Ability of eight multi-joint models to compensate for soft tissue artefacts using global optimisation - An in vivo study of knee kinematics during squats

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An in vivo study of knee kinematics during squats

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Abstract- Soft tissue artefacts (STA) distort marker-based knee kinematics. Global optimization (GO) compensates for STA, but it lacks of direct validation on subjects. This study evaluates the performance of eight multi-joint models used in GO. Ten subjects were recruited: five healthy and five osteoarthritis subjects. Each subject performed dynamic squats recorded with a motion capture system (KneeKG™), and a quasi-static squat recorded with a low-dose upright biplanar radiographic imaging system (EOS®). The eight multi-joint models were evaluated by comparing dynamic knee kinematics optimized with GO to quasi-static knee kinematics measured by EOS®. The mean RMSE values ranged from 1.5-11.4° for rotations and 1.4-6.2 mm for translations. Some models were able to compensate for STA along one axe of movement but not along another. None of these models seemed optimal for STA compensation along all axes of movement. Future studies should investigate new models based on subject-specific joint geometry.

Keywords: motion capture; soft tissue artefact; knee kinematics; optimization; squatting activity.

1. INTRODUCTION

Calculating knee kinematics from trajectories of markers glued on the skin of the lower limbs, or mounted on specific tools attached to the thigh and shank, is a frequently used technique in gait analysis. However, this technique is influenced by the motion of markers relative to the underlying bones, known as soft tissue artefacts (STA), which generate large knee kinematic errors [1]. STA have a frequency domain similar to that of bones motion, and are subject- and task-dependent, making them difficult to remove [2]. STA still remain the main obstacle to be overcome in gait analysis since no compensation method seems entirely satisfactory [2].

Among the various methods compensating for STA, global optimization (GO) provides the optimized position of the lower limbs by minimizing the differences between measured and model-predicted markers coordinates under kinematic constraints [3]. Several kinematic constraints were tested with GO – for example knee joint was modeled as a spherical joint [3], a hinge joint [4], a sliding hinge joint [5], or more recently as a parallel mechanism [6] – but few direct validation on subjects were performed. To the best of our knowledge, only three recent studies validated GO by comparing knee kinematics derived from skin markers with that derived from fluoroscopy [7, 8] or bone pin markers [9]. All these studies concluded that actual GO did not reduce STA. It is worthwhile to note that these studies tested only few sets of kinematic constraints despite their great influence on the knee kinematics [6]: ankle, knee, and hip joints were modeled as spherical joints for [7] and hinge or spherical joints for [8, 9].

Develop a method to obtain accurate subject-specific knee kinematics is a fundamental step before transferring motion analysis to clinics [7]. Indeed, this could be essential for a better understanding of pathologies such as osteoarthritis (OA) and its impact on knee mechanics. But GO has never been validated in this context. The goal of this study was, therefore, to evaluate the performance of eight multi-joint models used in GO to compensate for STA on healthy and OA subjects performing squats.

2. MATERIAL AND METHODS

Subjects

Ten subjects volunteered to participate and gave informed consent: five healthy subjects (54.8 years, 68.5 kg, 166.4 cm, 24.6 BMI) and five OA subjects (58.2 years, 84.1 kg, 156.4 cm, 34.3 BMI). All of them underwent medical examination before their trials, including one X-ray of the knees. The healthy subjects showed no previous knee injury, no knee pain, nor any evidence of knee attrition. The OA subjects were waiting for a total knee replacement surgery. The study was approved by the ethics committees of CRCHUM and ÉTS.

Instrumentation

Knee kinematics was recorded with a non-invasive motion capture tool: the KneeKG™ (Emovi Inc., Laval, QC, Canada). KneeKG™ markers were measured by a Polaris Spectra® camera (60-Hz, NDI, Waterloo, ON, Canada). Knee bone positions were recorded with a low-dose upright biplanar radiographic imaging system: the EOS® system (EOS imaging Inc., Paris, France).

