Anatomy-based Optical Motion Capture for Integral Joint Motion Visualization and Analysis

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Abstract

We propose a methodology to improve the accuracy of joint motions optical acquisition and enhance the visualization of the virtually replicated motion for biomedical applications. The joint of the subject is reconstructed from medical images including the 3D shapes of the bones and kinematical data such as the joint center for motion simulation. The subject visualization model is built by inserting the reconstructed joint inside an H-ANIM model fitted to the real measurements of the subject. Finally, the visualization model is calibrated and the captured motion mapped onto the anatomical visualization model.
This methodology provides a subject-fair visualization model for optical motion capture based on the morphology and anatomy of the volunteer so that the motion simulated from the subject is closer to the real situation. It also provides an integral visualization of joint motion by correlating the external motion of the subject is moving with the internal motion of the joint.

Keywords: optical motion capture, visualization, biomedical applications, musculoskeletal system, biomechanics

INTRODUCTION

The combination of optical motion capture and musculoskeletal system graphics visualization plays an important role in the area of qualitative and quantitative motion analysis. The resulting motion analysis is useful for assessing and guiding patients' recovery and evaluating their progress towards rehabilitation. Unfortunately, markers based-systems are prone to errors that greatly affect their accurate application for biomedical analysis of joint motion. Among these limitations we address the calibration and subject anatomy variability problems.

In [1], Arnold et al. conclude their paper by stating that the “accuracy with which musculoskeletal models represent individuals of different sizes, ages, and pathologies must be investigated before simulations can be widely used to guide treatment decisions for patients”. This issue is particularly critical when motion capture is applied for replicating and visualizing patients’ movements. Existing systems such as the SIMM (Software for Interactive Musculoskeletal Modeling) environment [3] can handle motion captured data and apply motion visualization and analysis for biomedical purposes. The SIMM framework provides facilities to automatically scale the graphical musculoskeletal model to represent the performer. However, scaling the graphical model to the performer only partly solves the problem of the performer morphology and anatomy variability.

Therefore, we propose a methodology to improve the accuracy of joint motions optical acquisition and enhance the visualization of the virtually replicated motion for biomedical applications. It is currently applied to the hip joint. This integrates volunteer‘s hip bones reconstructed from medical images, procedurally evaluated hip center of rotation, skin surface generation for the visualization model, real-time skinning, and optical motion capture. The first improvement is coming from the tight modeling of the volunteer skeleton in the hip region. Then, the addition of calibration posture offset in the motion capture

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converter to gain precision is required. Finally, the motion parameters have to be mapped onto the anatomically relevant axes.

The whole process is summarized in figure 1. In a first step, the joint of the subject is reconstructed from medical images. The joint reconstruction includes the 3D shapes of the bones and the estimation of kinematical data such as the joint center. The subject visualization model is built by inserting the reconstructed joint inside an H-ANIM model fitted to the measurements of the subject. Finally, the model is calibrated and the captured motion mapped onto the anatomical visualization model. This paper is logically organized to reflect these steps. In the first section, the hip joint complex reconstruction is described. Then the visualization model construction and calibration is explained in the next section. Finally, the motion acquisition and visualization are detailed prior to conclude and open future direction of research.

