PROPAGATION OF EPICONDYLES MISLOCATION TO KNEE KINEMATICS DURING STEP-UP/DOWN MOTOR TASK: EFFECTIVENESS OF SINGLE AND DOUBLE CALIBRATION

R. Stagni*, S. Fantozzi* and A. Cappello*

* DEIS, Alma Mater Studiorum, Università di Bologna, Bologna, Italy

rita.stagni2@unibo.it

Abstract: Soft tissue artifact and anatomical landmark mislocation have been recognized as the most critical sources of error in gait analysis. The newly proposed double calibration method was assessed to be extremely effective for soft tissue artefact compensation on knee kinematics in absence of anatomical landmark mislocation. The purpose of the present work was to assess the effectiveness of double calibration in reducing skin motion artifact effect on knee rotations when anatomical landmark mislocation is present on the epicondyles. The performance of the recently proposed technique was assessed on two selected subjects and compared with the results obtained with conventional single calibration during the execution of the step up/down. The soft tissue artifact propagated to knee kinematics was quantified simulating different mislocation errors on the epicondyles using both single and double calibration.
The double calibration technique was proved to perform very well on knee rotation and translations even with mislocation errors up to 15 mm on the anatomical coordinates of lateral and medial epicondyles.

Introduction

One of the main objectives in human motion analysis is the description of joint kinematics. The accuracy of this description is fundamental for clinical decisions. Several sources of error affect the estimates, in particular, soft tissue artefact (STA), and anatomical landmark mislocation (ALM). Both these sources of error have been analysed and quantified, in terms of their magnitude and of their propagation to relevant joint kinematics [1-2]. The former has been recognized to be the most critical source of error in motion analysis [3]. The propagation of soft tissue artifact strongly affects joint angles, in particular those characterized by a small range of motion, such as knee ab/adduction and internal/external rotation. This may be critical in the exploitation of gait analysis data for clinical decisions. Several methods for its compensation were proposed in the literature [4]. Most of these methods failed in their effectiveness on relevant joint kinematics [1]. A recent paper proposed a new compensation method based on double calibration, modulated by means of knee flexion. Its performance was validated on an innovative data-set with a gold standard based on 3D fluoroscopic analysis [5], in absence of anatomical landmark mislocation. In this operative condition, this newly proposed method was extremely effective on the compensation of soft tissue artifact propagation to knee rotations, in particular mean values of the root mean square error on ab/adduction and internal/external rotation angles decreased from 3.7° and 3.7° to 1.4° and 1.6°, respectively, with respect to single calibration. Mainly, knee translations calculated from stereophotogrammetric data using the proposed compensation method were found to be reliable with respect to the fluoroscopy-based gold standard. The residual mean values of the root mean square error were 2.0, 2.8, and 2.1 mm for anterior/posterior, vertical, and medio/lateral translations, respectively [5].

The purpose of the present work was to assess the performance of this double calibration compensation method, when mislocation errors are superimposed to the anatomical coordinates of the lateral and medial epicondyles (LE, ME).

Materials and Methods

A special data-set including synchronized measurements of skin marker trajectories and of corresponding bone poses during the execution of step up/down [6-7] was used. Bone poses were assessed by means of modern 3D fluoroscopy and skin marker trajectories by means of traditional stereophotogrammetry. Thus, the STA was characterized non-invasively, in-vivo and with no restriction to skin motion [7]. The data set was obtained from two subjects (age 67 and 64 years, height 155 and 164 cm, weight 58 and 60 Kg, Body Mass Index 24 and 22 kg/m2, follow-up 18 and 25 months) treated by total knee replacement (excellent Hospital for Special Surgery score 85-100, [8]). An up-right posture and six repetitions of step up/down were collected simultaneously by fluoroscopy (DRS, System 1694 D, General Electric CGR, USA) and stereophotogrammetry (Smart, e-Motion, Padova, Italy), at 5 and 50 frames per second, respectively.

