Accurate simulation of hip joint range of motion

MyungJin Kang\textsuperscript{a}, Hassan Sadri\textsuperscript{b}, Laurent Moccozet\textsuperscript{a}, Nadia Magnenat-Thalmann\textsuperscript{a}, Pierre Hoffmeyer\textsuperscript{b}

\textsuperscript{a} MIRALab – University of Geneva

24, rue du General-Dufour, CH-1211, Geneva, Switzerland

Email: \{MyungJin.Kang, Laurent.Moccozet, Nadia.Thalmann\}@miralab.unige.ch

\textsuperscript{b} Clinique d’Orthopédie, Hôpitaux Universitaires de Genève, Genève, Switzerland

Email: \{Hassan.Sadri, Pierre.Hoffmeyer\}@hcuge.ch

Abstract

This paper presents a hip joint motion simulation method using accurate hip joint center and hip range of motion. We calculate the extreme hip joint range of motion centered on the hip joint center (HJC) that is located by an automatic calculation algorithm on 3D reconstructed surface models. We make 3D bone surface models from CT (Computer Tomography) or MRI (Magnetic Resonance Imaging). The medical objective is to quantify hip kinematics in function of hip morphology. Because extreme ranges of motions are evaluated from bones only, we can estimate the motions that are restricted by bones impingements by comparing the computed values with real extreme range of motion.

1. Introduction

Hip pain related to the acetabular rim and labrum has received increased attention in the orthopaedic literature. Despite the current concept of osteoarthrosis (i.e. degenerative hip disease) originating within the hip joint secondary to overload and incongruency, a recent concept states that this condition often originates at the acetabular rim [1]. Furthermore, new clinical entities such as the « acetabular rim syndrome » [1,2] have been described and are beginning to influence treatment strategies in diverse hip pathologies especially in young adults. Therefore, it is essential to better understand hip kinematics and factors influencing hip range of motion, particularly in the extreme hip positions. In these positions, we are clinically aware of impingement (i.e. collisions) phenomena between the head-neck junction and the acetabular rim.

The purpose of this study is to better quantify hip kinematics in function of hip morphology to better understand the etiology of degenerative hip disease in young adults. In these young patients, this disease has a devastating influence on the quality of life and working capabilities.
As mentioned above, previous studies have considered that the femoral head shape is a sphere. These studies have been essentially concentrating on hip kinematics in hip reconstructive procedures with prosthetic devices. It is clear from daily clinical information that the femoral head is not a sphere and that this approximation is not valid for the purpose of understanding the origins of osteoarthritis in the young adult. This is clearly demonstrated on the photographs of two proximal femurs (figure 1).

In our solution to this problem, we use a computer-aided functional method to find the hip joint center. We reconstruct 3D surface models of the pelvis and femur bones from CT or MR images, and simulate the joint motions (internal/external rotations, flexion, extension, abduction, adduction) centered on a hip joint center keeping the distance between the pelvis and the femur head constant. We choose a hip joint center again until there is no collision in the acetabular rim during the motion of the hip.

2. Method

The complete process involves three steps: 1) reconstruction of 3D bone surfaces of the hip joint complex from medical images; 2) estimation of the hip joint center location using simple geometric constraints (based on the assumption that the center is the point of the femur head that does not move while performing hip circular movements); 3) computation of the maximum ranges of motions using the hip joint center as the center of rotation of a ball-and-socket joint that approximates the hip joint (in our current model, ranges of motions are only constrained by bone to bone collisions).

2.1 3D surface model reconstruction

We reconstruct the 3D surface model of hip bones (pelvis and femur) from images. CT data sets can be good candidates to make 3D bone surface model, but there is a problem in obtaining these images. The problem is with the resolution of the acquired images. If we want high-resolution images, it is risky to the patient because of high exposure to radiation. MRI data sets are good materials for making 3D surface models. In figure 2, (a) is the 3D surface model made using Mimics software with their data sets; 83 CT images of a child [12]. In figure 2, (b) is the other 3D surface model reconstructed using the VTK implementation of the marching cube algorithm [9] with MR images of a young healthy woman scanned at the Hospital University of Geneva.

