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On a “Columbus’ Egg” for the shape of asymptomatic, dysplastic and impinged hip joints

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ABSTRACT

Understanding morphological features that characterize normal hip joint is critical and necessary for a more comprehensive definition of pathological presentations, such as femoroacetabular impingement and hip dysplasia. Based on anatomical observations that articular surfaces of synovial joints are better represented by ovoidal shapes than by spheres, the aim of this study is to computationally test this morphological classification for the femoral head and acetabular cavity of asymptomatic, dysplastic and impinged hips by comparing spherical, ellipsoidal and ovoidal shapes. An image-based surface fitting framework was used to assess the goodness-of-fit of spherical, ellipsoidal and tapered ellipsoidal (i.e., egg-like) shapes. The framework involved image segmentation with active contour methods, mesh smoothing and decimation, and surface fitting to point clouds performed with genetic algorithms. Image data of the hip region was obtained from computed tomography and magnetic resonance imaging scans. Shape analyses were performed upon image data from 20 asymptomatic, 20 dysplastic and 20 impinged (cam, pincer, and mixed) hips of patients with ages ranging between 18 and 45 years old (28 male and 32 women). Tapered ellipsoids presented the lowest fitting errors (i.e., more oval), followed by ellipsoids and spheres which had the worst goodness-of-fit. Ovoidal geometries are also more representative of cam, pincer, mixed impinged hips when compared to spherical or ellipsoidal shapes. The statistical analysis of the surface fitting errors reveal that ovoidal shapes better represent both articular surfaces of the hip joint, revealing a greater approximation to the overall features of asymptomatic, dysplastic and impinged cases.

1. Introduction

Morphological variations of the hip joint anatomy, such as femoroacetabular impingement (FAI) and dysplasia, have been suggested to be linked to the lesion mechanism of articular cartilage and progress towards osteoarthritis (OA) [1–9]. It has been estimated that FAI morphology affects between 10% and 15% of the general adult population [10] and approximately 55% among young athletes [11]. Regarding hip dysplasia prevalence in adults, it exhibits high variability amongst different racial groups, going from approximately 6–21% [12]. Considering the young age of patients manifesting symptomatic FAI or dysplasia, they might be electable for hip conservative surgery and the application of a prosthetic device [6,13]. An early-stage intervention and appropriate diagnosis for these patients rely on the accurate morphological and geometric characterization of the underlying anatomic deformity [4]. However, consensus regarding the metrics that best identify the morphological deformities and the intervals in which they should be placed to distinguish normal from pathological hips has not been reached to date [3,6,14–17].

Regarding the shape of the hip joint, recent computational tests [18–24] are in line with medical evidence [25,26] which considers that ovoidal shapes represent the articular surface geometry better than the orthodoxal sphere [27,28]. Yet, current tools used by physicians to investigate morphological features of these structures and to guide them in the treatment of FAI and dysplasia, consider the sphere to be the shape that best fits both the femoral head and the acetabular cavity. Consequently, finding how appropriate are currently used 2D quantitative measurements and how well defined is the morphological difference between asymptomatic,

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femoroacetabular impingement, and hip dysplasia are interesting questions worth addressing.

On the other hand, there seems to be high variation in the definition of the physiological values for the metrics used to describe the geometry of these surfaces, such as α angle, centre-edge angle, acetabular index of Tönnis, among others. Different authors consider different intervals for these parameters, highlighting the ambiguity associated with the classification of hip joint morphology [6,14–16]. Novel hip joint shape models, along with new sets of parameters, would allow for clear and unambiguous classification and identification of the femoral head and acetabular cavity, regardless of the form.

In order to answer these questions, a comparative study between asymptomatic and pathological hip joints was carried out to understand their underlying morphology. Surface fitting analyses of both femoral head and acetabular cavity were performed upon 20 asymptomatic hips, 20 dysplastic and 20 FAI (cam, pincer, and mixed) hips to provide quantitative evidence supporting the series of anatomical observations that the hip joint exhibits morphological features that are more consistent with ovoidal shapes than spherical ones, given that these do not contain information on global geometric characteristics such as axial asymmetry and non-homogeneous curvature.

2. Materials and methods

2.1. Medical image data

We retrospectively studied adult patients undergoing computed tomography (CT) or magnetic resonance imaging (MRI) from January and December 2015. All eligible patients had completed a questionnaire regarding their clinical history, including current or past hip/groin pain, medical or surgical hip-joint conditions, history of childhood hip pathology, and/or hip trauma. Patients who gave a positive answer to one or more of these questions were excluded from the asymptomatic group. Additionally, all patients completed the non-arthritic hip score questionnaire. Any patient with less than the maximal possible score was also excluded from the asymptomatic cohort. Images were uploaded for analysis using Articulis (ArticulisTM; Clinical Graphics, Delft, The Netherlands) and semi-automatically segmented using this software, which had been previously validated for reliability and accuracy [29].

