17 Statistical and Biomechanical Analysis of Hip Dysplasia

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17.1 Introduction

Acetabular dysplasia may be the leading cause of premature osteoarthritis (OA) of the hip. However, the relationship between the altered geometry associated with dysplasia and the resulting stresses in and around the joint is poorly understood. The overall hypothesis of this research is that acetabular dysplasia causes alterations in hip joint biomechanics, which predispose the joint to cartilage degeneration. Subject-specific, three-dimensional finite element modeling techniques have been developed and validated to study hip joint biomechanics. Using three patient populations (normal, traditional dysplastic and retroverted dysplastic), patient-specific finite element (FE) models are used to determine stresses in and around the hip joint during simulated walking, stair-climbing, and descending stairs.

Many orthopaedic surgeons are unaware of multiple facets of the dysplasia diagnosis and their potential implications for joint degeneration. Recognizing the mechanical consequences of different and often subtle forms of dysplasia allows earlier identification of “at risk” hips, in turn allowing the initiation of earlier treatment, which may delay the need for total hip arthroplasty. This research will immediately help delineate the true spectrum of this three-dimensional pathology by quantifying stress transfer in the hip joint.

Patient-specific hip joint computational models also have a number of potential longer-term uses and benefits, including patient-specific approaches to treatment and prediction of the long-term success rate of corrective surgeries based on pre- and post-operative mechanics. This research will develop and validate methods that can be directly applied to quantify changes in mechanical loading due to surgical intervention. Quantifying these changes allows us to assess the efficacy of different approaches to osteotomy on a patient-specific basis. We also envision using these techniques for longer-term prospective studies, to correlate surgical correction with changes in mechanical loading and long-term outcome. Currently, long-term success is measured by avoidance of a total hip arthroplasty and is not correlated with any preoperative variable other than the relatively crude measurements made on an anteroposterior radiograph.

Scientific/Clinical Objectives:

Scientific Aim 1: Develop and validate techniques for subject-specific FE modeling of hip biomechanics, by performing simulations and experiments on cadaveric specimens, and assessing the sensitivity of predictions from this population of subject-specific models to input parameters.

Scientific Aim 2: Using three patient populations (normal, traditional dysplastic, and retroverted dysplastic), build and analyze group differences in patient-specific FE models to determine stresses in and around the hip joint during simulated walking, ascending, and descending stairs.

Collaboration Objectives: The collaboration aims will focus on several aspects of this ongoing project and will provide new technologies for achieving the scientific aims.

Collaboration Aim 1: Rapid, robust development of high-quality finite-element models of patient specific geometries, using an open-source segmentation and meshing pipeline.
than that found on the femoral side of the hip joint.

Consequently, it is thought that the altered biomechanics cause the cartilage and bone of the hip to degenerate prematurely, leading to early hip osteoarthritis. Dysplasia of the acetabulum is much more common than that found on the femoral side of the hip joint and thus acetabular dysplasia is the focus of the proposed research.

Symptoms and Diagnosis of Traditional Acetabular Dysplasia. Most patients with acetabular dysplasia will eventually become symptomatic, manifested by pain in the groin, greater trochanter, lower back, and buttocks. The onset of symptoms usually occurs at a relatively young age; over the last 6 years, the average age of presentation in the clinic of Dr. Peters was 28.3 ± 8.4 years. The onset of pain often begins while participating in sports that require running and/or impact activities, but can occur during daily activities such as walking and stair-climbing. It is important to note that greater than 2/3 of patients presenting with symptoms of hip dysplasia do not yet have any radiographic evidence of osteoarthritis. This is consistent with data from the Orthopaedics Clinic at the University of Utah. The most common type of acetabular dysplasia (referred to herein as “traditional dysplasia”) is diagnosed using measurements from a standard anterior-posterior radiograph: center edge (CE) angle of Wiberg, acetabular angle of Sharp, acetabular depth ratio, and femoral head coverage ratio. A CE angle less than 25° and an acetabular angle greater than 40° are generally sufficient to diagnose an antverted and dysplastic acetabulum. In addition, an acetabular depth ratio less than 250 and femoral head coverage less than 75% strongly indicate that the hip is pathologic. The acetabulum of these traditional dysplastic hips is generally excessively antverted.

