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Differences in knee adduction moment between healthy subjects and patients with osteoarthritis depend on the knee axis definition

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ABSTRACT

Objective: This study, firstly, investigates the effect of using an anatomical versus a functional axis of rotation (FAR) on knee adduction moment (KAM) in healthy subjects and patients with knee osteoarthritis (KOA). Secondly, this study reports KAM for models with FAR calculated using weight-bearing and non-weight-bearing motion.

Design: Three musculoskeletal models were created using OpenSim with different knee axis of rotation (AR): transepicondylar axis (TEA); FAR calculated based on SARA algorithm using a weight-bearing motion (wFAR) and a non-weight-bearing motion (nwFAR). KAM were calculated during gait in fifty-nine subjects (n = 20 healthy, n = 16 early OA, n = 23 established OA) for all models and groups.

Results: Significant differences between the three groups in the first peak KAM were found when TEA was used ($p = 0.038$). However, these differences were no longer present when using FAR. In subjects with established OA, KAMs were significantly reduced when using nwFAR compared to TEA models but also compared to wFAR models.

Conclusion: The presence of excessive KAM in subjects with established KOA showed to be dependent on the definition of the AR: anatomical versus functional. Therefore, caution should be accounted when comparing KAM in different studies on KOA patients. In patients with end-stage knee OA where increased passive knee laxity is likely to exist, the use of weight-bearing motions should be considered to avoid increased variability in the location and orientation of a FAR obtained from activities with only limited joint loading.

1. Introduction

Gait analysis has been widely used to assess changes in the kinematics and kinetics of weight-bearing joints in degenerative disorders such as osteoarthritis (OA). In patients with knee OA, changes in joint loading during gait have been evaluated indirectly using the knee adduction moment (KAM), whereby increased KAMs have been related to OA progression [1–8].

Many studies [9–15] on knee loading in OA used the trans-epicondylar axis (TEA), i.e. the axis defined between markers placed on the medial and lateral epicondyle prominences, to describe the joint axis of rotation (AR). However, this method relies on manual palpation of external anatomical landmarks, which, when placed incorrectly, can easily lead to errors in calculating the frontal plane angles in the presence of knee flexion, the so-called "cross-talk" phenomenon [16]. Therefore, this may introduce uncertainty and different results in the KAM.

The functional AR (FAR) is less commonly used when studying knee joint loading in patients with OA. The FAR is a motion-based AR, whose orientation and location represent the averaged orientation and location of the instantaneous ARs during knee motion [17]. FAR reduces the cross-talk effect on the knee kinematics in healthy and arthritic subjects [18]. Although knee kinetics computed using FAR and TEA have been compared during gait and side-cutting [19] in healthy subjects, the difference between both is still unknown in subjects with knee OA. Furthermore, it is unclear whether FAR should be calculated based on weight-bearing or non-weight-bearing motion. This is highly relevant as passive laxity [8] and lack of dynamic knee stability [8,20] are present in patients with knee OA and this might have an important effect on the calculated AR and consequently the calculated KAM.

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In our previous work [21], knee loading was assessed in terms of KAM and knee contact forces (KCF) by using an OpenSim modeling workflow in patients with early and established medial knee OA. Significant differences in the magnitude of the first peak KAM were found between the three groups. The current study was a secondary analysis of the aforementioned study [21]. The purpose was threefold: firstly, to investigate the effect of using an anatomical versus a functional AR on KAM in healthy subjects and patients with knee OA; secondly, to report the effect of using weight-bearing or non-weight-bearing motion to calculate the FAR on KAM; and finally, to assess whether the use of these different axes has an impact on the differences in KAM between healthy subjects and patients with knee OA. We hypothesize that (1) using TEA versus FAR will influence the differences in KAM between groups; (2) due to the presence of structural changes and unstable knee joints in patients with established OA, the KAMs calculated using FAR during weight-bearing motion are significantly different from those calculated using FAR during non-weight-bearing motion.

2. Methods

2.1. Participants

Patient selection and classification were described in Meireles et al. [21]. Briefly, fifty-nine female participants were divided into three groups (65 ± 8.7, 65 ± 6.0 and 66 ± 7.2 years, respectively): (1) asymptomatic healthy subjects ($n = 20$); (2) patients with early medial knee OA ($n = 16$, presenting knee pain and structural changes only observed on MRI [21]); and, (3) patients with established medial knee OA ($n = 23$, presenting structural changes (Kellgren–Lawrence $\geq 2^{+}$)). No significant differences in BMI were found between groups (25.0 ± 3.0, 26.5 ± 4.4 and 28.1 ± 4.5, respectively, control, early OA and established OA).

2.2. Data collection

Data collection was described in Meireles et al. [21]. Body motion was measured using 27 active markers attached to the subjects according to an extended Helen Hayes protocol [22] recorded at 100 Hz. Five technical clusters of 3 markers each, were attached bilaterally to the lateral thighs and shanks, and posterior to the pelvis. The remaining 12 markers were fixed bilaterally on 6 anatomical landmarks: anterior superior iliac spine, lateral femoral epicondyle, lateral malleolus, calcaneus, fifth metatarsal head and midfoot. Ground reaction forces were collected at 1000 Hz using a force plate embedded in the ground (Bertec Corporation, USA).