Experiemental protocol

The KneeKG™ was fixed on the left or right lower limb of healthy subjects (random) or on the pathological limb of OA subjects. Calibration was undertaken to identify hip, knee and ankle joint centers and anatomical landmarks as described previously [10]. Each subject performed dynamic squats and a quasi-static squat. Dynamic squats were recorded with the KneeKG™ and consisted of performing series of 0°-70°-0° knee flexion-extension during ten seconds. The quasi-static squat was recorded with EOS® and consisted of five positions of knee flexion (0°, 30°, 40°, 50° and 70°) maintained during five seconds. The two squatting conditions were standardized with a positioning jig and feet wedges.

Data processing

GO was performed using generalized coordinates as described in [6]. The eight evaluated multi-joint models corresponded to the following sets of joints constraints at the ankle, knee and hip joints: NNN, SSS, USS, PSS, SHS, UHS, SPS and PPS (where N, S, U, H and P standing for "no model", spherical, universal, hinge, and parallel mechanism joints). The parallel mechanism was composed of two sphere-on-plane contacts and three isometric ligaments the geometry of which was derived from *in vitro* measurements [11]. The optimization problem was solved by a Gauss-Newton algorithm using the generalized coordinates constructed at each frame from the KneeKG™ markers as initial values [12].

The five biplanar radiographs recorded with EOS® were used to obtain quasi-static knee kinematics. The radiographs at 0° of knee flexion were used to create subject-specific knee bone models. The models were then registered on the four other biplanar radiographs with a rigid 2D/3D registration. Generalized coordinates identical to those defined during GO were constructed at the five positions from the knee bone models.

Dynamic and quasi-static knee joint kinematics were defined according to the ISB recommendations [13] and were computed from the generalized coordinates derived from GO and knee bones models respectively. The eight multi-joint models were validated by comparing dynamic knee kinematics with quasi-static knee kinematics recorded with EOS® (gold standard) for the five positions where flexion angles were similar. The comparison was made by the Wilcoxon signed-rank test (p=0.05). Root mean square errors (RMSE) were computed and averaged for the ten subjects and the five positions. Data processing was performed with Matlab (R2012a, The MathWorks Inc., Natick, MA, USA).

3. RESULTS

Mean knee flexion angles achieved by the ten subjects during the quasi-static squat were 5.0±5.2°, 32.2±8.2°, 40.8±10.2°, 53.4±11.1°, and 65.9±12.5°. All subjects performed an average of 6±1.5 full flexion-extension during the 10 seconds dynamic squats. Mean internal rotation during the quasi-static squat was 16.0±4.2° for healthy subjects and 11.2±4.3° for OA subjects. Mean anterior translation during the quasi-static squat was 1.9±1.7mm for healthy subjects and 1.4±1.6mm for OA subjects.

Mean RMSE values for flexion-extension (FE), internal-external rotation (IER), abduction-adduction (AA), medio-lateral translation (MLT), proximo-distal translation (PDT), and antero-posterior translation (APT) are given in Table 1. Mean RMSE values ranged from 1.9±2.7° to 14.7±1.8° for rotations and from 1.1±0.7mm to 6.3±3.9mm for translations for the healthy subjects, and from 0.6±0.6° to 10.0±5.9° for rotations and from 1.3±0.6mm to 6.2±3.8mm for translations for the OA subjects, depending on the multi-joint model.

Fig. 1 and Fig. 2 show the mean dynamic knee kinematics of the eight multi-joint models used in GO, as well as the mean quasi-static knee kinematics recorded with EOS® on the healthy and OA subjects.

Table 1. Mean RMSE Values (SD) of Dynamic vs. Quasi-static Knee Kinematics for the Ten Subjects

