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Defining the medial-lateral axis of the femur: Medical imaging, conventional and functional calibration methods lead to differences in hip rotation kinematics for children with torsional deformities

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ABSTRACT

Hip rotation during gait is a major indicator for femoral derotation osteotomy. However, repeatability of hip rotation is poor because of discrepancies in determining the medial-lateral axis of the femur. Combining 3D gait analysis with medical imaging allows in vivo evaluation of current clinical methods. We used the condylar axis, identified from low dose biplanar radiographs (EOS imaging Inc), as our reference to evaluate conventional, functional calibration and freehand 3D ultrasound methods to define the medial-lateral axis in children with lower-limb torsional deformities.

Twenty participants underwent 3D gait analysis accompanied by freehand 3D ultrasound and biplanar radiographs. The condylar axis identified from biplanar radiographs provided the reference method used to construct the femoral coordinate system. This was used to evaluate a conventional, two functional calibration methods (axis transformation technique and 2DoFKnee) and freehand 3D ultrasound. We measured reliability of 3D localisation of skin markers and anatomical landmarks from the biplanar radiographs.

Localisation of skin markers (SD 0.4 mm) and anatomical landmarks (SD 1.3 mm) from the biplanar radiographs were reliable, leading to a precision of 1° for the condylar axis after registration in the motion capture system. The freehand 3D ultrasound produced similar results to the biplanar radiographs reference, with internal hip rotation during gait of 18° and 19° respectively. The conventional and functional calibration methods were predominantly external compared to the reference, with average hip rotation of 4–6° internal.

Freehand 3D ultrasound and biplanar radiographs provide reliable means to define the medial-lateral axis of femur for gait analysis, and aid clinical interpretation in children with torsional deformities.

1. Introduction

Accurate identification of joint centres and axes is important for the calculation of kinematics and kinetics in 3D gait analysis (Baker et al., 1999; Besier et al., 2003; Stagni et al., 2000). Registration of the lower-limb joints to the skin mounted marker set is also paramount for musculoskeletal computations, such as the calculation of muscle and joint contact forces (Lenaerts et al., 2009; Passmore et al., 2016b).

In the clinical setting, kinematics and kinetics during gait may be used to inform surgical decision making. For example, the amount of hip rotation during gait is considered a major indicator to perform a femoral derotation osteotomy, and a predictor of the outcome of this surgery (Ounpuu et al., 2002; Schwartz et al., 2014). However, the precision of hip rotation kinematics has raised concerns because it is one of the least repeatable parameters in clinical gait analysis (McGinley et al., 2009; Schache et al., 2006; Schwartz et al., 2004). The lack of repeatability in hip rotation kinematics is primarily attributed to difficulty in determining the secondary axis used to define the femoral coordinate system (Passmore and Sangeux, 2016; Schache et al., 2006). This secondary axis directly affects the medial-lateral axis of the femoral coordinate system which is formed orthogonal to the primary axis

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(knee joint centre (KJC) to hip joint centre (HJC)) and the cross product of the primary and secondary axes.

The conventional gait model uses the femoral epicondylar axis as the secondary axis to define the femoral coordinate system (Davis et al., 1991). This method requires palpation of the epicondyles and placement of markers or a knee alignment device over the bony landmarks. Alternatively, several studies have defined a functional axis of rotation, removing the reliance on accurate marker placement (Baker et al., 1999; Chang and Pollard, 2007; Ehrig et al., 2007; MacWilliams, 2008; Sangeux et al., 2017). Functional calibration methods use the movement between the femur and tibia to determine the axis of rotation, which is used as the secondary axis. However, these methods are susceptible to errors from soft tissue artefact and the quality of the calibration movement (Peters et al., 2012; Sangeux et al., 2017). Validation has largely been limited to evaluation on synthetic data, mechanical models and cadaver simulations (Cereatti et al., 2009; Chang and Pollard, 2007; Ehrig et al., 2007; MacWilliams, 2008). More recent studies have evaluated their performance in vivo but this has been limited to typically developing adults (Passmore and Sangeux, 2016; Sauret et al., 2016) and older adults post total knee arthroplasty (Sangeux et al., 2017).

In vivo evaluation used either freehand 3D ultrasound imaging or biplanar radiographs (Passmore and Sangeux, 2016; Sauret et al., 2016). Both methods define a bone fixed coordinate system registered with respect to the skin markers during a static standing pose. The secondary axis is defined from the condylar axis of the femur, which is identified using the posterior aspects of the femoral condyles. There is a growing body of medical imaging based studies supporting the premise of the condylar axis being a good approximation of the knee flexion-extension axis (Eckhoff et al., 2007; Iwaki et al., 2000; Johal et al., 2005; Yin et al., 2015). Both freehand 3D ultrasound imaging and low dose biplanar radiographs are appealing for clinical use with short scan times and no or low radiation exposure. However, evaluation in cohorts attending clinical gait analysis services is currently lacking. This is problematic since previous studies have highlighted that results obtained from typically developing populations do not necessarily translate to clinical populations (Assi et al., 2016; Peters et al., 2012).

