HIP JOINT RECONSTRUCTION AND MOTION VISUALIZATION USING MRI AND OPTICAL MOTION CAPTURE

N. Magnenat-Thalmann[1], L. Yahia-Cherif[1], B. Gilles[1], T. Molet[1]

[1]MIRALab, University of Geneva
E-mail:{thalmann, yahia, gilles, molet}@miralab.unige.ch

SUMMARY: We present a methodology for anatomical modeling, and motion visualization of the human hip joint using MR images and optical motion capture. Subject-specific hip and femur are reconstructed from MRI. The optical motion capture is used to record movements of the same subject resulting, after processing, in the visualization of the animated bones.

INTRODUCTION

Patients' anatomical models are increasingly used for both preoperative planning and postoperative guides. The joints motion visualization opens a new level of understanding and can be a valuable diagnosis tool. We propose here to use optical motion capture to simulate internal motions. The ability to image the articulation dynamically and non-invasively in vivo opens the way to the efficient and accurate design of patient-specific musculoskeletal functional models. The long term of our current project in CO-ME is to improve the success rate of orthopaedic surgeries by providing a new set of tools for anatomical and functional simulation of the full leg. This will help orthopaedists in diagnosing pathologies and in surgical planning.

Anatomical models are reconstructed from segmented medical images. Automatic bone segmentation is straightforward with CT modalities. Nonetheless, X-rays are harmful and not able to image the periarticular structures. MRI is non invasive, and suitable for imaging both bone and soft tissues. Acquisition of medical images has to be clinically achievable with respect to available resources (about twenty minutes for standard acquisition sequence). This constraint results in a low-resolution data acquisition. One goal is to be able to handle common medical data. In addition, an accurate bone model positioning method with optical motion capture is challenging because of measurement and skin/fat artefacts.

In our first case study, we focus on the hip articulation. The clinical application is to develop a pre-surgical planning tool for hip osteoarthritis (degenerative hip disease). Organs-specific MRI protocols are set up and used to acquire volumes of healthy hips. Generic models are built interactively, validated by our medical partners and deformed automatically to match patient organs geometry. These individualized models are animated with optical motion capture to simulate realistic hip joint motions.

MATERIALS AND METHODS

1. Image acquisition.

Bony structures are usually imaged by Computed Tomography (CT) modalities. These techniques provide high-resolution images with high bone contrast. However, they involve radiation exposure and do not highlight soft tissues such as ligaments, cartilage, and muscles. MRI provides excellent soft tissue contrast, multi-planar imaging capabilities, and does not use harmful ionising radiation. Moreover, MR has recently proven to be effective in imaging bone by use of suitable pulse sequences [1] [2].

MRI research-specific protocols are time-consuming and not directly applicable to patients. Hence, we have investigated many standard clinical MRI protocols to establish the best pulse sequences that highlight the bone and the periarticular structures and faster bone imaging techniques are under development. For the current study, we select two optimal protocols that best suit our requirements.

Two healthy adult subjects (a female and a male) have undergone the MRI scanning. The acquisition was performed at HUG[1] with a 1.5 T Intera station manufactured by Philips Medical systems. Four high-resolution MRI scans containing thin axial slices are obtained for each subject. The scanning ranges from the ilium crest to the knee based on an axial localizer. The scan is extended up to the knee in order to determine the anatomical axis of the femur to perform motions of the hip joint [4][8]. In the following, the acquisition protocol is detailed:

- Coil: Because both hips are involved, the first four series are performed in the body coil with a bone-specific sequence. The fifth series has a smaller FOV as it is dedicated to the cartilage.

- Patient positioning: Supine, the feet are taped together to reduce leg movement.

[1] Hôpitaux Universitaires de Genève

- Imaging protocol: Four series of T1-weighted spin echo images and one series of T1-weighted gradient echo images. Repetition time varies from 600 to 3000ms and Echo time is 15ms for bone sequences and 18ms for cartilage.

- Image resolution: The images have an in-plane resolution of 0.7mm x 0.7mm for the bone sequences and 0.9mm x 0.9mm for the cartilage. The in-between plane resolution depends on the anatomical region (Table1). The highest resolution is performed in the joint region (2 mm for bone and 1mm for cartilage), as this is a crucial region for our study.

