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Double calibration vs. global optimisation: Performance and effectiveness for clinical application

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ABSTRACT

For clinical application the quantification of the actual subject-specific kinematics is necessary. Soft tissue artefact (STA) propagation to joint kinematics can nullify the clinical interpretability of stereophotogrammetric analysis. STA was assessed to be strongly subject- and task-specific. The global optimisation, whose performance was assessed only on simulated data, is at the basis of several of the STA compensation methods proposed in the literature. On the other hand, the double calibration was recently proposed and resulted very effective on experimental data. In the present work, the performance of double calibration and global optimisation in reducing soft tissue artefact propagation to relevant knee joint kinematics was compared by using 3D fluoroscopy as gold standard. The mean RMSE over the repetitions for the double calibration is in the order of 1–2° for joint rotations and 1–3 mm for translation, while for the global optimisation is in the order of 10° and 10–15 mm, respectively. The double calibration should then be preferred for the quantification of the subject specific kinematics.

1. Introduction

One of the main objectives in human motion analysis is the description of joint kinematics. Stereophotogrammetry allows for the reconstruction of the trajectories of markers or fixtures, on which markers are mounted, attached to the skin surface of the body segments to be analysed. These trajectories are used to calculate the pose of the underlying bony segments, with the erroneous assumption that markers and bony segments are rigidly connected. It is well known that markers on the surface of the body move with respect to the underlying bones because of the interposition of soft tissues. This interposition is the origin of two different sources of error: anatomical landmarks misplacement and soft tissue artefact (STA). STA was recognized the most critical source of error in clinical motion analysis [1]. Several studies have been developed to quantify the motion of skin markers with respect to underlying bony segments using intracortical pins [2–9], external fixators [10,11], percutaneous trackers [12–14] and Roentgen photogrammetry [15–17]. A recent quantification study [18] assessed marker displacements up to several centimetres resulting in large errors on knee rotations and translations, during the execution of four motor tasks (flexion against gravity, chair rising/sitting, sit-to-stand/stand-to-sit, stair climbing), comparing stereophotogrammetric motion analysis results with a 3D fluoroscopic gold standard. In particular, STA propagation to knee kinematics resulted in making the quantified ab/adduction and internal/external rotation knee angles useless for clinical decision, because superimposed errors result two or three times the relevant angle and are time-variant, with a similar frequency content. These results were further verified by a more recent study [19], which replicated a similar experimental procedure. Given the criticality of STA, several compensation methods were proposed in the literature [20]. In 1999 Lu and O'Connor [21] proposed the original formulation of the global optimisation (GO) for the compensation for STA. GO was originally designed to overcome the most evident effect of STA propagation to joint kinematics, which was the compenetration of the body segments when animated with the reconstructed kinematics. Therefore, the GO method is based on the assumption of a predefined kinematic model of the body with specific constraints at the joints, then the motion of the markers with respect to the underlying constrained bony segments is minimised. The performance of GO was only assessed on simulated data [21]. GO is at the basis of a series of STA compensation methods, which have also been implemented in some commercial software tools for the elaboration of motion analysis data. More recently, the double calibration (DC) [22] has been proposed and assessed to be very effective in the reduction of noxious STA propagation to knee joint kinematics. Double calibration allowed to calculate even reliable knee translations, comparable with the 3D fluoroscopic gold

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standard, and was further assessed to perform well even with realistic anatomical landmark misplacements [23].

In the context of clinical application, the target is the quantification of the specific kinematics of the analysed subject, which should be improved by the STA compensation method adopted. The aim of the present work was to assess the performance of DC and GO in quantifying subject-specific kinematics, in order to point out their eligibility for clinical application, aiming at functional evaluation.

2. Methods

The kinematic dataset was obtained by the synchronous acquisition of traditional stereophotogrammetry and 3D fluoroscopy [18]. Using stereophotogrammetry the kinematics of the pelvis, thigh, and shank of each subject was acquired using the CAST experimental protocol [24], relevant anatomical reference frames were defined accordingly [25]. Synchronously, the kinematics of femur and tibia were acquired using fluoroscopy (DRS, System 1694 D, General Electric CGR, Issy-les-Moulineaux, France), and the 3D kinematics of these 2 bony segments was then reconstructed using an established CAD-model shape matching technique [26,18]. The accuracy of the 3D fluoroscopic kinematics was assessed to be within 1.5° and 1.5 mm for relative rotations and translations, respectively [18]. The data were obtained during the extension against gravity (EG), step-up/step-down (SUD), and sit-to-stand/stand-to-sit (STS) motor task from 2 female subjects treated by total knee replacement (P#1 and P#2, age 67 and 64 years, height 155 and 164 cm, weight 58 and 60 kg, body mass index 24 and 22 kg/m^2, follow-up 18 and 25 months), who gave informed consent. Three repetitions were acquired for each subject and motor task.

