Medical Engineering and Physics 000 (2016) 1–9

Contents lists available at ScienceDirect

Medical Engineering and Physics

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

Evaluation of predicted knee function for component malrotation in total knee arthroplasty

Valentine Vanheule[a,b,*], Hendrik Pieter Delport[c], Michael Skipper Andersen[d], Lennart Scheys[c], Roel Wirix-Speetjens[b], Ilse Jonkers[e], Jan Victor[f], Jos Vander Sloten[a]

[a] Biomechanics Section, Katholieke Universiteit Leuven, Celestijnenlaan 300C, 3001 Leuven, Belgium
[b] Materialise N.V., Technologielaan 15, 3001 Leuven, Belgium
[c] Department of Orthopaedics, University Hospital Pellenberg, Katholieke Universiteit Leuven, Weligerveld 1, 3212 Pellenberg, Belgium
[d] Department of Mechanical and Manufacturing Engineering, Aalborg University, Fredrik Bajers Vej 5, 9100 Aalborg, Denmark
[e] Department of Kinesiology, Katholieke Universiteit Leuven, Tervuursevest 101, 3001 Leuven, Belgium
[f] Department of Physical Medicine and Orthopedic Surgery, Ghent University, De Pintelaan 185, 9000 Ghent, Belgium

ARTICLE INFO

Article history:
Received 10 June 2016
Revised 14 October 2016
Accepted 4 December 2016
Available online xxx

Keywords:
Subject-specific
Alignment
Soft tissue balancing
Kinematic knee rig
In vitro

ABSTRACT

Soft-tissue balancing for total knee arthroplasty (TKA) remains subjective and highly dependent on surgical expertise. Pre-operative planning may support the clinician in taking decisions by integrating subject-specific computer models that predict functional outcome. However, validation of these models is essential before they can be applied in clinical practice. The aim of this study was to evaluate a knee modelling workflow by comparing experimental cadaveric measures to model-based kinematics and ligament length changes. Subject-specific models for three cadaveric knees were constructed from medical images. The implanted knees were mounted onto a mechanical rig to perform squatting, measuring kinematics and ligament length changes with optical markers and extensometers. Coronal malrotation was introduced using tibial inserts with a built-in slope. The model output agreed well with the experiment in all alignment conditions. Kinematic behaviour showed an average RMSE of less than 2.7 mm and 2.3° for translations and rotations. The average RMSE was below 2.5% for all ligaments. These results show that the presented model can quantitatively predict subject-specific knee behaviour following TKA, allowing evaluation of implant alignment in terms of kinematics and ligament length changes. In future work, the model will be used to evaluate subject-specific implant position based on ligament behaviour.

1. Introduction

Creating appropriate soft-tissue balance during total knee replacement surgery is mainly subjective and highly dependent on the surgeon's expertise [1,2]. Pre-operative planning incorporating predictive tools to evaluate functional outcome may support the surgeon by comparing different surgical treatments. Subject-specific musculoskeletal models have a high potential to be used as a predictive tool in clinical practice [3]. In detailed joint models, ligaments strongly influence kinematics since they are highly important structures for guiding and stabilising knee motion [4,5]. However, before applying such models in a clinical setting, validation is of paramount importance. The purpose of this study was to evaluate a computational efficient model that can predict subject-specific knee kinematics and ligament length changes for different implant alignments.

Recently, several studies explored methods that can simultaneously compute motions as well as muscle and contact forces. Hast and Piazza presented a dual-joint workflow in which the knee joint is alternated between a simplified knee joint representation for inverse dynamics and an unconstrained knee with elastic foundation contact [6]. Thelen et al. extended the computed muscle control algorithm (CMC) to co-simulate muscle and contact forces, using an elastic foundation model [7]. Guess et al. presented a two-stage modelling method, an inverse kinematics and a forward dynamics simulation, predicting muscle and contact forces concurrently [8].

