A METHODOLOGY TO DEVELOP A PATIENT-SPECIFIC 3D MUSCULOSKELETAL MODEL BASED ON MRI, GROUND REACTION FORCES AND MOTION CAPTURE DATA

A. Van Branteghem[1], J. Victor[2], P. De Baets[3] and M. A. Verstraete[2],

[1] Ghent University, Belgium
[2] Ghent University, Dept. of Physical Medicine and Orthopaedic Surgery, Belgium
[3] Ghent University, Dept. of Mechanical Construction and Production, Belgium

Abstract:

The well-documented dissatisfaction of patients with the results of their total knee replacement surgery has been the incentive for deeper research into the optimisation of knee prostheses. One way to optimise total knee replacements is to develop patient-specific 3D musculoskeletal models, enabling a better understanding of the kinematics and kinetics affecting the lower limbs of the patient. This paper suggests a particular methodology to build such personalised models, by implementing data of additional measurement systems. MRI scanning ensures a morphological match between the model and the patient. Additionally, ground reaction force measurements coupled with motion capture provide the kinematic input. A squat test was performed to illustrate the usefulness of the data obtained through the force plates. The combination of this data into the 3D models allows for a more precise calculation and simulation of knee joints. This will ultimately improve the quality of prosthesis testing in a knee-rig setup by providing more accurate boundary conditions.

Keywords: musculoskeletal model, MRI, motion capture, force plates

1 INTRODUCTION

General satisfaction in patients with knee prostheses has not been up to par compared to hip replacement surgeries[1-4]. Patients complain about pain, loss of functionality and mobility and an absent increase in general quality of life after total knee replacement (TKR) surgery. In order to raise the quality of knee replacement surgery, a better understanding of the kinematics and kinetics of the tibio-femoral joint and of a prosthesis' impact on the lower limb must be developed. Musculoskeletal modelling has been used for decades, but it still falls short in enabling precise clinical decision-making[5]. The objective is thus to enhance these 3D models, using additional data, and consequently translate the acquired knowledge to realistic boundary conditions for the UGent knee-rig. This test set-up simulates the motion of the knee joint during activities of daily living on cadaveric subjects. The aim is thereby to optimise the surgery and achieve a better patient reported outcome. In this paper a methodology is described to enhance existing models by introducing patient-specific properties. Morphological features like bone and muscle structure are introduced to the model using output of MRI scans. Additionally, movements and ground reaction forces are synchronously recorded with a motion capture system and a combination of force plates respectively.

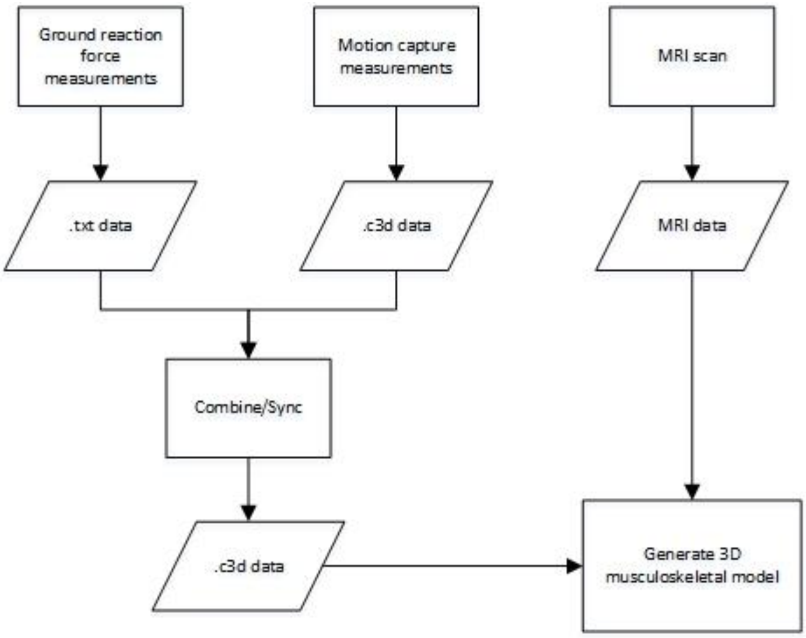

Figure 1: Flowchart of methodology

2 THE METHODOLOGY

2.1 Ground reaction force measuring

The most widely used method to measure ground reaction forces is by positioning the test subject on one or more force plates, depending on the type of measured movement. The force plates used in this setup consist of four tri-axial force sensors, with three quartz plates per sensor that yield electric charges which are in turn converted to analogue voltages. These sensors are designed to accurately quantify the applied force in three dimensions. Using a data acquisition device (USB-6218, National Instruments, Laguna Hill, CA, USA) and LabVIEW (National Instruments, Laguna Hill, CA, USA) software, these voltages are then transformed into force components. The values of each component are written to a text file, where they await further processing in order to become useful towards implementation into a musculoskeletal model. Note that the ground reaction force is the negative of the resulting force as measured by the plate.

