4-2020

Abduction Contractures within Infants with Developmental Dysplasia of the Hip

Nathan Stanton

ABDUCTION CONTRACTURES WITHIN INFANTS WITH DEVELOPMENTAL DYSPLASIA OF THE HIP

by

Nathan Stanton

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science of Mechanical Engineering at Embry-Riddle Aeronautical University

Embry-Riddle Aeronautical University

Daytona Beach, Florida

April 2020

ABDUCTION CONTRACTURES WITHIN INFANTS WITH DEVELOPMENTAL DYSPLASIA OF THE HIP

by

Nathan Stanton

This thesis was prepared under the direction of the candidate's Thesis Committee Chair, Dr. Victor Huayamave, Visiting Assistant Professor, Daytona Beach Campus, and Thesis Committee Members Dr. Eduardo Divo, Department Chair, Daytona Beach Campus, and Dr. Charles Price M.D., Orlando Health, and has been approved by the Thesis Committee. It was submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

Thesis Review Committee

V Huayamave

Victor Huayamave, Ph. D.
Committee Chair

Eduardo Divo

Eduardo Divo, Ph. D.
Department Chair,
Mechanical Engineering

Charles T. Price, M.D.

Charles Price M.D.
Orthopedic Pediatrician
Orlando Health

04/23/2020
Date

Acknowledgements

My sincere gratitude goes to Dr. Victor Huayamave for the support and guidance as well as keeping me focused. I would not be where I am at today without your mentorship and belief. My family, as always, has been instrumental in pushing me forward and helped me believe that even the most monumental tasks could be accomplished. I am also very grateful for all of the help and direction I received from my girlfriend, who helped me achieve so many breakthroughs within the study. Finally, I would like to thank my Master’s Family and the BioLab for their support and for dealing with my insanity.

Abstract

Researcher: Nathan Taylor Stanton

Title: Abduction Contractures within Infants with Developmental Dysplasia of the Hip

Institution: Embry-Riddle Aeronautical University

Degree: Master of Science in Mechanical Engineering

Year: 2020

Developmental Dysplasia of the hip is a condition that affects 1 to 3 of every 1000 infants born globally. It is a pathology that involves the instability, subluxation, or dislocation of the femoral head from the acetabulum. Through a rating system by the International Hip Dysplasia Institute or Graf System, hips are rated based on their level of instability or dislocation and the infant is then prescribed a treatment. While Finite element models of dysplastic hips have been developed previously, a study that seeks to understand the contribution of an abduction contracture of the hip has yet to be performed. This assessment and evaluation could impact the way future models are made and could provide guidelines for what muscles are taken into account during modeling. Therefore, through the evaluation and comparison of three models with varying levels of abduction contracture, conclusions can be drawn as to the importance of various muscles and their contribution to developmental dysplasia. These models were developed from a set of CT scans and then used current musculature and skeletal properties in order to properly construct the hip joint. Comparisons between the stresses in each of the models are then made between the hip joints as well as between simulated values and currently available experimental values. The models then show, through engineering stress distributions and concentrations, how detrimental an abduction contracture can be to an infant and that if the condition is prolonged there is a possibility of development of dysplasia or, at minimum, a malformation of the acetabulum.

Table of Contents

Table of Figures

List of Tables

Chapter 1

Introduction:

Developmental Dysplasia of the hip (DDH) is a pathology that affects 1-3 out of every 1000 children born, depending on geographic location (Ardila et al., 2013; Graham, Manara, Chokotho, & Harrison, 2015; Huayamave et al., 2015; Kotlarsky, Haber, Bialik, & Eidelman, 2015; Zwawi et al., 2017). This pathology is one that "represents a spectrum of disease from transient neonatal hip instability to established dislocation," (T. C. Clarke C., Judd J., 2016b). Meaning that within the hip joint of the infant there is some instability that can, if left untreated, allow for dislocations of the hip joint as well as long term pathologies such as osteoarthritis. The hip joint itself is composed of the acetabulum and the femoral head as well as surrounding blood vessels and soft tissue. The femoral head is the spherical bony portion of the femur that fits into the acetabulum, also known as the hip socket as seen in Figure 1.

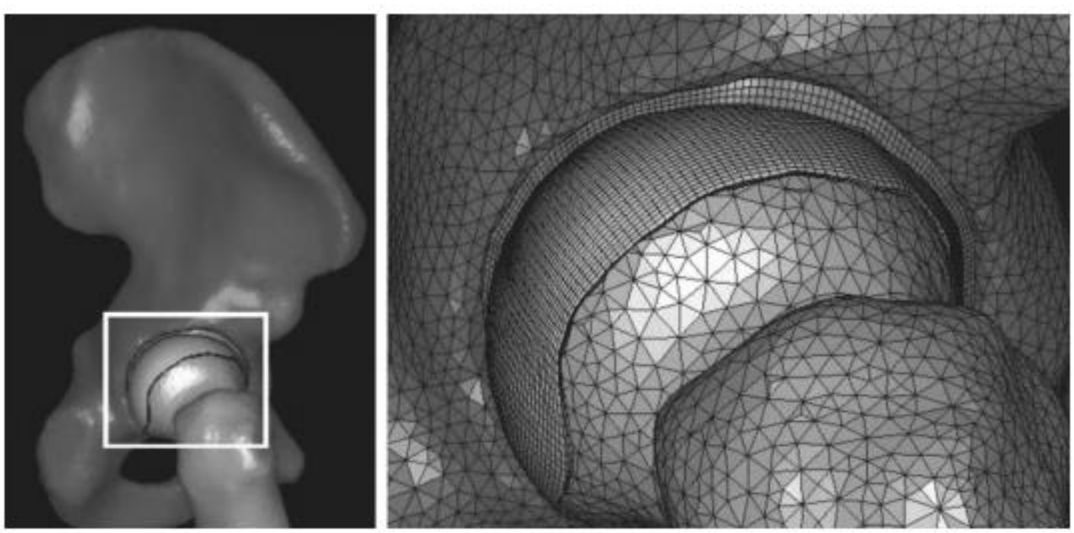

Figure 1: The hip joint as rendered by (Anderson, Ellis, Maas, Peters, & Weiss, 2008)

The femoral head, as well as the acetabulum, can be malformed or be the reason for the dislocation. The femoral head, without proper movement or in conjunction with other contributing factors, can cause improper morphogenesis of the hip joint and therefore can result in DDH occurring within the infant (Giorgi M., Carriero A., Shefelbine S., Nowlan N., 2015).

There are a variety of risk factors associated with DDH. These include being female, the left hip, birthing in the breech position, being a first born, postural deformities, oligohydramnios (a deficiency of amniotic fluid during pregnancy), and a previous family history of hip dysplasia. (Kotlarsky et al., 2015). However, the most important risk factor is being born in the breech position, regardless of a normal birth or cesarean section (Kotlarsky et al., 2015). Being female is also a large contributing factor to the risk of DDH, with 80% of all cases being female (Kotlarsky et al, 2015, Giorgi et al, 2015). This is most likely due to ligamentous laxity as a result of a maternal hormone, relaxin, that circulates through the body during pregnancy (Kotlarsky et al., 2015). However, these are all risk factors that are involved in the prenatal period of the child's life. It is also possible for the child to develop dysplasia over time due to injury, improper swaddling, improper baby wearing, and a variety of other occurrences during the neonate's life (Kotlarsky et al, 2015, Graham S., Manara J., Harrison W., 2015).

Each case of DDH is rated using a variety of testing methods such as the Barlow and Ortolani Method and often times follow ups for infants with suspected DDH are screened again with Ultrasonographic techniques (Dezateux C., Rosendahl K., 2007). Once these evaluations are performed the hip is then rated according to the Graf or International Hip Dysplasia Institute scale from I-IV. Where 1 is a normal hip and 4 is complete dislocation of the hip (Kotlarsky P., Haber R., Bialik V., Eidelman M., 2015, Huayamave V., Rose C., Serra S., Jones B., Divo E., Moslehy F., Kassab A. Price C., 2015).

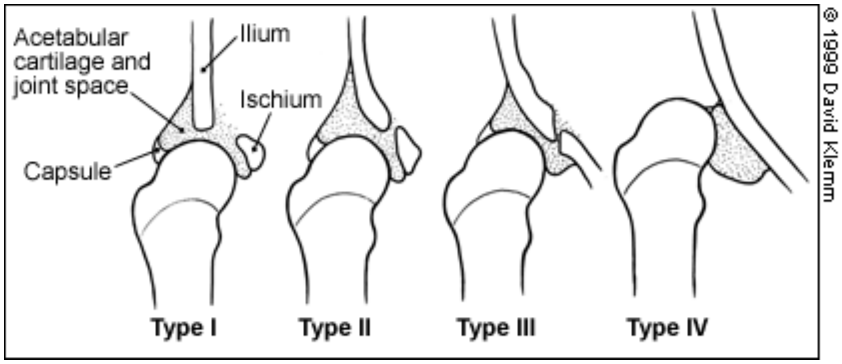

Figure 2: Example of Graf Rating System for Hip Dysplasia where Type 1 is normal, Type 2 is mildly dysplastic, Type 3 is subluxated with a shallow acetabulum, and Type 4 where the femoral head is completely dislocated from the acetabulum (French & Dietz, 1999).

The Graf rating system for dysplastic hips is based on the study done by Graf R. in 1984 where 3500 infants were evaluated via ultrasound due to a suspected instability within the hip. After the children were evaluated a baseline set of parameters were set up in order to create a consistent evaluation structure for the hip joint. This resulted in four types of dysplasia (Figure 2) where type one hips are normal (stable), type two hips are mildly dysplastic (slightly unstable), type three hips are subluxated with a malformed acetabulum (major instability), and type 4 hips which have a femoral head that is entirely dislocated from the acetabulum (French & Dietz, 1999; Graf, 1984). These four types represent the majority of infant hips within Graf's studies and this rating scale is still used today. There are however, minor changes to the rating system or other rating systems that by name are different but are similar in concept to the Graf System. One of the major systems that is similar to the Graf system is the International Hip Dysplasia Institute which uses a similar 4 type system and rates hips within that scale ("Developmental Dysplasia of the Hip - International Hip Dysplasia Institute," 2020). This 4-type rating system is used consistently when seeking to diagnose hip dysplasia in infants and depending on the type of hip a certain device or procedure is described for treatment. (Huayamave et al., 2015). This classification and treatment method is extremely important due to the possibility of long-term side effects of DDH.