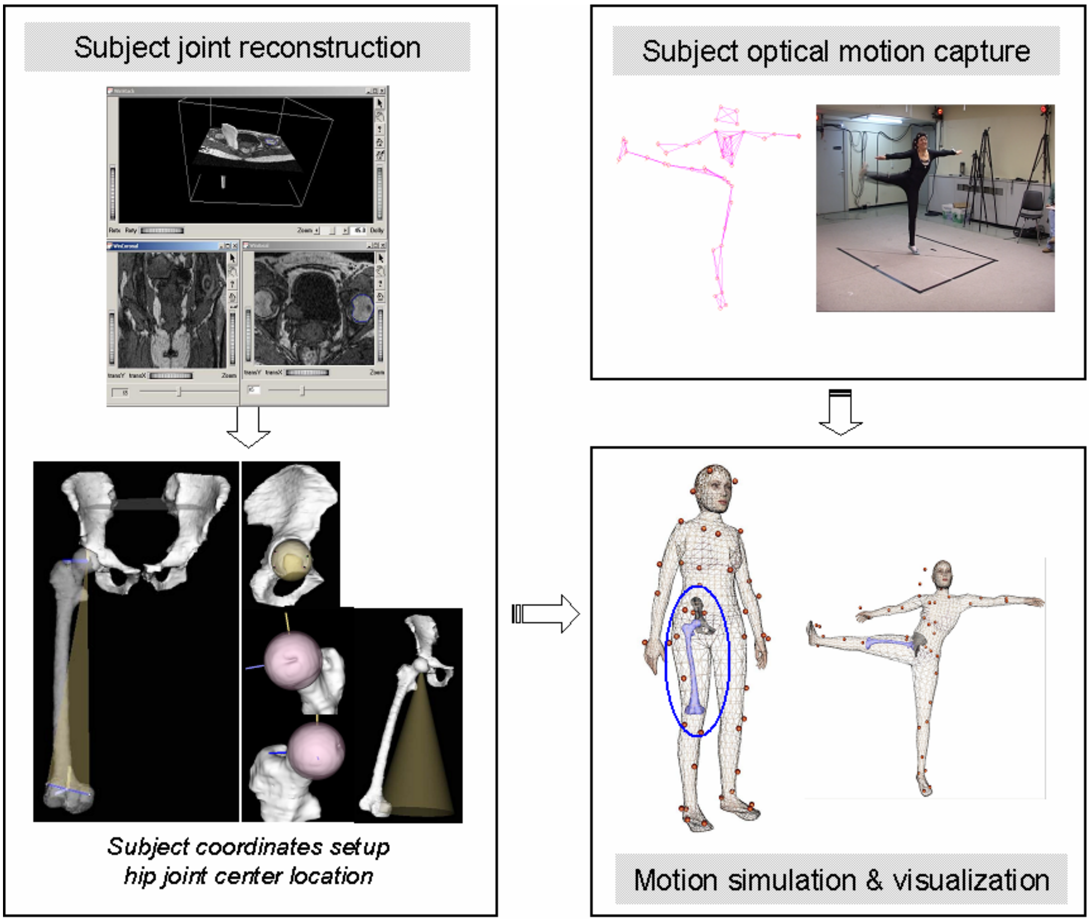


Figure 1 – Overview of the methodology process and workflow

HIP JOINT COMPLEX RECONSTRUCTION

Data 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 ionizing radiation. Moreover, MR has recently proven to be effective in imaging bone by use of suitable pulse sequences [2][4].

Two healthy adult volunteers (a female and a male) have undergone the MRI scanning. The acquisition was performed 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 volunteer. 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 [7][11].

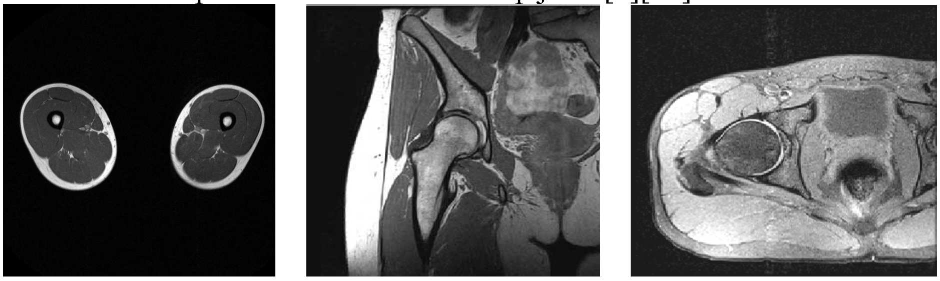


Figure 2 – Examples of magnetic resonance images

Joint bones reconstruction

Segmentation is performed using a custom-written discrete snake procedure [9] 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 3). The active contour is then used to best fit the actual boundary (Figure 3). This provides an accurate location of the bone contour sufficiently near the initialization curve.

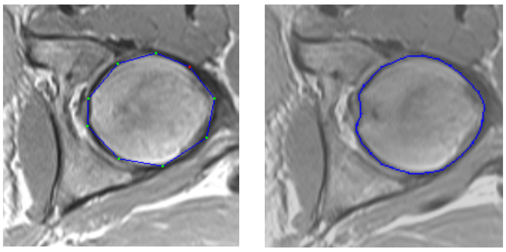


Figure 3: Manual digitising of the articular boundary and fitted active contour

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.

