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Estimation of 3D Biomechanics Parameters of Patellar Movement using Dynamic CT Images*

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Abstract— **Multislice CT scanners have characteristics that offer advantages in clinical applications. The technology is particularly suited for medical applications that require high time performance and high spatial resolution. Patellofemoral tracking is one application that can benefit from multi slice CT characteristics. It is performed to study disturbances in the normal tracking mechanism of the patellar femoral joint. The patellofemoral instability is one condition that generates pain, functional impairment and often requires surgery as part of orthopedic treatment. The analysis of the patellofemoral dynamics has been performed by several medical image modalities. However, most of the methods are based on measurements in 2D images, such as the patellar tilt angle and the lateral shift. Besides, the acquisition protocols are mostly performed at fixed angles. The use of helical multislice CT scanner can allow the capture and display of the joint´s movement performed actively by the patient. In this work we evaluate the use of multi slice high resolution CT technology to evaluate the biomechanics of the patellofemoral joint. The quantitative analysis of the movement is performed by extracting displacement parameters in 3D images between different knee positions. Analyses of these parameters for all frames provided real 3D information about the patellar displacement.**

I. Introduction

Computed Tomography (CT) imaging procedure has been greatly improved by the use of helical multi slice CT scanner technology, which allowed enormous advances in scanner capability, image quality, and patient throughput [1].

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Multislice CT scanners have a set of characteristics that offers many advantages in clinical applications: increase in volumes imaging time up to four times in a single rotation, greater rotation velocities, decrease in slice width and improved X-ray utilization [2].

The technology is particularly suited for medical applications that require high time performance and high spatial resolution. Patellofemoral tracking is one application that can benefit from multi slice CT characteristics. However, orthopedic applications of this scanner have not yet been standardized or widespread.

Patellofemoral tracking is performed to study disturbances in the normal tracking mechanism of the patellar femoral joint [3], which may be related to many patellar main syndromes. Among those syndromes, the patellofemoral instability is a frequent diagnostic in patients with knee pain [4]. It is a condition that generates pain, functional impairment and often requires surgery as part of orthopedic treatment.

Patellofemoral tracking and stability relies on several factors, such as limb alignment, the congruence and geometry of the patella and femur, and the integrity of soft-tissue constraints [5]. In this way, the instability can have multifactorial causes. In order to restore the proper functioning of the limb it is frequently necessary to perform a ligament reconstruction around the patella, changing the mechanics of the knee. These alterations are not always well-succeeded because the knee movement is created by the interaction of a large number of different muscles and tendons acting in a complex fashion and it is not always clear which changes will create a balanced response in the patient movement [6].

The use of medical imaging technologies is an effective way of evaluating the effectiveness of the surgeries on the patients. The patellofemoral tracking evaluation and analysis using medical images has been performed for more than three decades [7]. The first quantitative methods for analysis of patellofemoral biomechanics have been described for conventional radiographic images in the 70´s [7]. Since then methods of analysis in other medical image modalities – like computed tomography and magnetic resonance – were described [8,9,10]. Several measures have then been used to characterize the patellar alignment.

However, most of the measurements used to analyze the patellar movement are constrained to two-dimensional (2D) images [9, 10, 11]. These methods present two main drawbacks: a) they depend on manual inspection by an expert that identifies the set of points needed for the calculations; b) they are 2D approximations of a 3D movement. As such, a measurement might contain elements of more than one single 2D movement, which can be a composition of a real linear displacement added to a tilt, and the 2D measure is not able to isolate the contribution of each component. The real 3D movement of the patella is much more complex, and in order to be fully understood a 3D measurement is needed.

Another important characteristic of the imaging techniques for analyzing patellar movement is that most acquisition protocols are performed with the knee laying static at fixed angles. The effects of active muscle contraction on patellar tracking cannot be observed and studied using such acquisition protocols. Macintyre et al [14] described a method that relates the patterns of patellar spin, tilt and lateral translation with patellofemoral pain syndrome. In their work the authors track the patellar movement using six parameters associated to the motion (three rotation angles and three translations), calculated for low resolution Magnetic Resonance images whose structures are identified by registering the current images with previous labelled high resolution images of the same subject.

In this work we evaluate the use of multi slice high resolution CT technology to evaluate the biomechanics of the patellofemoral joint. The quantitative analysis of the movement is performed by extracting 3D displacement parameters between different knee positions.

