SIMULATION AND BIOMECHANICAL EVALUATION OF RECONSTRUCTIVE SURGERY OF THE HIP IN CHILDREN

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Abstract: Hip dysplasia is a deformation of the hip joint leading to instability and a decrease of the contact surface between femur and acetabulum. When diagnosed too late, an operation is needed to cut the pelvis and reposition the acetabulum. The goal is to lower the contact pressure in the joint. While planning the operation, surgeons mostly use two-dimensional anatomical parameters such as angles or distances, measured on a frontal roentgenogram of the patient. This paper reports on the development of a three-dimensional and patient specific simulation and evaluation environment for reconstructions of the pelvis. The environment is created in Matlab and Mechanical Desktop (MD, C++ in ObjectARX). The data of the reference patient was obtained from S.L. Delp *et al* [1]. One procedure calculates the resultant hip force and its location (six degrees of freedom) from static equilibrium equations. Another procedure calculates the resultant contact surface in the hip joint using a distance criterion. The model is validated for a patient with a normal joint. The resultant force points through the centre of the joint and corresponds to measurements in instrumented hip prostheses at slow gait.

Introduction

Hip dysplasia is a deformation of the hip joint. This deformation leads to instability of the joint and a reduction of the contact surface between the femur head and the acetabulum. When untreated, the cartilage in the hip joint will disappear due to the high stress in the joint and at an older age the patient will suffer from arthritis [2].

When considering hip dysplasia in young children, this deformation is known as developmental hip dysplasia or DHD. Because the hip is still developing, it is relatively easy to correct this type of deformation. The physical problem is a too high level of pressure in the joint due to the abnormal anatomy of the hip. All interventions aim to reduce this pressure. When DHD is diagnosed after the age of two, an osteotomy is the best solution because the hip has already developed considerably at this stage. Although there are several types of surgical interventions to address this problem, this work is restricted to the reorientation osteotomy techniques.

The planning of such an osteotomy can still be improved considerably. Today, surgeons mostly use two-dimensional anatomical parameters such as angles or distances, measured on a frontal roentgenogram of the patient [3]. A 3D visualisation could give a much better representation of the deformation of the hip joint. Further improvements include a virtual simulation of the osteotomy and the calculation of the forces in the joint on one hand and the contact surface in the joint on the other hand. Another important aspect is the patient specificity. Since the anatomy and type of deformations can vary substantially, it is important that for each patient a 3D file can be constructed and that all biomechanical parameters that are specific to this particular patient can be calculated, saved and retrieved. All the above features should be integrated into a user friendly environment.

Materials and Methods

Osteotomy types

Three types of osteotomies that are being performed on a regular basis in the orthopaedics section of the University Hospital Leuven are discussed here. The first one is the basic single osteotomy of Salter [4], shown in figure 1. The figure shows a patient with a normal right hip and a dislocated left hip.

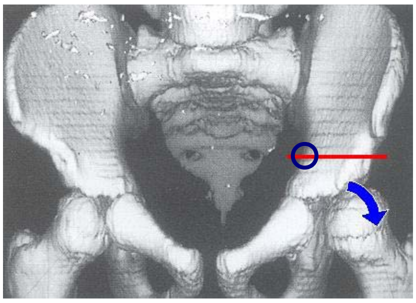

Figure 1: Schematic view of Salter osteotomy [4]

When performing a Salter osteotomy, the surgical cut is made above the acetabulum in the ileum and is a full cut of the bone. The arrow in figure 1 shows the displacement of the acetabulum. The surgeon moves the acetabulum over the femur head, i.e. a more anterior-lateral position as opposed to the femur head. This rotation increases the contact surface between both

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surfaces, which reduces the pressure inside of the joint. Theoretically, there should be one single point where both parts of the pelvis are still making contact, represented by the blue circle in figure 1. In the opening that is created between the upper and lower pelvic part, a bone graft is placed for the reorientation to be permanent (figure 2). In most cases, this bone graft is taken from the iliac crest, as also seen in figure 2. For fixation of the different bone parts, Kirschner pins are used. They are schematically drawn on figure 2 as thin black lines.

