Biomechanical analysis of the hip joint during extreme movements

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Abstract—Hip osteoarthritis (OA) is one of the most common forms of musculoskeletal disorders. Different studies have shown that hip OA is a multi-factor disease. Malnutrition, genetics, obesity and infections were identified as marginal factors and the abnormal hip morphology as the most common reasons. Nevertheless, hip OA is considered idiopathic and needs, hence, to be further investigated. The aim of the study is to investigate the link between extreme repetitive movements and the development of hip OA. A subject-specific and non-invasive approach, which jointly considers anatomy, kinematics and dynamics, is proposed to analyze the mechanical behavior of cartilage during movements. This combination offers new opportunities to individualize the diagnostic and to understand the pathology. This approach is used to assess the stress distribution and damage onset in dancers’ hip joint during different movements. The correlation between the simulation results and a clinical analysis performed by medical experts, strongly suggests that extreme movement could lead to early hip OA. Index Terms—simulation Anatomical and kinematic modeling Hip osteoarthritis Extreme movements Simulation Anatomical and kinematic modeling Hip osteoarthritis Extreme movements

I. INTRODUCTION

Hip OA is characterized by the breakdown or the degeneration of the articular cartilages. Bones are thus uncovered and rub against each other, causing pain and limitation of range of motion. Different studies were conducted to investigate the causes of hip OA. Therefore, different hypotheses related to kinetics and kinematics were proposed to explain the mechanisms of degeneration. Some studies suggest that hip overloading or excessive forces supported by the joint may over time become excessive and lead to hip joint degeneration especially in presence of other factors such as structural abnormalities [1], [2]. Others studies associated repetitive micro-trauma and shearing of cartilage due to hip instability and abnormal movement with the development of hip OA. Indeed, certain movements practiced by athletes in their daily exercises were reported as potential risks [3]–[5]. In any case, it is evident that these hypotheses need to be investigated by analyzing the contact mechanics in the hip joint (e.g., cartilages stresses) [6].

Several biomechanical studies were conducted to quantify the intra-articular contact stress of the hip joint. Experimental measurements (in vitro and in vivo) [7], [8] were performed but these approaches were limited or highly invasive. Numerical models [2], [9] were proposed as alternative, but the developed models were not fully subject-specific and the studied movements were limited to routines activities.

To address this issue, we present a numerical approach based on subject-specific models to analyze the biomechanical behavior of the hip joint under movement. The hip analysis is performed for a female professional ballet dancer performing four different extreme motions. The simulation results are compared with the results of radiological and morphological analyses performed by medical experts.

II. PROPOSED APPROACH

Our functional approach (see Fig. 1) uses non-invasive modalities (Magnetic Resonance Imaging (MRI) and motion capture system). From Acquired MRI data, a segmentation approach [10], [11] based on robust deformable models is used to reconstruct the subject-specific anatomical models (bones and cartilages). Segmented models are subsequently converted to volumetric meshes in order to be used in physically-based simulations. To produce tetrahedral meshes of satisfactory quality and complexity suitable for simulation, we use a method [12] based on medial axis analysis and Octree subdivision of deformable meshes. Subject-specific kinematical modeling is achieved by using an optical motion capture system. This modality allows the recording of larger ranges of motion. A correction method [13] combining nonlinear optimization and joint motion constraints is applied to reduce the errors due to skin artifacts (STA) [14]. Since there is not a non invasive method to measure directly the subject joint reaction force, we made use of and focused on neuromuscular simulations [15], [16]. Our neuromuscular simulation pipeline starts by scaling a generic model to match the anthropometry of the subject. Then, motion capture data are used in an inverse kinematics step. Finally, the inverse dynamics approach is applied to estimate the loads on the subject hip joint.

The resulting data of the different methods are finally used in a physically-based simulation to compute the joint mechanics. This simulation [12], [17] is based on a specific implementation of a Finite-Element model offering high-efficiency simulation in the context of nonlinear behaviors related to large deformations and collisions.

III. RESULTS

A. Clinical (Morphological/Radiological) analysis

A morphological analysis was performed to evaluate the prevalence of the subjects’ hip joint. Based on subject-specific data (MRI and 3D bones reconstruction), standard morphological measurements [18], [19] were performed according to three anatomical parameters: acetabular version, acetabular depth and alpha angle. According to the results, experts concluded...
that no morphological abnormalities were detected for this subject. The same radiological experts performed a consensus reading of the subjects’ MR images. Acetabular cartilage and labral abnormalities were assessed qualitatively. Acetabular and labral lesions were diagnosed in the posterior part of the acetabular rim in the subject hip.

B. Simulation analysis

Our simulation is performed for four dancing movements, Circumduction, Arabesque, Développé latéral and Développé avant. These movements are characterized by the leg in air position with extreme hip flexion and/or abduction. According to the mechanical properties of bones and cartilage, we consider in our simulation bones as rigid. Therefore, the physical model consists of the tetrahedralized acetabular and femoral cartilages. Nonlinear elastic and isotropic material properties were adopted for the cartilages. In our study, the computed stress refers to the stress along the direction of the maximal compression. Given the applied loads, the stress is computed for each frame of the movement. The location of the stress peaks is also of paramount importance. While the stress-angle relationship could be guessed by observing a movement, the exact location of the stress peak can only be computed by a simulation. The simulation results showed that usually the stress peaks were located in the superior parts of the acetabulum rim. The left side of Fig. 2 shows some locations of stress peaks observed during the simulation.

IV. DISCUSSION AND CONCLUSION

The results of clinical analysis indicated that no potential morphological problems were reported for the subject. However, lesions were observed in the superior part of the cartilages. By correlating the location of lesions with the stress analysis of the simulation, we suggest that extreme or repetitive movements may explain these lesions of idiopathic OA. In fact, the cartilage high stresses were located in the superior area of the acetabular rim, which corresponds to the localization of diagnosed lesions (see Fig. 2). Thus assumption was moreover supported by the nature of the dancer movements. Indeed, dancing movements are usually fast which increase the load and consequently the stress in the hip joint. Nevertheless additional work is required to validate more thoroughly some simulation components in order to fully accept the result. We need to evaluate the accuracy of the different models (volumetric meshes, loads, material properties) and their influence on the simulation results. Eventually, to improve the significance of our results, we plan in a future work to analyze more subjects.

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REFERENCES


