

SOFT TISSUE ARTEFACTS CAUSE AN UNDERESTIMATION IN KNEE FLEXION ANGLE IN SKINMARKER BASED SQUAT SIMULATIONS

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Simulated muscle forces provide crucial knowledge for rehabilitation and training exercise design. To accurately simulate the internal loading conditions, input kinematics of the skeletal structures without soft tissue artefact (STA) are required. The aim of this study was to evaluate the ability of two numerical approaches to reduce STA for squat kinematics. Squat repetitions of 6 elderly subjects were examined using skin markers and video-fluoroscopy. Kinematic analysis was performed with a segmental and musculoskeletal simulation approach and compared to fluoroscopic data. The averaged RMS errors relative to the maximum knee range of motion were 8.8%, 32% and 49% for flexion/extension, ab-/adduction, and internal/external rotation, respectively. Skin marker based underestimation of the flexion angle could be corrected with a linear factor of 1.15.

KEY WORDS: STA, knee bending, video fluoroscopy, motion capture

INTRODUCTION: The magnitude of force production in specific muscles represents a crucial, but hardly accessible factor in designing strength training protocols for injury prevention, rehabilitation, and performance enhancement. So far, only musculoskeletal simulation (MS) provides the potential to non-invasively investigate the joint contact and muscle forces (Schellenberg et al., 2015). However, for movements involving high knee flexion, the success of predicting internal joint contact forces using even subject-specific musculoskeletal models remains limited. One plausible reason for such inaccuracies is the critical role that kinematics play on the simulation results and particularly the accuracy of skeletal motion. Whole body motion is generally captured using opto-electronic systems, which have the advantage of allowing dynamic movements to be recorded with a large field of view. However, these approaches are subject to soft tissue artefact (STA), where the skin moves over the underlying skeletal structures, and represents one of the key factors currently limiting the accuracy of musculoskeletal simulation results. The high range of motion (RoM) exhibited during strength training, as well as the task dependent STAs, challenge the ability to provide accurate body kinematics as an input for task simulation (Cappello et al., 2005). In order to address these problems, the assessment of skeletal kinematics using video-fluoroscopy offers the ability to accurately track 3D tibio-femoral motion without STA, but is limited by the restricted field of view.

In addition to the optimization of skin marker placement, numerical approaches are used to reduce the influence of the STA on kinematic results. The whole body MS approach aims to reduce the STA by using a least-square error optimization to match the virtual markers with the recorded marker kinematics for all segments. Such strategies for minimizing STA could offer a comprehensive approach to provide accurate input for MS of the internal loading conditions. Therefore, the aim of this study was to evaluate the ability of these two model approaches to reduce the effects of STA on the kinematics compared to the outcome of the gold standard video-fluoroscopy.

METHODS: Five squat exercises, performed by 6 subjects (5M, 1F, aged 68±5 years, mass 88±12 kg, height 173±4 cm) with Innex knee implant (Zimmer, Switzerland; type FIXUC) were measured in a synchronized measurement setup including video-fluoroscopy (FLU) and optical motion capture. For the 3D tibio-femoral motion, computer-aided design (CAD) models of the implant components were used for 2D/3D registration of the fluoroscopic images. In addition, body motion was assessed using reflective markers and an optical motion capture system with 22 cameras at a sampling frequency of 100 Hz (Vicon, UK). The subjects performed a set of basic motion tasks for functional determination of joint centers

