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Defining the medial-lateral axis of an anatomical femur coordinate system using freehand 3D ultrasound imaging

Elyse Passmore [a,b,c,*], Morgan Sangeux [a,b,c]

[a] Hugh Williamson Gait Analysis Laboratory, The Royal Children's Hospital, Melbourne, Australia
[b] Murdoch Childrens Research Institute, Melbourne, Australia
[c] Department of Mechanical Engineering, The University of Melbourne, Australia

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ABSTRACT

Hip rotation from gait analysis informs clinical decisions regarding correction of femoral torsional deformities. However, it is among the least repeatable due to discrepancies in determining the medial-lateral axis of the femur. Conventional or functional calibration methods may be used to define the axis but there is no benchmark to evaluate these methods. Freehand 3D ultrasound, the coupling of ultrasound with 3D motion capture, may provide such a benchmark.

We measured the accuracy *in vitro* and repeatability *in vivo* of determining the femur condylar axis from freehand 3D ultrasound. The condylar axis provided the reference medial-lateral axis of the femur and was used to evaluate one conventional method and three functional calibration methods, applied to three calibration movements. Ten healthy subjects (20 limbs) underwent 3D gait analysis and freehand 3D ultrasound. The functional calibration methods were a transformation technique, a geometrical method and a method that minimises variance of knee varus-valgus kinematics (DynaKAD). The conventional method used markers over the femoral epicondyles.

The condylar axis determined by 3D ultrasound showed good accuracy *in vitro*, 1.6° (SD: 0.3°) and good repeatability *in vivo*, 0.2° (RSMD: 2.3°). The DynaKAD method applied to the walking calibration movement determined the medial-lateral axis closest to the ultrasound reference. The average angular difference in the transverse plane was 3.1° (SD: 6.1°).

Freehand 3D ultrasound offers an accurate, non-invasive and relatively fast method to locate the medial-lateral axis of the femur for gait analysis.

1. Introduction

Gait analysis provides quantitative information of a subjects gait pattern in the form of joint angles, moments and powers. In the clinical setting, it informs decision making regarding surgical correction of gait deformities. For example, the hip rotation profile during gait is a major determinant in recommending femoral derotation osteotomy and in predicting functional outcomes [1]. However, hip rotation kinematics has been found to be among the least repeatable data from gait analysis [2–4].

The lack of repeatability of the hip rotation profile can primarily be attributed to a lack of repeatability in determining the frontal plane of the femur anatomical coordinate system. The frontal plane of the femur is defined by the cross-product of its longitudinal axis (hip joint centre to knee joint centre) and its medial-lateral axis. It is the difficulty in determining the medial-lateral axis of the femur that affects hip rotation kinematics [4]. Conventional gait models, widely implemented in commercial software packages (e.g. Plug in Gait, Vicon motion systems, Oxford UK), define the medial-lateral axis of the femur by the transepicondylar axis. This axis is identified by placement of markers over the medial and lateral epicondyles of the femur, or the positioning of a Knee Alignment Device (KAD) which clamps on the medial and lateral epicondyles [5].

Alternatively, several functional calibration methods have been proposed. These use the motion of the femur and the tibia during a calibration movement to determine the axis that best describes the flexion–extension movement of the knee joint. The knee axis is then used, explicitly [4,6] or implicitly [7], as a proxy to define the

* Corresponding author at: The Royal Children's Hospital Melbourne 50 Flemington Road Parkville Victoria 3052 Australia. Tel.: +61 3 9345 5354.
E-mail addresses: elyse.passmore@gmail.com, elyse.passmore@rch.org.au (E. Passmore).

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medial-lateral axis of the femur. These methods have the advantage of removing the need for precise marker placement over anatomic landmarks but may be sensitive to the type of calibration movement and soft tissue artefact between the skin-mounted markers and the underlying bones. The majority of functional calibration methods model the movement of the knee by a fixed single axis of rotation. This is seen in axis transformation techniques (ATT or SARA) [8] as well as in geometrical methods [6,8–10]. An alternative to the single axis of rotation approach are those methods which determine an axis which minimises the variance of the frontal plane (varus\valgus) knee kinematics [4,11–13]. These methods assume the variance is a result of cross-talk from the sagittal plane movement.

Validation of the methods to define the medial-lateral axis of the femur are limited due to the absence of a benchmark able to provide the respective position of the femur anatomical coordinate system to the skin-mounted markers. Currently, validation has been limited to *in silico* data [8,10], mechanical or surrogate models [14], or *in vivo* data with indirect outcome measures such as inter-/intra-assessor repeatability of the hip and knee kinematics or the absence of cross-talk [4,6,7].

Coordinate systems that are anatomically sound (coordinate systems that match the bone/segment planes) and repeatable are required to ensure accurate gait analysis results. We hypothesized that a freehand 3D ultrasound method may be used to define an anatomical coordinate system of the femur that is more accurate and repeatable than conventional and functional calibration methods. Freehand 3D ultrasound combines ultrasound imaging with 3D motion capture [15] and has been utilised in gait analysis to determine the location of the hip joint centres [16–18]. Freehand 3D ultrasound allows for the position of the bones to be determined in relation to the skin-mounted markers. We propose to use the most posterior aspects of the medial and lateral condyles to define the medial-lateral axis of the femur. This corresponds to the table top axis described by Murphy and Simon [19] for measuring femoral torsion, also called femoral anteversion, and to the condylar axis presented by Eckhoff et al. [20].