Treatment of Hip Dysplasia. If DDH is diagnosed during infancy, non-invasive treatment is possible. Treatment begins early (e.g., 6 months) using a Pavlik harness. If the femoral head will not remain in the socket after 3 weeks of Pavlik harness, the child is placed in a spica cast. Finally, if casting is not effective, an open reduction of the hip will be performed to reorient the muscles and remove unnecessary soft tissue in and around the acetabulum to create more room and realign the ball so that it sits well inside the socket.

If DDH remains silent until adolescence or adulthood, surgical intervention is often necessary. The objective of surgical correction is to establish normal hip biomechanics by restoring the center of rotation, acetabular coverage, femoral head containment, abductor mechanics and limb length. Surgical correction of the anatomic abnormalities associated with hip dysplasia is performed via pelvic osteotomy, which preserves the native hip and entails redirection of the acetabular osteotomy. The rationale for this treatment is that the associated reduction in stresses will reduce or eliminate pain and reduce the likelihood of developing osteoarthritis. Surgical correction can move the area of contact in the acetabulum and the center of rotation, and improve acetabular coverage of the femoral head. Although the pelvic osteotomy procedures generally produce good medium- and long-term outcomes, there is a population of patients who still have progression of degenerative changes and/or require total hip arthroplasty.
Relationship between Hip Dysplasia and Osteoarthritis of the Hip. Osteoarthritis (OA) is the loss of articular cartilage in the predominately load bearing areas of the joint, with eburnation of the underlying subchondral bone and a proliferative response characterized by osteophytosis. These alterations usually occur over a period of years and include a generally progressive loss of articular cartilage, accompanied by the effects of natural processes associated with cartilage repair. OA of the hip affects nearly one in six adults over the age of seventy. OA continues to be a significant problem in the elderly population due to pain and loss of mobility, leading to poor productivity and quality of life. OA was once thought to be primary or idiopathic in nature. However, considerable clinical, epidemiological, and experimental evidence supports the concept that mechanical demand greater than some critical level has a major role in the development and progression of joint degeneration for all forms of OA that can be related to occupational demands and/or obesity. Many available treatments for OA, including pelvic osteotomy in the hip, are based on the concept that reducing mechanical stress will decrease symptoms, slow the progression of OA, and possibly stimulate restoration of the articular surface in patients with OA. Excessive mechanical stress can directly damage articular cartilage and subchondral bone and it can adversely alter chondrocyte function, including the balance between synthetic and degradative activity.

In the context of pelvic dysplasia, the biomechanics of the hip appear to play an important role in the development of osteoarthritis in the affected joint. Several studies have shown that mild developmental dysplasia may indeed be the leading cause of osteoarthritis in the hip. In contrast to the reports demonstrating the high incidence of dysplasia among patients with hip OA, other studies have failed to find a statistically significant relationship between acetabular dysplasia and the risk of hip OA. The discrepancies in the literature motivate an improved understanding of the biomechanics of the dysplastic hip. The standard for quantifying OA, which consists of two-dimensional measurements of joint space and CE angle, are not sufficient to prove or disprove the hypothesis that dysplasia predisposes the hip to OA. Dysplastic hips have thicker articular cartilage than normal hips and cartilage may actually swell in the early stages of OA. Moreover, the CE angle does not alone predict the prognosis of OA of the hip joint; a hip joint with a larger CE angle may develop OA faster than a hip with a smaller CE angle. Furthermore, many patients with a retroverted acetabulum, another manifestation of dysplasia, have a CE angle that is normal, yet these patients are still symptomatic. Finally, and perhaps most importantly, dysplastic hips typically have reduced congruency and the CE angle does not directly provide a measurement of congruency and its effect on contact and cartilage stresses.

