Gait & Posture 63 (2018) 171–176

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Computation of hip rotation kinematics retrospectively using functional knee calibration during gait

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ARTICLE INFO

Keywords:
Knee
Kinematics
Functional calibration
Hip rotation
Principal component analysis
Torsional deformities

ABSTRACT

Background: Hip rotation kinematics during gait is a key parameter to support clinical decision making, for example in children with lower limb torsional deformities. However, hip rotation kinematics is also one of the least repeatable parameter because it is difficult to locate the position of the medio-lateral axis of the femur. Functional knee calibration provides an alternative to locate the medio-lateral axis of the femur and may be performed retrospectively, using the movement of the knee joint during gait. Although not necessarily more anatomically accurate, functional calibration may lead to increased repeatability between sessions, which would be useful to compare gait analysis data from sessions pre- and post-treatment, or to reprocess data in large gait databases.

Methods: This study presents a workflow to perform knee functional calibration using knee kinematics during gait and update hip rotation kinematics accordingly. The workflow was applied to investigate the inter-subject, inter-session and inter-trial variance components of multiple calibration methods in a group a 10 typically developing children.

Results: Results indicated that one or two degrees of freedom functional calibration methods were more repeatable inter-session (SD: 1.8°) than conventional calibration using the knee alignment device (SD: 4.7°). However, simulated reduced range of movement at the knee during gait increased inter-session variance for the functional calibration algorithms. Functional calibration did not provide any improvement over the conventional calibration when knee range of movement was reduced and flexion greater than 20° during gait, i.e. 'crouch gait'.

Significance: The workflow presented allows the re-processing of gait analysis data using knee kinematics during gait only. The workflow may also be used to investigate functional axes of other joints, for example the ankle.

1. Introduction

Determining the orientation of the medio-lateral axis of the femur in gait analysis is difficult, and prone to variability between sessions, intra- and inter-examiners. As a result, hip rotation kinematics is one of the least repeatable parameter from clinical gait analysis [1]. This is a problem because hip rotation kinematics is also a key parameter for clinical decision making [2,3].

Functional calibration may be used to define the medio-lateral axis of the femur computationally, using the movement of the knee joint. Since functional calibration does not depend on the examiner, decreased variability of hip rotation kinematics between sessions may be achieved. Although more repeatable, knee functional calibration may not be more accurate at defining an anatomically sound medio-lateral axis of the femur [4]. This is because the modelling assumption (single axis hinge joint, or two degrees of freedom joint) may not represent the behaviour of the subject's knee, and soft tissue artefact may affect the accuracy of the algorithms. However, in the absence of medical imaging data, having access to both conventional and functional calibrations of the medio-lateral axis of the femur may be useful.

Initially, functional knee calibration required capturing additional calibration trials such as open-chain, or closed-chain, knee flexion-extension movements [5,6]. However, recent studies reported similar accuracy and repeatability of knee functional calibration using walking trials [4,7]. Thus, knee functional calibration may be performed retrospectively using clinical gait analysis data. Applying knee functional calibration retrospectively may be useful for two reasons. Firstly, it may improve repeatability of hip rotation kinematics between sessions of the

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https://doi.org/10.1016/j.gaitpost.2018.05.011
Received 28 February 2018; Received in revised form 3 May 2018; Accepted 7 May 2018
0966-6362/

same child. Secondly, retrospective knee functional calibration would allow us to quantify the effect of hip/knee rotation uncertainty on clinical decision making, and in cohort studies using large clinical databases.

Most functional calibration algorithms require the orientation of the femur and tibia segments, but only joint kinematic data may be available retrospectively. The primary objective of this article was to present a workflow to perform knee functional calibration retrospectively from gait kinematics data. A secondary objective was to apply the workflow to estimate the repeatability of hip rotation kinematics between sessions of the same assessor.

2. Material and methods

2.1. Workflow to perform knee functional calibration retrospectively

Functional calibration algorithms may be calculated retrospectively from the knee rotation matrix (T_{knee}), which describes the orientation of the femur coordinate system in the tibia coordinate system:

$$T_{knee} = R_{Tibia}{}^{-1}R_{Femur}$$

With R_{Tibia} and R_{Femur} the 3 × 3 matrices representing the orientation of the tibia and femur coordinate systems in the laboratory coordinate system.

In the conventional gait model, T_{knee} is decomposed using a mobile axes cardan sequence corresponding to Grood and Suntay's joint coordinate system [8,9]. The first rotation corresponds to flexion-extension around the medio-lateral axis of the femur (Y), the second rotation corresponds to ad-abduction around the anterior-posterior axis of the femur after the first rotation (X'), and the third rotation corresponds to internal-external rotation around the longitudinal axis of the tibia, which coincides with the longitudinal axis of the femur after the first 2 rotations (Z''). The mathematical expression for T_{knee} is:

$$T_{knee} = \begin{bmatrix} c_3c_1 - s_3s_2s_1 & -s_3c_2 & s_1c_3 + s_3s_2c_1 \\ s_3c_1 + c_3s_2c_1 & c_3c_2 & s_1s_3 - c_3s_2c_1 \\ -s_1c_2 & s_2 & c_2c_1 \end{bmatrix} \tag{1}$$

Where c and s denote the cosine and sine functions and the indices $_1$, $_2$, $_3$ denote the angles of rotation, (r1–r3) in radians, around the first (Y, flexion-extension), second (X', ad/ab-duction) and third (Z'', internal/external rotation) axes.