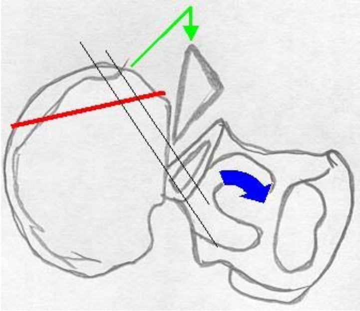


Figure 2: Schematic representation of bone graft insertion and fixation of bone parts [4]

When hip deformation is more severe, and therefore a higher degree of reorientation is required, two other osteotomies are performed. The first one is the double osteotomy of Sutherland [5]. The extra rotational freedom comes from the removal of a part of the pubic symphysis, as seen in figure 3a. Another, more aggressive possibility is to completely detach a part of the pelvis (including the acetabulum) and to fixate it again in any direction wanted by the surgeon (Steel osteotomy [6]). This can be seen schematically in figure 3b.

a. b.

Figure 3: Schematic view of double osteotomy of Sutherland (a) and triple osteotomy of Steel (b) [4]

Bone fixation is in both cases done in a similar way as shown in figure 2.

Visualisation

The first step in the simulation of a hip osteotomy is the creation of a patient specific 3D model of the hip. This model is based on patient CT data. Figure 4 shows a schematic view of the operations that are performed in order to obtain the 3D model. Firstly, bone representing pixels are selected from the CT sectional data using Mimics© software from Materialise (segmentation).

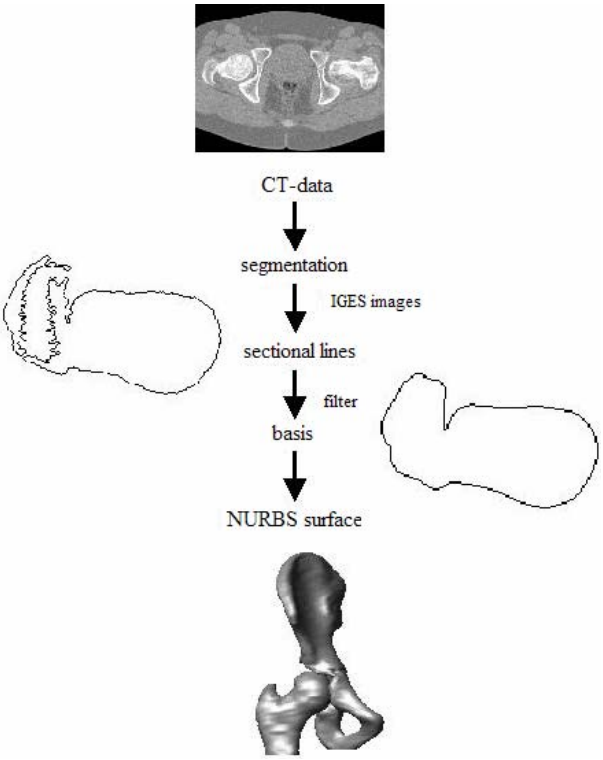


Figure 4: Overview of the visualization procedure

This data is exported in IGES format and imported in Mechanical Desktop (MD, C++ in ObjectARX). It consists of a number of sectional lines as seen on the left in figure 4. A filtering and stitching procedure is then used to close and smoothen these sectional lines. The result of this procedure is seen on the right in figure 4 for one sectional line. From these smoothened splines, NURBS (Non-Uniform Rational B-Splines) surfaces are calculated for both pelvis and femur. The result is shown in the lower part of figure 4.

From this 3D visualization, the contact area between femur and acetabulum is calculated using a simple distance criterion. Figure 5 shows the calculated contact area for a normal hip joint and compares it to an indicative contact area shape from literature.