Biomechanics of Hip Dysplasia. Toward a quantification of the degree of stress in OA that could be considered “pathological”, a handful of studies have inferred joint contact pressures in dysplastic hips as a means to differentiate their mechanical environment. Although these studies further support the notion of pathological biomechanics and, in particular, increased contact stresses in the dysplastic hip, they neglect several important aspects of the biomechanics. With the exception of Hipp et al., these studies used idealized geometry to represent all or part of the hip articulation, neglecting the issues of regional and patient-specific congruency between the femoral and acetabular cartilage layers. Explicit modeling of cartilage deformation was either not included or was based on linear elastic models.

If cartilage damage due to habitual mechanical overload is the instigating factor in the onset of OA, this implies that mechanical measures of stress and strain are the critical factors defining the overload conditions. Thus, our clinical hypothesis entails direct and indirect measures of deformation and stress. Contact stress and contact area provide indirect insight into material stresses. We evaluate contact stress via the contact stress overload criterion, derived from the area engagement histogram, proposed by the Iowa group. Experimental studies of mechanical damage in articular cartilage have shown that maximum shear stress predicts the location of failure. The importance of quantifying these attributes further motivates the need for patient-specific finite element (FE) modeling techniques for representing bone and cartilage geometry.

Dysplasia due to Retroverted Acetabulum. Historically, dysplasia of the acetabulum was viewed as consisting of a relatively small spectrum of pathology, usually characterized by a steep, shallow acetabulum that insufficiently covered the femoral head (for reference, see Figure 17.1). These studies suggest that there could be a broader spectrum of pathologies associated with the dysplastic hip. Subpopulations of dysplasia, especially difficult to diagnose using standard radiographic measurements, could potentially explain the discrepancies in the literature regarding the correlation between dysplasia and OA.

Recently, a specific variant of acetabular dysplasia - retroversion of the acetabulum - has been reported. The condition may be part of a complex dysplasia or a single entity. Dr. Peters has used computer-aided manufacturing methods to build physical and computer models of retroverted acetabulae to study this condition and for
Figure 17.1: Anatomy of the hip shows the relationships of shapes we will characterize, the acetabulum and the femoral head, relative to other nearby structures.

Figure 17.2: A) Schematic of normal pelvis. The line of the edge of the posterior wall is located at or even to the center of the femoral head. B) Retroverted hip. The line of the posterior wall is located medial to the center of the femoral head.

patient surgical planning. In both normal and retroverted conditions, the mouth of the acetabulum spirals gradually into increasing anteversion distal to the roof edge. However, in the retroverted acetabulum (Figure 17.2), despite the progress distally into anteversion, the anterior edge of the mouth remains in a more lateral position than is normal and the posterior edge is more medial. The prominent anterolateral edge of the acetabulum creates an obstacle to flexion and internal rotation, predisposing the hip to femoroacetabular impingement and leading, over time, to anterior labral and adjacent cartilaginous lesions.

The Orthopaedics Clinic became interested in retroversion because the disorder may have a different natural history than traditional dysplasia. The geometric differences are subtle, which makes retroversion difficult to diagnose with traditional methods. It is likely that the obscurity of the retroverted acetabulum has often lulled the clinician into prescribing passive treatments for a potentially aggressive pathology. Retroversion can be diagnosed on standard radiographs if the surgeon or radiologist has been trained to look for the subtle alterations in geometry. In the practice of Dr. Peters, 3D reconstructions from patient CT arthrography data have dramatically improved his ability to correctly diagnose acetabular retroversion.
17.3 Significance

This project presents some important challenges for algorithm and software development in the CIBC. Aim 1 consists of two parts: i) segmentation and ii) meshing. Currently, the Musculoskeletal Research Laboratory (MRL) relies on the commercial package, Amira, for this functionality. Our hypothesis is that the patient-specific FE pipeline will benefit from the reduced user assistance (hundred of person-hours per model) and improved element quality available in the Seg3D-BioMesh pipeline. The challenges will be achieving the level of robustness able to compete with the commercial pipeline and validating the quality of the elements in the biomechanics applications. Also, the current FE models of hip joints in the MRL include cortical bone, which is modeled as a thin shell using a triangular surface, and the softer trabecular bone, which is modeled with solid, tetrahedral elements. One of our goals is to make the functionality available to introduce triangular prism elements for the dense, rigid cortical shell.