As a convention, flexion, adduction (or varus), and internal rotation are positive angles in gait analysis. Thus, (r1–r3) are multiplied by $(-1, 1, 1)$ and $(-1, -1, -1)$ for the left and right sides respectively. Calculation of T_{knee} from the outputs of the conventional gait model therefore requires applying these multiplications beforehand.

Ehrig et al. [10] detailed the algorithm, called ATT, to find the best one degree of freedom fixed functional knee axis using T_{knee} as input.

In the conventional gait model, the longitudinal axis of the femur (perpendicular to the transverse plane) is considered the primary axis and the medio-lateral axis lies in the transverse plane. We calculated α_{ATT}, the angular difference between the original medio-lateral axis and the functional axis, projected in the transverse plane of the femur. α_{ATT} was defined as positive if the functional axis was more internal than the original medio-lateral axis of the femur. Thus, hip rotation kinematics using functional calibration would be increased by $+\alpha_{ATT}$. Hip flexion and adduction kinematics are not affected by functional calibration.

Functional calibration affects knee kinematics in the three planes. We calculated the orientation of the updated femur, R_{Femur}^{new}, by premultiplying R_{Femur} by a rotation of α_{ATT} around the Z axis of the femur.

To simplify the calculations and without loss in generalisability, we may consider the femur as stationary and aligned with the laboratory coordinate system. Hence $R_{Femur} = I$ with I the identity matrix and:

$$R_{Femur}^{new} = R_z^{\alpha}I = \begin{bmatrix} c_\alpha & -s_\alpha & 0 \\ s_\alpha & c_\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

In addition:

$$T_{knee} = R_{Tibia}{}^{-1}I = R_{Tibia}{}^{-1}$$

As a result, the new knee rotation matrix T_{Knee}^{new} may be calculated with:

$$T_{Knee}^{new} = R_{Tibia}{}^{-1}R_{Femur}^{new} = T_{Knee} \times \begin{bmatrix} c_\alpha & -s_\alpha & 0 \\ s_\alpha & c_\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

T_{Knee}^{new} is then decomposed by the YX'Z'' cardan sequence using Eq. (1).

$$\text{Flexion–extension } (°) = \frac{180}{\pi} \times \text{atan2}(T_{Knee}^{new}(3,1),\ T_{Knee}^{new}(3,3))$$

$$\text{Varus–valgus } (°) = \frac{180}{\pi} \times \text{asin}(T_{Knee}^{new}(3,2)) \times \left| \begin{array}{l} 1\,\textit{for the left side} \\ -1\,\textit{for the right side} \end{array} \right.$$

$$\text{Internal–external rotation } (°) = -\frac{180}{\pi} \times \text{atan2}(T_{Knee}^{new}(1,2),\ T_{Knee}^{new}(2,2)) \times \left| \begin{array}{l} 1\,\textit{for the left side} \\ -1\,\textit{for the right side} \end{array} \right.$$

Where *asin* is the inverse sinus function and *atan2* is the inverse tangent function taking two arguments; the sine and cosine values to return an angle in the range $[-\pi, \pi]$.

We considered two other functional calibration algorithms that model the knee as a two (flexion and rotation) degrees of freedom joint. Both methods, 2DoF and trajAJC, have been presented in detail previously [11–13]. The 2DoF method rotates the femur coordinate system to minimise the variance of knee varus-valgus kinematics [11]. The algorithm for the 2DoF method outputs the angle between the functional axis and the femur medio-lateral axis in the transverse plane directly: α_{2DoF}.

The trajAJC method projects a marker on the shank [12] or the ankle joint centre [13] onto the transverse plane of the femur during the movement, and finds the best orthogonal regression fit to the marker's trajectory. The axis perpendicular to the fitted line defines the functional axis. We do not have access to the trajectory of the shank markers when using kinematics data only, but the trajectory of the ankle joint centre, located on the longitudinal axis of the tibia, may be calculated. The angle of interest, $\alpha_{trajAJC}$, is calculated as the angle between the medio-lateral axis and the axis perpendicular to the line fitted to the trajectory of the ankle joint centre in the transverse plane of the femur, cf. Fig. 2 in [13] for a graphical illustration.

Baudet et al. published an algorithm to calculate knee kinematics that minimises the presumed cross-talk [14], which has been identified as a means to re-process knee kinematics data retrospectively [15]. However, the algorithm did not provide updated hip rotation kinematics. The method applies principal component analysis to determine new knee kinematics based on linear combinations of the input kinematics. The linear combinations are computed so that the first combination captures the maximum variance in the data across time, the second capture the maximum of the remaining variance while being perpendicular to the first, and the same for the last combination. This process is markedly different from all the other methods since there is no guarantee the linear combinations obtained represent an angular decomposition around fixed, or mobile, axes of rotations embedded in the segment coordinate systems. There is also no guarantee the order of the combination respects the order of the inputs (i.e. flexion, varus, internal rotation) and the output vectors need to be re-ordered to align best with the input vectors. We applied the method of Baudet et al. and defined α_{Baudet} as the average offset between the input and presumed output knee rotation kinematics. Fig. 1 presents the outputs of Baudet et al. method.