Developmental Dysplasia of the hip is known to cause problems within the adult hip if left untreated. Severe cases often are due to a lack of diagnosis within the childhood of the individual. While these cases are rare, it is possible for a child with DDH to go unnoticed or untreated during the early portions of life. If this occurs there are severe implications for the individual later in life. The most common problems that are seen are a limp, bone deformities, and osteoarthritis (Michaeli D., Murphy S., & Hipp J., 1997). Usually the limp is the first sign of a deformity or problem within the adult or adolescent hip. The individual will compensate for the lack of proper femoral head positioning by favoring one side or the other. However, if the limp is not present severe pain due to early onset osteoarthritis is another likely indicator that there is a problem for the hip joint. Once a problem has been identified by the individual and they seek treatment, it is usually then that the dysplasia is identified and deformities and treatment options discussed (Michaeli, Murphy, & Hipp, 1997). Often times with late identification the femoral head has impounded into the pelvis so much and the head has spent so much time in a specific place outside the acetabulum that a new "socket" has formed (often a Graf IV). After these pathologies have been identified a treatment is enacted to help reduce the hip or change the location of the femoral head within the pelvis.

Treatment and Prevention of Developmental Dysplasia of the Hip

With the knowledge that cases of hip dysplasia that are left untreated can cause long term side effects in a patient it is important to look at the treatments available to an infant with the pathology. The most common treatment for DDH is a harness that the infant wears in order to attempt to correct DDH during the first few months of life (Singh, 2015; Suzuki, 1994; Wilkinson, Sherlock, & Murray, 2002). The most prevalent of these harnesses is the Pavlik Harness. The Pavlik Harness seeks to eliminate the DDH through the abduction and flexion of the hip (Ardila et al., 2013). The harness uses stirrups and straps that attach around the infant in order to keep the infant's hips in an abducted and flexed position for an extended period of time so that the acetabulum can properly form. This allows the femoral head to wear into the socket and be properly seated within the acetabulum. Other harnesses such as the Craig Splint, the von Rosen splint, and the Ilfeld abduction orthosis are used to treat DDH but with the high rate of success achieved by the Pavlik harness, around 98%, it is the most common choice for harnesses (Atrey & Katchburian, 2010; Kotlarsky et al., 2015; Ömeroğlu, Köse, & Akceylan, 2016). The harnesses have been known to fail however. In particular, if the classification of the hip is above a Graf III the hip often cannot or will not be reduced through the use of a harness. Therefore, when a harness fails or the infant is too old for the treatment to be effective, surgery is often performed in order to correct the condition. The two types of surgery that are commonly performed are a closed reduction and an open reduction. A closed reduction often is a reduction of the hip without the manipulation of the pelvis or the cutting of any portions of the bone (Zwawi et al., 2017). An open reduction is often an osteotomy, where the pelvis or femur is cut and the acetabulum or femoral head moved to a better position and then reattached using screws and other components. After the surgeries, an infant is often put in a Spica cast in order to keep the hip reduced and allow for the reformation of the acetabulum for proper seating of the femoral head. The cast, unfortunately, does have to be removed and reapplied on a regular basis due to the growth of the child and often requires multiple doses of general anesthesia. In addition to the repeated removal of the cast, it is possible that the child could develop an abduction contracture. This is when the abductor muscles tighten and/or shortened due to the constant abduction the spica cast requires during the healing process. It is then possible that the contraction could contribute to additional incidents of dysplasia. This and the severity of the initial surgery are not ideal and due to the developmental component of the pathology it is important that prevention of DDH be a primary concern.

Most importantly, is the recognition that Developmental Dysplasia of the Hip is a developmental disease more often than it is a congenital one. There are risk factors associated with having an ancestry of hip dysplasia as well as some conditions at the time of birth (Dezateux & Rosendahl, 2007; Kotlarsky et al., 2015). However, it is known as a developmental issue due to the fact that there is evidence of hip dysplasia being more related to improper swaddling techniques, improper baby wearing, or leaving a child in a position where the hip has the ability to dislocate or subluxate (Graham et al., 2015). Therefore, it is incredibly important to recognize the environmental factors that play a role in the development of hip dysplasia and through studies such as the one performed by Graham S. et al. 2015 it is seen that the way a child is worn or carried can play a pivotal role in the development of the child's hip.

Figure 3: Back Carrying example from Malawi (Graham S. et al. 2015).

This study in addition to others, such as the initiative in Japan to change the swaddling style of children, have granted insight into the development of hip dysplasia as well as brought to light the need for a model to represent a neonate's hip (Graham et al., 2015; Roper, 1976). With a truly accurate and adaptable model, computational evaluations would become available in order to help determine the viability of treatments and other preventative measures.

Abduction Contractures within the Hip

An abduction contracture within the hip is when muscles within the hip abductor sub-group experience an increase in the tightening of the muscle fibers or the fibers become shortened within the body due to genetic or environmental factors (Green & Griffin, 1982; Halanski & Noonan, 2008; Proske & Morgan, 2001; Shen, 1975). These contractures are often presented as indentations on the skin, improper gaits, or the inability for the child to properly adduct or abduct the hip. These contractures, if left untreated, can lead to further gait cycle problems as well as other deformities such as a shortening of the leg. The muscles within the abduction group vary depending on publication however, it is commonly accepted that the Gluteus Medius, Gluteus Minimus, and the Tensor Fasciae Latae are the primary abductors (Duda, Brand, Freitag, Lierse, & Schneider, 1996; Flack, Nicholson, & Woodley, 2012; Merchant, 1965; Neumann, 2010).

Computational Models and Evaluations

Computational methods and models have become an incredibly useful tool within the sciences. With properly developed and accurate models and even with basic models, behaviors of a variety of phenomenon have been modeled and simulated in order to evaluate designs and naturally occurring structures. Computational models have grown in accuracy and have recently become a part of the biomedical field in the study of hips (Bachtar, Chen, & Hisada, 2006). These models, while few exist, have allowed for contact analysis of the hip joint as in the study done by Bachtar et al (2005), energy analysis within the surgical procedure of closed reduction from Zwawi et al (2016), and several other hip joint analyses (Ardila et al., 2013; Bachtar et al., 2006; Chegini, Beck, & Ferguson, 2009; Girish, 2017;

Henak et al., 2011). These analyses provide insight into the development, actions, morphology, stresses, strains, and forces that occur within the hip joint. However, while these models provide insights into the phenomenon that occur at the hip joint there are often sacrifices made in the development of the model or within the simulation such as in the study done by Ardila O. et al in 2013. Due to these constraints, some of the inaccuracies within the models, and the limited number of models that exist overall there is room for models to expand the accuracy of hip dysplasia simulations.

While a great deal of experimental data exists and there are studies that have defined some best practices within certain parameters. There is not enough justification mathematically or computationally for the clinical findings within baby wearing and treatment for developmental dysplasia of the hip. **Therefore, the purpose of this study is to create an accurate representation of an infant's hip joint with varying levels of an abduction contracture. In particular, models will be developed that can be used to computationally evaluate hip joint reactions, morphology, and growth patterns associated with abduction contractures that can be used in the prevention and treatment of hip dysplasia. These models will include important muscle and skeletal structures that will be able to be manipulated in order to represent an infant with varying levels of an abduction contracture.**

With these objectives in mind, three hypotheses can be developed:

- With a complete skeletal model of the hip joint, the core structures important to the hip joint with hip dysplasia and an abduction contracture are the Gluteus medius and minimus and these muscles allow for the proper distribution of stress within a healthy joint.
- With the inclusion of the aforementioned structures, passive stresses that are developed within the healthy hip joint will resemble previous studies.
- Abduction contractures contribute to the development or re-development of hip dysplasia and the level of contracture as well as grade of dysplasia contributes to this development.

Having limited computational evaluations for developmental dysplasia of the hip in conjunction with the problems, such as osteoarthritis, it is known to cause, it is imperative that models, such as the one proposed, evaluate varying diagnoses. This would not only answer the above questions, but also to allow for more accurate studies to be performed. These studies, when using an accurate model of the hip joint, would allow for the evaluation of new surgical, non-invasive, and preventative measures to be developed. In addition to new methods being developed, current treatment methods and assumptions could be evaluated to create a better treatment plan for patients and an easier regimen for parents. It also would allow for the evaluation of current preventative measures such as baby wearing and swaddling techniques. With each of these possibilities and previous limitations and studies in mind this model has the potential to change the way developmental dysplasia of the hip is analyzed and treated.

Chapter 2

Literature Review

Developmental Dysplasia of the Hip (DDH) is a prevalent disorder within infants that describes a condition in which a child's hip is on a spectrum of instability that ranges from minor instability to complete dislocation and irreducibility of the hip (Dezateux & Rosendahl, 2007). DDH replaced the previous terminology of Congenital Dysplasia of the Hip (CDH) after studies found that while there were genetic factors that played a part in the disorder it was possible to develop the condition over time and that the identifying factors for the disorder also changed over time (Aronsson, Goldberg, Kling, & Roy, 1994). With this observation and change in name, came a recommendation that examinations change from the original single exam at birth to a series of examinations that occurred during the growth of the child. This recognition, as well as the change in name, shifted the view of dysplasia from one that could only appear at birth to one that could develop during the early stages in life (Aronsson et al., 1994). Because DDH is a disorder that encompasses such a variety of hip maladies it is important to define what the maladies may include or what may be seen during a screening. "DDH includes hips that are unstable, malformed, subluxated, or dislocated," (Aronsson et al., 1994; Dezateux & Rosendahl, 2007). At its core, instability of the hip is "the inability to resist an externally applied force without developing a subluxation or dislocation," according to Aronsson et al., 1994. Meaning that if an external force is applied in any direction to the hip and the hip joint moves close to out of socket or completely out of socket then the hip is dysplastic. Subluxation, is a partial dislocation of the femoral head from the acetabulum. Therefore, if an external force is applied to the hip, the femoral head will shift to a position that is not entirely out of socket, but instead may be sitting on the posterior, lateral edge of the acetabulum or at a different position within the acetabulum. A complete dislocation is when the femoral head moves entirely out of the socket and rests outside of the acetabulum (Aronsson et al., 1994; T. C. Clarke C., Judd J., 2016b; French & Dietz, 1999).

