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Effects of soft tissue artifacts on differentiating kinematic differences between natural and replaced knee joints during functional activity

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ABSTRACT

Functional performance of total knee replacement (TKR) is often assessed using skin marker-based stereophotogrammetry, which can be affected by soft tissue artifacts (STA). The current study aimed to compare the STA and their effects on the kinematics of the knee between twelve patients with TKR and twelve healthy controls during sit-to-stand, and to assess the effects of STA on the statistical between-group comparisons. Each subject performed the sit-to-stand task while motions of the skin markers and the knees were measured by a motion capture system integrated with a three-dimensional fluoroscopy technique. The bone motions measured by the three-dimensional fluoroscopy were taken as the gold standard, with respect to which the STA of the markers were obtained. The STA were found to affect the calculated segmental poses and knee kinematics between the groups differently. The STA resulted in artefactual posterior displacements of the knee joint center, with magnitudes significantly greater in TKR than controls ($p < 0.01$). The STA-induced knee external rotations in TKR were smaller than those in controls with mean differences of 2.3–3.0°. These between-group differences in the STA effects on knee kinematics in turn concealed the true between-group differences in the anterior–posterior translation and internal/external rotation of knee while leading to false significant between-group differences in the abduction/adduction and proximal–distal translation.

1. Introduction

Total knee replacement (TKR) has been one of the most effective treatment options for advanced osteoarthritis of the knee. To improve its long-term survivorship and performance in restoring the normal function of the knee, assessment of TKR during functional activities has been performed mainly using skin marker-based motion capture systems [1,2]. However, these endeavors have been hindered by soft tissues artifacts (STA) [3] caused by the movement of the skin markers relative to the underlying bones during movements. The STA are associated with muscle contractions, marker positions [4], physical characteristics [5] and tasks [6]. The STA are non-linear over the movement cycle [7] and difficult to eliminate non-invasively [8], and thus reduce the accuracy of the assessment of the knee function.

Given the geometric and kinematic differences between TKR and normal knees [9], the STA and the calculated kinematic variables may be different between the groups, affecting the outcome of between-group comparisons. For patients with TKR, the movements of skin surfaces relative to underlying bones are altered by the surgical procedure, including incising the soft tissues over the knee, removing the cruciate ligaments and replacing the articular surfaces with prosthetic components, which also affects the control of the passive kinematics of the joint [10]. Moreover, subject-specific and task-related STA have been demonstrated to produce different errors in the calculated biomechanical variables of the knee [11,12], which may further affect the between-group comparisons in clinical studies. However, while the STA can be different between people with TKR and natural knees, no study has examined how the between-group differences in the STA would affect the between-group differences in the calculated kinematic

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variables of the segments and joint. To resolve the problem, the true effects of STA on differentiating the kinematic differences between patients with TKR and healthy controls should be identified.

The technique of integrating a motion capture system with a fluoroscopic or a radiographic system has been used to measure the STA and quantify their effects on the calculated kinematic and kinetic variables in individual subject groups [11–16]. Therefore, using a similar approach, the purposes of the current study were to compare the STA of the skin markers and their effects on the segment and joint kinematics of the knee between patients with TKR (TKR group) and healthy controls (Control group); and to assess the effects of STA on the outcome of statistical comparisons of knee kinematics between the groups. It was hypothesized that the STA would have different effects on the segment and joint kinematics of the knee in patients with TKR and healthy controls, and would affect the statistical outcome of between-group comparisons.

2. Materials and methods

2.1. Subjects

Twelve patients (seven females and five males; age: 77.7 ± 6.5 years; mass: 63.7 ± 11.9 kg; height: 157.0 ± 2.0 cm, BMI: 26.0 ± 5.2) with posterior cruciate-retaining mobile-bearing TKR (LCS, DePuy, Warsaw, USA) and 12 healthy male adults (age: 22.3 ± 1.4 years; mass: 77.3 ± 10.5 kg; height: 171.8 ± 8.7 cm; BMI: 26.3 ± 3.9) participated in the current study with informed written consent as approved by the Institutional Research Board. Each subject wore six infrared retro-reflective markers on the thigh and four markers on the shank of the tested limb following previously reported protocols [11,12] (Fig. 1a). Among the markers selected, seven are frequently chosen in human motion analysis [17,18], namely lateral and medial epicondyles (LFC and MFC), mid-thigh (T2), fibular head (FH), tibial tuberosity (TT), medial and lateral malleoli (MMA and LMA) [19]. Three additional technical markers on the thigh (T1–T3) were also included because they are sometimes used in motion analysis [19]. These skin markers were placed on the segments with double-sided adhesive tape by a well-trained physical therapist (MYK) to ensure high repeatability.