The 3D positions of the two prosthesis components were reconstructed from each 2D fluoroscopic projection in the fluoroscope reference system with a well established iterative procedure using a shape matching technique based on the knowledge of corresponding CAD models [9]. Previous validation work [9] had shown that position and orientation of each component in the sagittal plane can be estimated with an accuracy of better than 0.5 mm and 1 degree, respectively.

Six mm diameter reflective markers were uniformly attached on the lateral aspect of the thigh and shank, 19 and 10 respectively in subject #1, and 25 and 10 in subject #2. One rigid plate mounting 4 markers was attached to the pelvis using a modified Milwaukee orthosis [10]. The 3D kinematics of pelvis, thigh and shank was reconstructed in the stereophotogrammetry reference frame using the CAST experimental protocol [10-11]. The position and orientation in space of each cluster was reconstructed using the Singular Value Decomposition algorithm [12].

For the combination of stereophotogrammetry and fluoroscopy, one reflective/radiopaque marker with 12 mm diameter was attached on the patella and 4 on the fluoroscope field of view in order to obtain time synchronization and spatial registration, respectively. Spatial registration between the two measurement systems was obtained by defining a common absolute reference frame by means of the 4 reflecting/radiopaque markers (Figure 1). The temporal synchronization was obtained by matching the fluoroscopic with the resampled stereophotogrammetric trajectories of the patellar marker. Skin marker trajectories obtained from the stereophotogrammetric system and the 3D poses of the prosthesis components obtained from 3D fluoroscopy were then reported in the same absolute reference frame.

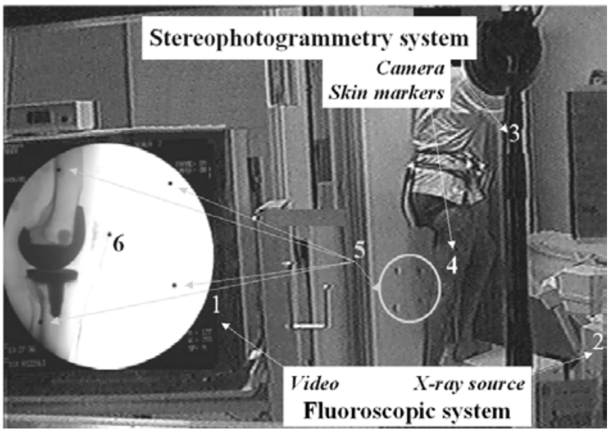

Figure 1: Experimental set-up. 1: Real-time visible feedback of the fluoroscopic images acquired. 2: X-ray source of the fluoroscope. 3: One of the five cameras of the stereophotogrammetric system. 4: Skin markers on the lateral aspect of the thigh and the shank. 5: The four specialized radiopaque/reflecting markers for spatial registration. 6: The specialized radiopaque/reflecting marker for temporal synchronization.

The possible misalignment of the prosthesis component frame with respect to the relevant anatomical reference frame was calculated in the static up-right posture, considered as the reference position, and the fluoroscopy-based 3D pose of the anatomical reference frame was calculated accordingly.

The calibration of the anatomical landmarks in the anatomical reference frame was performed physically once by means of a pointer. Subsequently, two body postures at the extremes of the expected full range of motion of each motor task were identified and relevant calibration of the anatomical frame, and therefore of the anatomical landmarks, was calculated in the marker cluster technical frame. In this way, the calibration of the anatomical landmarks, in itself, in the two body postures introduced no mislocation error.

The calibrated anatomical coordinates of the LE and ME were then altered adding error vectors uniformly distributed at 30° in the femoral sagittal plane with a magnitude of 5, 10, and 15 mm. A sketch of how calibration mislocation error was superimposed to the coordinates of the LE, for instance, is presented in Figure 2.