The force plates (type 9260AA manufactured by Kistler) used in this setup are designed specifically for gait and balance analysis. Their load limit is 5 kN. They cannot measure or even withstand sudden impacts, which means that highly dynamic testing is impossible. Therefore, limitations are set on the movements made by the test subjects. Walking or balancing experiments are the main focus here. Some tests that are worth looking into are the squat and lunge motion, since these are reproducible in a knee-rig. A particular interesting aspect is the behaviour of the horizontal shear forces at different positions of the knee during a typical squat. For instance, Figure 3 describes the force components of a test subject (male with healthy knees, weighing about 90 kilograms) performing a squat. A clear change in the medio-lateral shear force component (Y-component in this case) is noticeable. The initial value of about 40 N of outwardly directed shear force along this axis on each force plate is due to the wide stance the subject was taking prior to commencing the squatting motion. As the subject is lowering its body through bending of the knees (starting around the 50th sample in the graphs), the shear forces become inwardly directed, since its knees are pointing slightly more outwards.

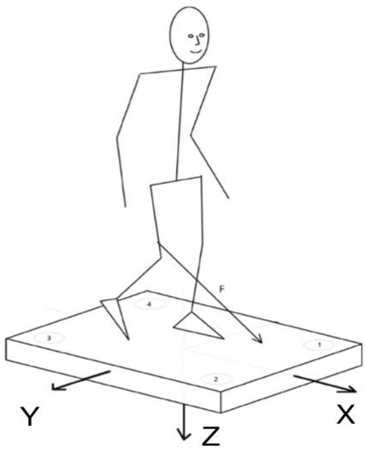

Figure 2: Reference frame for both force plates in the squat test

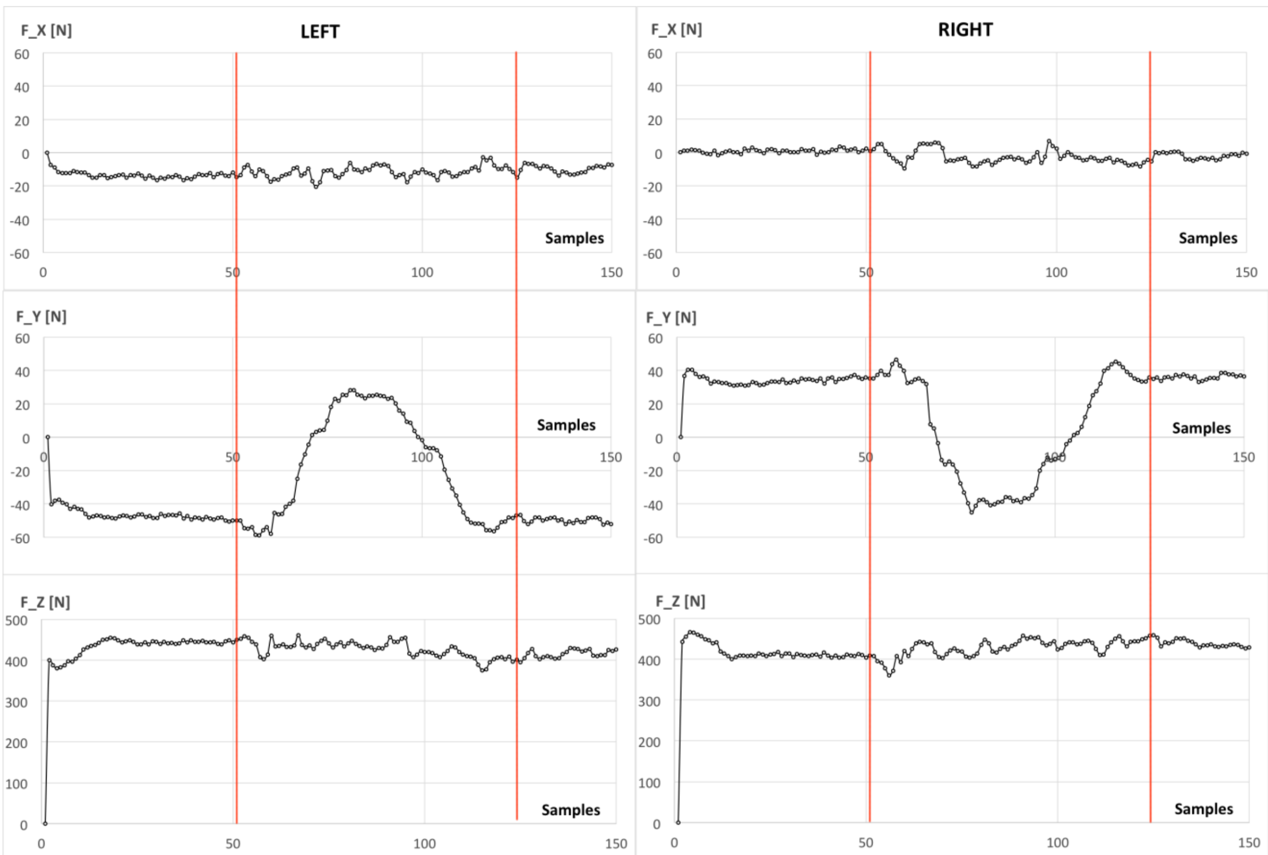