Table 1: Imaging protocol

Anatomical region	Matrix	Thickness (mm)	Gap(mm)	FOV
Ilium-femoral neck	512x512	2	0.5	400
Thigh	512x512	12	0.6	400
Knee	512x512	4	0.9	400
Cartilage	256x256	1	0	240

2. Delineation of anatomical structures

Segmentation is performed using a custom-written discrete snake procedure [5] to extract the hip and femoral contours. On each MRI slice, an initial set of points is digitized along each articular curve with a coarse spacing of 1-2cm (Figure 1). The active contour is then used to best fit the actual boundary (Figure 1). This provides an accurate location of the bone contour sufficiently near the initialization curve.

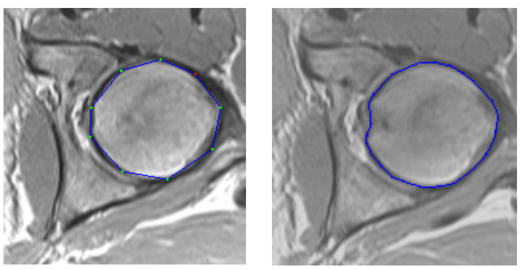

Figure 1: Manual digitising of the articular boundary and fitted active contour

Although the snakes have proven to achieve high accuracy while decreasing the time required for manual segmentation, manual corrections are necessary on the slices with fuzzy edges. Moreover, the segmentation is validated by the medical experts before the reconstruction process to ensure 3D models' accuracy.

3. Anatomical structures reconstruction.

The Marching Cubes algorithm, originally proposed by W. Lorensen [6], is considered to be a standard approach to the problem of extracting iso-surfaces from a volumetric dataset. Many implementations are available both as part of commercial systems or as public domain software. We use the Visual Toolkit[2] implementation of the Marching Cubes algorithm to generate iso-surfaces from the segmented volume. The resultant polygonal surface is simplified with Schroeder decimation algorithm [12]. This technique is based on multiple filtering passes that remove vertices passing a minimal distance or curvature angle by analysing the geometry and topology of a triangle mesh locally. This decreases the total number of polygons while preserving intricate surface details.

The decimated polygonal surface is smoothed by adjusting the coordinates of the vertices using Laplacian smoothing. The effect is to "relax" the mesh, making the cells better shaped and the vertices more evenly distributed.

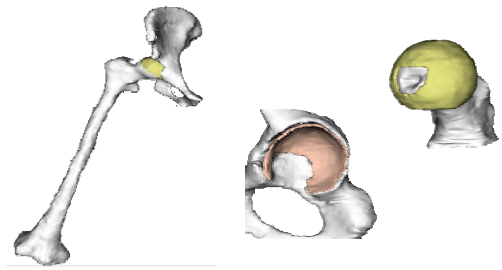

Figure 2: Femur, hip and cartilage generic models.

The hip (femur) model is reconstructed with 42,944 vertices and 84,313 triangles, the femur model with 27,608 vertices and 53,534 triangles. Cartilage models are reconstructed with 5856 vertices and 11454 triangles for the acetabular cartilage and 10241 vertices and 20 360 triangles for the femoral cartilage.

4. Bone models individualization

Due to the large amount of textural information, noise, low contrast and resolution, bone segmentation is often a difficult task. Despite many researchers have tried to provide robust and fully automatic segmentation tools, no method has proven to be generic and manual corrections are generally required.

First, the generic model is elastically initialized with a landmark-based approach and Thin-Plate-Splines interpolation [11]. Then, the model is deformed automatically by optimization of an energy function which is composed of an external energy term, measuring the matching between the model and image edges, and an internal energy term that maintains a

[2] www.vtk.org.

smooth and connected model. External energy is calculated from the MRI oriented gradient images and model normals. The internal energy derives from deformation spheres [7] that constraint model deformation. In order to avoid convergence into local minima, we use a multi-resolution approach and deformation spheres with decreasing radius (the model's deformability increases).

It takes on average one hour for a model with 40,000 vertices to deform (Pentium4, 2GHz). The automatic method has been successfully tested and validated on four different pelvis and femurs with the same parameters: deformability (radius from 2cm to 1cm), number of iterations (10000), number of landmarks (16) and number of resolutions (3). The difference between manual and automatic segmentation is less than 15% of the total number of voxels for bones (Figure 3).