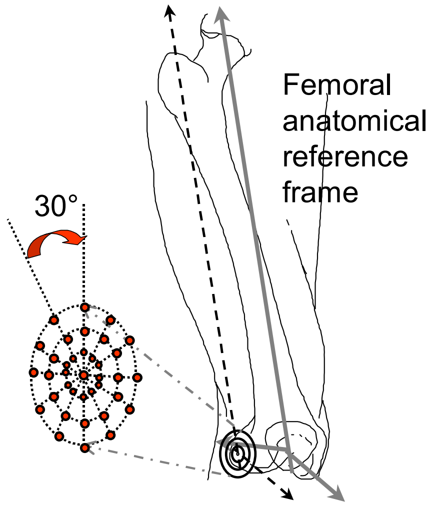

Figure 2: Sketchy depiction of how calibration mislocation error was superimposed in the sagittal plane to the anatomical coordinates of the lateral epicondyle. The reference position of the LE is the centre of the circumferences.

Knee joint kinematics is estimated, at each instant of time, from the 3D pose of the thigh and shank, the proximal and distal body segment, respectively. According to ISB recommendations [13], knee rotations are calculated using the Grood and Suntay convention [14]. In this study, knee translations, anterior/posterior (AP), medio/lateral (ML) and vertical (Vert), are defined as the translations of the origin of the thigh anatomical frame in the shank frame [11]. The 3D kinematics of the bony segments is defined on stereophotogrammetric data using the CAST protocol [11], the relevant anatomical frame defined from these landmarks has the x axis positive anteriorly, the y axis positive proximally and the z axis positive laterally.

The compensation was performed interpolating the two calibration configurations acquired at the extremes of the motion with respect to knee flexion angle according to the double-calibration approach [5]. In the double-calibration approach [15], it is assumed that the shape of the marker cluster and the position of the anatomical landmarks in the relevant technical frame change significantly during motion. Two body postures are identified within the expected full range of motion in the specific task under analysis, typically the two extremes of motion. In these two postures the calibration procedure is performed [11]. The choice of only two calibration positions is a compromise between the best possible result and the lowest time expenditure. The hypothesis is that the local coordinates of the anatomical landmarks in the relevant technical frame and the shape of the cluster change in a coherent manner during the motor task between the two extreme postures collected, so that some kind of interpolation can be performed between the two calibrations.

Considering a single segment and giving the relevant coordinates of the m markers in the laboratory (global) frame, in the first ($_1$) and second ($_2$) calibration postures:

$$^{G}\mathbf{P}_1 \doteq {}^{G}\left[\mathbf{p}_{1,1}\ \mathbf{p}_{1,2} \ldots\ldots \mathbf{p}_{1,m}\right] \quad (1)$$

$$^{G}\mathbf{P}_2 \doteq {}^{G}\left[\mathbf{p}_{2,1}\ \mathbf{p}_{2,2} \ldots\ldots \mathbf{p}_{2,m}\right] \quad (2)$$

where G refers to global coordinates.

The technical frame is defined as the laboratory frame translated to the cluster centroid

$$^{G}\overline{\mathbf{p}}_1 \doteq \frac{\sum_{k=1}^{m} {}^{G}\mathbf{p}_{1,k}}{m} \quad (3)$$

in the first calibration posture.

The cluster model in the first calibration posture is then:

$$^{C}\mathbf{P}_1 = {}^{G}\mathbf{P}_1 - {}^{G}\overline{\mathbf{p}}_1\mathbf{w} \quad (4)$$

where C refers to technical (cluster) frame and w is a (1 x m) vector with all elements equal to 1.

In order to model cluster deformation in the technical frame, the cluster in the second calibration posture must be registered to the first by a least-squares optimisation approach:

$$\min_{\mathbf{R},\mathbf{O}} \left\| {}^{C}\mathbf{P}_1 - \mathbf{R}\ {}^{G}\mathbf{P}_2 - \mathbf{O} \right\|^2 \quad (5)$$

where $\|\cdot\|$ is the Euclidean norm. R can be estimated by the Singular Value Decomposition [12] of the cross-dispersion matrix

$$\mathbf{G} = {}^{C}\mathbf{P}_1\ {}^{G}\mathbf{P}_2^T \quad (6)$$

and [17]

$$\mathbf{O} = -\mathbf{R}\ {}^{G}\overline{\mathbf{p}}_2 \quad (7)$$

The cluster model in the second calibration posture is then:

$$^{C}\mathbf{P}_2 = \mathbf{R}\ {}^{G}\mathbf{P}_2 + \mathbf{O} \quad (8)$$

The two cluster models are now centered in the origin of the technical frame and differ only for a shape deformation.