Diagnosing DDH

DDH, being a disorder that falls on a spectrum, can be diagnosed in a couple of ways. These diagnoses techniques are performed in two ways, physically and through imaging instrumentation. The standard for physical examination was implemented in "many countries after the publication of two landmark studies in 1962," (French & Dietz, 1999). The two primary physical examination techniques used for diagnosing hip dysplasia are the Ortolani and Barlow maneuvers (French & Dietz, 1999). These maneuvers both require the infant to be calm and in no way fussy. This is primarily due to the fact that if the neonate is moving erratically the muscle activation within the legs may inhibit the movement of an unstable hip (French & Dietz, 1999). If the hip is being moved erratically or the infant is flexing the muscles surrounding the hip the results of the tests will be distorted and normally the results will not be used in a diagnosis. However, if the child is relaxed it is possible to perform the tests and arrive at a possible diagnosis. Both tests, through the movement of the hip, seek to feel for instability or a dislocation within the hip. Before the neonate has the tests performed on the hips identification of possible dislocation or instability is possible through observation (Aronsson et al., 1994). The examiner is attempting to identify any asymmetry between the two lower limbs. This asymmetry could appear in the form of asymmetric thigh folds, an appearance of having a shorter leg, a prominent greater trochanter, or limited abduction or adduction of the hip (Aronsson et al., 1994). Once one of these observations has been made, the Ortolani or Barlow test is done. According to French and Dietz, "for the examinations the infant's hips are flexed to 90 degrees; the thumbs of the examiner are placed on the medial proximal thigh, and the long fingers are placed over the greater trochanter," (1999). This however, is where the two tests begin to differ.

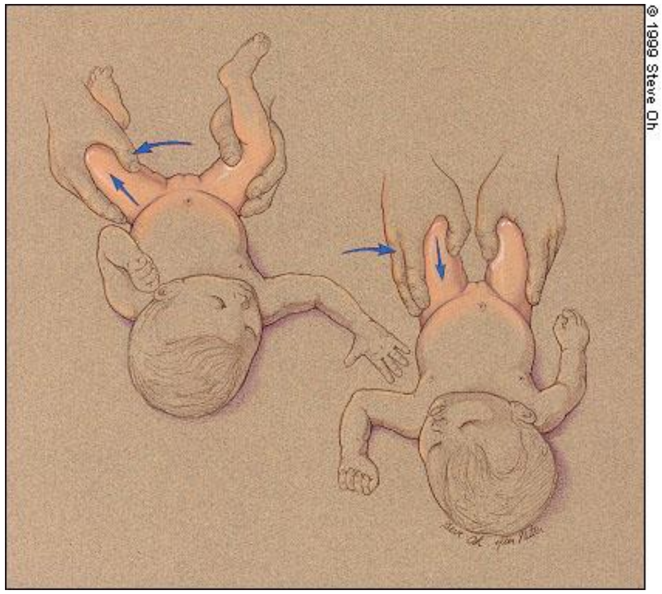

Figure 4: The Ortolani Maneuver (Left) and the Barlow Maneuver (Right) (French & Dietz, 1999).

For the Ortolani maneuver, with the thumb placed on the medial proximal thigh, and the long fingers placed on the fingers over the greater trochanter, the physician seeks to feel or even hear a “clunk” as the femoral head moves over the acetabulum (Dezateux & Rosendahl, 2007; French & Dietz, 1999). If this clunk or any instability is felt there is a possibility of diagnosis. In addition to the dislocation, if the femoral head is already dislocated the movement can also be used to test the ability of the femoral head to reduce back into the socket (Aronsson et al., 1994). If the femoral head is able to reduce back into the socket then the hip is considered reducible.

The Barlow test still attempts to dislocate the hip as seen in figure 4. However, the test attempts to dislocate the hip through the adducting the hip and gently applying pressure towards the posterior of the infant via the knee (Aronsson et al., 1994). If the hip slips over the posterior of the acetabulum there is normally an audible “clunk” indicating the dislocation of the femoral head. This test is usually performed in tandem with the Ortolani test in order to increase the likelihood of dysplasia detection.

Unfortunately, these tests usually only can be performed during the first 10 to 12 weeks of life due to the reduction of ligament and capsular laxity (Aronsson et al., 1994).

However, if both hips are dislocated or have severe instability it can be more difficult to detect the inconsistencies within the leg length or the irregular thigh folds, thereby making the tests circumstantial in effectiveness. In addition to the lack of external observational signs it is possible that due to the severity of the dislocation that the hips will in no way reduce or maneuver in a way that makes the “clunking” sound and therefore may cause the severe dysplasia to go undetected. As the child ages there may be other physical signs as well, in particular, when the child approaches walking age there can be a significant limp or oddities within their gate that can indicate DDH (Aronsson et al., 1994; Dezateux & Rosendahl, 2007; Kotlarsky et al., 2015).

Imaging for Diagnosis

In addition to the physical clinical examinations it is also possible for hip dysplasia to be detected through imaging examinations (Clarke C., Taylor C., & J., 2016; Dezateux & Rosendahl, 2007; Kotlarsky et al., 2015). There are a few imaging examinations that are commonly used in addition to the physical examinations. It is common for imaging techniques to be used after instability or dislocation is detected within the hip from a physical examination these examinations include sonograms, radiographs, and magnetic resonance imaging (MRI). However, there are some countries where imaging is required upon the birth of the child. There have been issues with overdiagnoses due to the use of imaging examinations and the requirement of imaging to detect DDH is still debated.

The most common form of electronic imaging used for diagnoses is an ultrasound. This is primarily due to the ability to diagnose the infant relatively quickly and that the ultrasound does not introduce high levels of radiation to the infant. Meaning that even when the infant is within its first week or even day of life an ultrasound can be used in order to properly diagnose the infant with DDH.

The ultrasound is also the means by which the Graf system of categorizing hips was developed. Through the screening of over 3000 infants the classification system was developed and is still in use today. This procedure is done with the infant in the static decubitus position with the hip at 35 degrees of flexion and 10 degrees of internal rotation (Aronsson et al., 1994). Three lines are then drawn on the image and a series of angles are measured between the three lines. (Figure 4)

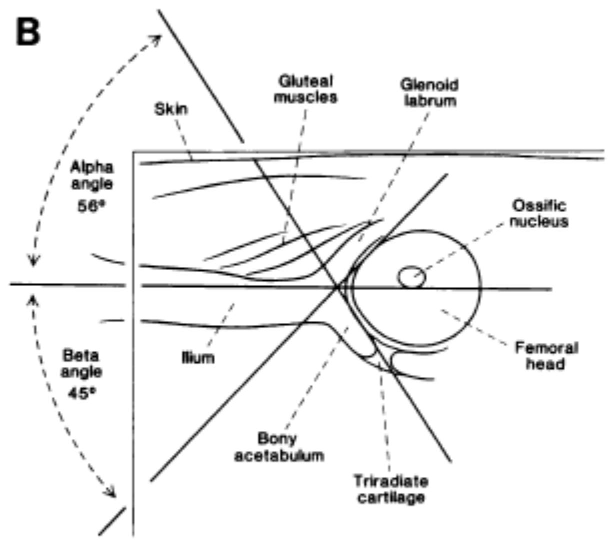

Figure 5: Ultrasound drawing of a 7-month old infant with the three lines and two angles used in static ultrasound examination (Aronsson et al., 1994).

These angles are then used to determine the level of dysplasia within the hip. In particular, if the alpha angle is measured to be greater than 55 degrees the angle is thought to be normal and for the beta angle if it is measured to be less than 72 degrees it is thought to be normal (Aronsson et al., 1994). However, there are problems with the static method. The largest problem being that the alpha and beta angles are not easy to reproduce when attempting to take images of the infant repeatedly and if the image is not precise or the placement of the infant is not correct than the hip may appear to be more dysplastic than it really is (Aronsson et al., 1994). In addition to the static method of examination there is also the dynamic method described by Aronsson et al, 1994. This method seeks to observe the Barlow and Ortolani maneuvers. Just like the physical examination posterior stress is applied to the knee and subluxation or dislocation is noted. In addition to any motion felt by the examiner the imaging will also show the movement and allow for a better diagnosis. After the Ortolani and Barlow tests are performed with the ultrasound additional images are taken in the transverse plane in order to visualize "the position of the femoral head with respect to the triradiate cartilage of the acetabulum." (Aronsson et al., 1994). After both forms of dynamic screening a diagnosis is then given to the infant. However, the use of the ultrasound has resulted in a high false positive rate as well as a high treatment rate (Aronsson et al., 1994; Dezateux & Rosendahl, 2007).

Ultrasounds are not the only form of imaging used on infants during early life in the diagnosis of DDH. Radiographs are another common imaging technique used with infants in order to determine dysplasia or the type of dysplasia the infant may have. Unfortunately, the radiograph is difficult to interpret during the neonatal period due to the cartilaginous nature of the femoral head and the pelvis (Aronsson et al., 1994; Kotlarsky et al., 2015). Therefore, the radiograph is usually unreliable until ossification has occurred within the femoral head. This ossification normally occurs around 6 months of age and it is then more reliable. In addition to the radiograph, Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) have been used to examine infant hips. However, while there is limited exposure to radiation with the CT scans there is still radiation involved and for that reason the MRI is preferred to the CT. Unfortunately, the MRI is not always consistent with respect to protocols used in the process of obtaining the images and may sometimes require sedation of the infant (Kotlarsky et al., 2015). Therefore, with the drawbacks of most imaging processes it is common to see the ultrasound used in addition to the clinical examinations. After diagnosis, a treatment plan is then issued to the infant in order to correct the dysplasia.

DDH Treatments

There are a wide variety of treatments for DDH but overall, there are two groups for the treatment, surgery and harnesses/external treatment devices (Kotlarsky et al., 2015). After diagnosis and based on the severity of the DDH a treatment is prescribed in order to correct the instability or dislocation within the hip. This treatment normally comes in two forms. First, a harness is prescribed to the patient in order to attempt reduction of the hip and correction of the hip dysplasia over time. This is normally an effective form of treatment and the standard in most societies is the Pavlik harness (Ardila et al., 2013; Aronsson et al., 1994; Atrey & Katchburian, 2010; Dezateux & Rosendahl, 2007; Kotlarsky et al., 2015). The Pavlik Harness and the other harnesses are often prescribed within the first few weeks of the neonate's life and seek to correct the current type of Hip Dysplasia as well as prevent further development of hip dysplasia within the neonate. If the harness is ineffective or doesn't correct the dysplasia fast enough a surgical approach may be taken. The surgical approach is often done in more severe cases or in cases where the hip does not reduce or improve with previous treatment (Kotlarsky et al., 2015). There are two surgeries that are normally performed and they are known as open and closed reduction surgeries. These surgeries seek to force the femoral head back into the acetabulum and in severe cases change the angle and location of the acetabulum or the anteversion of the hip (Zwawi et al., 2017). However, due to the need to use general anesthesia on the infant during the surgery and for the removal and replacement of the casts every few weeks after the surgery, the operations are seen as a last resort in treatment.