(fCoR) in the hip, knee, and ankle joint (List et al., 2013). In the segmental approach (SEG), the relative position and orientation to the reference of the proximal and distal segment was analysed using a least-square fit of the marker point clouds (Gander and Hrebicek, 2011). For the whole body approach, the MS were performed in Opensim (Delp et al., 2007) using the reference “Gait2392” model (Anderson and Pandy, 2001; Delp et al., 1990; Yamaguchi and Zajac, 1989). Virtual markers were implemented in the joint centers of the model for scaling based on the fCoR determination of the skin marker kinematics. For the inverse kinematics of the MS, the same skin marker trajectories of all skin markers of the SEG approach in addition the fCoR and the pre-calculated joint angles were used as input. The knee axis definitions of the SEG simulation, as the conventional and more accessible method, was defined as the reference system and therefore the 3D tibio-femoral motion of the FLU and the MS body kinematics were projected on this reference for feasible comparison. In the analysis of the spatial deviation of the CoR (Δd), the SEG CoR location was compared to the FLU ($\Delta d_{\text{SEG-FLU}}$) and MS ($\Delta d_{\text{SEG-MS}}$) CoR positions in the anatomical directions. The mean joint angles and the RMS error (RMSE) for all trials as well as for all subjects were calculated. Additionally, the RMSE relative to the total RoM of the knee flexion was also analysed.

RESULTS: The Δd were smaller than 3cm in all anatomical directions. The smallest Δd for both $\Delta d_{\text{SEG-FLU}}$ and $\Delta d_{\text{SEG-MS}}$ was found in the medial plane (Figure 1A). In the posterior direction, Δd was small at low flexion angles (Figure 1B); whereas in the proximal direction Δd converged closer towards higher flexion angles (Figure 1C).

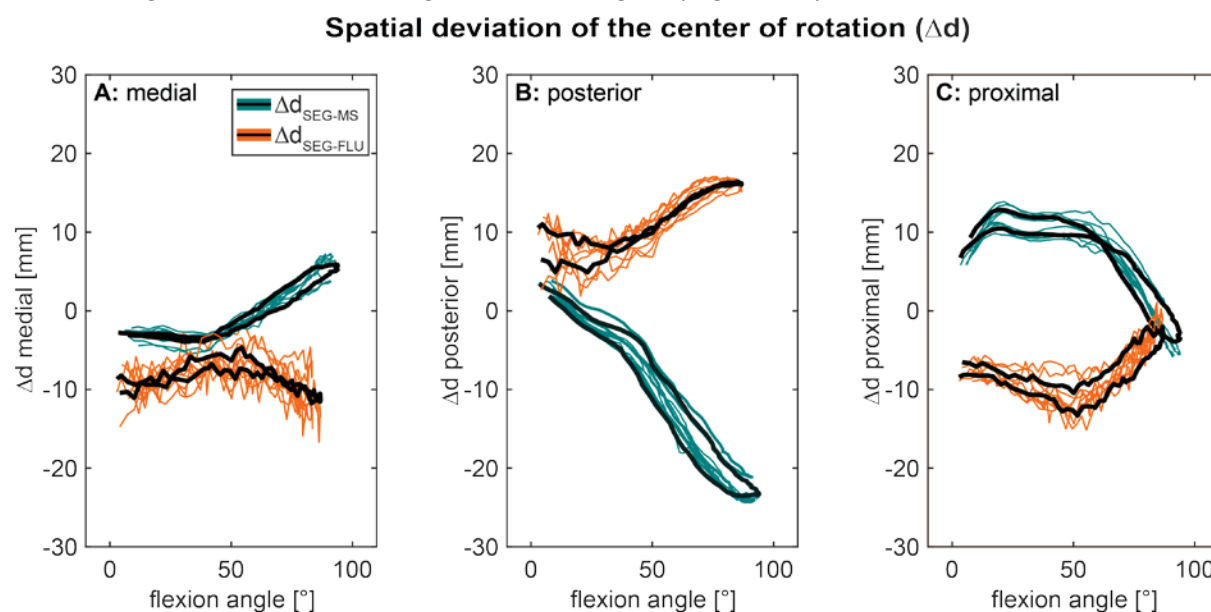


Figure 1: One representative subject, spatial deviation Δd of the center of rotation (CoR) between the segmental (SEG) and the musculoskeletal (MS) approach ($\Delta d_{\text{SEG-MS}}$, green) as well as between the SEG and the fluoroscopic (FLU) approach ($\Delta d_{\text{SEG-FLU}}$, red). Deviations are applied to the anatomical directions (A: medial; B: posterior; C: proximal).