Andersen et al. introduced an alternative approach, called force-dependent kinematics (FDK), that extends the fast inverse dynamic simulations with the ability to estimate secondary joint kinematics [9]. This method relies on an assumption of quasi-static force equilibrium in the secondary joint kinematics at each time step during the analysis. In 2014, the FDK method was applied and knee

---

[*] Corresponding author at: Biomechanics Section, Katholieke Universiteit Leuven, Celestijnenlaan 300C, 3001 Leuven, Belgium.

E-mail addresses: valentine.vanheule@kuleuven.be, valentine.vanheule@materialise.be (V. Vanheule).

http://dx.doi.org/10.1016/j.medengphy.2016.12.001
1350-4533/© 2016 Published by Elsevier Ltd on behalf of IPEM.

Please cite this article as: V. Vanheule et al., Evaluation of predicted knee function for component malrotation in total knee arthroplasty, Medical Engineering and Physics (2016), http://dx.doi.org/10.1016/j.medengphy.2016.12.001

contact forces were validated during walking activities in the winning model of the Grand Challenge competition [10].

Musculoskeletal models have the ability to explore the relationship between implant alignment and functional outcome for different activities of daily living. Others investigated the effects of implant alignment variation during a simulated squat, however, without collecting experimental evidence for the malaligned configurations [11,12]. In our study, we modelled different implant alignment variations and additionally, performed a cadaveric study to validate the predicted knee function for each alignment. FDK was used to simulate knee kinematics and predict ligament length change patterns for three cadaveric knees with TKA performing a squat motion. In addition to the standard implant, malrotation in the coronal plane was introduced by using tibial inserts with a built-in varus or valgus offset [13]. For each specimen, three squats were performed with the knee in neutral, varus, or valgus alignment. The model outputs were validated by comparing experimental and model-predicted tibio-femoral motion and ligament length changes. To our knowledge, this is the first study to both simulate and validate the impact of implant alignment on kinematics and ligament length changes as predicted by computer models.

2. Methods

2.1. Experimental data collection

2.1.1. Specimen preparation and imaging

Three cadaveric knee specimens were used for squat simulations in a dynamic knee simulator system. The methodology of the specimen preparation was similar to the workflow described by Victor [14]. The study protocol was approved by the local Ethics Committee.

After thawing the fresh frozen specimens, full leg T1-weighted opposed-phase spoiled gradient echo magnetic resonance imaging (MRI) scans were obtained using a 3T scanner (Ingenia, Philips Healthcare) to visualise soft tissues. The slice thickness was 2 mm and all slices had an in plane resolution of 0.9 mm × 0.9 mm. Subsequently, frames (Medtronic, MN, USA) with reflective spherical markers were rigidly attached to femur, tibia and patella. Each frame carried four markers, which were 6 mm in diameter. The femoral frame was inserted within 21 cm from the joint line, the tibial frame within 18 cm from the joint line and the patellar frame was inserted onto the patella. The tibio-femoral joint line in the native knee can be defined as the tangent of the cartilage contact surface between the medial and lateral tibial plateaus with the femoral condyles. This joint line was defined through palpation and indicated with a skin marker following which amputation was performed at the predefined distances. To allow accurate three-dimensional motion tracking, a six-camera motion capture system (Vicon MX40, Oxford, UK) was used. The optical markers could accurately be located on the pre-operative and post-operative computed tomography (CT) scans.

Volumetric CT scans of the full lower leg with the attached markers were obtained on a dual-source multidetector CT scanner (SOMATOM Definition Flash, Siemens), equipped with two 64-detector row units, using a slice thickness of 0.75 mm and a pitch of 0.8 mm/rev. The images were processed in Mimics v. 17.0 (Materialise, Leuven, Belgium) to construct the bone models of femur, tibia and patella. These bone geometries were used to identify bony landmarks.