There are a variety of harnesses used throughout the world including the Pavlik Harness, Craig Splint, the von Rosen splint, and the Ilfeld abduction orthosis (Sankar, Nduaguba, & Flynn, 2015; Wilkinson et al., 2002). Each of the harnesses seek to reduce and confine the hip in slightly different ways. These devices, at their core, seek to reduce the hip if it is in anyway dislocated, hold the hip in an orientation that is conducive to proper growth, and allow for enough movement to prevent avascular necrosis (Suzuki, 1994; Wilkinson et al., 2002). These devices accomplish this by moving the hips to an abducted and flexed position. In this position the hip is the most likely to reduce and is conducive to proper femoral head and acetabulum development (Suzuki, 1994). However, there are fundamental differences in how these harnesses accomplish this position. For this reason, certain harnesses or splints are preferred over others and certain harnesses/splints are more effective than others.

Currently the Pavlik harness is the most popular form of treatment due to its high success rate although it is possible that other harnesses could be more effective (Kotlarsky et al., 2015).

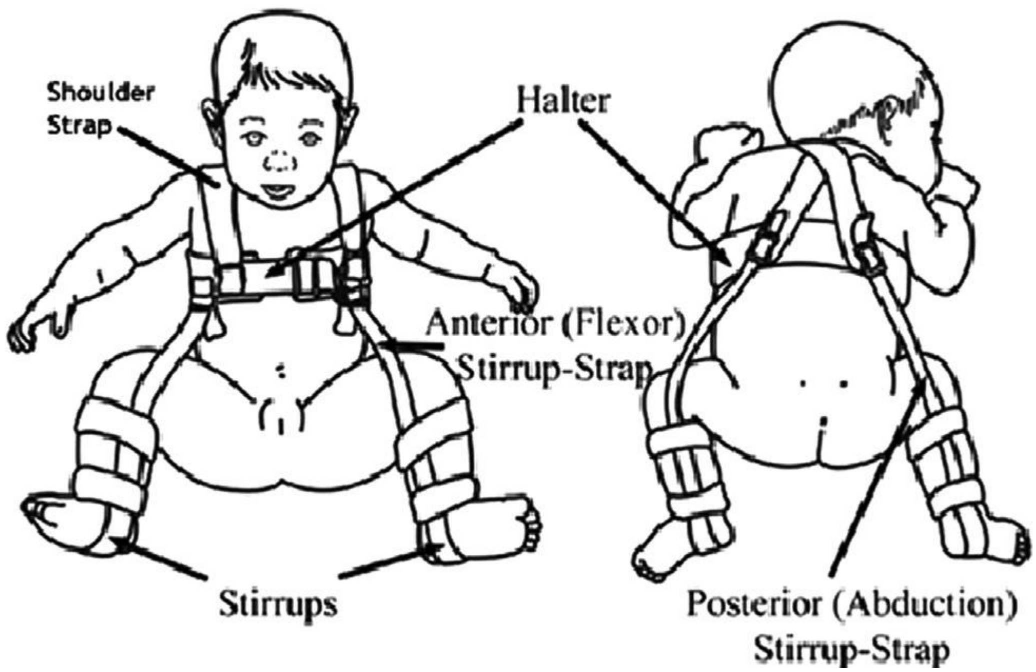

Figure 6: Pavlik Harness applied to an infant (Ardila et al., 2013).

As previously the Pavlik harness is the most common form of treatment for neonates after a diagnosis of DDH. This harness has been proven to be effective in up to 99% of all Graf III or lower cases and has been used extensively throughout the world (Atrey & Katchburian, 2010; Kotlarsky et al., 2015; Ömeroğlu et al., 2016). The system works by placing the feet of the infant in stirrups and using the anterior and posterior stirrup straps to abduct (posterior) and flex (anterior) the hips in a position determined by the attending physician for the treatment of the child. These straps are held in place using a touch fastener or buckles that are attached at the halter to the shoulder straps (Ardila et al., 2013). Often times a mark is placed on the straps in order to ensure that the harness is put in the same place after each removal. The system is preferred due to its pliability and high success rate. The pliability is important due to the need of the infant to be able to move its' hips during the treatment because without movement there is an increased likelihood of avascular necrosis. The system also can adapt to the shape of the child and is easy to adjust as needed by the attending physician. However, there are instances where this treatment is ineffective and therefore more drastic action must be taken in order to prevent further development of hip dysplasia.

After the failure of harness or splint treatment, the next step is surgery (T. C. Clarke C., Judd J., 2016a; Dezateux & Rosendahl, 2007). The surgeries are either open or closed reduction and both seek to force the femoral head back into the acetabulum. This is usually done through an osteotomy or a femoral head correction. An osteotomy is where the acetabulum is identified as malformed, underdeveloped, or is simply angled wrong within the pelvis to allow for the proper seating of the femoral head. Therefore, during an open reduction the pelvis is cut and the acetabulum is rotated in order to properly align it with the femoral head (Clarke C. et al., 2016). The femoral head is then placed back within the socket and the pelvis is put back together using screws and other devices to ensure there are no further problems with the hip joint during growth or adulthood. There is also a possibility that the femoral head is malformed within the hip joint. This can be due to developmental problems during the prenatal state or developmental problems that occur once the child is born. If the femoral head is deformed and is the cause of the dysplasia, surgical action is taken to correct the deformity and allow for proper growth.

After the hip has been reduced via surgical means it is then important to ensure that the hip remains properly positioned to allow for morphological changes to occur. This then requires the hip joint to be fixed or restrained in some manner to allow for proper healing. Often times this restraint is in the form of the spica cast. Treatment with a spica cast takes the infant and places a cast around the lower limbs with the hips both abducted and flexed. With the hips flexed and abducted healing process can then begin. Over the course of a few months the child's hip heals and develops the proper morphological interference between the femoral head and the acetabulum. During this time the femoral head takes its spherical shape and the acetabulum matches that shape as the socket. However, there are some risks involved. This includes skin deterioration or irritation, repeated exposure to anesthesia, and muscle contractures such as an abduction contracture (Halanski & Noonan, 2008; Kotlarsky et al., 2015; Reed, Carroll, Baccari, & Shermont, 2011; Sankar et al., 2015).

Abduction Contractures

An abduction contracture is an uncontrolled stiffening or contraction of the hip abductor muscles. This condition is known to be both congenital as well as developmental. Thereby meaning that an infant can be born with the condition or, as discussed earlier, it can be developed through injuries or treatments such as the spica cast. Due to the harsh level of abduction needed for the treatment of hip dysplasia during the casting process the hips can be left in a position that can cause a contracture. There are a few muscles most commonly associated with an abduction contracture including the following: Gluteus Maximus, Gluteus Medius, Gluteus Minimus, Tensor Fasciae Latae, and the Piriformis. These muscles, when uncontrollably stiffened or tightened, are known as an abduction contracture and often present themselves as an abnormal indentation in the skin, abnormal sitting conditions, gait cycle problems, or the inability to perform certain lower body movements such as squatting (Green & Griffin, 1982; Shen, 1975). These abnormalities have long standing negative effects and are therefore often met with surgery or physical therapy to help reduce the stiffness within the muscles. While a few clinical studies have been performed in order to understand the role abduction contractures may play in the development of DDH there is no definitive answer to whether or not an abduction contracture can cause hip dysplasia. There however, is an established connection between abduction contractures and contralateral DDH.

It is important to note that while no finite element models have been developed for abduction contractures there have been some clinical studies. Within those studies performed by Green et al. (1982), Somerville et al., and Shen (1975) it was observed that the contractures were linked to contralateral dysplasia of the hip with an increased level of force or stress on the acetabulum of the hip joint with the contracture. It has also been observed that when there is also an abnormal indentation of the skin there is also likely a skeletal skew (Green & Griffin, 1982; Shen, 1975; Somerville & Macnicol).

Gluteus Medius

The Gluteus Medius is considered the primary abductor of the hip and an important stabilizer of the pelvis (Retchford, Crossley, Grimaldi, Kemp, & Cowan, 2013). This muscle originates at the top of the iliac crest and inserts at the femoral head as seen in Figure 7. The Gluteus Medius is, like many other muscles including the Gluteus Minimus, a sheet of muscle. In addition to being a sheet of muscle it is also innervated by the gluteal nerve. This sheet of muscle is broken up into three sections known as the posterior, middle, and anterior parts as seen in Figure 7.

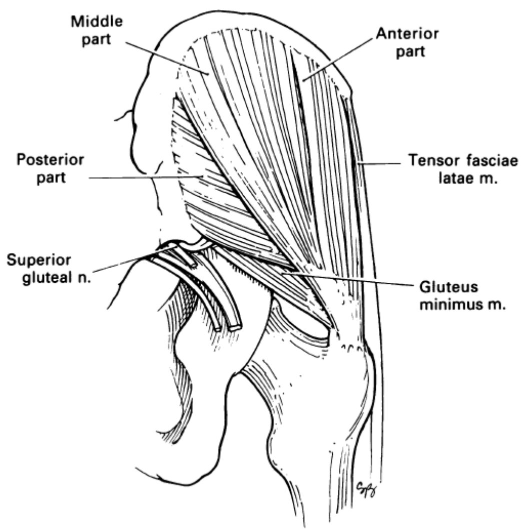

Figure 7: Drawing of the Gluteus Medius and Minimus (Gottschalk, Kourosh, & Leveau, 1989)

The break-up of the muscle into three separate sections is also important to note due to the phasic activation the muscle experiences during various activities such as walking or standing. (Gottschalk et al., 1989; Retchford et al., 2013)

Gluteus Minimus

The Gluteus Minimus, is similar to the Medius in several ways. Primarily the gluteus minimus is known as a hip abductor but it also is known for playing a major role within the stabilization of the hip. This stabilization comes into play primarily during walking or standing and is known to help keep the femoral head properly seated within the acetabulum (Flack et al., 2012; Gottschalk et al., 1989). Similarly, the medius also is a sheet of muscle but, due to its consistent muscle fiber orientation is not always broken into three distinct sections. The Gluteus minimus lies underneath the medius and originates from the anterior inferior iliac spine to the posterior inferior iliac spine as seen in Figure 8. Its insertion point is at the inner aspect of the anterosuperior margin of the greater trochanter (Flack et al., 2012; Gottschalk et al., 1989; Robertson et al., 2008).