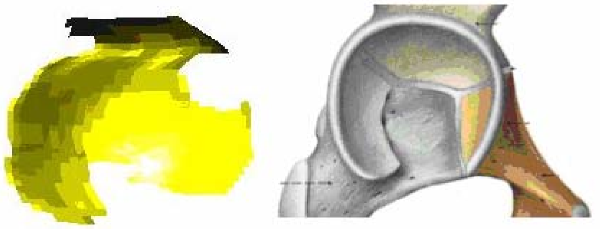


Figure 5: Calculated joint contact area for normal hip (left) and indicative contact area shape from literature (right) [7]

Hip model

The goal of an osteotomy on a dysplastic hip is to reduce the pressure in the joint. For this purpose not only the contact area is important but also the resulting force (both magnitude and direction) acting in the hip joint. To calculate this resultant hip joint force, a number of parameters are to be known. These are the subject's body weight, the locations of the muscles in the hip region and the force exerted by each of these muscles. The latter parameter consists of a value for the maximum force one particular muscle can exert and a muscle activation value between 0 and 1 that defines how large a fraction of this maximum force is actually exerted by the muscle.

The hip force model is based on a person standing on one leg in a static position (figure 6).

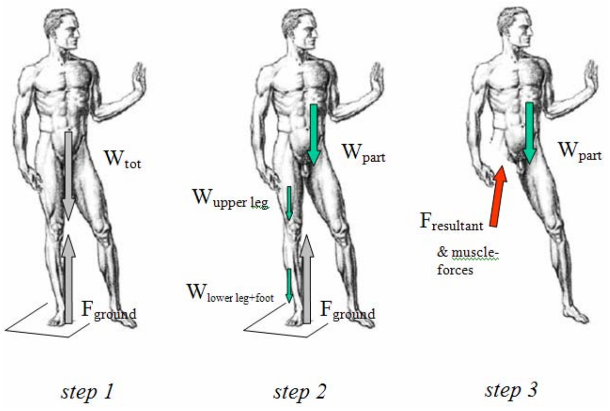


Figure 6: Force calculation in the hip joint through free body diagram

Step 1 shows the calculation of the ground reaction force based on total body weight. In a second step total body weight is divided into weight of the upper and lower leg and the foot on one side and the rest of the body (W_{part}) on the other side. Centres of mass of foot and upper and lower leg are derived from literature [8]. From this information the centre of mass of the rest of the body can be calculated. In a third step the supporting leg is removed and replaced by the resultant force in the hip joint and the forces exerted by the muscles on the hip. The magnitude and direction of the resultant force vector can then be calculated from the six equations of static equilibrium.

This equation system can only be solved if the muscle forces are known. There are 19 muscles that act on the hip region. Some of these are relatively wide and have therefore been divided into multiple parts. This gives a total number of 27 muscle segments for which muscle forces are calculated corresponding to Zajac [9] To guaranty static equilibrium in a patient specific way using this model, an optimisation procedure is required. This optimisation algorithm searches the energetically most favourable solution for the static equilibrium system by minimizing the summation of the activation values for the muscles. This optimization procedure is written in Matlab.

Muscle scaling

The muscle model is based on the Lower Extremity Model of Scott L. Delp [3]. The Delp patient is an adult male weighing 61 kg. To make the muscular model as patient-specific as possible, a scaling procedure is integrated in the simulation programme. The scaling code is written in C++ and integrated in Mechanical desktop using the ObjectARX module. Muscle trajectories on a visualized part of the bone keep the same relative position to the bone as for the DELP reference case. Coordinates of other attachment points are scaled with the outer dimensions of the pelvis. Muscle parameters are scaled with the length of the trajectory and the cross section of the muscle. Figure 7 shows the validation result of the muscular model on a normal hip. The calculated force direction is shown in yellow and lies through the centre of the joint. It corresponds to measurements in instrumented hip prostheses at slow gait [10].

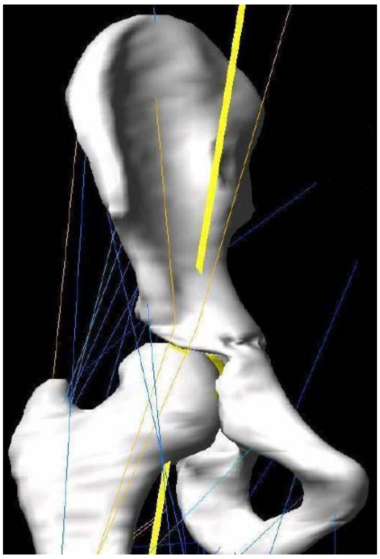


Figure 7: Result of the visualization and muscle calculation process.