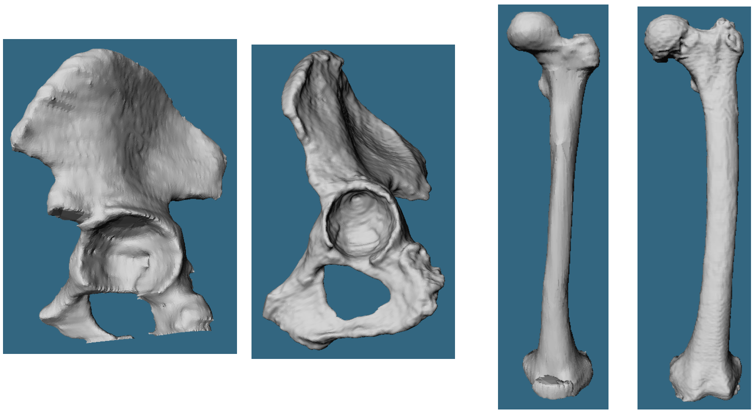


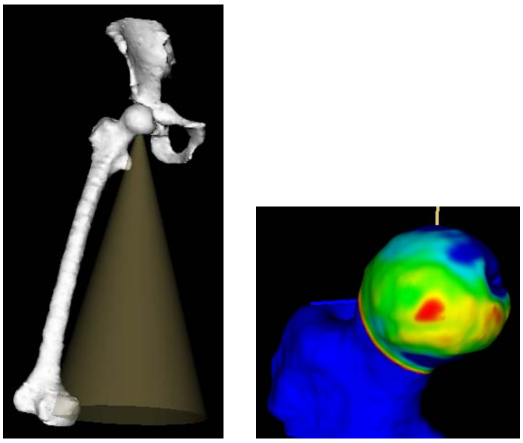
Figure 4 – 3D shape reconstruction for the hip bones (pelvis and femur)

The Marching Cubes algorithm, originally proposed by Lorensen [10], 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 (figure 4) 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 analyzing 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.

Hip joint center location estimation

Estimating accurately the location of Hip Joint Center (HJC) is an important issue because the approx1imation error can be palpable to the relevant kinetics and kinematics [8]. As the femoral head is hardly ever a perfect sphere, approximating the HJC as the center of a sphere fitted to the femoral head is far from being accurate. Such a rough evaluation is irrelevant for most medical diagnosis.

Once the 3D surface models of the hip bones are reconstructed, the motion of the femur is simulated in order to locate the HJC (figure 5). Based on orthopedic surgeon's experience, the HJC is defined as the point inside the femoral head that remains fixed during motion of the joint for a restricted range of motions.



(a) (b)

Figure 5 – Conical motion simulation (a) for evaluating the HJC (b)

Based on the complete anatomical reconstructed models, the pelvic and femoral coordinates systems are implemented following the ISB (International Society of Biomechanics recommendation) recommendation (figure 6) [15]. The two coordinates systems are evaluated from landmarks defined on the reconstructed surface of the hip and femur bones.

According to surgeon's experience, the HJC can be estimated as being fixed with respect to the femoral head in first approximation. The improved accuracy of the method lies in the location of the center. Hence, the HJC is further used for calculating the hip joint motions as the center of a ball and socket joint.

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[2] www.vtk.org.

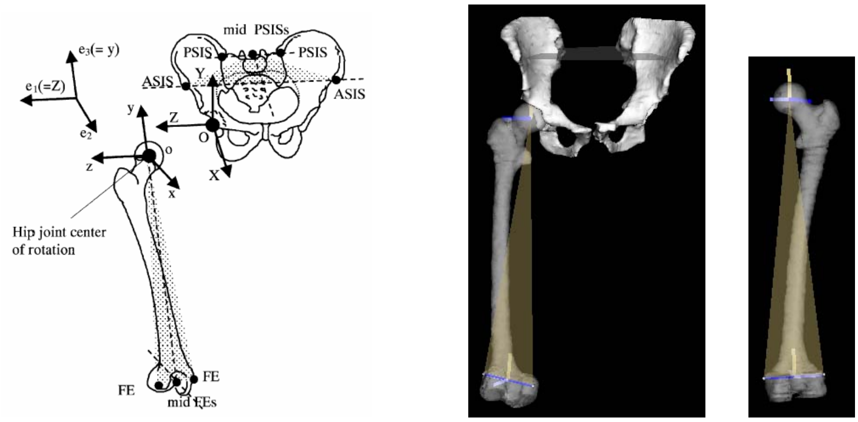


Figure 6 – ISB pelvis and femur coordinate systems

VISUALIZATION MODEL CONSTRUCTION AND CALIBRATION

For computer animation applications, the variability in shape and proportion between the performer and the virtual character can be handled with motion retargeting [5]. Such an approach is not valid for biomedical applications as the visualization model as to replicate the real motion of the performer as close as possible. 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 [14]. The 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.