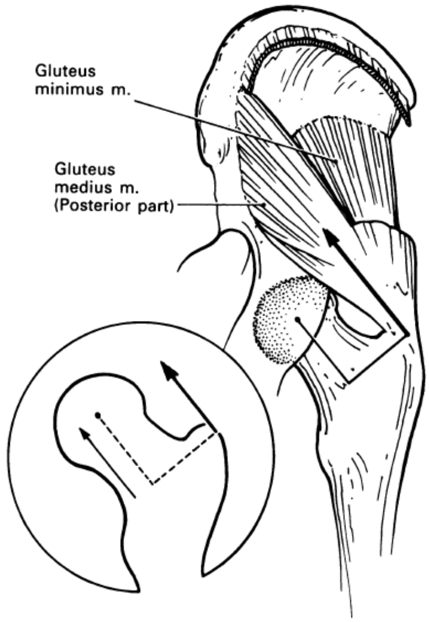

Figure 8: Gluteus Minimus insertion and origin

Prevention of DDH

It is always better to prevent DDH rather than having to diagnose and treat an infant for the condition. Unfortunately, DDH cannot always be avoided due to some of the genetic factors and predispositions certain infants may have due to the nature of their birth. It is possible however, to prevent certain cases of hip dysplasia and in particular allow for the proper development of the hip. Therefore, it is important to not only look at the state at which an infant is born but also at the way a hip is swaddled and positioned during the development of the infant in the early stages of life. Some of these preventative measures include babywearing and proper swaddling techniques. Preventative measures in baby wearing primarily rely on the abduction and flexion of the hips of the infant. This preventative measure has been observed naturally in places like Africa, China, and Northern Canada where the children are commonly worn on the mother during the first few months of life (Figure 9).

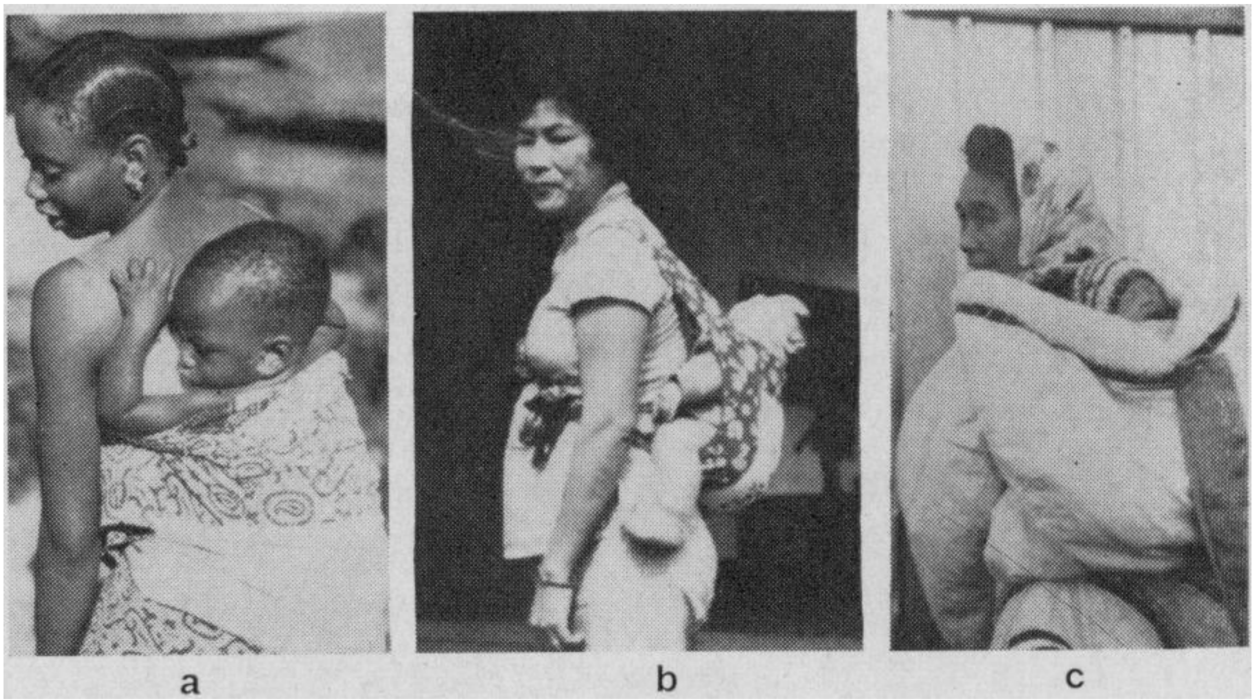

Figure 9: (a) – Nigerian woman carrying her child on her back, (b) – Chinese infant being carried in a sling with the hips observably abducted and flexed, (c) – Northern Canadian Eskimo carrying her infant on her back with the hips in an abducted and flexed position. (Girish, 2017; Graham et al., 2015)

This position has been used by these groups for extended periods of time and due to the similarity of the carrying method to that of the treatment of the Pavlik harness it is likely that baby wearing in these positions can help reduce the number of incidents of DDH in infants. In addition to the groups mentioned in Figure 9 there are other groups such as the Bantu as well as the native population of Malawi that have shown a small incidence of DDH (Graham et al., 2015; Roper, 1976; Salter, 1968). While genetic factors may still play a large part in the low incidence of dysplasia, it is likely that the environment and positioning of the hip still play a large role in the development of the hip overall. This has been validated by the treatments used to prevent DDH as the hip is placed in a manner that is abducted and flexed in a similar fashion to the way infants are carried in Africa, China, and Northern Canada.

In addition to the way the infants are carried by the mothers there are other environmental factors that can play a role in the development of hip dysplasia. In particular, improper swaddling techniques have been attributed to the malformation of infant hip jointss in specific groups of people. These improper swaddling techniques normally include the extension and adduction of the hips so that the infant is laying in a flat and extended position as seen in Figure 10.

Figure 10: Infant swaddled with the hips extended and adducted on a cradleboard from a Northern Canadian Indian tribe (Salter, 1968).

The infant above is swaddled in a manner where the legs are tightly held in the adducted and extended position and is believed to contribute to a higher incidence of developmental hip dysplasia (Salter, 1968). With this type of swaddling identified, other groups with similar swaddling styles were identified as well with similarities existing between some Northern Italian, Northern Scandinavian, and Japanese swaddling techniques (Graham et al., 2015; Salter, 1968). After these techniques were identified as possible causes for dysplasia, a program in Japan was implemented to change the swaddling habits of the local population and after enacting new techniques the program was able to reduce the rates of DDH in Japan from 1.1% to 3.5% pre-1965 to around .2% (Graham et al., 2015). Thereby meaning that through the introduction of proper swaddling techniques or reducing the time infants are swaddled in an adducted and extended position DDH can be reduced significantly in a population. With this in mind it is important to then develop proper models of infant hips in order to allow for the simulation of various baby wearing techniques in order to determine which positions allow for proper formation of the hips.

Modeling DDH

There are models that currently exist of the infant and adult hip. Some of these models are dysplastic in nature or are meant to represent a dysplastic hip while others seek to accurately simulate healthy hips or specific portions of the hip joint. These models are useful when looking at specific cases and often allow for conclusions or assumptions to be made about the human hip. For DDH a few models exist and while some models do contain some structures of the hip none of the models contain most of or all of the structures within the hip (Ardila et al., 2013; Bachtar et al., 2006; Chegini et al., 2009; Giorgi, Carriero, Shefelbine, & Nowlan, 2015; Henak et al., 2011; Huayamave et al., 2015; Zwawi et al., 2017). Each of the models also focus on a particular problem or seek a specific solution for DDH.

An example of such a model was created by Chegini et al 2009 and sought to analyze walking and sitting in conjunction with DDH. This model looks at the relationship between impingement of the femoral head and dysplasia of the hip with sitting and walking. Von Mises stresses were observed within the acetabular cartilage for a variety of joint geometries and these stresses were then used to determine possible wear patterns and damage that could occur to the hip joint. After data collection, it was compared to previous clinical and experimental data and verified by the similarity of their simulation to observed wear patterns and stresses. This simulation accurately represented previous data and observations of the acetabular cartilage and the labrum. However, it is important to note their assumptions. In particular the generalization of the articular cartilage, the model not being generated through segmented geometry from a scan of an actual patient, and the need to smooth out geometry for computational simplicity to reduce complexity are important (Chegini et al., 2009). While generalizations can be made from this model and it does match current clinical studies and observations. This study also does not seek to simulate the hip of an infant but instead the hip of an adult. Conclusions were made based on the measured data and most significantly it was concluded that stresses within the hip depend "on joint geometry, motion and load," and that degeneration of the dysplastic joint is likely unavoidable (Chegini et al., 2009).

The next model is a contact analysis of the hip joint that represents three daily activities for an adult: walking, rising from a chair, and knee bending (Bachtar et al., 2006). This model in particular used scans of a 71 year old female cadaver and used an assembly of the pelvis and femur created within PATRAN; MSC Software, USA (Bachtar et al., 2006). After the creation of the model using the CT scans simulations were run for each of the activities mentioned above. The analysis was done using a non-linear finite element method which allowed for the determination of the maximum stress in the hip joint during various daily activities. Again, a smoothing algorithm was used in order to reduce computational complexity but the results are comparable to previous experimental results (Bachtar et al., 2006). The highest levels of stress within the hip joint being located on the femoral head in the superior and antero-superior regions. However, it was concluded that the stresses varied based on the activity that was occurring during the analysis (Bachtar et al., 2006).