Concerning the angles, the SEG presented similar results to the MS approach (Figure 2). In comparison with the FLU approach, both, the SEG and the MS approach, showed an increasing underestimation of the flexion angle with deeper knee flexion (Figure 2A) and a small general overestimation in the RoM for the adduction angle (Figure 2C). When considering the subjects individually, no clearly visible patterns were observed for the internal/external rotation (Figure 2B). The RMSE between the SEG and FLU approach for the knee flexion angle increased almost linearly with a higher flexion angle (Figure 2D). The concentric part of the movement showed a consistently higher RMSE compared to the eccentric part. While the average RMSE for the knee flexion angle was 7.1° (min/max 4.3° - 8.3°) with an RMSE_{rel} of 8.8%, the RMSE for the adduction was 1.8° (min/max 0.9° - 4.9°) with

an $RMSE_{rel}$ of 32%, and the RMSE for the external rotation was 3.5° (min/max 1.5° - 6.11°) or 49%.

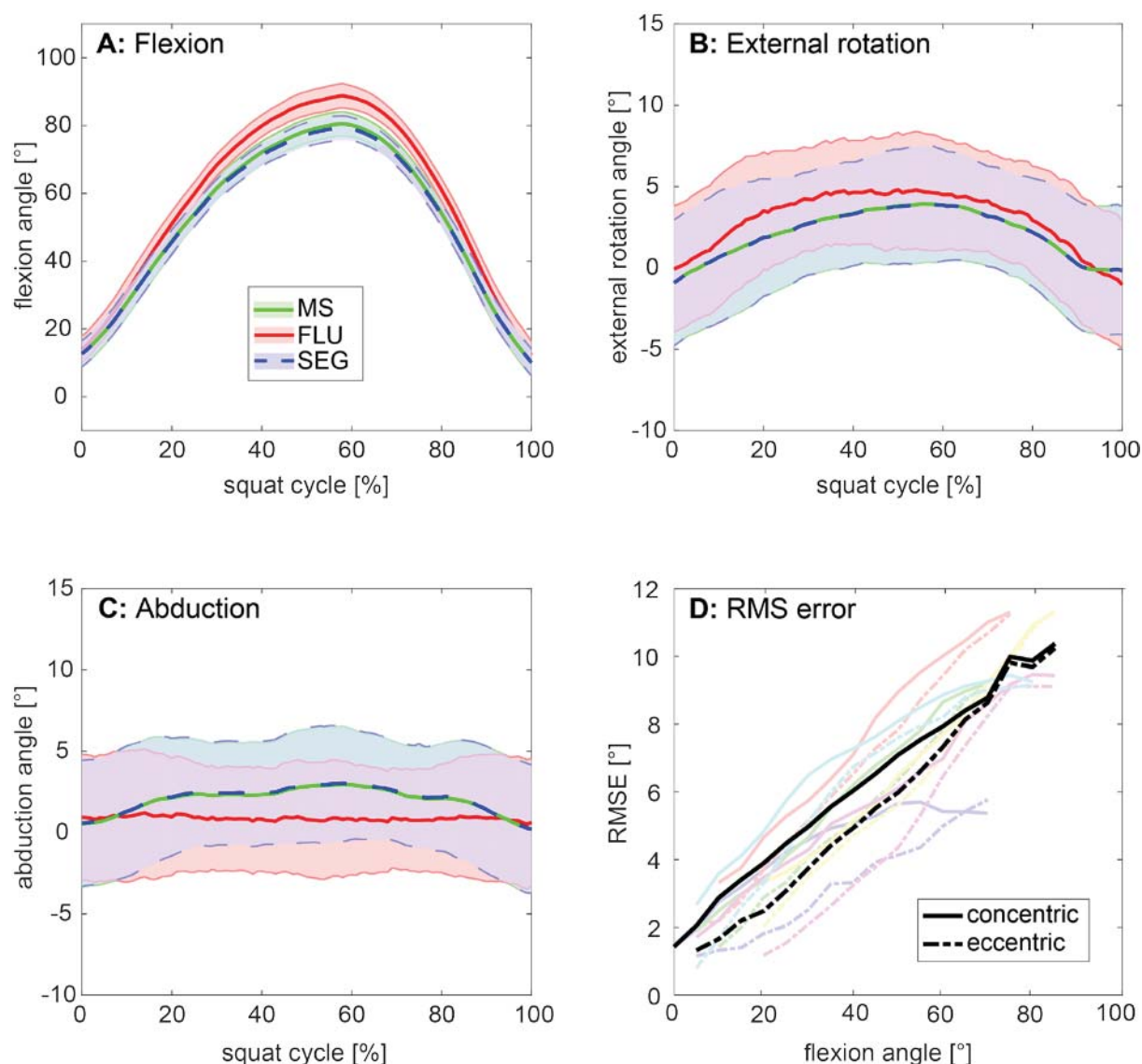


Figure 2 A-C: Knee angles (mean and Std) during the squat cycle for the SEG (dashed-blue), MS (green) and FLU approach (red) represented in the anatomical planes (A: Flexion; B: External rotation; C: Abduction). D: RMS error (RMSE) of the flexion angle in [°] between the SEG and the FLU approach for each subject (faded colors) and mean RMSE for all subjects (black) in the eccentric (dash-dotted) and concentric phase (solid).

DISCUSSION: For the first time, the SEG and MS approaches have been evaluated against each other for their ability to reduce STA compared to the gold standard video-fluoroscopy. While there were almost no differences in the joint angle descriptions between the two approaches, differences in the spatial deviation of the CoR (Δd) could be observed, especially in the posterior direction. The rather small difference in the knee angles between the SEG and MS methods could indicate a robust scaling and weighting of the simulation input parameters for the inverse kinematics. The increased difference observed between SEG and MS flexion and extension could be related to the largest movement in the