Each subject in the Control group received a computed tomography (CT) scan (PQ-5000, Picker International, USA) of the tested knee joint, with a voxel size of 1 mm × 0.625 mm × 0.625 mm. The subject-specific CT data were then segmented and reconstructed to obtain the volumetric and polygon-meshed models of the femur and tibia/fibula [20]. For the TKR group, subject-specific polygon-meshed surface models of the knee prostheses, namely the femoral and tibial components, were used instead of the CT-based bone models because the metal prosthesis models were more accurate. This also reduced the radiation exposure to the patients. The anatomical coordinate systems (ACS) for each segment were determined by the markers on bony landmarks, as well as the geometrical features of the condyles of the bones and prosthesis components following the literature [21,22], with the *x*-, *y*- and *z*-axis directed anteriorly, superiorly, and to the right, respectively.

2.2. Measurements using integrated fluoroscopy and motion capture system

Prior to motion data collection, the intrinsic and extrinsic parameters of the fluoroscope (Advantx LCA, GE, France) and motion capture system (VICON, Oxford Metrics, UK) were determined via a calibration procedure. The distortion parameters and position of the point source of the X-ray of the fluoroscopy system were determined using a self-designed calibration object [23]. The global coordinate system was taken to be coincident with that of the motion capture system. A transformation matrix describing the coordinate transformation between the coordinate systems of the fluoroscopy and motion capture systems ($T_{\text{gcs}}^{\text{fcs}}$) was also determined via another calibration object with five non-planar markers with known positions visible to both systems. Temporal synchronization of the two systems was achieved using an electrical trigger.

The task of sit-to-stand (STS) was selected in the current study because it has been shown to be a valid biomechanical method for assessing the performance of the TKR [24]. In an angiography room, individual subjects performed the STS task at a self-selected speed from an armless chair at a height of 115% of the knee-heel distance while the knee motion was recorded simultaneously by the fluoroscope at a frame rate of 30 fps, and by the motion capture system at a sampling rate of 60 Hz (calibration residual error: 0.4 mm; VICON 512, Oxford Metrics, UK). A successful trial, as well as data during quiet standing with the knee fully extended, were collected for each subject.

2.3. Determination of STA-free segment poses

For the control group, the 3D poses of the femur and tibia/fibula were described by the bone ACS relative to the fluoroscopy coordinate system, $T_{\text{fcs}}^{\text{acs\_b}}(t)$, which were determined by registering the CT-based volumetric models to the corresponding fluoroscopic

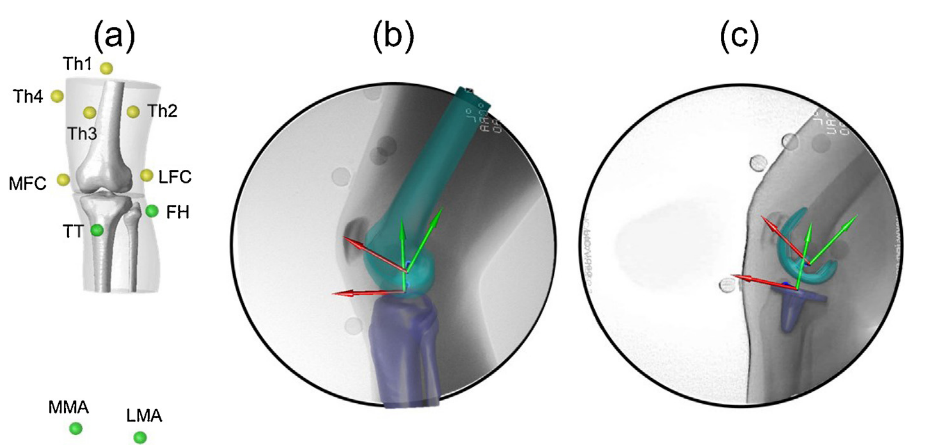

Fig. 1. (a) Markers used to track the motions of the thigh and shank segments. (b) For the natural knee, the three-dimensional (3D) positions and orientations of the femur and tibia/fibula were determined by registering the computed tomography-based bone models to the fluoroscopic images. (c) For the total knee replacement, the 3D positions and orientations of the prosthesis components were determined by registering their computer-aided design models to the fluoroscopic images.