The objectives of this study were (1) to determine the accuracy and repeatability of defining the femoral coordinate system from low dose biplanar radiographs and (2) to use this method as a reference to evaluate the conventional gait model, several functional calibration methods and freehand 3D ultrasound imaging to define the medial-lateral axis of the femur in children with lower-limb torsional deformities.

2. Methods

2.1. Participants

This was a prospective cohort study of patients referred with symptomatic lower-limb torsional deformities. Patients aged 8–18 years were included if they were referred to our clinical gait analysis service for surgical decision regarding derotation osteotomy. Patients were excluded if they were unable to walk unassisted, had bony surgery within the past 12 months or had received Botulinum-Toxin A inter-muscular injections within the past six months. Written, informed consent to participate in the study was received from each participant's parent or guardian. Ethics approval for the study was granted by The Royal Children's Hospital Melbourne Ethics Committee (HREC 34255A).

Twenty patients participated in this study, aged 12 years (SD 3 years), height 1.50 m (SD 0.14 m) and weight 44 kg (SD 12 kg). Of the twenty participants, eleven had idiopathic torsion and nine had a diagnosis of spastic diplegic cerebral palsy. Torsional deformities were quantified from CT imaging using the protocol described by Sangeux et al., (2015). The cohort had mean (SD) femoral neck anteversion of 39° (9°) and external tibial torsion 37° (11°).

2.2. Gait experiments and imaging

All participant underwent 3D gait analysis followed immediately by low dose biplanar radiographs (EOS imaging Inc, France). The 3D gait analysis consisted of a static standing calibration trial, functional calibration movements, walking at a self-selected speed and freehand 3D ultrasound imaging of the posterior aspect of the femoral condyles (Passmore and Sangeux, 2016). For the 3D gait analysis, passive reflective markers were attached to the patient's lower limbs according to the plug-in-gait marker set (Davis et al., 1991) with additional cluster markers on the thigh and shank to enhance segment tracking (Passmore and Sangeux, 2016). A ten-camera video motion capture system (Vicon TX 160, UK) recorded marker positions at 100 Hz. The 3D marker positions were filtered using a Woltring filter (MSE = 15) (Woltring, 1985). Biplanar radiographs were acquired in the sagittal and frontal plane simultaneously with the participant standing one foot in front of the other to allow visualization of both sets of femoral condyles (Chaibi et al., 2012) (Fig. 1A). The markers used for 3D gait analysis were left in place and visible on the radiographic images.

2.3. Registration from biplanar radiographs to the motion capture system

For all participants, two trained operators performed the following procedure independently on two separate occasions. Using the dedicated software, sterEOS shape models were fit to the femur and tibia and 14 mm spheres were fit to the skin markers to match the contours of the radiographic images in the frontal and sagittal views (Fig. 1B).

Accuracy of marker localisation on the biplanar radiographs was calculated using the reproducibility variance ($\mathrm{SD}_{\mathrm{Ri}}^2$) (Glüer et al., 1995). This includes both intra- ($\mathrm{SD}_{\mathrm{ri}}^2$) and inter-assessor ($\mathrm{SD}_{\mathrm{Li}}^2$) repeatability variances.

$$SD_{Ri}^2 = SD_{ri}^2 + SD_{Li}^2$$

Registration of the skin marker positions from the biplanar radiographs to the motion capture system was performed using least squares fitting (Soderkkvist and Wedin, 1993). Reliability of the registration was calculated as the root mean square difference (RMSD) between the biplanar radiographs based marker set and the motion capture system based marker set after registration, per body segment.

2.4. Reference femoral coordinate system

Patient-specific femoral coordinate systems were defined from anatomical landmarks on the femur shape model, referenced to the skin markers (Fig. 1B). The coordinate system was defined as follows. The primary axis was the superior-inferior axis (Z- axis) and defined by the vector from KJC to HJC. The KJC was defined by the femoral intercondylar fossa and the HJC as the centre of the femoral head. The anterior-posterior axis (X- axis, perpendicular to the frontal plane of the femur) was determined by the cross-product of the Z-axis and the condylar axis of the femur. The condylar axis of the femur was defined as an axis passing through the most posterior aspects of the medial condyle (MCP) and lateral condyle (LCP). The Y-axis of the femur was defined as the cross-product of the Z- and X-axes, which corresponds to the condylar

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