The next study again is an analysis of the adult hip but in particular it sought to analyze the role of the Labrum in load support within the hip joint (Henak et al., 2011). The model was developed through the use of volumetric CT data. A finite element analysis was performed on a hip joint with and without the labrum as well as a dysplastic and non-dysplastic hip (Henak et al., 2011). This allowed for the observation of the role the labrum plays in the hip in regards to load support in hips that are properly formed as well as in hips that have dysplasia. The study concluded that within the dysplastic hip the labrum was more important in the support of loads than in the normal hip (Henak et al., 2011). This greater support is attributed to the location of the femoral head within the acetabulum for hips with acetabular dysplasia.

In addition to models created to simulate the adult hip a variety of models have been created to simulate infant hips with DDH. These include a simplified model that sought to analyze reductions of the hip in regards to the Pavlik Harness, morphogenesis of the prenatal hip joint, a patient specific model of the biomechanics of hip reduction for low to severe grades of hip dysplasia, and the path of least energy for closed reduction of the hip. Each of these models seek to develop or confirm data in a computational method and through various model types creates useful information and practices for the treatment of hip dysplasia in neonates.

The first of these models was developed by Ardila et al (2013) and used FEA to obtain a detailed analysis of DDH reductions during the use of the Pavlik harness. This model sought to simulate reduction of the hip joint with the Pavlik harness using a simplified model of the pelvis, five muscles (Pectineus, Adductor Longus, Adductor Brevis, Adductor Magnus, Gracilis), and the femur (Ardila et al., 2013). Through this simplified model the five muscles were concluded to be influential in the reduction of the hip for Graf III and lesser rated hips and detrimental to reduction in the Graf IV hip. In addition to the conclusion on the muscles the data noted that reduction occurs in two distinct phases: Release and reduction. This data and the study as a whole was consistent with previous observations and studies and possibly provides ways to better issue treatment to neonates with Graf I-III DDH (Ardila et al., 2013).

In addition to the previous study that sought to look at five specific muscles for Pavlik Harness reduction of the hip this study “A patient-specific model of the biomechanics of hip reduction for neonatal Developmental Dysplasia of the Hip: Investigation of strategies for low to severe grades of Developmental Dysplasia of the Hip" used the same five muscles when looking at a more complex model of the hip based on the CT scans of a 10 week old female infant (Huayamave et al., 2015). This model, due to its complexity, offered new insights into the usefulness of the five adductor muscles for hips from Grades 1-4. The study concluded that passive muscle force contribution to hip reductions are a function of the severity of the dysplasia and that non-surgical treatments could be improved. In addition to the findings there is also a plan to include more muscles and structures in order to properly represent the hip joint.

The next model is within was developed by Zwawi et al., (2017) and sought to find a path of least energy for the reduction of the hip in a Grade IV dislocation. The model was constructed using a combination of MRI and OpenSim data in which the right half of the pelvis and the right leg were constructed skeletally. This study identified two pathways of reduction and both pathways were in accordance with previous clinical observations (Zwawi et al., 2017). These two pathways are identified as the Papadimitriou and the Hoffman-Daimler pathways with the Hoffman-Daimler being the pathway that requires the least energy overall. However, some assumptions such as the assumption that the system was frictionless and the assumption that there was no cartilage deformation within the model are drawbacks within the model and therefore require further investigation with more structures (Zwawi et al., 2017).

The final model developed and analyzed by Giorgi et al., (2015) sought to observe and simulate the morphogenesis of the prenatal hip joint. While this model is not part of the study within DDH for a neonate it does have implications for the neonate. In particular, it demonstrates that normal fetal movements are important to the development of the infant's hip in particular when it came to the depth and shape of the acetabulum. It also demonstrates that abnormal movements, such as those that cause the infant to enter the breech position, are a part of the reason that infants born in that position have a predisposition to DDH (Giorgi et al., 2015).

The proposed model seeks to develop accurate representations of three infant hips with varying levels of dysplasia and abduction contractures. Through the combination of structures mentioned above and using similar methods in regards to the collection of CT data and model creation the three models seek to be usable models within this study as well as other studies. Applying proper boundary conditions and functions by which the muscles will perform will allow for the accurate representation of the three dysplastic neonatal hips and therefore accurate simulations of abduction contractures within infants with hip dysplasia. With accurate simulations in place for the three hips in various conditions it is possible that best practices or new practices may be established in the endeavor to treat and prevent developmental dysplasia of the hip.

Chapter 3

Methods:

Dysplastic Hips have been evaluated in both clinical and experimental studies throughout the study of DDH. Some of these methodologies have particular applications when it comes to treatment, evaluation, or ascertaining better understanding of the complexities involved with DDH, these being studies such as the one performed by Zwawi et al. (2017) where a path of least energy was developed to help improve the reducibility of a hip as well as the study performed by Suzuzki (1994) where visual evidence of hip reduction due to the use of the Pavlik harness was presented. However, when it comes to the creation and evaluation of models that will be used in the simulation of the disease there are many studies that follow a strict set of methodology that allow for useful outcomes to be achieved. A few of these studies include similar methodologies in order to achieve an understanding of the hip joint and DDH as well as the treatments used to eliminate the condition(Ardila et al., 2013; Bachtar et al., 2006; Chegini et al., 2009; Huayamave et al., 2015; Zwawi et al., 2017). In particular, Bachtar et al., Henak et al., Huayamave et al., and Zwawi et al. all used similar methodologies in the creation and evaluation of hip models in order to accurately portray the condition of DDH. Each of the studies first required data from actual patients who had the disease. This included CT or MRI scans from patients affected by DDH and then a reconstruction of the scans using a segmenting software that would properly layer and develop a rough 3D model of the pelvis and femur. This rough model was then processed in order to reduce any inconsistencies or jagged surfaces that existed on the pelvis due to the CT or MRI scans as well as potentially reduce the amount of computational power needed in order to simulate the hip. These models were created using a variety of software including ABAQUS, SolidWorks, and PATRAN with segmentation from CT and MRI scans processed from ScanIP, Amira, and Mimics. The software allows for the proper reconstruction of patient data as well as the smoothing and correction of the 3D models produced. After developing the models of the bones based on patient data the muscles were modeled using mathematical models and estimations that have been previously established (Huayamave et al., 2015; Zou, Chávez-Arreola, Mandal, Board, & Alonso-Rasgado, 2013).

The similarities between this study and the study performed by Huayamave et al., 2015, the methodology and procedures used will be similar in nature. After the modeling of the soft tissue the models can then be assembled and evaluated primarily for stresses and contact surfaces (Ardila et al., 2013; Bachtar et al., 2006; Chegini et al., 2009; Giorgi et al., 2015; Henak et al., 2011; Huayamave et al., 2015). After the aforementioned values are obtained, they will then be compared to previous studies as well as the studies listed above.

Padua Specimens and Muscle Choice

For the purposes of this study, both photos and scans of two specimens from the collection of infant bones in Italy were given to us through collaboration with Dr. Charles Price M.D. These specimens were of infants still in early life and were each given a rating for the level of dysplasia the hip displayed. The specimens, as seen below, are the following: Specimen 387 Left Hip – Grade A Dysplasia, Specimen 387 Right Hip – Grade B Dysplasia, and Specimen 30 – Grade C Dysplasia. Once the photos and scans were obtained, they were then uploaded into ScanIP for proper segmentation and meshing.

Figure 11: Specimen 387 Complete Pelvis

Figure 12: Specimen 30 Complete Pelvis with Femurs

Scans and Segmenting

This study, like many before it, required the use of actual patient data so that accurate models of each of the Graf rated hips can be evaluated. (Ardila et al., 2013; Bachtar et al., 2006; Chegini et al., 2009; Huayamave et al., 2015; Zwawi et al., 2017) Therefore, 3 sets of CT scans were collected of three infant dysplastic hips from the Padua collection and are estimated to be within the first year of life. Each of the initial specimens were evaluated and assigned grades of dysplasia prior to scanning as stated previously. The acquisition of CT scans allowed for accurate measurements of the pelvis, femur, and the surrounding musculature. Once the scans were acquired, they were segmented using ScanIP. While this data will be accurate to the patient data, there is a limitation within the software as we were segmenting them off of CT scans. These limitations primarily come in the form of resolution issues such as a CT scan taking pictures in slices of a few millimeters or even within the smoothing algorithms that create a geometry that is easier to work with computationally. This piece of software allowed for the segmentation and generation of 3D models based on a composition of scans. The scans themselves were uploaded into the processing software and then stacked three dimensionally to produce a solid geometry. The data was then cleaned and refined using data filters within the segmentation software to allow for the extraction of structures key to the study. After proper filtering and extraction, a 3D mask was created representing the specimen's musculoskeletal structure as in Huayamave et al. where a multi part model was developed using the CT scans of the particular specimen in order to have bone geometry for the study.

Assembly

Once each of the aforementioned steps were completed and verified for a single model the remaining fourteen models were developed in the same manner. The fifteen models consisted of 5 models each developed for one particular specimen. Each specimen was divided into 5 different levels of abduction contracture. Therefore, specimen 30 had 5 levels of contracture consisting of 15 degrees of adduction, the anatomical position, 15 degrees of abduction, 30 degrees of abduction, and 45 degrees of abduction. These levels of adduction and abduction were then replicated in the following two specimen 387 models. An example of the progression of the models is seen in the figure below.

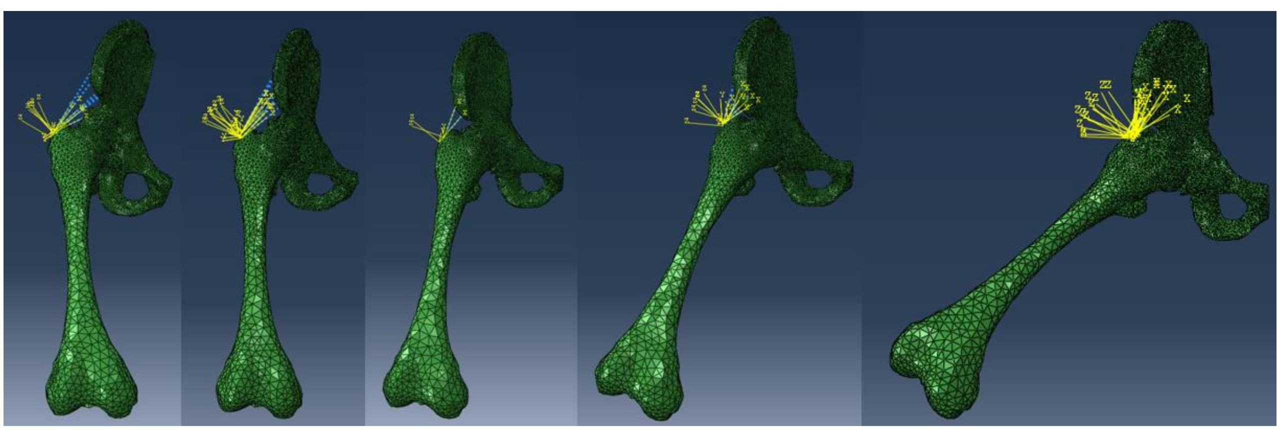

Figure 13: Progression of abduction in Specimen 30

It is also important to note that the femur was put in a position of flexion at 20 degrees to prevent impingement of the femur on the acetabular rim during the assembly process. This change in flexion recommendation was due to instruction by Dr. Charles Price M.D. to prevent the impingement.