The objectives of this study were (1) to determine *in vitro* the accuracy of the freehand 3D ultrasound system to locate the medial and lateral condyles, (2) to determine *in vivo* the repeatability of defining an anatomical coordinate system of the femur using freehand 3D ultrasound imaging and (3) to use the anatomical coordinate system of the femur from freehand 3D ultrasound as a benchmark to evaluate conventional and functional methods commonly used in gait analysis.

2. Methods

Five reflective markers were rigidly attached to a 59 mm Echo Blaster 128-1Z ultrasound probe (Telemed, Lithuania). The coordinate system of the probe was built from the marker positions and the pose of the probe tracked using least squares fitting [21]. A calibration procedure using the Cambridge stylus method was performed to determine the position of the ultrasound image in the coordinate system of the probe [18]. A ten-camera video-motion-capture system (Vicon Motion Systems) recorded marker positions at 100 Hz and a radio frequency button triggered the motion-capture and ultrasound systems simultaneously.

Ten healthy adults (5 males, 5 females), mean age 29 $\pm$ 9 years and BMI of 24.4 $\pm$ 3.1 kg/m^2 with no history of gait pathology, joint disease, injury or neurological problems were recruited to evaluate the freehand 3D ultrasound protocol *in vivo*. The participants gave written informed consent and ethics approval for the study was granted from the local institutions ethics committee.

Each subject underwent 3D gait analysis and freehand 3D ultrasound imaging of the posterior aspect of the femoral condyles. The gait analysis protocol consisted of a static standing calibration, functional calibration movements, and walking at self-selected speed. Passive reflective markers were attached to the subject according to the Plug-in-Gait marker set [22] (Vicon Motion Systems) with additional markers on the thigh and shank, Fig. 2(a). An experienced tester (EP) performed marker placement for each subject.

We defined the medial-lateral axis of the femur as the condylar axis [23,24]. The condylar axis models the posterior aspect of the medial and lateral condyles as spherical or cylindrical. The medial-lateral axis of the femur is defined by the line connecting the centres of the medial and lateral spheres/cylinders that best fit the posterior aspects of the condyles [25,26]. In our freehand 3D protocol, we used the most posterior aspect of the condyles which were identified with the subject standing, Fig. 2(b). The probe was positioned over the knee popliteal fossa in a medial-lateral orientation, the image depth was set at 60 mm with focus between 20 and 30 mm. The probe was moved up and down to identify the most posterior aspect of each condyle. The freehand 3D ultrasound images were loaded into the software Stradwin [15] and two landmarks were positioned manually to locate the most posterior aspect of the condyles, Fig. 2(c). For some subjects it was impossible to view both condyles simultaneously and separate images and landmarks were obtained for the medial and lateral condyles.

The conventional method utilised markers over the medial and lateral epicondyles to define the medial-lateral axis of the femur, Fig. 2(a). Three functional calibration methods were tested, each applied to three different calibration movements. The calibration methods were: the ATT [8], which determines the knee axis that moves the least during the calibration movement, the geometric method of Chang and Pollard [10], which assumes marker trajectories form concentric circles around the knee flexion axis and the DynaKAD method [4,11], which minimises variance in the frontal plane (varus\valgus) knee kinematics. The calibration movements were three repetitions of active knee flexion–extension (open kinematic chain), bilateral squats (closed kinematic chain) and walking strides at a self-selected speed. Markers on the thigh and the shank (Fig. 2(a)) were tracked using least squares fitting [27] for the functional calibration methods.

The reference anatomical coordinate system of the femur was determined as follows. The primary axis was the longitudinal axis of the femur (Z- axis) and defined by the vector from knee joint centre to hip joint centre. The positions of the hip and knee joint centres were determined from the static calibration using Plug-in-Gait (Vicon motion systems). The anterior-posterior axis (X- axis, perpendicular to the frontal plane of the femur) was determined by the cross-product of the longitudinal axis and the medial-lateral axis of the femur as identified by freehand 3D ultrasound imaging. The Y- axis of the femur was defined as the cross-product between the Z- and X- axes, which corresponds to the medial-lateral axis projected onto the transverse plane of the femur.

Similar coordinate systems of the femur were constructed for the conventional and functional methods. For all methods, the longitudinal axis of the femur coordinate system was the same because the locations of the hip and knee joint centres were held constant. However, each conventional or functional method led to a different estimate of the medial-lateral axis of the femur and therefore led to a different frontal plane of the femur. The conventional and functional calibration methods were compared to the freehand 3D ultrasound method as the reference. The angular difference between the frontal planes of the femur was calculated for each method\calibration movement. This angular difference reflects the offset in hip rotation that would be observed