For Aim 2, we plan to use the statistical shape tools in ShapeWorks to build sets of statistical models of the entire hip socket. The challenge will be to extend the tools in a general way to deal with these open geometries, to address some of the issues of building joint models (multiple surfaces) with tight tolerances (bones separated by cartilage), and to address the challenge of proper anatomical alignment of the bones. We also intend to extend the modeling system so that it dovetails with the FE simulation environment, enabling the MRL to perform group-averaged biomechanical simulations and examine sensitivity to statistically derived anatomical shape. Accomplishing these goals will entail some significant developments in ShapeWorks.

17.4 Rationale and preliminary results

17.4.1 Collaboration Aim 1: Patient specific FE models

For preliminary results, we have segmented and constructed meshes from CT of several hip joints using BioMesh (see Section 9.3.2) and associated, ongoing algorithmic developments. Figure 17.3 shows a mesh of the pelvis created with BioMesh3D.

17.4.2 Collaboration Aim 2: Statistical shape models of the hip joint

We have conducted a small pilot study of femoral head shape in order to demonstrate the feasibility of this aim. The pilot study consisted of 8 segmented femoral heads of patients that were determined to have normal hip anatomy. The analysis consisted of rough alignment using the method in,\(^6\)\(^7\) smoothing using the tightening method described previously, and the automatic placement of 300 particles (point samples) interleaved with a procrustes alignment as in.\(^6\)\(^8\) The particles were constrained to the open surface representing the femur head by a cutting plane, which was systematically positioned based on user-defined landmarks at the top trochanter and the center of the femoral head. Figure 17.4 shows the group mean shape (surface reconstructed from the landmark points) and several modes of variation. We see that even with such few examples, these statistical variations have meaningful geometric and anatomical interpretations. For instance, the first mode shows a systematic relationship between the size of the femoral head and the length of the neck as well as a surprising
constancy in the position and size of the fovea capitis (indentation on the femoral head—attachment point for ligaments). Second and third modes show differences in femoral head shape (deviations from roundness) and differences in the ways in which the femoral head joins the neck. These results demonstrate feasibility, but also some challenges. One challenge appears to be a consistent alignment of the top of the femur and/or femoral head in a way that does not significantly impact the shape quantification. Consistent, stable definitions of the extent of these features and similar delineation of the acetabulum will also be challenging.

17.5 Methods

17.5.1 Collaboration Aim 1: Patient specific FE models

For this aim, we will work with the MRL and associated students/staff to deploy Seg3D and BioMesh software and facilitate its use. We will compare these open source tools with current methodologies in the MRL as follows:

1. Segmentations are currently done by hourly employees. Through hourly documentation, we can compare work loads for different tool sets.

2. Mesh generation via Amira requires user input for quality control and refinement. We will compare amounts of user input as the MRL group and CIBC staff become proficient with the software and data, respectively.

3. We will compare mesh quality parameters between the current system and BioMesh for geometric fidelity, triangle shape, and tetrahedral shape, as well as stiffness matrices.
In this DBP, this aim will also drive the underlying technologies of Seg3D and BioMesh. For this, we will pursue the following:

1. We will develop the machine learning techniques for image segmentation in the Image-Based-Modeling TRD, as described in Section 9.4.1, for the segmentation of cortical and trabecular bone.

2. We will develop the integrated prims-tetrahedral meshing capability, as described in Section 9.4.2, for the meshing of cortical and trabecular bone regions in femoral head and acetabulum.

17.5.2 Collaboration Aim 2: Statistical shape models of the hip joint

For this aim, we will apply and extend the software tools available in ShapeWorks. The strategy will be to examine the efficacy of the current technology and extend it, as necessary, to be able to address the needs of this DBP. Based on the preliminary results, we have several needs.