II. METHODS

A. Image Acquisition Protocol

Two sets of DICOM images[1] were acquired using an Aquilion ONE™ Toshiba 320 CT scanner located at the Imaging Department of the Heart Institute - University of Sao Paulo Medical School. The imaging procedure was performed with the patient supine while moving the knee from a flexed to an extended position. There was no apparatus to constrain the movement. The image acquisition consisted of twenty volumes of six hundred 0.5 mm slices of 512x512 pixels (0.3 mm pixel resolution). Pixel depth was 16 bits, leading to a total data volume of 315 MB per acquisition volume, or 6.3 GB for the whole acquisition per patient.

The patients were trained to perform the movement in the smoothest possible way. However, even with enough training it is very difficult to achieve complete control and uniformity of movement. One of the patients was able to perform a smoother movement thus generating a more suitable set of image data. Nevertheless, in both cases the frames were not acquired at regularly spaced angles.

On figures 1 and 2 it is possible to see the different positions of the knee throughout the whole acquisition (frames ordered from left to right and top to bottom). In the worst acquisition case (Figure 1) there were a large number of data volumes close to the initial and the final positions. Figure 2 presents the same information for patient 2.

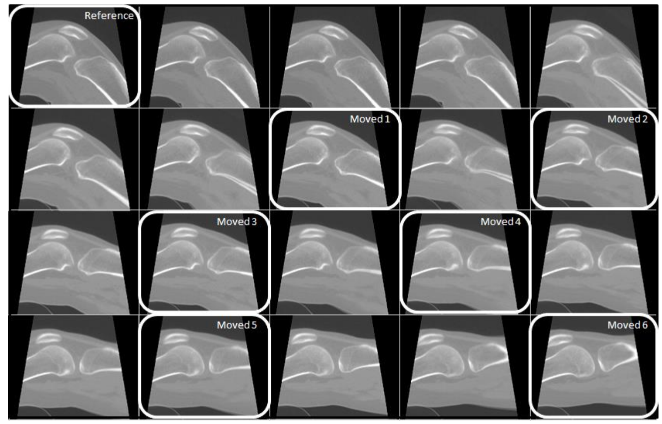

Figure 1 - Sagittal slice of the 1st patient volume acquisitions. The figure depicts the knee movement from a flexed position (top left image), which was assumed to be the reference image to an extended position (bottom right image).

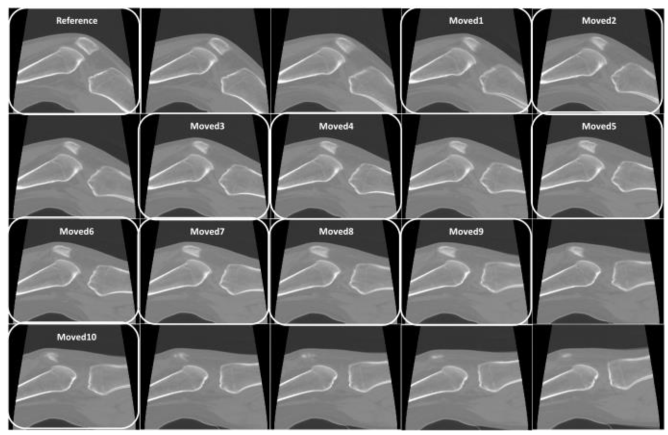

Figure 2 - Sagittal slice of the 2nd patient volume acquisitions. This patient performed the same movement as in figure 1 in a smoother pace than patient number 1.

B. Flexion Angle Determination and Volume Selection

For regular acquisition protocols performed at fixed angles, the flexion angle can be obtained directly from the DICOM image header. The option for an acquisition protocol consisting of active contraction during the knee movement imposes a need for determination of an angle that describes the flexion of the limb based solely on image. In this work, we defined the flexion angle as the angle formed by the medial lines of the femur and the tibia measured on the sagittal image planes, as shown in figure 3.

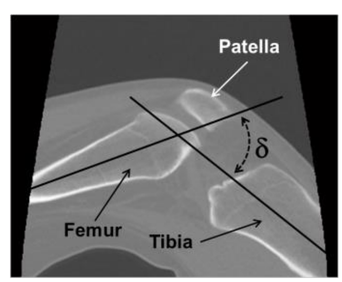

Figure 3 - Sagital plane of the first volume acquired showing the defined flexion angle ($\delta = 67^o$).

[1] The images are from patients enrolled in a clinical trial at the Department of Orthopedics and Traumatology, School of Medicine - University of São Paulo (HC.FMUSP) aiming at the study of patellar recurrent instability.

