner around the perimeter of the stump in an effort to cover the most critical areas that possible deformation might occur (Fig.1). A high resolution laser-based 3D digitizer (Konica Minolta, VIVID 910) was then used to scan the 3D geometry of the stump-skin surface and the patient’s socket. The carefully donned amputee stump-socket complex with all the markers was then scanned with a Computed Tomography (CT) imager (Fig.1c) (slice spacing 0.5mm, 1000x1000 pixels matrix, GE, St. Luke’s Hospital, Aurora Health System, Milwaukee WI). The patient was then asked to perform several sudden-fast-stop movement trials (n=3) in the direction of progression during running and the task of coming down from stairs (while landing on the prosthesis (stair height: 22 cm)) (n=3) that were assessed using DRSA (IMEROSINTM, Bioimerosin Laboratories SA, Milwaukee, WI) and force plate instrumentation 1, 2, 3.

Tracking of the high speed kinematics of the orthogonal skin meshes, the residual bone edges, the knee joint prosthesis and all the tantalum markers was possible using marker based and markerless tracking software 1, 2, 3.

Results: The method’s static and dynamic accuracy were 0.03±0.06mm and 0.09±0.05mm respectively. Minimum and maximum dynamic errors in determining the 3D distance were between 1 to 2.3 percent of the original known distance between two rigidly attached socket markers (SoMMAnt and SoMLOs, Fig.1b). The assessment of overall dynamic accuracy indicated that rms errors in any one direction were less than 0.50 mm for the femoral prosthesis and less than 0.40 mm for the socket. Finally, the assessment of overall dynamic rotational accuracy indicated that rms errors in flexion extension, ab-adduction and internal-external rotation were less than 1.03, 0.29 and 1.12 degrees respectively. Dynamic skin slippage was assessed by plotting the relative 3D displacement of a skin-marker with respect to the socket. Figure 2 shows the respective proximity 3D pathway for characteristic skin markers and the 3D kinematics (telescoping motion) of the femoral/tibia prosthetic components at four time instants (t1: 0.0 sec, t2: 1.46 sec, t3: 1.8 sec, t4: 2.14 sec) after impact with the ground during the step-down trial 2. It was observed that the characteristic slippage patterns of skin markers skDAnt, skDL, skDPos, and the femur and tibia prosthesis 3D displacement were the most amplified immediately after impact. In addition the femoral/tibia prosthetic components moved 25mm vertically with respect to the socket (Fig.1, 2). The results demonstrate a downward, anterior-posterior shift of a whole group of distal, lateral and posterior region skin-markers after impact. The respective deformation between skin-to-socket marker-pairs reached maximum values of almost 22%. The deformation between the tibia prosthetic component and skin/socket marker-pairs reached maximum values of almost 100%.

Discussion: The new marker-and-markerless socket-stump-internal prosthetic kinematics assessment method a) is one order of magnitude or greater of improvement in accuracy from existing conventional motion analysis techniques, b) allows the use of the markerless and marker based methods interchangeably to track the different hard and soft segments/components in a completely unobtrusive way c) employs new representations of this hard-to-soft- tissue interaction with 3D visualization paradigms that the prosthetist is trained to interpret and d) provides information that is not possible with other in-vivo dynamic tracking techniques. This highly-accurate in-vivo patient-specific unobtrusive assessment of the dynamic socket-stump 3D slippage and residual bone telescoping motion, can significantly impact the iterative cycle of socket fitting and evaluation.


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