Next, the hip and foot were removed from the full leg, with a femoral cut 32 cm proximal of the joint line and a tibial cut 28 cm distal from the joint line. The quadriceps muscle was dissected and its preserved tendon was fixed into a clamp. In addition, the semitendinosus together with the semimembranosus muscle, as well as the biceps femoris muscle were dissected and suture wires were attached to the preserved tendons. The proximal femur and distal tibia were then embedded in aluminium containers, preserving the physiologic alignment in the coronal plane and parallel with the container in the sagittal plane.

Two extensometers (MTS, Eden Prairie, MN, USA) were sutured to the medial and lateral collateral ligaments by an experienced surgeon. The fixation of the extensometers was centred over the joint line, on an unloaded and fully extended knee [15]. During the measurements, ligament length change relative to the extended knee was calculated using the formula $\varepsilon = (L - L_r)/L_r$, where L was the instantaneous length of the extensometer arms connected to the ligament and L_r was the reference length at full extension.

2.1.2. Total knee replacement and imaging

An experienced surgeon (HD) performed the total knee arthroplasty on each specimen using a posterior-stabilised total knee arthroplasty (Performance, Biomet Inc., Warsaw, IN, USA). In addition to the tibial implant placed with standard alignment instrumentation, two variations of the tibial insert were designed through additive manufacturing. These variations were able to artificially simulate a TKA coronal malalignment by their built-in varus or valgus design. The inserts were modelled so that the central height was preserved while making one side thicker and the other side thinner than the neutral insert. For each specimen, three squat trials were performed. Specimen 1 underwent squats with neutral insert, 5° varus insert and 5° valgus insert. Specimen 2 and 3 underwent squats with neutral insert, 3° varus insert and 3° valgus insert. The tibial insert thickness for specimen 2 and 3 was smaller, leading to a smaller varus and valgus angle due to design limitations. The valgus insert squat of specimen 3 is not shown in the results since the quadriceps ruptured during the last experiment.

After the trials, post-operative CT scans were made with the optical markers still attached on the same scanner as the pre-operative scans, allowing to accurately document the implant position.

2.1.3. Knee simulator set-up

The specimens were mounted onto a dynamic knee simulator system, based on the Oxford rig [16]. This mechanical system permits six degrees-of-freedom (DOFs) for both the tibio-femoral and the patello-femoral joint. The femoral container was connected to an artificial hip assembly and the tibial container to an artificial ankle assembly. The quadriceps clamp was connected to an actuator that could apply a variable quadriceps load. Both hamstring wires were connected with constant-force springs of each 50 N (Type KKF 8077, Lesjöfors, Karlstad, Sweden). The hip assembly could slide vertically and flex and extend, the ankle assembly allowed rotation in all three directions and translated mediolaterally. Sensors detected the quadriceps force, ankle force and relative hip height and these real-time data were processed in a closed feedback system (LabVIEW, National Instruments, Texas, USA), allowing the performance of a squat motion by moving the hip assembly and applying a variable quadriceps force to induce a vertical ankle force of 111 N. The quadriceps load increased during knee flexion, starting from a few hundred Newton at the beginning of the experiment and the load could go up to 2000 N at deep knee bend. A full squat motion began around 30–40° knee flexion and went up to 110–120°. The squat did not begin at full extension to prevent hyperextension [14].

Six infrared emitting cameras (MX40, Vicon, Oxford, UK) tracked the reflecting light from the rigidly attached optical markers on femur, tibia and patella at a sampling frequency of 100 Hz. This provided us an accurate measurement of the knee joint motion during squat. Throughout knee flexion, the three-dimensional (3D) coordinates of the passive markers were tracked and the relative position of all the important landmarks on femur and

Please cite this article as: V. Vanheule et al., Evaluation of predicted knee function for component malrotation in total knee arthroplasty, Medical Engineering and Physics (2016), http://dx.doi.org/10.1016/j.medengphy.2016.12.001