Analogously, the anatomical landmark positions in the technical frame can be estimated as follows. Given the laboratory (global) coordinates of the n anatomical landmarks in the first and second calibration postures:

$$^{G}\mathbf{A}_1 = {}^{G}\left[\mathbf{a}_{1,1}\ \mathbf{a}_{1,2} \ldots\ldots \mathbf{a}_{1,n}\right] \quad (9)$$

$$^{G}\mathbf{A}_2 = {}^{G}\left[\mathbf{a}_{2,1}\ \mathbf{a}_{2,2} \ldots\ldots \mathbf{a}_{2,n}\right] \quad (10)$$

the anatomical landmark coordinates in the technical frame are given by:

$$^{C}\mathbf{A}_1 = {}^{G}\mathbf{A}_1 - {}^{G}\overline{\mathbf{p}}_1\mathbf{w} \quad (11),$$

$$^{C}\mathbf{A}_2 = \mathbf{R}\ {}^{G}\mathbf{A}_2 + \mathbf{O} \quad (12)$$

The cluster geometry and landmark position at each instant of time during motion are modeled through interpolation between the two calibration postures assuming the Fl/Ex angle as the weighting function:

$$^{C}\mathbf{P}(t) = {}^{C}\mathbf{P}_1 + \left({}^{C}\mathbf{P}_2 - {}^{C}\mathbf{P}_1\right)\frac{f(t) - f_1}{f_2 - f_1} \quad (13)$$

$$^{C}\mathbf{A}(t) = {}^{C}\mathbf{A}_1 + \left({}^{C}\mathbf{A}_2 - {}^{C}\mathbf{A}_1\right)\frac{f(t) - f_1}{f_2 - f_1} \quad (14)$$

where $f(t)$ is the Fl/Ex angle, at time t, f_1 and f_2 are the Fl/Ex angles at the two calibration postures. In general, $f(t)$ also depends on $\mathbf{P}(t)$ and $\mathbf{A}(t)$. As the Fl/Ex angle was assessed to be the least influenced by STA [1], it is assumed to be calculated with single calibration.

The evolution of this method from its basic implementation (linear time interpolation) comes from the observation that the propagation of the STA to the joint kinematics depends on the Fl/Ex range [16]. The dependency of the artifact on the knee Fl/Ex angle was then linearly modeled, as it was the simplest possible choice.

Equations (13), (14) are the basis for anatomical landmark estimation during a given motor task. At each frame, the optimal cluster registration is computed:

$$\min_{\mathbf{R},\mathbf{O}} \left\| {}^{G}\mathbf{P}(t) - \mathbf{R}\ {}^{C}\mathbf{P}(t) - \mathbf{O} \right\|^2 \quad (15)$$

and then used for the anatomical landmark reconstruction:

$$^{G}\mathbf{A}(t) = \mathbf{R}\ {}^{C}\mathbf{A}(t) + \mathbf{O} \quad (16)$$

Equation (16) allows the reconstruction of the anatomical frames associated to the two segments. A scheme of this procedure is reported in Figure 3.

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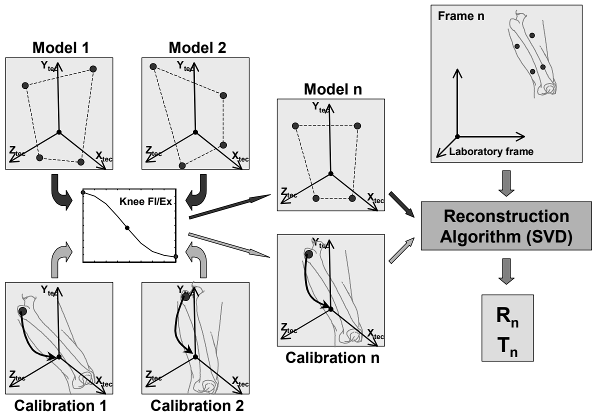

Figure 3: Sketchy representation of the double calibration approach based on the flexion-extension angle interpolation.