Results and discussion

A graphical user interface (GUI) (for the moment only in Dutch) is constructed as a user friendly environment for use of the hip osteotomy simulator. It automatically converts and filters the femur and pelvis IGES files, and calculates the muscular model. Figure 8 shows the interface, the input body weight (45kg), the calculated resultant force in the hip joint (208% of body weight), the calculated contact surface area (11.86cm²) and the cutting planes for a Steel osteotomy as chosen by the user. In this case the contact surface area is calculated using a distance criterion of 6mm. Figure 9 shows the result for this osteotomy and a rotation of 20° around the anterior-posterior axis and 5° around the medial-lateral axis. In this example no re-optimization of the muscle activations was performed. This gives a new hip resultant force of 222% of the total body weight but and a surface area of 16.25mm². A comparison coefficient is calculated as: $\frac{F_{osteo}/A_{osteo}}{F_{init}/A_{init}}$, with F_{init} and A_{init} the force and surface area in the joint before the osteotomy and F_{osteo} and A_{osteo} the force and surface area in the joint after the osteotomy. In this case the comparison factor has a value of 78%. This means that the small rise in the hip joint force is countered by the relatively large rise in contact area. The comparison factor has to be used carefully since it does not establish a comparison between the pressures in the joint. It is merely a rough estimation of such a comparison.

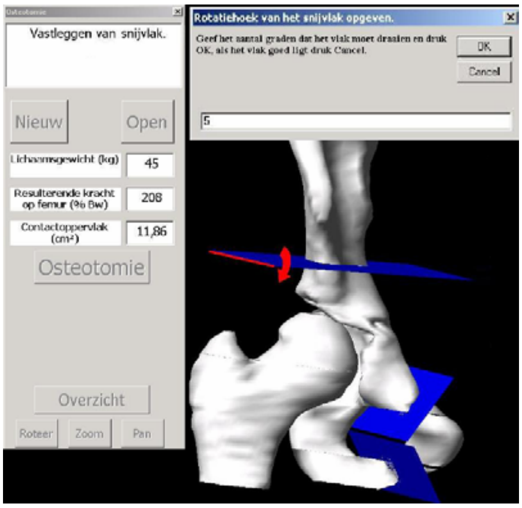

Vastleggen van snijvlak.
Rotatiehoek van het snijvlak opgeven.
Geef het aantal graden dat het vlak moet draaien en druk OK, als het vlak goed ligt druk Cancel.
5
Lichaamsgewicht (kg): 45
Resulterende kracht op femur (% Bw): 208
Contactoppervlak (cm²): 11,86

Figure 8: GUI and visualization of cutting planes

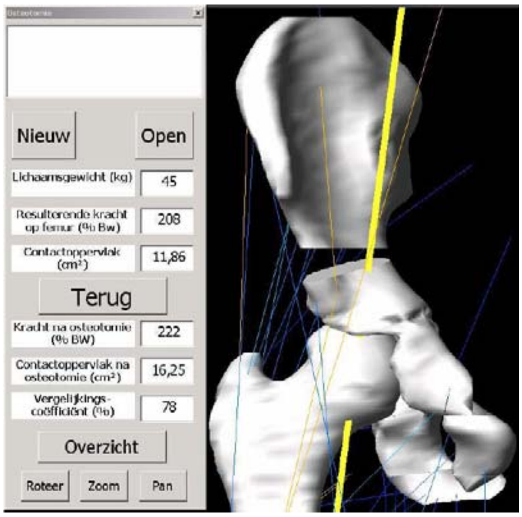
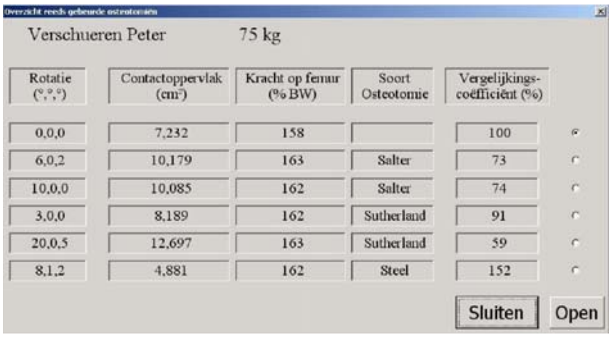