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 [12] takes into account the geometry of the skeleton model, motivating further the accurately matched subject to model process.

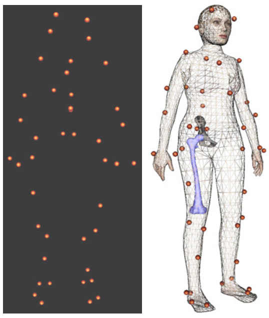
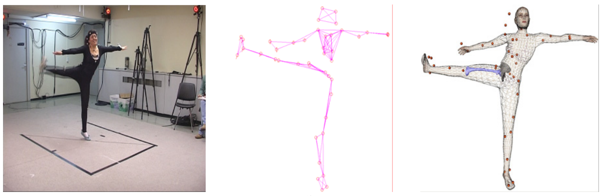


Figure 7 - Markers and model in stand-up calibration posture after fine-tuning registration

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 7). This offset posture is then used in place of the model's default posture in the process.



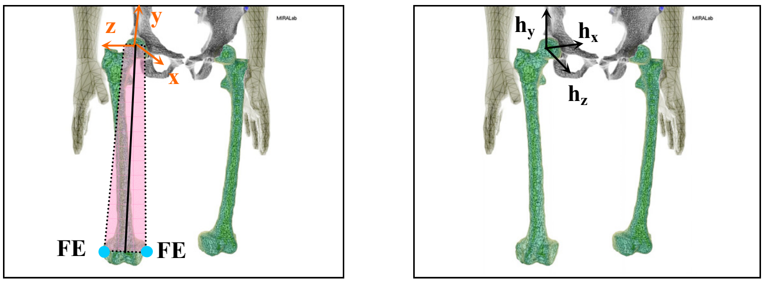
(a) (b) (c)

Figure 8 - Woman subject motion capture (a), (b) and model motion mapping (c)

MOTION ACQUISITION AND VISUALIZATION

The virtual human model follows the H-ANIM [6] standard that defines simplistic joint coordinate systems since all of them share the same orientation as defined by the H-ANIM world coordinate system. The motion capture converter is based on a technique [12] initially designed for application in the animation domain. Figure 10 (left) shows the coordinate system of the right hip joint in the default model posture. In fact, within the H-ANIM standard the characterization of a joint is therefore reduced to the specification of the location of its center of rotation. This is obviously not acceptable for medical applications where the rotations must be expressed according to anatomically relevant references.

The ISB proposes geometrical construction of joint coordinate systems based on Cartesian coordinate systems associated to bones [15]. We can conciliate standard approaches by means of transformation of the H-ANIM-based animation into the biomechanical parameters.



(a) (b)

Figure 9 – (a) ISB recommended femoral coordinate system from medial and lateral FEs landmarks,
(b) H-ANIM coordinate system for the hip joint

According to the ISB definition, the axes of the pelvis coordinate system and the femoral coordinate systems are not parallel. Nevertheless, to compute the three anatomical rotations of the hip (e.g. flexion/extension, adduction/abduction, and internal/external rotation) we have to map the H-ANIM hip 3D rotation onto the new systems of coordinate (Figure 10). It can be done using the following procedure involving few matrices multiplications:

$$\text{ISBHipRot} = \text{ISBPelvis2HanimHip} * \text{HanimHipRot} * \text{HanimHip2ISBFemur}$$

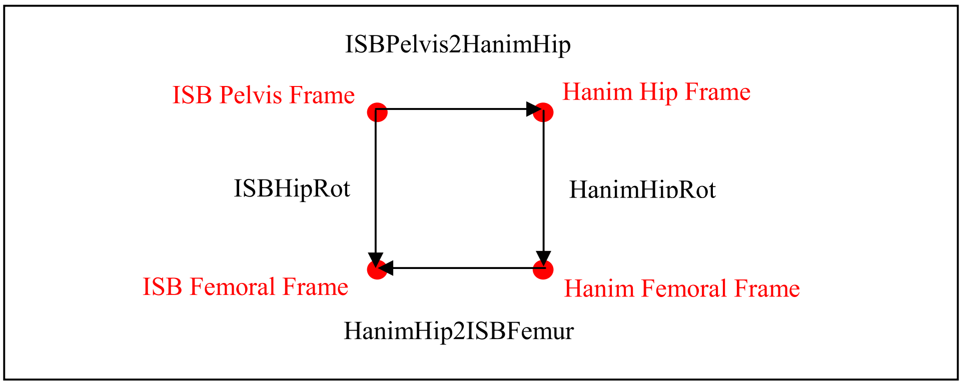


Figure 10 - Mapping Hanim rotation onto ISB references

With the following 3D rotations (e.g. 3x3 matrices):