The single and double calibration method was used to calculate knee rotations and translations using correct and mislocated anatomical coordinates of the LE and ME. For the application of double calibration any possible couple of mislocated coordinates was used, in order to simulate the experimental independence of the calibration at the beginning and at the end of the motion.

Knee rotation angles and translations estimated by fluoroscopy were assumed as the "gold standard". The Root Mean Square Error (RMSE) for knee rotations and translations was calculated with respect to this gold standard for double and single calibration technique with and for the single calibration without mislocation error superimposed to the anatomical coordinates of the LE and ME.

Results

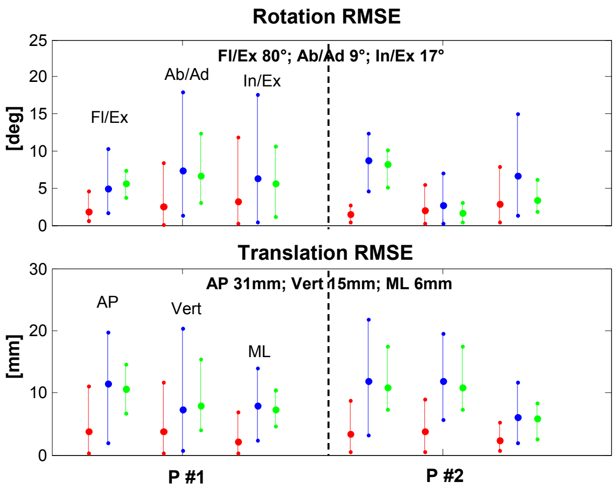

Figure 4: Mean, maximum and minimum value of the RMSE on knee rotation and translation for the two subjects for double calibration (red) and single calibration (blue) with, and for single calibration (green) without mislocation errors.

The root mean square error (RMSE) on knee rotations and translations produced by the mislocation introduced was almost identical for the LE and for the ME. The calculated mean, maximum and minimum RMSE are shown in Figure 4 for the LE.

The mean values of the RMSE on Flexion/Extension, Ab/Adduction, and Internal/External rotation, respectively, were 6.8°, 5.1°, and 6.5°, for single calibration with landmarks mislocation, 7.0°, 4.2°, and 4.5°, for single calibration without landmarks mislocation, and 1.6°, 2.3°, and 3.0°, for double calibration with landmarks mislocation. While, the residual mean values of the RMSE on anterior/posterior, vertical, and medio/lateral translations, respectively, were 11.7, 9.6, and 7.0 mm for single calibration with landmarks mislocation, 10.8, 9.9, and 6.6 mm, for single calibration without landmarks mislocation, and 3.7, 3.9, and 2.3 mm, for double calibration with landmarks mislocation.

Discussion

The effectiveness of double calibration in limiting the propagation of skin motion artefact propagation to knee kinematics was tested simulating mislocation errors up to 15 mm superimposed to the anatomical coordinates of the LE and ME. Even in this operative condition the newly proposed compensation method proved its effectiveness, providing significantly small residual errors on knee rotation and translations, not only with respect to single calibration with landmarks mislocation, but even with respect to single calibration without landmarks mislocation. In particular, the performance of the compensation method makes the estimation of knee translation reliable even in presence of large epicondyles mislocations.

Conclusions

The double calibration technique was proved to perform very well on knee rotation and translations even with large mislocation errors on the anatomical coordinates of LE and ME. Therefore, the newly proposed method can be considered a robust tool for the reduction of the noxious effects of skin motion artefact propagation to motion analysis data in operative conditions.

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