Ideally all frames should have been used for movement analysis. Due to the lack of uniformity during the movement some volume frames are in a position very close to previous or later frames. The volume frames selected for movement analysis were those whose flexion angles were at least 6 degrees smaller than the angle of the previous selected volume.

C. Description of the Patellar Movement

The dynamic behavior of the patella was described by computing its 3D transformation matrix from the original flexion angle (Reference Frame) to a posterior position. The coordinate system for describing the patellar movement is shown in figure 4.

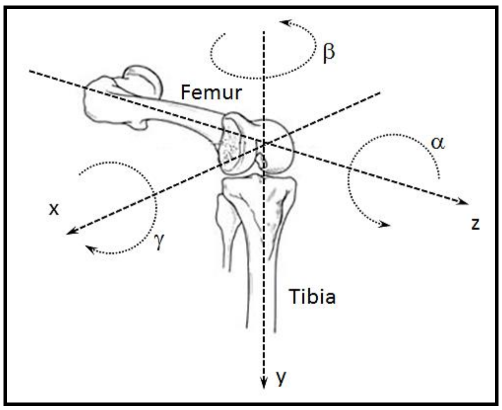

Figure 4 - Coordinate system for describing the patellar rotations and translations

The transformation matrix between the reference image (see figures 1 and 2) and the following images was calculated following the steps: (1) Segmentation of the bone structures; (2) Labeling of the segmented objects; (3) Identification of the femur using a priori information of size and position; (4) Registration of the labeled reference and following labeled images based on the Femur position; (5) Identification of the patella on the transformed labeled image using a priori information of size and position; (6) Calculation of the transformation matrix of the patella object, by registering the images of the patella at the two angle positions.

The segmentation of the bone structures was based on k-means clustering. The main task of k-means clustering technique is to partition a data set composed of *n* observation into *k* clusters [15]. For this particular application the clusters were based on the voxel intensity and the number of clusters was empirically set to 4. In figure 5 we present an output example of clustering process applied to a volume of patient number 1.

The four clusters depicted in figure 5.b (white portions) roughly describe the four elements of the image: the portion of the image that is outside the field of view of image acquisition; the background (air); soft tissues and inner bones; outer bones. The structures of interest are all bones and hence the method picks the cluster for which the mean intensity value is higher than 300. This value was the derived Hounsfield value determined for inner bones structures for the scanner used in image acquisition [16]. The clustering output image provides the bone structures and some *a priori* information about the main structures in the image can be used to extract the femur and patella.

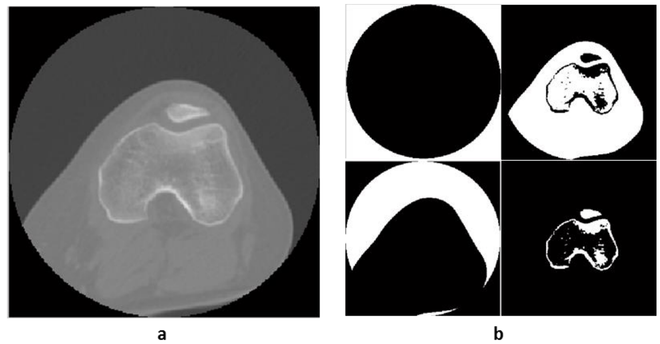

Figure 5 – (a) A transverse slice of a volume frame from patient number 1. (b) four output clusters from intensity k-means algorithm applied to image a.

As the patient is capable of freely move the leg, there is the possibility of leg movements on undesired directions. For example, the patient can twist slightly the thigh during the movement for accommodation, changing the relative position of all structures of the leg. Since the chosen coordinate system is not tied to the anatomical structures, it is necessary to compensate for the movement.

In order to avoid the influence of undesired thigh movement's one condition was established that the femur should remain static along all the shin movement. The segmented femur of the first frame was used as a reference and all other images were registered in relation to this reference. By using an intensity-based registration method it is possible to find the transformation matrix that best fits the femur from the first frame with the femur the subsequent frames, creating a set of matrix transformations, one for each pair <frame1, frame i+1> from i=1 to N (N being the number of volume images considered for movement analysis). The transformation matrix produced from the registration is of the form presented in equation 1 [17].

$$T = \begin{pmatrix} \cos\alpha\cos\beta & \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma & \cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma & x_t \\ \sin\alpha\cos\beta & \sin\alpha\sin\beta\sin\gamma - \cos\alpha\cos\gamma & \sin\alpha\sin\beta\cos\gamma + \cos\alpha\sin\gamma & y_t \\ -\sin\beta & \cos\beta\sin\gamma & \cos\beta\cos\gamma & z_t \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (1)$$

where α, β and γ are the rotation angles and x_t, y_t and z_t are the displacements at axes x, y and z, respectively, of the patella as it moves from the reference image position to the following image position.

