MODELING THE KNEE JOINT IN DEEP FLEXION: "THIGH AND CALF" CONTACT

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ABSTRACT

The objective of the present work is to determine the effects of the "thigh and calf" contact that occurs while the knee is maximally flexed, up to 165 degrees of knee flexion, on the loads transmitted across this joint. A two-dimensional anatomically based mathematical model of the human knee joint was used for this purpose. In this model, a single force was used to represent the resultant of the "thigh and calf" non-uniform contact stresses that act either on the tibia or the femur.

Results were obtained to simulate isometric quad contractions associated with hamstrings co-contractions at a position of maximum knee flexion. Numerical calculations indicate that the predicted knee response differs greatly as you introduce the "thigh and calf" contact. This shows the importance of including this force when developing models that predict the response of the joint when it is maximally flexed.

INTRODUCTION

The present-state-of-the-art of knee mechanics does not provide an accurate understanding of how this joint functions in deep flexion (maximum flexion) in normal individuals making thus our understanding on the complex three-dimensional tibio-femoral and patello-femoral motions past 140 degrees of knee flexion limited [1]. Literature review indicates that very few and limited studies have been published to describe the knee response in deep flexion [2-4]. Yet all these studies were limited in that they did not consider that when executing a deep squat a point is reached where the posterior thigh and calf come into contact with each other, and start deform. A contact force will then be generated between the tibia and femur, namely the "thigh and calf" contact force.

Deformation of human flesh due to flexion of members is a very challenging task [5] where solutions to this problem were proposed to create a realistic virtual human. Two approaches have been identified for deformable animation of articulated characters: Geometric Deformations and Physically Based Deformation [6]. In the first technique, some type of implicit surfaces such as ellipsoidal metaballs are deformed using space-filling functions. In the second technique, mass-spring systems are employed. While the physically based modeling techniques produce very realistic deformations, they involve a large amount of computation [6].

The focus of this work is to determine the effects of the "thigh and calf" contact on the loads transmitted to the knee joint. Because of this, we are not interested in modeling the flesh deformation, but only in determining the loading on the femur and the tibia due to the "thigh and calf" contact. Hence, a simple model is proposed to solve the "thigh and calf" contact. Results are presented to assess the value of including this contact force in deep knee flexion models.

METHODS

A two-dimensional model was developed to determine the behavior of the knee joint and its structures when it is maximally flexed during deep squat. This model, shown in Figure 1, includes 3 body segments involving the tibio-femoral joint and the patello-femoral joint, accounts for quadriceps and hamstring co-contractions, allows for deformable contact at the articular surfaces, and allows for the "calf and thigh" contact that occurs in deep flexion.

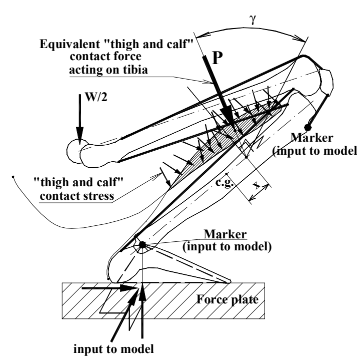

Figure 1.

The reaction forces were measured using force plates. A single force was used to represent the resultant of the "thigh and calf" non-uniform contact stresses that act either on the tibia or the femur when the knee is maximally flexed in deep squat. This equivalent force is shown in Figure 1 and its line of action is assumed to be parallel to the normal to the line bisecting the angle between the tibial and femoral shafts.

Hence only 2 quantities are required to fully define this force: its magnitude, P, and its location along the tibial axis, x.
X-rays were used to determine the mathematical representation of the tibial and femoral articular surfaces. Two polynomials of the 10th order were used to describe the femoral profile (including the different portions of the condyle and the posterior and distal edge of the femoral shaft) and the different portions of the tibial plateaus. respectively. The patellar articular surface was represented as a straight line.
Ten nonlinear springs were used to model the ligamentous structures to include the cruciate and the collateral ligaments along with the posterior capsule. The patellar tendon force was assumed as a linear spring. Other forces included the patellar tendon force, two muscle forces: quad and hamstrings, and tibio-femoral (TF) and patello-femoral (PF) contact forces. Three local systems of axes were defined on the tibia, femur and patella. Model equations consisted of 15 equations in 15 unknowns. The first nine equations included 3 equations of equilibrium for each of the tibia, patella and femur. A simple deformable contact algorithm was used to model the deformable contact at the TF and PF articular surfaces. In the analysis, two equations were written to model each of the TF and PF deformable contact as the TF and PF contact forces were assumed proportional to the shortest maximum penetration distances between the articular surfaces. The last two equations were written to model the wrapping of the quadriceps tendon around the femur and the wrapping of the patellar tendon around the tibia. The unknowns included the patellar flexion angle, the x- and y- coordinates of the origin of the tibial and patellar systems of axes with respect to the femoral system of axes, the local x-coordinate of each of the two points defining the shortest maximum penetration between the TF and PF articular surfaces, respectively, the 2 quantities defining the "thigh and calf" contact (P and x), the hamstring and quad forces, and the local x-coordinates of the two wrapping points.