For the trial and evaluation of the ShapeWorks tools in this DBP, we will pursue the following:

1. We will apply the ShapeWorks tools to develop statistical models of the femoral head for the three patient groups. We will perform group comparisons and characterize any significant shape differences between groups. A challenge will be the overall alignment of the structures and a protocol dictating where to restrict (cut off) the analysis of the head or top of femur. For this protocol, we will rely on domain knowledge of colleagues in orthopaedics. We will also consider data-driven strategies such as hierarchical schemes, where the larger sections of the femur (e.g., the entire femur) are covered with landmarks and aligned. This alignment and parameterization can be used for subsequent localized analyses. For instance, the global femoral alignment could be used to systematically define the extent and orientation of the femoral head.

2. We will apply the ShapeWorks tools for characterizing the shapes of the acetabulum in the three patient groups and perform group comparisons as in the previous item. These comparisons will include a joint analysis of femoral head and acetabulum. Our ability to capture the shapes within the tolerances needed to allow these two bones to properly interact is an open question, as is developing a systematic way to define the extent and pose of the acetabulum (e.g., the area making contact with cartilage). This analysis will include quantitative and qualitative analyses of group differences.

3. We will develop tools for comparing individuals against groups and computing likelihoods based on the dense sets of automatically generated landmarks from ShapeWorks.

4. We will integrate the shape models into the biomechanical simulation tools available in the MRL, perform simulations on the group-based geometries, and study sensitivities to shape perturbations derived from the modes in the data. This will entail creating a link between the shape analysis tools in ShapeWorks and the meshing tools in BioMesh. We plan to create this link by using the dense landmarks to construct and group-average implicit model, e.g., by a thin-plate-spline interpolation using the landmarks and distance transforms of individuals, from which to build the full, group-average mesh.

17.5.3 Milestones and timeline

We have established several milestones that will help measure progress in this project. Months are total from the start of the project.

Development of initial meshes—6 months. Here we will compare mesh quality using geometric-and simulation-based measures on 3-4 patients.

Femoral head analysis—9 months. Here we will complete the model building, including segmentation, develop a systematic definition of the boundaries, and perform group analysis on approximately 40 subjects.

Femoral head and acetabulum—18 months. Here we will perform a joint model of the acetabulum and femur and perform group comparisons. These will include delineations (possibly manual) of the boundaries between the acetabulum and the rest of the hip.
Simulations on aggregate models—28 months. We will build FE models (tetrahedral meshes) from the statistical surface representations and generate FE results (e.g., pressures on cartilage) for statistically significant variations and for different patient groups. A challenge will be developing an adequate geometric description of the cartilage.

Quantitative evaluation of patient groups—36 months. We will compare individuals with known diagnosis against patient groups and evaluate the effectiveness of the shape models in quantifying abnormalities in hip geometry.

17.5.4 DBP interaction and management

We will meet regularly (monthly/bimonthly) at both the SCI Institute and the Orthopaedics Center. The communication is ongoing, due to the proximity of these different groups. We plan papers to include work on the femur alone, the femur and acetabulum jointly, and the combination of statistical analysis and simulation.

17.6 Impact

Much of orthopaedics is governed by mechanics and much of mechanics is dictated by shape. Thus, we believe that the potential impact of robust, open-source software tools for meshing and statistical shape analysis is profound. The ability to study statistical shape models in a biomechanical context has several important implications. One is the ability to drive the biomechanical simulations of patient groups using group-averaged geometries, which will help alleviate the effects of imaging noise and small errors in segmentation and preprocessing. A second implication is the ability to make group comparisons of both geometry and biomechanical parameters in a way that systematically captures group variability. Finally, studying statistical shape models in a biomechanical context will enable the study of sensitivities in biomechanical outcomes with respect to geometric variability consistent with naturally occurring variabilities based on systematic empirical models.

We believe that a wide range of other applications of shape analysis exists in disciplines such as orthopedics, cardiology, and cell biology, where the geometric underpinnings of normal and pathophysiologic structures will benefit from the ability to capture anatomical variability in a systematic manner. This DBP will allow us to push the current state of the art in meshing and statistical shape representation to better address that potential.