Simulation of hip forces with a human multibody model

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Introduction

Total hip replacement includes the replacement of the acetabulum of the hip joint and the head of the upper thigh bone (which is called femur). The artificial cup is mounted at the hip bones and the artificial femoral component is inserted in the femoral bone. The location of the joint center of the replaced hip joint may differ from the one of the original joint because of the process of surgery.

When total hip replacement is performed, an anatomically correct position of the acetabular component is an importment goal. Acetabular component loosening with large bone losses make a correct positioning particularly difficult. Little is known how the hip joint forces change when the joint centre is altered. Therefore, we decided to test joint and muscle forces acting at the hip when systematically varying the joint centre.

The forces of the muscles crossing the hip joint have to keep the body in balance during stance. These forces contribute to the hip joint load, together with body weight. Any dislocation of the hip joint center changes the lever arms of the muscles /1/ and therewith joint load and muscle forces.

An ADAMS multibody model is used to describe the relation between the joint load and muscle forces and the location of the hip joint center with the method of simulation. Our interest is focused on the following question:

Does a displacement of the hip joint center change the resultant hip force and the muscle forces acting at the hip joint ?

Method

The ADAMS model used in the present work consists of 15 parts. Its mass and inertial properties represent the 50^{th}-percentile rank of a male adult. A standard body position was defined by single leg stance where the model's center of mass had to be exactly above the fthe standing foot. Fig. 1 shows the model in default position and in single leg stance. Three hip muscles (gluteus max., gluteus med. and piriformis muscle) being important to establish the equilibrium conditions were implemented at the right hip (which was the one of the standing leg). The hip joint center was displaced in steps from the original position and the simulation results of muslce and joint forces were requested. The step size was 1 mm and ten steps were tested in each positive and negative direction on all three axis. Consequently, a cube containing $21^3 = 9261$ different hip joint centers were analyzed. The results were plotted in two- and threedimensional graphs.

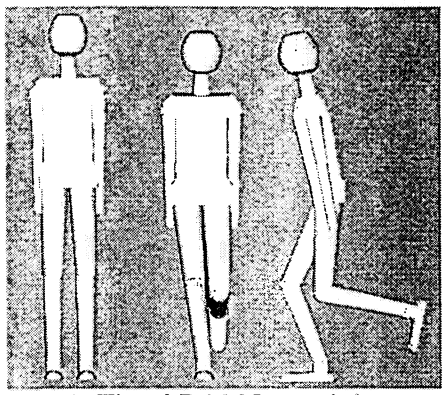
Fig. 1 The ADAMS model

As every step of dislocation changes the model´s equilibrium conditions, it is not possible to generate the complete dataset for all 9261 points within a single simulation. Thus, we developed a study design, which performed a single simulation for each of the points. Each of the simulations contained the shift from a two leg stance (where every simulation starts because of model definition) to a balanced single leg stance and processing of the requested results. The model was enhanced with an automatic regulator to control balance without the neccessity of manual aid. This was done by an integration regulator. The "tfsiso-command" of ADAMS could not be used, because this command cannot control joint motions directly. The joints were controlled with motion velocities proportional to the horizontal distance between the model´s center of mass and its fixation point. Further analyses were done in order to optimize and visualize the dynamic behaviour of this controller.
The concept of the study was to perform simulations with different hip joint centers and store the results. "ADAMS View" was not used here, because it is difficult to handle such a large study with View. Also View does not offer a datafile interface. A Pascal programm was written, which offers the following possibilities: In the original ADAMS model three text variables are implemented. These variables can replace any number in an ADM-File (e.g. coordinates, variable numbers, etc.). From this modified file the program generates new models by replacing the text variables with numbers again in a way that the three text variables create a threedimensional room. In our case this means that the coordinates of the hip joint markers were substituted. The program then created the 9261 copies of our model, each fitted with a set of coordinates. The files are not generated at the same time. However, the solver processes them parallel to the creation of each model "case". Also parallel process the program selects the results from the output-files which were generated by the solver and stored them in a datafile before deleting the evaluated files. This multitasking process avoided exessive growth of directories on the hard disk.
The results were then transferred to Microsoft Exel.

Results

The results are displayed in two dimensional charts. The forces of the three muscles and the joint load are plottet with respect of one of the axes. The absolute coordinates are used. Note that a positive X refers to the left, and a positive Z to the anterior direction of the model.

As shown in Fig. 2, the joint load decreases when the hip joint center (HJC) is moved from lateral to medial direction, although the force of the gluteus max. muscle increases. The gluteus med. muscle decreases to about 1000 N, and the piriformis muscle to about 500 N.