The accuracy of the 3D surface model affects the result. For accurate functional modeling, the 3D surface model should be particularly precise at the joint. Creating a high-resolution surface model around the joint and a rough approximation for all others parts can be useful in tuning the accuracy of the results and the computation time required for the simulation.

2.2 Hip joint center location

Experiments with cadaver material on hip range of motion have shown us that the center of rotation of the femur head can be calculated using a circumduction of the hip by a minimization method. This calculation focuses on the only point that does not move while performing limited hip circular movements and is sufficiently precise for clinical purposes.

Once the 3D surface model of the hip bones is constructed, we simulate the motion of the femur in order to locate the HJC. The HJC is the point of the femoral head that remains fixed during motion of the joint for a
restricted range of motions. We determine it as being the point of the femur head, defined as the joint center of rotation, so that the distance between the acetabular rim (figure 3) and the femoral head is kept constant and so that no collisions occur with the acetabular rim for limited ranges of motions. We consider the cartilage as a constant distance between the acetabular rim and femoral head (figure 4).

Fig 4. The constant distance between acetabular rim and femoral head, for the location of hip joint center

For this simulation, we restrict the collision detection to the acetabular rim region for the pelvis. The acetabular rim defines the contact surface between the cartilage covering the femoral head and the cartilage covering the acetabulum. Therefore, no collision between the femur head and the acetabular rim can occur for the proper hip joint center. The HJC location process is summarized in figure 5.

Fig 5. Hip joint center location

An initial temporary HJC is chosen as a median center of the femur head. It is computed using the midpoint of the maximum and minimum points of femoral head along each axis X, Y and Z. We simulate the motion of the femur centered at this temporary center. For each kind of motions the range is restricted to 15 degrees. If there are collisions between the acetabular rim and the femur head during motions, another candidate is selected. The new candidates are iteratively selected inside a cube of given length (currently, 3mm) centered at the initial HJC. Each new temporary center is computed from the previous one by an incremental predefined displacement step (currently, 0.02mm along the each axis of the cube). For each candidate, we calculate the same motions. This iterative process is performed until there is no collision between bones keeping the constant distance. The current temporary center that satisfies the previous conditions is then associated to the Hip Joint Center.

3. Result

We simulated the maximum internal/external rotations, flexion/extension, and abduction/adduction of hip joint center on the HJC, and we compared the result with the surgeon’s diagnosis based on the medical images. The computed results proved to be compatible with the medical diagnosis. However, a more precise validation will be made in the future work.

We can find the HJC location within ±0.1mm tolerance. As expected, when we tested it using low-resolution 3D surface models, the variations increased.

Computed hip movements show that the flexion/extension components are particularly sensitive to variance in hip joint center location, and the abduction/adduction movement is the second largest affected quantity.
Some simulation results of hip joint ranges of motions of 3D surface models of bones are presented in figure 6. The first row is the result of 3D surface bone model from the child dataset, and the second row is from the young woman dataset. Each column is the result of full flexion, full abduction, and full adduction. Bones impingements (figure 7) are not the only factor that affects the joint range of motion. As the hip joint model is currently restricted to bones, the movements can exceed the real maximum range of motion of the patient in certain cases, for example when applying successively extension, 90 degrees flexion and internal/external rotation. In the case of flexion, abduction, and adduction, it appears that bones impingements are the factors that restrict joint movement, as the computed ranges of motion are bigger than the real ones.

We are planning to integrate cartilage into the acetabulum and femoral head to examine its effect on the femur-pelvis impingements and on the hip joint motion.

Further research will incorporate additional components such as cartilage, capsule with ligaments and muscles in order to determine the factors that limit the hip joint range of motion.

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6. References