- ISBHipRot: the desired hip rotation around anatomical frames
- ISBPelvis2HanimHip: the transformation between the ISB pelvis frame and the Hanim hip frame
- HanimHipRot: the rotation input from the motion capture engine
- HanimHip2ISBFemur: the transformation between the Hanim hip frame and the ISB femoral frame

The two transformations are constructed at initialization time using the coordinate system definitions of the ISB bones and the H-ANIM hip coordinate system in the neutral posture. In this pose the H-Anim Hip and Femoral Frames are equivalent because the rotation is set to identity.

Anatomically correct coordinate systems are of importance for presenting meaningful values to medical doctors, comparing results with other biomedical studies, and -down to the computer animation domain- for providing more intuitive rotation axes to animators.

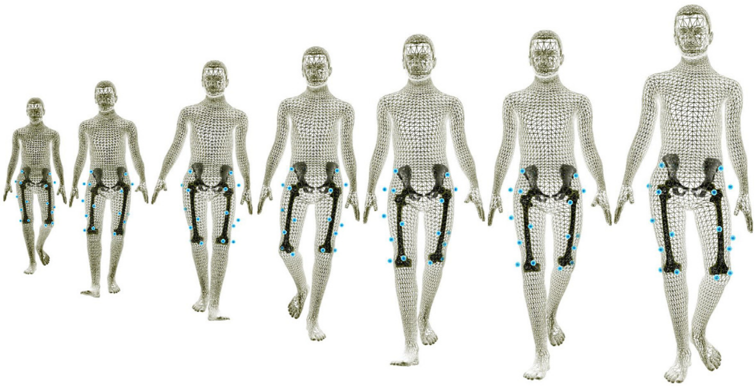


Figure 12 - Frames from a captured walk sequence

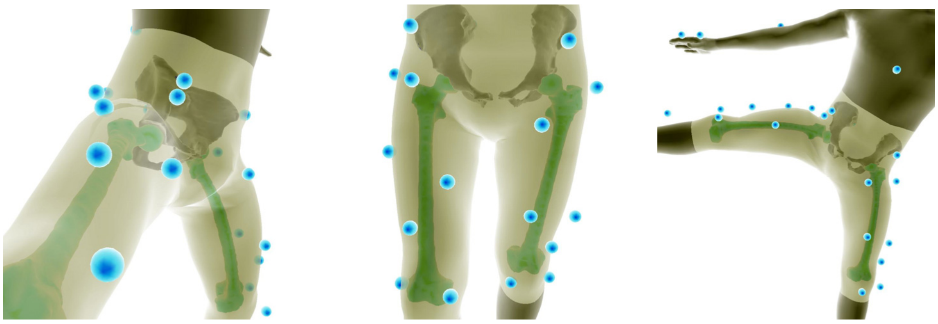


Figure 13 – Frames from various captured postures sequences

Figures 12 and 13 shows some frames from various captured postures and motions such as walking. The accompanying video[3] demonstrates the visualization of the internal and external motion of the hip joints during a captured sequence.

CONCLUSION

We have presented a methodology for volunteers' hip joints modeling and motion visualization using a non-invasive approach. This methodology provides a subject-fair visualization model for optical motion capture based on the morphology and anatomy of the volunteer. As the visualization model corresponds to the subject's real anatomy in the focus area (e.g. hip joint), the visualization of the motion recorded from

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[3] Available at http://personal.miralab.unige.ch:1312/l.moccozet/IWVR04/demo_iwvr04.mpg

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. Moreover the combined external/internal visualization provides the practitioner with a comprehensive view of the joint configuration during motion and is expected to support his/her analysis of the joint status by visually correlating the motion of the patient with the internal joint motion.

This methodology can be extended and applied to any joint in order to obtain individualized and animated models. Furthermore, we plan to improve the estimation of bones position in motion capture by using a model of bones/markers relative position in order to remove artifacts due to skin and fat deformation. This model will be carried out using dynamic MRI where bones and markers positions are tracked.

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