Lichaamsgewicht (kg): 45
Resulterende kracht op femur (% Bw): 208
Contactoppervlak (cm²): 11,86
Kracht na osteotomie (% BW): 222
Contactoppervlak na osteotomie (cm²): 16,25
Vergelijkingscoëfficiënt (%): 78

Figure 9: GUI and Steel osteotomy result

The visualization and calculation of the muscular model for the pre-operative 3D model takes about 5 minutes (Pentium 4, 1 GHz processor, 256 Mb RAM). This calculation has to be done only once. The simulation of an osteotomy takes about 3-5 minutes depending on the number of cutting operations. Each specific cut and rotation is saved and can be loaded through an overview screen of all simulated cuts for a particular patient (figure 10). The top of this screen states the patient name and weight. The first column shows the rotation of the acetabulum around the anterior-posterior, cranial-caudal and medial-lateral axis. The second and third columns show the joint contact area (cm²) and resultant force in the joint (% of body weight). Fourthly the type of osteotomy is stated and he fifth column shows the calculated comparison coefficient (%).

Table 1 shows an overview of some simulated osteotomy results with a distance criterion for joint contact surface area of 5mm. As stated above, a Matlab optimization method is available which solves the static equilibrium equations while optimizing the muscle activations for minimal total muscle energy use. In some cases no optimization is performed. This means that the activation values of the pre-operative state were used. One can see that for smaller rotations (10° around anterior-posterior axis) the error on the calculated force magnitude is about 10%. For larger rotations (20° around anterior-posterior axis and 5° around medial-lateral axis), the error is already about 30%. Re-optimization in Matlab of the calculated activations is therefore found to be very important. The communication between Mechanical Desktop and Matlab still requires some user interference. This is an important issue that needs to be addressed in the future. Further, for a small acetabulum rotation using a Salter osteotomie the joint contact area is calculated to increase from 7.18 to 10.84mm². When performing a Steel osteotomy more rotational freedom is attained and then an increase of the joint contact area to 12.57mm² is calculated. When looking at pressure though, one has to take into account that the force in the hip joint will rise substantially. Both factors have to be taken into account. For future work, it might be interesting to try and assess a better 3D pressure criterion than the comparison coefficient for optimizing towards the best choice of osteotomy type and rotation values.


Overzicht reeds gebeurde osteotomieën

Verschueren Peter 75 kg

Rotatie (°,°,°)	Contactoppervlak (cm²)	Kracht op femur (% BW)	Soort Osteotomie	Vergelijkings-coëfficiënt (%)	
0,0,0	7,232	158		100	●
6,0,2	10,179	163	Salter	73	○
10,0,0	10,085	162	Salter	74	○
3,0,0	8,189	162	Sutherland	91	○
20,0,5	12,697	163	Sutherland	59	○
8,1,2	4,881	162	Steel	152	○

Figure 10: Overview screen of already simulated osteotomies for a specific patient

Table 1: Result overview of simulated osteotomies

Rotation (°A-P, °M-L)	Opt.?	$F_{resultant}$ (%B)	A (cm²)
Preopt (0°, 0°)	/	208	7,18
Salter (10°, 0°)	No Yes	216 199	10.84 10.84
Steel (20°, 5°)	No Yes	222 297	12.57 12.57

Even though the hip osteotomy simulator is already operative, further validation is still required. A recent CT scan of a 2-year old patient with hip dysplasia who is being treated at University Hospital Leuven has been acquired. A follow-up study of this and other patients in the future will also provide for further data and validation purposes.

For further validation and investigation of the use of the osteotomy simulator in clinical practice, a cadaver study has been performed. Results of this study still need to be examined more thoroughly.

Acknowledgements

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