After the compensation of the femur movement, the patella was extracted and its position along the time frames was calculated by using the transformation matrix presented in equation 1. The resulting angles and linear displacements are going to be used as parameters for describing the patellar movement.

The methods were implemented in the MATLAB® (R2013a) programming environment using both built-in functions and specially designed functions. A dedicated function was built for the segmentation step. **Labeling** was performed using MATLAB® built-in function *bwlabeln* that connects components in n-D binary image. **Registration** was done using MATLAB® built-in function *imregister*, which performs intensity based image registration. For the **Identification** of the femur and patella we used *a priori* information about relative sizes and position.

III. RESULTS

In figures 1 and 2 we presented a sagittal slice throughout the acquisition volume set for two different patients. In figure 6, a 3D rendering of the bones at the first flexion angle of patient 1 allows a better visualization of all structures involved in the movement.

As mentioned before, the acquisition protocol leads to an experimental problem related to the freedom of movement. The lack of uniformity of the patient´s leg can generate a set of images where the movement is concentrated in a small number of frames. This effect can be observed specially in the acquisition of patient number 1, for which the movement is mostly concentrated in the second half of the second line and first half of the third line of figure 1. The overall result is the reduction of effective positions for calculation of the movement parameters. Following the rule described in section **Volume Selection** the analysis of patellar movement was performed on five volume frames. The effect was less pronounced in the acquisition of patient number 2. In this case, it was possible to select 10 volume frames for movement analysis.

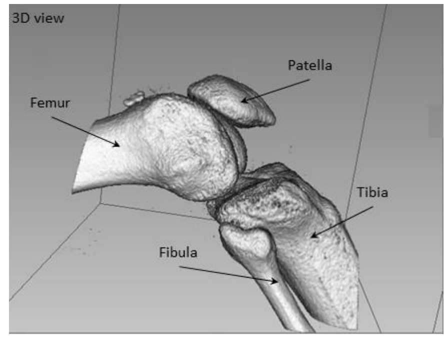

Figure 6 - View of the bones at the first flexion angle using free software 3D Slicer

In figure 7 we present the rotation angles α, β, γ and the displacements of the patella in x, y and z obtained for the two acquisitions. One should notice that the flexion angles of the leg are different for each acquisition.