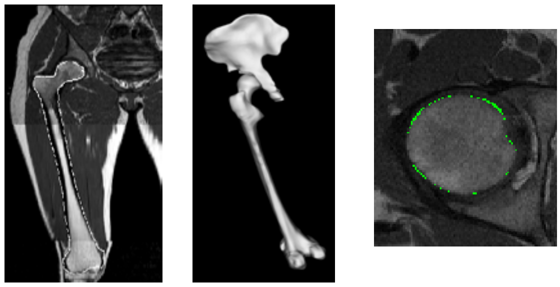

Figure 3: Automatic bone segmentation on a sample slice, corresponding 3D models and difference between manual and automatic segmentation on a sample slice

5. Subject-fair visualization model creation

The reconstructed bone surfaces are simplified in lower polygon count to allow real-time display. They are inserted in a virtual human skin surface generated from adaptation of a generic model according to manual measurements of the subject's segments [13]. Additionally the high-resolution reconstructed bones are used for evaluating the hip joint centre position in a dedicated application [3]. This hip joint centre (HJC) is then set on the subject's technical skeleton model. This step ensures that the model's HJC matches the precisely evaluated HJC therefore providing realistic animation visualization. As a result we obtain a visualization model composed of fairly accurate hip joints with bones within an approximated subject's body deformable envelope (Figure 4).

One key interest of our approach lies in the fact that the visualization model corresponds to the subject's real anatomy in the focus area (e.g. hip joint). The visualization of the motion that is as well recorded from the subject herself/himself is therefore closer to the real situation. That way, we removed the mapping on a subject-unrelated model bottleneck that gives little confidence in the visualization process given the variability in anatomy among different subjects.

Figure 4: Male subject model (volunteer) with hip reconstructed bones and body-sized skin

6. Subject-fair external motion capture

For recording of subject movements, we use an optical motion capture system composed of 8 video cameras. Spherical skin markers are placed on anatomical landmarks of the subject. The recorded markers trajectories are then converted into the joint space parameters of the subject's model. The converter technique [9] takes into account the geometry of the skeleton model, motivating further the accurately matched subject to model process. A record of the subject in stand-up calibration posture is used as a subject/model posture mapping reference. The model posture can be fine tuned with respects to the subject's recorded posture before converting the trajectories into animation. This is done in practice by visualization of the markers position in the stand-up posture and adjusting the model posture, thus creating an offset posture (Figure 5). This offset posture is then used in place of the model's default posture in the process.

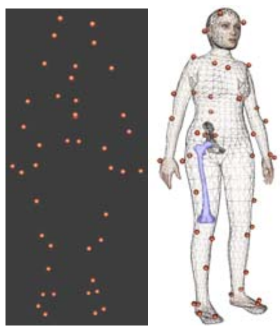

Figure 5: Markers and model in stand-up calibration posture after fine-tuning registration

Unlike MRI scanner, the optical system allows the recording of large range motions (Figure 6) that are typically used for detection of impingements. We record hip abduction/adduction (Figure 7), rotation, flexion, and conical motion. The positions of optical markers are visualized at the same time as the model during its animation; this serves as reference to assess the reliability of the animation mapping.

(a) (b) (c)

Figure 6: Woman subject motion capture (a), (b) and model motion mapping (c)

Although we are concerned primarily by the study of the hip joints, we believe that providing a more complete, yet less accurate, animated visualization of the rest of the body is desirable as it confers a panel of views from general to detail. Similarly while the skinning of the model is purely geometrical, it is less abstract than pure optical markers and bones display.

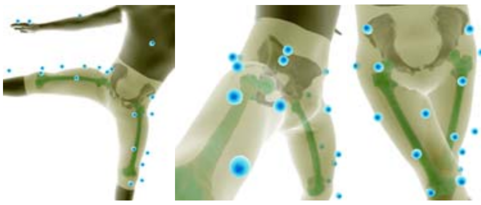

Figure 7: Large hip range of motion visualization example: abduction/adduction

The real-time visualization application we have developed is based on the VHD++ middleware framework [10]. For the purpose of this work, we integrated the management of optical markers animation and enhanced the virtual human production pipeline to satisfy the constraints of anatomical accuracy.

CONCLUSION

We have presented a methodology for patients' hip bones modelling and motion visualization using non invasive approaches. This methodology will be applied to the knee and ankle in order to obtain individualized and animated models of the full leg. Furthermore, we planned to improve the estimation of bones position in motion capture by using a model of bones/markers relative position in order to remove artefacts due to skin and fat deformation. This model will be carried out using dynamic MRI where bones and markers positions are tracked. In addition, soft-tissue modelling is under investigation inside the framework of our project. They will be integrated into the motion visualization framework in order to express relevant information for clinical diagnosis (i.e. cartilage stress and strain).

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