RESULTS

Results were obtained to show the effects of including the "thigh and calf" contact force on model predictions. Figure 2 shows model predictions for the location of TF and PF contact when the knee was flexed to 168 degrees of knee flexion. This figure shows that contact occurred occurs near the posterior edge of the tibia. To achieve equilibrium, the quadriceps and hamstring forces were calculated as 2800 N and 2240 N, respectively. The forces in the anterior fibers of the PCL and the deep MCL were found to be 267 N and 624 N. The tibio-femoral and patello-femoral contact forces were calculated as 1018 N and 3600 N, respectively. At this position, the posterior fibers of the PCL and both anterior and posterior fibers of the ACL were found not to carry any load.

DISCUSSION

This work is part of a larger study aiming at understanding the mechanics of the knee joint in deep flexion. Spanu and Hefzy [2] developed a two-dimensional model to predict the response of the joint during deep squat. In their model, they did not include the "thigh and calf" contact force. In this work, we present a modification to this model to include this contact force. In addition, their model was limited in that they did not include the patello-femoral joint.

Model predictions show that the tibio-femoral contact occurs proximally on the posterior condyles, close to the posterior edge of the femoral shaft. This is in agreement with the previous model predictions [2]. On the other hand, it appears that including the "thigh and calf" contact force has a large effect on model predictions for internal loads. In this work, it was found that a quad force of 2800 N was required to maintain equilibrium at this position. In our previous model, we reported that much larger values, greater than 3500 N, were required to maintain equilibrium at this position. Also, the present predictions for the tibio-femoral and patello-femoral contact forces are lower than the previous predictions [2].

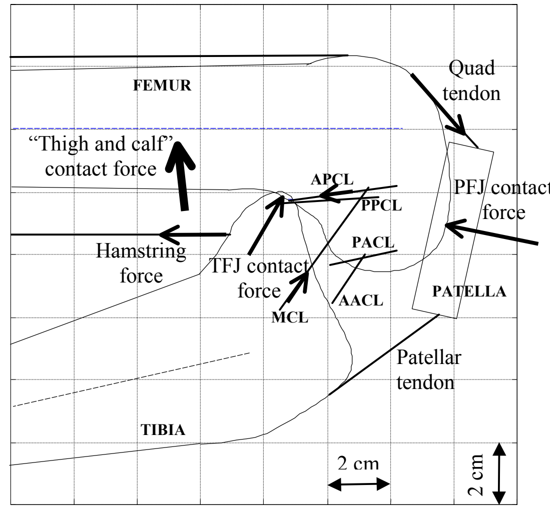

Figure 2. This figure shows that the "thigh and calf" contact force works with the quad force to achieve equilibrium in deep flexion

Looking at figure 2, one can explain the large differences between present and previous model calculations. The "thigh and calf" contact force produces a moment around the joint that is in the same direction of the moment produced by the quad tendon. This means that the "thigh and calf" contact force has en effect of stabilizing the joint at this maximally flexed position. Ignoring this force in model developments may lead to erroneous conclusions as to the function of the different structures comprising the joint. For instance, it was found that the forces in the medial collateral ligament when the "thigh and calf" contact force is considered is larger by 50% than when this contact force is not considered.

This study shows the importance of including the "thigh and calf" contact force in future model developments to predict the response of the knee joint in deep flexion. A major limitation of this study is that it is two-dimensional. This model needs to be further developed to include a three dimensional and more realistic representation of the knee joint that accounts for its asymmetry.

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