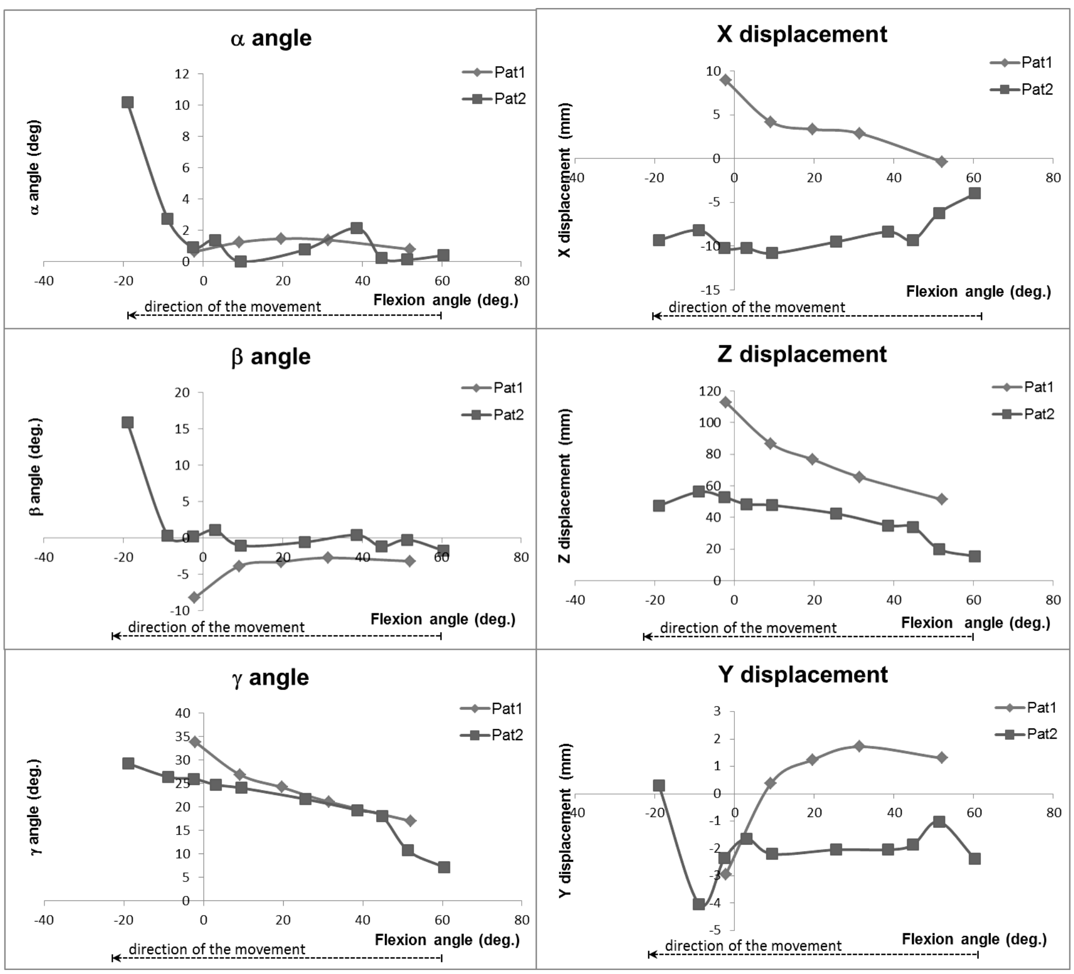

Figure 7 - Rotation angles and displacements as depicted in figure 4 obtained for the 2 patients. The direction of the knee movement – from the flexed to the extended position – is represented by the arrow under the graph.

From figure 7 it is possible to observe that the most noticeable movements for the two patients are the rotation around x axis (γ angle) and the displacement in *Z* direction. The *Z* displacement and the γ angle must be related to the normal trajectory of the patella while moving from the relaxed to the extended position.

The α angle would be expected to be the measurement more related to the most the conventional 2D tilt angle [18] (performed in a transverse slice of the 3D volume). Due to the irregular shape of the patella the points used for determination of the 2D measurement in the transverse slice varies not only with rotation at x-y plane but also with rotations at the other 2 planes, specially the x-z plane (β angle). Therefore, the 2D tilt angle is the result of a combination of 3D tilt, 3D spinning and 3D flexion of the patella. Experimental results seem to show the rotation around x-z plane accounts for most of the movement.

The movement in X direction is closely related to the 2D measurement Axial Linear Patellar Displacement [19]. This last measure, when performed in 2D, is also a combination of the displacement in the x-y plane and of the three rotation components, as well as the displacement in the other planes.

IV. Summary and Conclusions

The use of helical multi slice CT scanner imaging can provide a valuable tool for the evaluation of patellar instability by displaying physiology during muscle contraction. The technique has the ability to provide the spatial and time resolution required for tracking the patellar movement.

However, in order to become an effective tool, an effort has to be done in improving the acquisition protocol, which must achieve as much uniformity of the knee movement as possible. The analysis of the two acquisition sets presented in this work showed that a high number of volume frames acquired is around the both extremes of the movement. In the most severe case, only five points were available for parameters extraction between these two extremes, which is clearly a very small number of points for movement analysis. On the other side, due to the very nature of dynamic acquisition the flexion angles will vary for each new acquisition. Thus, in order to be able to compare images from different subjects as well as images from the same subject under different conditions it is vital to obtain a number of angles suitable for measurements, which will create the graphs of rotation angles and displacements. The acquisition of patient number 2 that roughly provided a volume at each ten degrees of knee flexion (with a total of 10 volume frames suitable for movement analysis) is closer to the expected acquisition quality. But the problem still remains that the acquisition quality and suitability for analysis is dependent on the patient performance. One possible solution is to pre-evaluate the acquisition quality just after it is finished and repeat it until it reaches the expected performance. There is however a radiation dose related issue that prevents the adoption of this simple solution [20].

Unlike the work of Macintyre et al all, calculations of the movement parameters in this work were performed using a single set of high resolution images. The characteristics of CT images allowed the identification of the structures of interest based on intrinsic image features (Hounsfield values) and some a priori information about knee bone structures.

The use of 3D parameters has the potential to provide a more precise way to quantify the normality (or deviation from normality) of the movement. Further comparison of 3D and 2D measurements are necessary to compare the results obtained in both approaches in order to assess the full potential of the method. In order to fully understand the relationship of these 2D measurements with the 3D parameters a comprehensive study including normal subjects and patients with known pathologies must be performed.

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