	NNN	SSS	USS	PSS	SHS	UHS	SPS	PPS
FE	1.5 (2.1)	1.6 (2.0)	1.7 (2.0)	1.7 (2.5)	1.9 (2.1)	2.0 (2.2)	1.7 (2.1)	1.8 (2.0)
AA	5.6 (1.4)	6.2 (1.1)	6.4 (1.1)	7.0 (0.6)	5.3 (0.5)	5.3 (0.5)	6.0 (0.5)	6.0 (0.5)
IER	8.8 (4.8)	7.7 (3.9)	7.9 (3.6)	11.4 (1.3)	11.2 (6.2)	11.2 (6.2)	8.5 (0.7)	8.5 (0.6)
MLT	2.8 (1.4)	1.4 (0.8)	1.4 (0.8)	1.4 (0.8)	1.4 (0.8)	1.4 (0.8)	1.8 (1.0)	1.8 (1.0)
APT	6.2 (3.9)	2.0 (1.1)	2.0 (1.1)	2.0 (1.1)	2.0 (1.1)	2.0 (1.1)	3.0 (1.8)	3.0 (1.7)
PDT	3.9 (2.0)	1.7 (1.0)	1.7 (1.0)	1.7 (1.0)	1.7 (1.0)	1.7 (1.0)	2.9 (1.6)	2.9 (1.6)

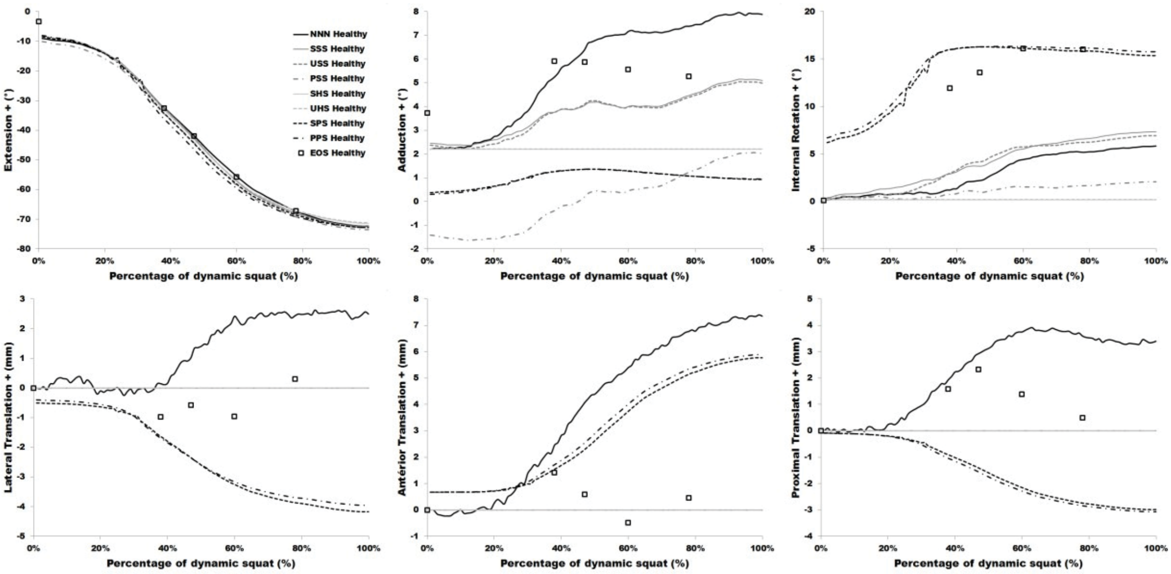

Figure 1. Mean Knee Kinematics of the Eight Multi-joint Models Used in GO on the Five Healthy Subjects

The performance of the eight multi-joint models varied according to the movements and to the positions which were analyzed (Fig. 1 and Fig. 2). For example, for the ten subjects, AA derived from NNN, SSS and USS models showed no significant difference compared to the AA derived from EOS™ for the five analyzed positions, whereas IER derived from these models showed significant differences for the four last analyzed positions. Conversely, AA derived from SPS and PPS models showed significant difference compared to the AA derived from EOS™ at the five analyzed positions, whereas IER derived from these models was the only one without significant differences for the three last analyzed positions. Similarly, APT derived from SSS, USS, PSS, SHS and UHS models showed no significant difference compared to the APT derived from EOS™ for the five analyzed positions, whereas APT derived from NNN, SPS and PPS models showed significant differences for the three last analyzed positions.