specific plane of motion. However, since not only the angle played a key role in the MS but also the spatial position of the joint centres, the large Δd could lead to errors in the simulated loading conditions, and results should therefore be interpreted with caution. Comparing the methods with the gold standard, this study demonstrated the ability to calculate flexion angles with a relatively low error, while angles in other anatomical planes seemed to be more difficult to

assess correctly. While investigating different anatomical landmark calibration methods for STA reduction in two subjects, Cappello et al. (2005) found RMSEs for the knee flexion angle of 5-10°. Furthermore, similar $RMSE_{rel}$ of 8.1-23.4% for knee flexion and 14.9-104.2% for ab-/adduction and 21.7-61.8% for knee rotation were found while investigating the influence of different marker configurations (Stagni et al., 2005). As a result, the internal/external rotation and ab-/adduction of the knee seems to be substantially more affected by STA than flexion/extension (Benoit et al., 2006; Leardini et al., 2005; Reinschmidt et al., 1997). The RMSE in flexion angle between the two methods and the reference FLU approach increased almost linearly with increasing knee flexion, hence allowing the formulation of an estimated angle dependent correction factor of 1.15. As limitations of this study, the low number and absence of healthy subjects and the possible influence of the BMI (Body Mass Index) on STA need to be considered.

CONCLUSION: The results showed similar outcomes between different skin marker simulation approaches but differences to the gold standard fluoroscopy. While flexion angles can be reasonably represented and corrected with a factor of 1.15, the angles in the ab-/adduction and rotational direction seem to be more difficult to estimate and might therefore impact the simulation of internal loading and muscle forces. To reduce this error, further investigations should focus on the behaviour of STA in other high flexion strength exercises and its impact on the knee ab-/adduction and rotations.

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