Figure 3: Graphs of each force component of a test subject performing a squat motion

2.2 Motion capture measuring

In order to couple the force plate data to real-time movements of the test subject, a motion capture system, consisting of eight infrared cameras and an adequate number of applied reflective markers, is used. To obtain useful data to be implemented later on in the 3D model, the number of markers and their exact position are two important parameters that should be carefully considered. The force plates are fitted with markers as well to describe their position unambiguously relative to the test subject performing the experiment. The lower-limb marker landscape considered in this paper is pictured in Figure 4, where 27 markers are applied to the subject: five on the pelvis, six on each leg and five on each foot.

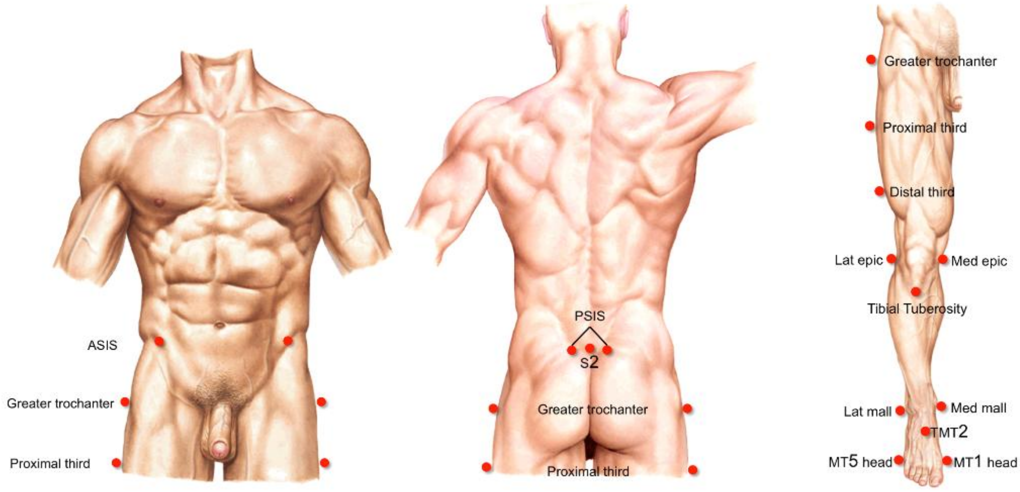

Figure 4: Marker landscape used in the squat test

The motion capture setup, OptiTrack (Natural Point Inc., Corvallis, Oregon), takes images at a predefined frequency by firing its infrared strobes, which are reflected by the markers and consequently recorded by the cameras. By using the complementary software, Motive (Natural Point Inc., Corvallis, Oregon), each marker can be tracked as long as it remains visible to at least two different cameras in the setup. These marker trajectories are then exported as a *.c3d* file and are ready for building a 3D model.