CT scans of the asymptomatic pelvis (512 × 512 acquisition matrix, in-plane and resolutions = 0.602–0.869 mm, slice thickness = 1.5–2 mm, 262–929 slices) from 20 individuals with ages between 18 and 45 years (32.9 ± 8.5 years, 9 males and 11 females) were acquired with a Siemens Emotion 16 (Siemens Healthineers, Germany). Patients were positioned in a standard supine position with legs parallel in neutral rotation and received no additional radiation beyond that required for the CT ordered to evaluate their medical condition. The pelvis was reconstructed with 1 mm thickness from the anterosuperior iliac spine to the lesser trochanters. As for symptomatic pelves, MRI scans ((224–256)×(224–256) acquisition matrix, in-plane and resolutions = 0.703–0.804 mm, slice thickness = 0.7–0.8 mm, 96–128 slices) were acquired from 20 individuals with dysplastic hips with ages between 14 and 49 yr (34.0 ± 9.8 years, 6 males and 14 females), and of impinged hips ((224–256)×(224–256) acquisition matrix, in-plane and resolutions = 0.703–0.804 mm, slice thickness = 0.7–0.8 mm, 96–128 slices) from 20 subjects with ages between 21 and 53 yr (38.9 ± 6.8 years, 13 males and 7 females) using a T1-VIBE Fat-suppressed sequence performed by a Siemens MAGNETOM® 3T Verio (Siemens Healthineers, Germany) and an eight-channel body matrix phased-array surface coil (which was placed over the hip of the patient) and a six-channel spine matrix coil (which was integrated in the patient table) were used. As part of the routine MR protocol in patients, a three-dimensional (3D) data set of the whole pelvis was obtained with an axial water excitation true fast imaging with steady-state precession (FISP). MR was performed in standard supine position with legs parallel in neutral rotation. The pelvis was reconstructed with 1 mm thickness slices from the antero-superior iliac spine to the lesser trochanters. All data sets were anonymized. Informed consent was obtained for the use of the CT and MRI data sets from all subjects.

Cam-type deformities at the femoral head-neck junction were defined as an α angle greater than 55° at any location around the femoral neck [9,30]. Pincer type and acetabular dysplasia were considered if lateral center edge angle was greater than 40° or inferior to 20°, respectively [8,10,12]. Mixed FAI cases had both characteristics of Pincer and CAM cases.

2.2. Surface shapes

Based on results from a previous study that indicates that ellipsoids and egg-like shapes are better suited to fit the femoral head when compared to the sphere shape [23], we adopted the same assumption and considered the following shape models: sphere (S), ellipsoid (E) and tapered ellipsoid (TE). These shapes reveal an increasing degree of complexity to account for as many variations as possible within the set of subjects being considered in the study. The mathematical expressions for the considered shapes (implicit representation) are written as

$$\text{sphere}\quad \boldsymbol{F_S}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z}) = (\boldsymbol{x}/\boldsymbol{a})^2 + (\boldsymbol{y}/\boldsymbol{a})^2 + (\boldsymbol{z}/\boldsymbol{a})^2 \tag{1}$$

$$\text{ellipsoid}\quad \boldsymbol{F_E}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z}) = (\boldsymbol{x}/\boldsymbol{a})^2 + (\boldsymbol{y}/\boldsymbol{b})^2 + (\boldsymbol{z}/\boldsymbol{c})^2 \tag{2}$$

$$\text{tapered ellipsoid}\quad \boldsymbol{F_{TE}}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z}) = \left(\frac{\boldsymbol{x}/\boldsymbol{a}}{\boldsymbol{T_x z}+1}\right)^2 + \left(\frac{\boldsymbol{y}/\boldsymbol{b}}{\boldsymbol{T_y z}+1}\right)^2 + (\boldsymbol{z}/\boldsymbol{c})^2 \tag{3}$$

where x, y, z are the local coordinates of the point in space that belongs to the surface; a, b, c represent shape dimensions or semi-axis radii; T_x and T_y are the tapering values in the x and y directions.

2.3. Surface fitting and error analysis

The surface fitting framework presented by Lopes et al. [23] was used to reconstruct three-dimensional bone structures from the images and to fit well-defined mathematical surfaces (Fig. 1). Note that all the 3D reconstructed articular surface meshes correspond to the interface between cortical bone and cartilage (i.e., geometric modeling does not take into account soft tissues, merely the outer boundary of bony tissue and not the free surface of the articular surface).

From the medical images, each bone structure is segmented separately using a semi-automatic method that relies on active contour evolution [31] using ITK-SNAP software tools (version 3.4). Afterwards, the resulting segmented images were reconstructed into 3D surface meshes in ParaView (version 4.3.1) with the marching cubes algorithm [32,33]. Since the marching cubes meshes present a characteristic stair-step shape surface and an excessive and redundant amount of vertex information, mesh adjustment operations, namely smoothing and decimation, were then applied to the reconstructed 3D surface meshes, in order to guarantee homogeneous nodal distribution and eliminate these artifacts that result from 3D reconstruction from scanned image data. From the 3-D models, which presented non-articular bony surfaces

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