4. DISCUSSION

Study results showed that dynamic knee kinematics obtained after GO greatly depended on the constraints imposed by the multi-joint models, except knee flexion-extension, as stated in [6]. Moreover, although some multi-joint models were able to compensate for STA along some axes of movement and for some positions, mean RMSE values remained relatively large. None of the eight multi-joint models seemed perfect for STA compensation for healthy and OA subjects. This is consistent with the conclusions drawn from the studies [7, 8] which tested SSS and HHS models and found RMSE similar to those of the present study.

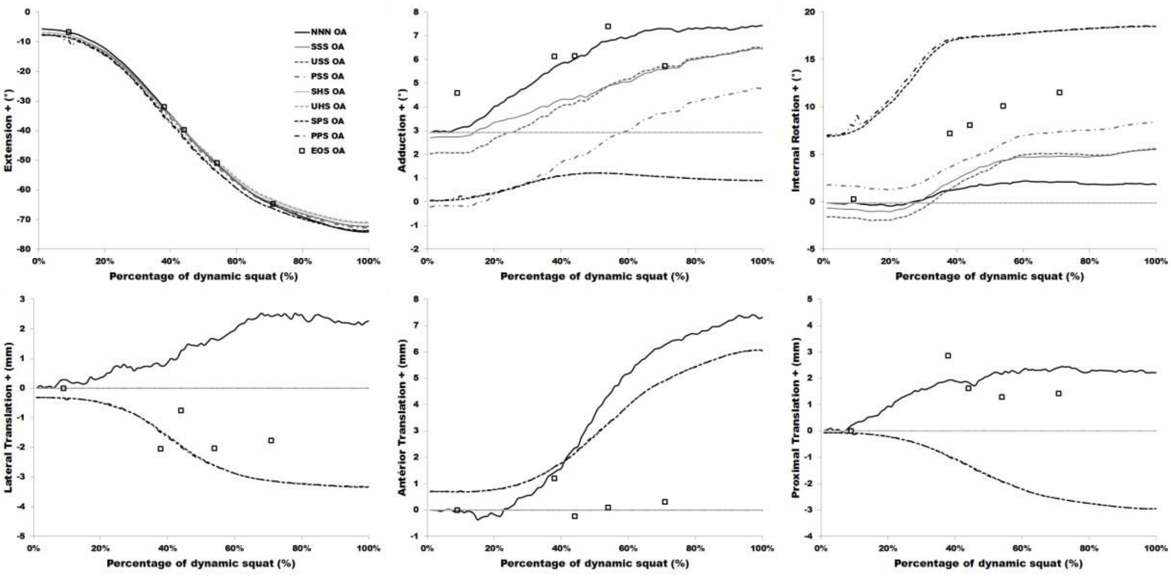

Figure 2. Mean Knee Kinematics of the Eight Multi-joint Models Used in GO on the Five OA Subjects

Despite the results, GO remains interesting and is increasingly used in gait analysis since it does not require multiple calibrations and easily enables computing inverse dynamics and developing musculoskeletal models [6]. The use of knee kinematic constraints defined from a parallel mechanism is also quite interesting since it is the only model to consider the complexity of the knee and to allow translations. However, in the present study the parallel mechanism was constructed from *in vitro* geometry data, which resulted in a similarity of the healthy and OA kinematic curves, a reduced inter-subject variability, and a loss of specific kinematic data such as the decrease of internal rotation in OA subjects.

One limitation of the study lies in the fact that dynamic and quasi-static knee kinematics were not recorded simultaneously, which is a source of bias. However, our previous study [14] showed that dynamic and quasi-static squats were similar from a knee kinematics point of view.

Future studies should investigate new parallel mechanism models based on the subject-specific knee joint geometry and physiology – e.g. irregular articular surfaces and four or more deformable ligaments – to improve the performance of GO and provide knee kinematics suitable for clinical applications.

5. Acknowledgment

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7. Conflicts of Interest

Nicola Hagemeister and Jacques A. de Guise have professional (scientific advisor) and proprietary interest in Emovi Inc respectively. None of these interests influenced the position presented in this manuscript. The other authors declare that they have no conflict of interest.

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