2.3 Synchronising and combining

The difficulty in making a useful system out of two pieces of technology that are not embedded by default, lies in combining the two types of data. The first important aspect to effectively combine data is to make sure that measurements are running synchronised in real time. To facilitate this, one of these two systems acts as a slave to the other. In this case the force plates are the master system and dictate when the motion capture instruments need to be shooting pictures. This is achieved by implementing an external synchronisation input signal to the OptiTrack system, which is generated by the data acquisition device of the force plates. Thus, when a measurement is started on the force plates, the cameras are obligated to record images. Conveniently, this ensures that whatever frequency is used to measure ground forces, is also used for the cameras, or in other words: for every measurement of force there is one image being shot by the camera setup.

Synchronisation involves more than the master-slave interaction between both systems. There is still an internal delay to be accounted for in the camera setup due to the implementation of the sensors in the OptiTrack cameras. The exact moment of exposure of the cameras is not perfectly coincident with the triggering signal. This delay time is calculated based on the specific parameters of the set-up, and ranges between 0 – 65 ms.

Besides a time synchronisation, there is a need for an unambiguous definition of the position of the forces measured through the force plates in relation to the test subject. As previously stated, a number of reflective markers are added to each force plate. This way their dimension and the relative position of the subject is known at each instant of the test by using the same OptiTrack system. These stationary markers are the basis for defining the confinements of the plates in AnyBody. In total nine markers are used per force plate to describe all of its planes.

Combining the two types of data, once both of their time-scales are equal, requires computational software along the likes of MATLAB, yielding the final *.c3d* file to be implemented into the 3D musculoskeletal model.

There are, however, a couple of drawbacks inherent to the use of markers applied to skin, like for instance the uncertainty in their relative motion to the bone structures of the subject[7]. For obvious reasons markers cannot be applied directly to the bone of the subject. Therefore, this offset must be accounted for when building the musculoskeletal model. Additionally, an amount of interference is inevitably present on this type of measurement as described by Delaney[8]. Other drawbacks relate to the fact that applying the markers remains a time-consuming task, the need for a controlled environment to obtain data with sufficient quality and the possibility of the markers influencing the subject's movement. Research into different motion capturing techniques like the one by Andersen et al.[9] is therefore receiving more attention as the goal is to move to pure computer vision solutions without the need for reflective markers[10]. An alternative would be to track movements through means of an exoskeleton with mechanical measurement sensors at its joints. Mobility is obviously hindered with this method, which explains its infrequent use. Another example of a current alternative to the usage of markers is a non-optical system based on miniature inertial sensors. This technology finds its application in motive controllers for gaming platforms, since its wireless capabilities are advantageous hereto. The downside here is its position drift and low positional accuracy.

2.4 MRI scan

Musculoskeletal modelling has often been confined to the usage of average adult models. There is a lot of uncertainty as to the applicability of simulation results and conclusions to subjects with strongly differing morphology. This is where the need for subject-specific models comes in, as explained by Blemker et al.[5] In order to make the 3D musculoskeletal model patient-specific, a MRI scan of the relevant parts of the body is the best option. Less efficient alternatives include X-ray scanning, which does not give much information on softer tissues. Bone structure, muscle architecture and all other soft structures like ligaments, cartilage etc. are effectively evaluated with an MRI scan and can consequently be imported into the model[11]. Only when the model resembles the exact morphology of the patient can the additional data be fitted onto it. Especially when it comes to adding the motion capture data to the model, it is of great importance that the dimensions of the body matches the relative distances between the markers. The more accurate the fit and thus the model, the more accurate the results coming from the subsequent simulations are.

2.5 Generating a 3D musculoskeletal model

With all the data described in previous subsections, a patient-specific musculoskeletal model can be developed using the AnyBody Modeling System (Anybody Technology A/S, Aalborg, Denmark)[6]. By adding the combined *.c3d* files, subject-specific morphology, kinematics and kinetics become part of the model, allowing for more accurate simulations in terms of the tibio-femoral joint forces, which are the main focus in this case.

3 CONCLUSIONS

The incorporation of MRI, ground reaction force and motion capture data into the three-dimensional musculoskeletal models enables a more precise calculation and simulation of the knee joint. This looks promising in light of prosthesis testing in knee-rig setups. More accurate boundary conditions in terms of the exact muscle forces to be applied at specific moments in the movement in the rig will contribute to the optimisation of knee prostheses. Along with the better understanding of patient-specific kinematics and kinetics, this will generate valuable insights for orthopaedic surgeons towards improving procedures of TKR surgery, resulting in a more tailored knee implant, ultimately leading to greater patient satisfaction.

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