Meshing

After proper segmentation and mask creation the model was then meshed using Simpleware ScanIP. A mesh was applied to the pelvis and the femur using the ScanIP auto-meshing features as seen below.

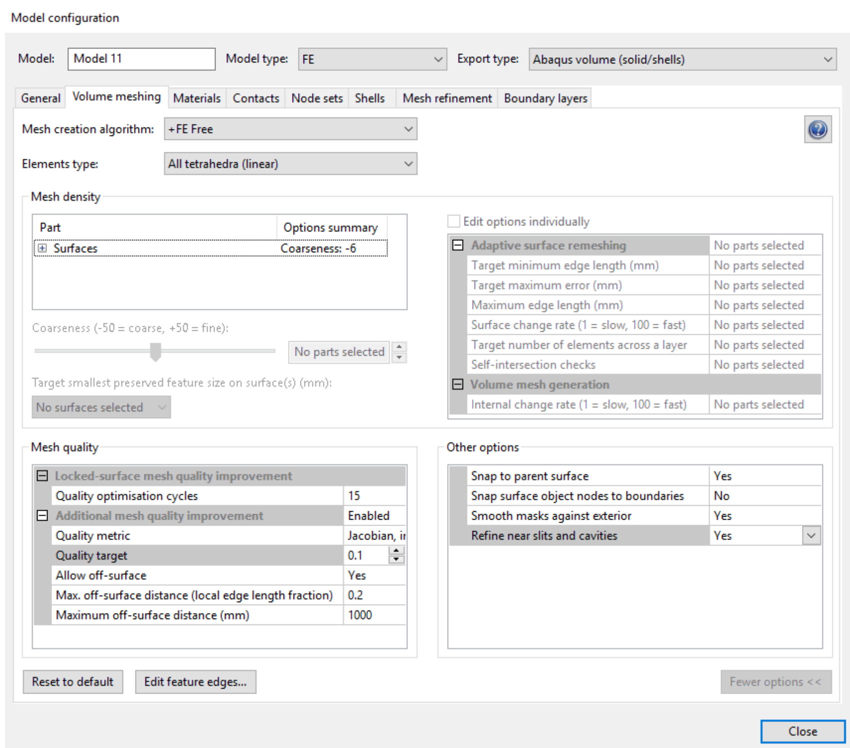

Figure 14: Meshing Interface for ScanIP

Within this interface, for each of the 15 models generated, varying values of coarseness were assigned to each of the models in order to determine the number of elements that would make up the model. The coarseness was the only setting within the meshing process that varied. Otherwise, each of the models were meshed with linear tetrahedra, were smoothed against the exterior, refined near slits and cavities, and were also given 15 quality optimization cycles to ensure that each mesh was able to properly run with contact interfaces with ABAQUS.

However, before any simulations can actually occur material properties need to be applied to the system in order to properly analyze the forces, stresses, and strains that are occurring within the system. While most bone structures are treated as solids in adults, in infants the bones that make up the hip have not yet fully ossified. Therefore, the bones themselves cannot be treated as complete solids and are usually considered cartilaginous. In addition to representing the bones as cartilaginous the muscles also need to be assigned proper stiffness values to truly be able to represent an abduction contracture.

Material Properties

Modeling the femur and the pelvis as cartilaginous structures was done through an isotropic elastic material based on previous values established by Shefelbine et al. 2004. The cartilaginous material properties are representative of an infant in the early stages bone development with a Young's Modulus of 5.96 MPa and a Poisson's ratio of .49 (Shefelbine & Carter, 2004). Therefore, making the materials fairly incompressible and giving them ability to deform or change morphologically over time.

Muscles

It is important to note, that the muscles also need to be given proper material properties in order to correctly represent an abduction contracture within an infant with DDH. As stated previously the muscles chosen for the study were the Gluteus Medius and the Gluteus Minimus. Based on the muscles' shape, and using OpenSim as a reference, the muscles were modeled as muscle lines of action (Blemker & Delp, 2005; Delp et al., 2007; Delp et al., 1990; Flack et al., 2012; Kumagai, Shiba, Higuchi, Nishimura, & Inoue, 1997; Merchant, 1965; Retchford et al., 2013). This consisted of developing 6 lines of action to represent each component of only the Gluteus Medius and Minimus as seen in both

OpenSim and a finalized model below. The Gluteus Medius and Minimus were chosen due to their lack of muscular wrapping within the OpenSim model as well as the knowledge that they are two of the primary hip abductors (Flack et al., 2012; Kumagai et al., 1997; Merchant, 1965; Somerville & Macnicol).

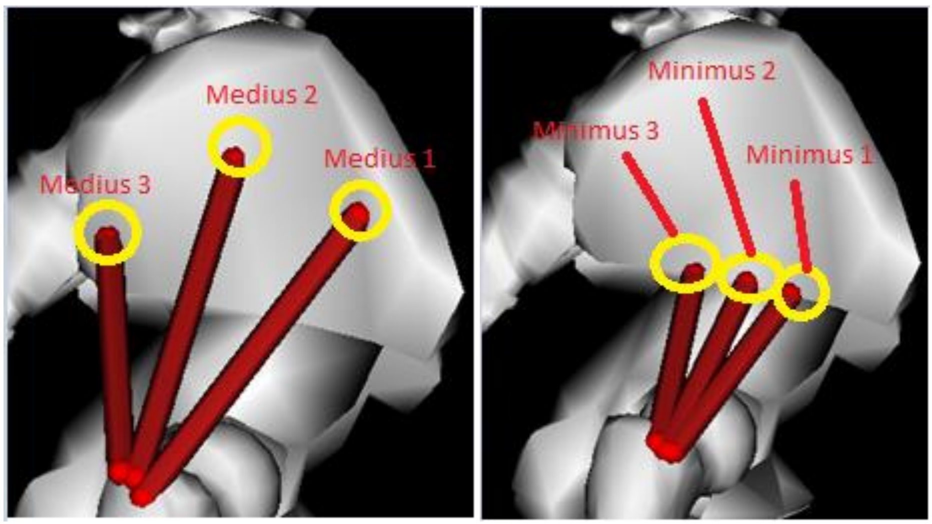

Figure 15: Muscle Lines of Action within OpenSim (Delp et al., 2007; Delp et al., 1990)

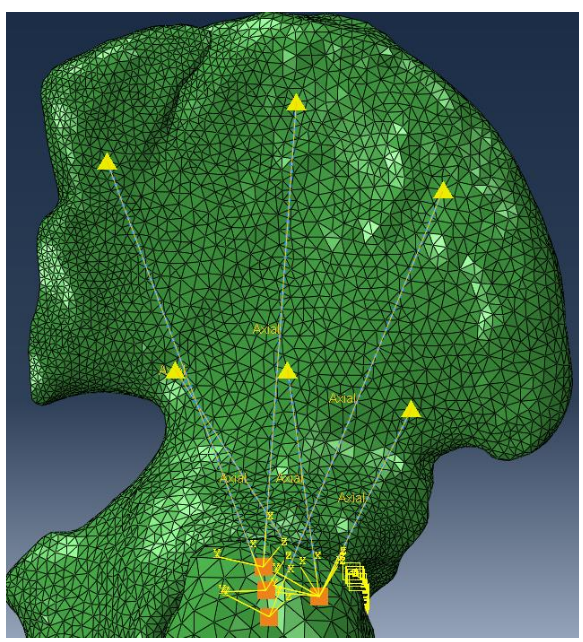

Figure 16: Muscle Lines of Action as established within the models and based on OpenSim

As seen in the figures above, the Gluteus Medius and the Gluteus Minimus are broken up into three separate lines of action and are labelled as such. These lines of action are also assigned varying muscle properties depending on their location and physiological cross sectional area which will be defined later.

While the muscle lines of action do represent the actual functionality of musculature within the human body well it is not necessarily capable of completely capturing every function or force output the muscle can develop. Therefore, while the lines of action are accurate representations there are still limitations to their capabilities and therefore limitaions on the model.

The muscles were modeled using Fung/Hill models "which are extensively used for biological soft connective tissue based on the experimental observation that such tissue exhibits a linear relationship between the differential Young's modulus and stretch leading to an exponential behavior of the force-stretch curve" (Huayamave et al., 2015). A Hill-based model has been proposed and was used in Huayamave et al., 2015 that estimates "passive muscle force by normalizing it using a peak isometric muscle force (PIMF)." This normalization is shown within Eq. (1):

$$F^{PE} = \frac{F}{F_o^M} \tag{1}$$

The above equation describes the normalized passive muscle force. This force is the force that is present when the muscle is not being contracted through communication with the brain and this force is described as F^{PE}. However, in order to find the passive force F, the muscle force, and the PIMF, F_o^M. In addition to providing an estimation for the passive muscle forces it also provides a solution for the PIMF which is shown in Eq. (2):

$$F_o^M = C(PCSA) \tag{2}$$

Where C has a value of $25N/cm^2$ (Huayamave et al., 2015) and is used to estimate the PIMF using the physiological cross-sectional area (PCSA). The PCSA is based on adult cadavers and was scaled appropriately to the infant models. Using a shape factor based on a ratio between an adult adductor brevis PCSA and a two-week old infant, as seen in Huayamave et al., 2015, a ratio of .036 was developed in order to properly scale the muscles used within this study from an adult set of PCSA's. As seen in the table below, the adult PCSA's were scaled using the .036 ratio in order to get a proper estimation of each infant muscle's PCSA.