2.3. Musculoskeletal model

A generic musculoskeletal lower extremity model (OpenSim 3.0) was used in this study [23]. The model consists of eleven rigid-body segments, each defined by a local reference frame: a pelvis, left and right thigh, shank, talus, calcaneus and toes. Joints define the relative motion of two reference frames (Fig. 1), one attached to the parent segment and one attached to the child segment that do not necessarily coincide with the segment local reference frames. In the generic model, the pelvis is modeled as a free joint with 6 degrees of freedom (DoF), the hip as a ball-in-socket joint with 3 DoF, the knee as a sliding hinge joint with 1 DoF and the ankle as a hinge joint with 1 DoF.

The origin of the femoral reference frame (f_{RF}) is located at the hip joint centre (HJC, i.e. the centre of the femoral head). The axes of the f_{RF} are defined as follows: the Y-axis is oriented along the line passing through the midpoint of the epicondylar markers and the HJC, pointing superiorly; the Z-axis lies in the plane defined by the HJC and the epicondylar markers, and is perpendicular to the Y-axis, pointing to the right (laterally for the right leg model); finally, the X-axis is perpendicular to the Y-axis and the Z-axis, pointing anteriorly. The origin of the tibial reference frame (t_{RF}) is located in the tibia at the midpoint of the transepicondylar markers. The axes of the t_{RF} are defined parallel to the f_{RF} in the anatomical position (i.e. with knee in full extension).

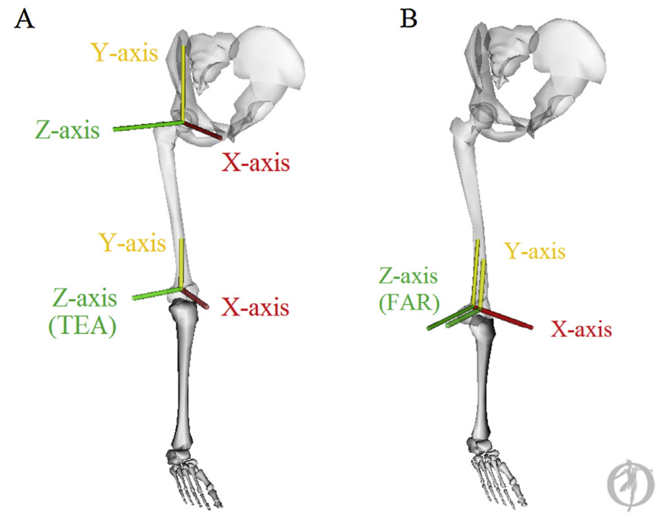

Fig. 1. OpenSim's musculoskeletal lower extremity generic model [23] including the knee joint reference frame relative to the femur and the tibia based on a transepicondylar axis (A) and a functional axis (B).

In the generic OpenSim model, the flexion-extension knee axis is defined about an axis through the epicondyles (TEA) (Fig. 1A). In other words, the knee joint reference frames coincide with respectively the f_{RF} and t_{RF} and, therefore, the knee joint flexion axis is parallel to the Z-axis of both f_{RF} and t_{RF}. The position of the TEA in the f_{RF} depends on the knee flexion angle and is modeled as described by Yamaguchi et al. [24]. An additional rotational DoF about an axis parallel to the X-axis of f_{RF} was added to allow knee abduction-adduction (ab-adduction) motion.

The SARA algorithm [25] was selected (see Supplementary material – Part 1) to calculate the FAR, i.e. the averaged orientation and position of the knee flexion-extension axis throughout the motion in both the f_{RF} and t_{RF}, based on the coordinates of four markers on the thigh and four on the shank. The knee joint centre (KJC) is defined as the intersection of the FAR and the XY-plane of, respectively, the f_{RF} and t_{RF}. The orientation of the ab-adduction axis was then defined as the cross product of a unit vector pointing from the HJC to the KJC and the FAR. Hence, the ab-adduction axis is perpendicular to the flexion-extension axis and the plane in which the flexion-extension axis and the HJC lay. To include the FAR in the OpenSim model, the joint axis definition relative to the f_{RF} and t_{RF} was changed in each scaled model. To implement the FAR with respect to the f_{RF}, the knee joint reference frame with respect to the f_{RF} was redefined such that corresponds to the calculated location and orientation of the functional knee joint axis in the f_{RF}. To implement the functional axis with respect to the t_{RF}, the t_{RF} was adapted such that its origin coincides with the functional KJC and the Z- and X- axes of the t_{RF} coincide with respectively the knee flexion-extension and ab-adduction axes. To implement this change in segment reference frame, the locations of the tibia markers with respect to the t_{RF} were adapted. Furthermore, the location of the ankle joint with respect to the tibia was also adapted such that the position and orientation of the ankle joint with respect to the markers was preserved. Therefore, the knee joint reference frame expressed in tibia still coincides with the t_{RF} (Fig. 1B).