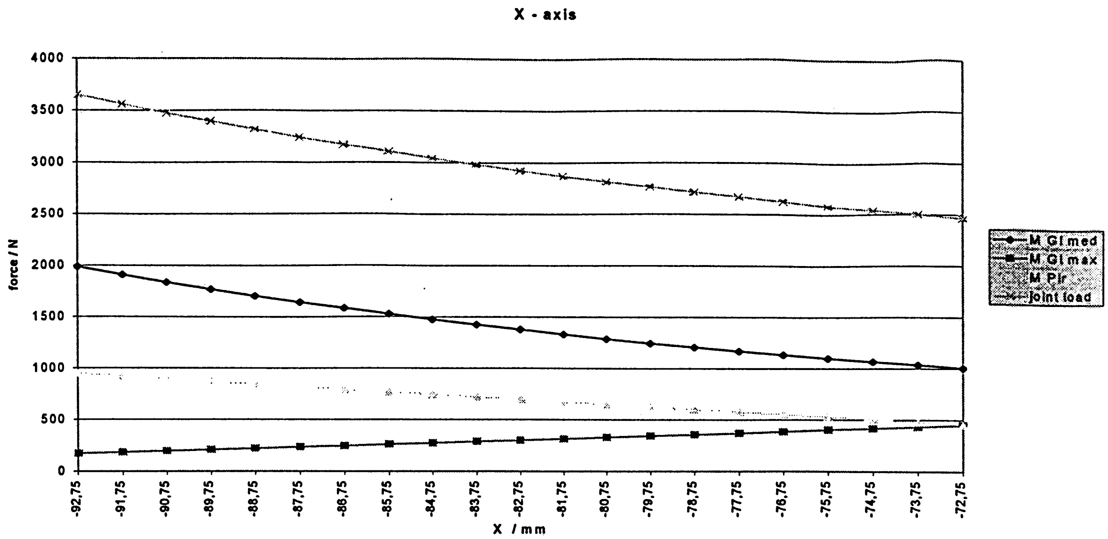

Fig. 2: Results with repect of the X-axis

Moving the HJC from cranially, (see Fig. 3) all muscles forces increased. Joint load reaches almost 1000 N during this simulation. The curves behave almost linear as none of the muscles passes the joint tightly.

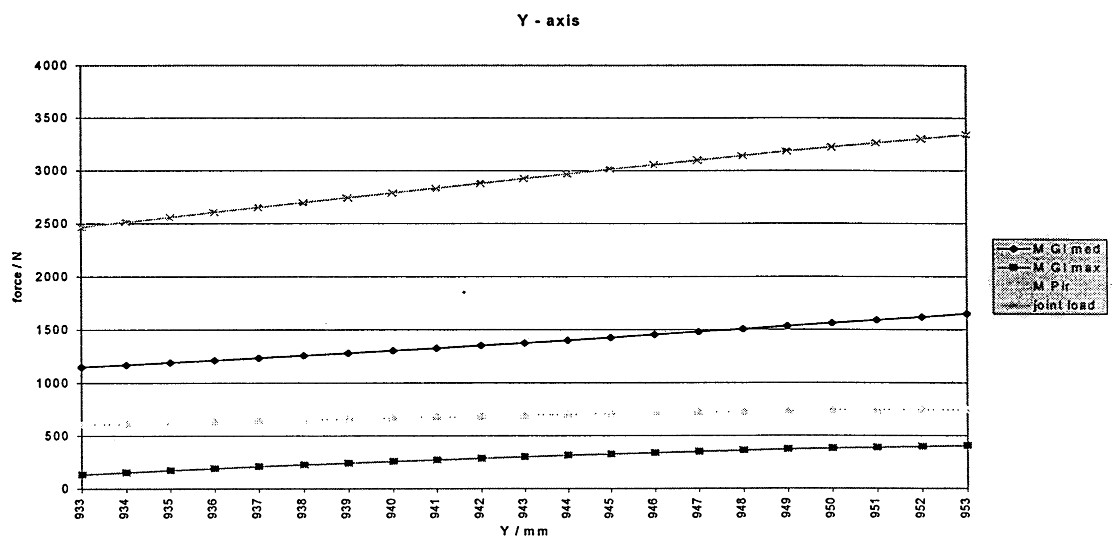

Fig. 3: Results with respect of the Y-axis

Fig. 4 shows that the displacement the HJC to the posterior direction causes M. gluteus max., M. piriformis and thereby the resultant to increase rapidly. M. gluteus med. is keeping its force meanwhile. When moving the HJC to posterior direction the lever arms of M. gluteus max. and M. piriformis become shorter, beeing the reason for the force increase.