GO [21] and DC [22] were applied to stereophotogrammetric data to compensate for STA on the reconstructed kinematics of the relevant body segments, as well as the conventional single calibration (SC) [24]. GO [21] was implemented assuming a ball and socket model for the hip, knee and ankle joints, then the kinematics of the relevant body segments was estimated fitting the global trajectories of the markers in a weighted [21] least squares sense according to the proposed multilink model of the lower limb. The least square fitting was implemented considering 2 cluster conditions: (i) the whole cluster acquired for both thigh and shank or (ii) clusters of 4 markers for both thigh and shank, as in more conventional protocols. For the 4 marker cluster 2 markers were positioned in the area of relevant anatomical landmarks: Greater Trochanter and Lateral Epicondyle for the thigh and Head of Fibula and Lateral Malleolus for the shank. For the definition of an appropriate technical frame the remaining two markers were placed according to Cappozzo et al. [27]. DC [22] was implemented interpolating 2 calibration configurations acquired at the extremes of the motion, for each motor task, with respect to knee flexion angle. Knee rotation angles, flexion/extension (Fl/Ex), ab/adduction (Ab/Ad), internal/external rotation (In/Ex), were then calculated using the Grood and Suntay convention [28], according to ISB recommendations [29,30]. Knee translations were calculated as the translations of the centre of the femoral anatomical frame (midpoint between the 2 epicondyles) along the antero/posterior (AP), medio/lateral (ML) and vertical (Vert) axes in the tibial anatomical reference frame [18].

The knee rotation angles and translations reconstructed using 3D fluoroscopy are assumed as gold standard. The root mean square error (RMSE) of knee rotations and translations reconstructed using double calibration and global optimisation was calculated over the repetitions for each subject and motor task with respect to the fluoroscopic gold standard.

3. Results

The joint angle curves calculated using GO and DC resulted smooth and did not show non-physiologically wide ranges, although they were different, especially considering Ab/Ad and In/Ex at the knee. Knee translations resulted substantially different, due to the fact that no translation could be quantified using GO, due to the characteristics of the compensation method. These results can be observed in Fig. 1, where Fl/Ex, Ab/Ad, and In/Ex angles, and AP, ML, and Vert translations were plotted for one representative subject (#2) and motor task (stand-to-sit). For each trial GO provides 2 different curves (dashed grey and dotted grey) depending on the calibration position adopted (flexed or extended). Curves obtained using GO resulted extremely sensitive to the calibration position. The criticality of the calibration position for GO is particularly evident looking at the GO Fl/Ex curves reported in Fig. 1 with the calibration in the extended position (dotted grey). In this particular case, the underestimation of the flexion angle is evident, although not usual. The curves obtained

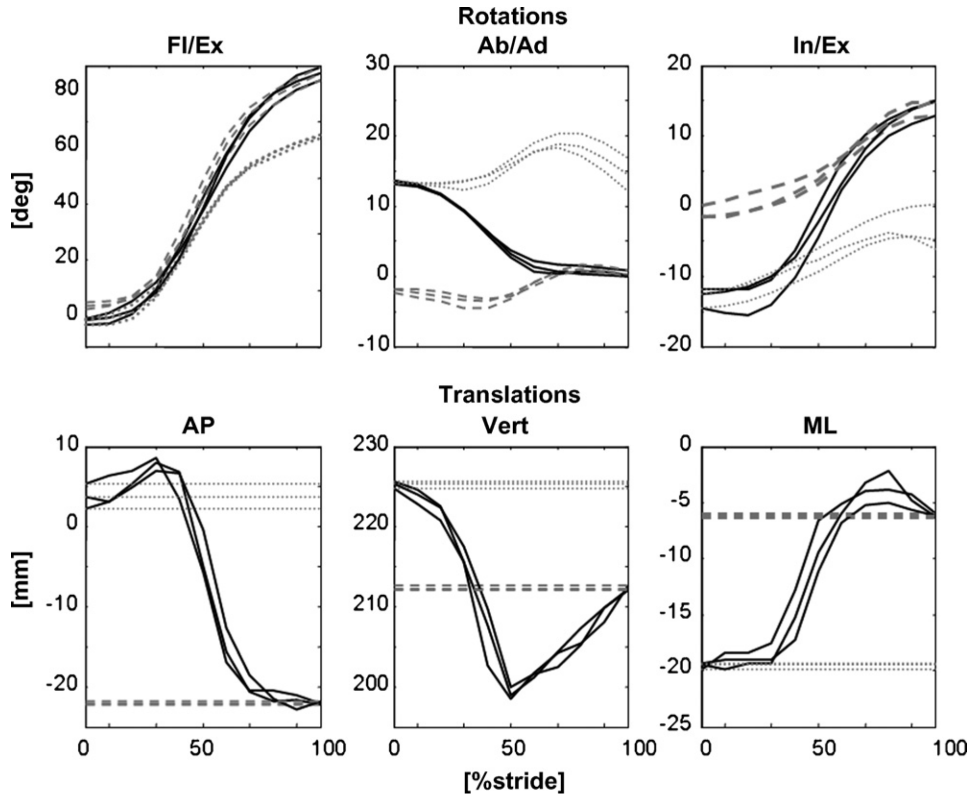

Fig. 1. Knee joint rotation angles and translations curves for 3 repetitions of stand-to-sit by subject #2. The curves estimated using DC (solid black) and GO using calibration in extended position (dotted grey) and flexed position (dashed grey).