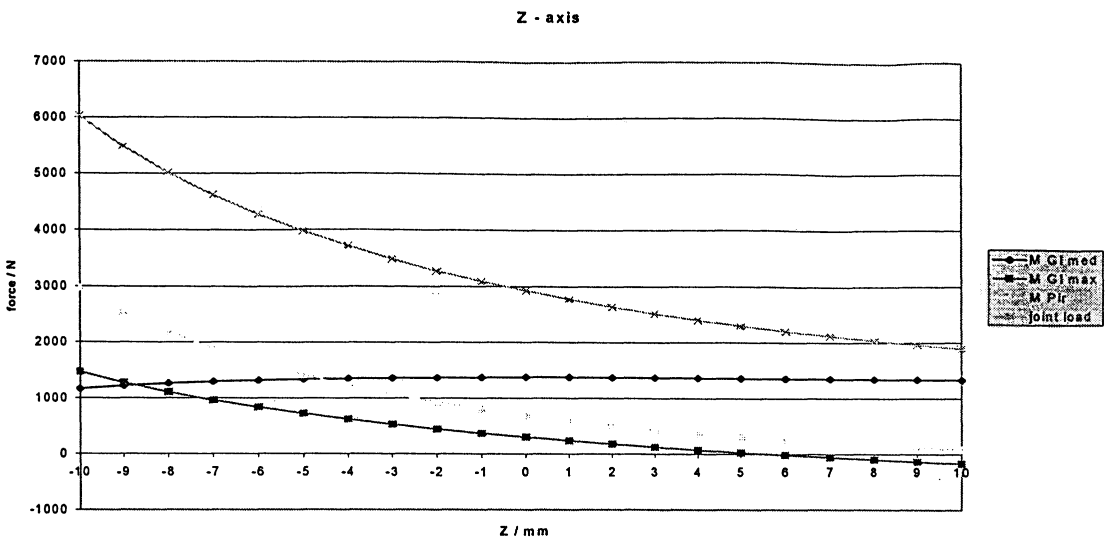

Fig. 4: Results as functions with respect of the Z-coordinate

Discussion

Multibody analysis is a powerful tool to analyse biomechanical systems. The model we used is based on realistic values of masses and inertial properties as well as of joint geometry. As no dynamic analyses were performed, no damping properties are needed to generate any "wobbeling mass". There is no friction implemented in joints or body parts either. Thus in the case of steady state in single leg stance, it is acceptable to use ideal body parts and joints and the results may be regarded as reasonable.

Anterior dislocation reduces the gluteus maximus muscle to negative values of force. Instead of pulling this muscle would push. Clearly, extreme displacements of the joint center do not match the reality, at all. In the real human body this muscle gets passive and antogonistic muscles might get activated.

The number of muscles implemented in the hip region is restricted to three. In reality there is a larger number of muscles, of course. However, controlling balance by more than three muscles in the computer model would result in a redundancy problem: The degree of freedom of the uncontrolled model is three as the vector of the inner joint torque has three dimensions. It is possible to enhance the model by additional muscles. But this would need cost functions (for example the minimization of total energy).

In this work we concentrate on single leg stance only. This body position is characterized by particularly high joint loads.

On the other hand the process of gait is complex and dynamic analysis would be neccessary. As mentioned above, the model does not provide the properties needed to perform a dynamic simulation.

Although the results differ strongly in other body positions, it is possible to derive general statements from our dataset. We obtain information about the forces relative to geometrical parameters rather than the exact forces in vivo.

Conclusion

The human multibody model, presented here, represents a fast testing system of hip joint forces. There is reasonable agreement with the literature data and the basic trends of force changes when displacing the hip joint centre can be detected. In order to avoid the unsolved redundancy problem, the number of muscles included in the study is restricted to three. Clinical relvance is given in the field of revision surgery after total hip joint loosening. Bone defects in the cranial and posterior region of the acetabulum should be fully reconstructed in order to avoid extreme hip joint loads. Future developments should evaluate the load cases of a complete walking cycle and should include further muscles.

Literature

/1/ LENGSFELD, M., T. PRESSEL, U. STAMMBERGER: Lengths and lever arms of hip joint muscles: geometrical analyses using a human multibody model. Gait & Posture 6 (1997), 18-26