Muscle	PCSA Infant (cm^2)	PCSA Adult (cm^2)
Med1	0.9	25
Med2	0.5832	16.2
Med3	0.7632	21.2
Min1	0.244	6.78
Min2	0.2952	8.2
Min3	0.432	12

Table 1: Scaled Infant PCSA's based on .036 Ratio (Chang, Rupp, Kikuchi, & Schneider, 2008; Huayamave et al., 2015)

After properly scaling the PCSA's, using equation 2, the PIMF was estimated for each of the muscles. With the PIMF, we can then use equation 3, developed based on the Hill model from Huayamave et al. 2015, to develop an estimated passive force for each individual line of action.

$$F_P = PCSA[a(e^{b(\lambda-1)} - 1)] \begin{cases} a = \frac{C}{e^{K^{PE}}-1} = 0.466\ (\frac{N}{cm^2}) \\ b = \frac{K^{PE}}{\varepsilon_o^M} = 6.667 \end{cases} \quad (3)$$

Where F_P, is the passive tension force within the muscle, a is a constant, consisting of the shape factor (K^{PE}) from OpenSim with a value of 4, b is also a constant consisting of the given shape factor (K^{PE})

and the passive muscle strain (ε_o^M) with a value of .60 for young adults, and lastly λ is the optimal muscle-fiber length (stretch) which, in the case of the abduction contracture, is set to have a value of 1.2 (Delp et al., 2007; Delp et al., 1990; Huayamave et al., 2015). With these appropriate muscle force estimations, the muscles can then be modeled in conjunction with the skeletal structure in order to provide a musculoskeletal structure that represents the anatomy of the infants being used for the models. The overall value of each muscle was estimated by taking the passive force and dividing it by the length of the muscles, measured within ABAQUS, based on the insertion and origin points previously established. The spring constant (K) values used within each model can be seen below.

Specimen 387 Left Hip K VALUES		Specimen 387 Right Hip K VALUES		Spec30 Right Hip K VALUES	
Muscle	K (N/mm)	Muscle	K (N/mm)	Muscle	K (N/mm)
Med1	.039	Med1	.039	Med1	.039
Med2	.021	Med2	.021	Med2	.021
Med3	.030	Med3	.030	Med3	.030
Min1	.012	Min1	.012	Min1	.012
Min2	.016	Min2	.016	Min2	.016
Min3	.025	Min3	.025	Min3	.025

Table 2: List of all spring constants used as muscle properties within the models. It is important to note that each of the spring constant values are the same across the specimens due to their reliance on the PCSA

Boundary Conditions

After establishing all structural models and material properties of those models it is then necessary to establish the boundary conditions that will exist for the FEA. The most important of these boundary conditions is fixing the pelvis at the sacroiliac joint and the pubic arch as it is fixed in the human body. In addition to fixing the pelvis a sliding contact between the femoral head and the acetabulum was established in accordance with the knowledge that the sliding between the two pieces of cartilage is almost frictionless (Zou et al., 2013). Within each of the developed models ABAQUS established the contact as an interference contact and the friction coefficient was set to .01 to ensure there would be very little friction between the femoral head and the acetabulum in accordance with the nature of cartilage. These sets of boundary conditions will allow for the hips to be properly evaluated. An example of a modeled hip joint within ABAQUS is seen below in Figure 17.

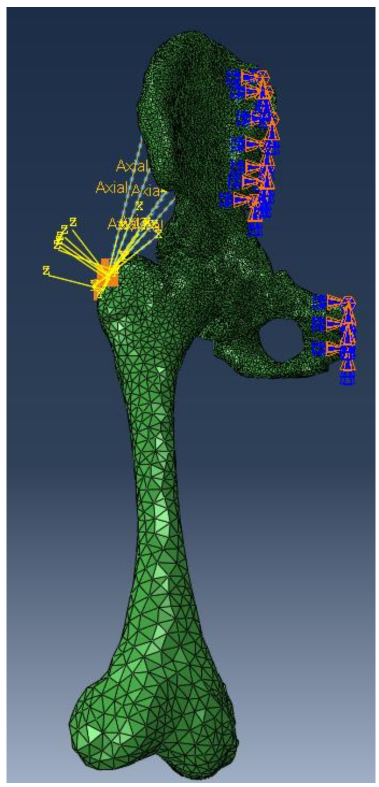

Figure 17: Specimen 387 – Right Hip in the anatomical position with musculature and boundary conditions

Even though these material properties and boundary conditions have been previously established in former studies there are still some limitations to the properties that are applied. In particular it is important to note that material properties of bone and soft tissues can vary from patient to patient for a variety of reasons. This makes the lessons learned from the study useful but not necessarily exactly what the results will be for each specimen and it is therefore important that each specimen be reviewed on a case by case basis for specific results in regards to stresses and stress locations within the specific hip joint.

Muscle Adaptation

It has been well established that muscles within the body adapt to stresses and strains over time. In particular, when a muscle is left or restrained to a particular position for an extended period of time or if the muscle is exercised the muscle will adapt in length and develop a new level of tension (Proske & Morgan, 2001). This is key to this study of an abduction contracture as, in this study, conditions are applied to the infant hip that assume the muscle has had time to adapt to the current contracture and therefore that has become the new standard position for the limb. Thereby meaning that, as discussed above, the muscle will then only have an active stretch component (λ) of 1.2. This active stretch component provides the active tension when applying the loading conditions discussed in the next section and represents the abduction contracture within the infant at varying levels of abduction.

Finite Element Analysis Loading Conditions and Steps

Having established the boundary conditions for the hip, the passive forces that occur at the acetabulum can then be calculated through a finite element analysis (Zou et al., 2013). After establishing the mesh, contact interface, boundary conditions, material properties, muscle insertion and origin points, it is then important to develop proper evaluation steps within ABAQUS to ensure a successful and accurate run of the model. Within ABAQUS specific time-based options were chosen, as seen in figure 18, to ensure that each model could run with the same parameters regardless of the changes in geometry or muscle properties.

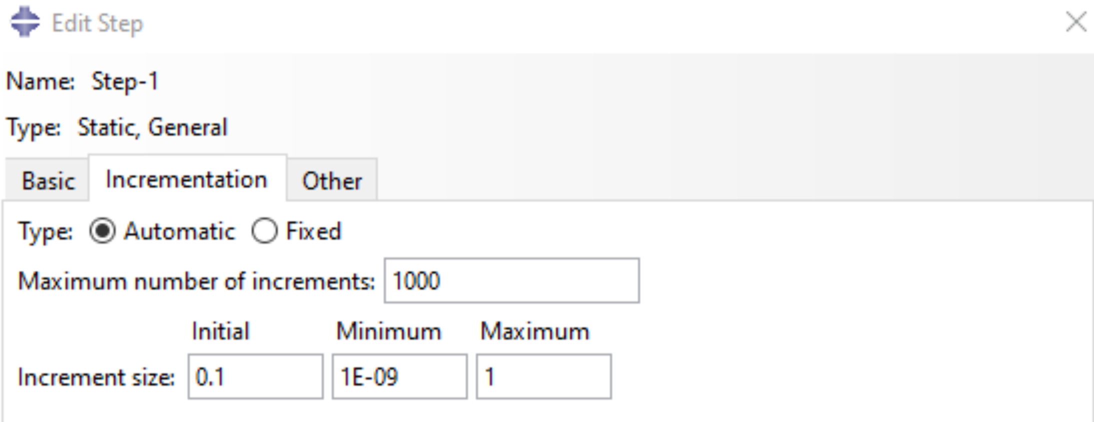

Figure 18: Step Properties for each simulation

The analysis type chosen was static general, due to the adaptation of muscles over time as previously discussed. Within that step the total number of increments was increased to 1000 to ensure that each model, no matter how complex the geometry, would still be able to properly move through the simulation. In addition to the increase in increments the minimum time step was decreased to allow for the solver to account for any major deformations or increases in stress such as those found in the models with 45 degrees of abduction. The initial time step was also reduced to ensure that each simulation would progress through a number of steps before concluding to increase the accuracy of the simulation.

After setting up the time settings for the step loading, conditions were then applied to the models in order to complete the requirements for the simulation. In order to load the model appropriately a concentrated force was placed perpendicular to the distal end of the femur to replicate a physician or parent applying 5lbs of force to the end of the femur. With each of these conditions established for all fifteen models the simulations were then run to the completion of a single time step of 1 second.

Chapter 4

Results

Each of the models was run in accordance with the steps set out above to ensure consistency of results. While there were small variations in the location of the insertion and origin points of muscle lines of action between models they were consistently within the same area and in accordance with the OpenSim 2392 model as stated previously. With this consistency between the models we will be comparing not just the models to themselves in various levels of abduction but also to one another to ascertain the influence the dysplasia may play in the stress and stress locations that occur within the acetabulum. It is also important to note that the stresses developed in each of the figures are in megapascals.

Specimen 387 Left Hip – Grade A

Specimen 387 Left Hip (387L) is the model with the lowest rating of dysplasia meaning it has little to no dysplasia present within the specimen. This provides a look into a normal hip joint and some of the stresses that can develop during an abduction contracture. To begin looking at the output of the models we will start with 387L in 15 degrees of adduction (-15 degrees abduction).

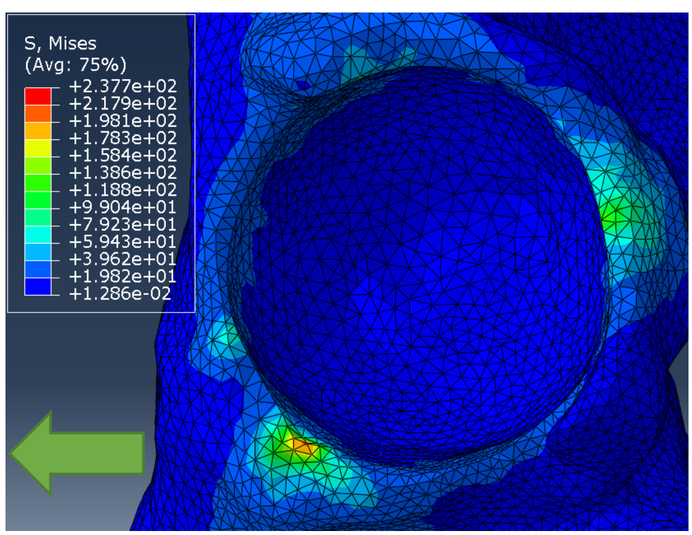

Figure 19: 387L at 15 Degrees of Adduction. Anterior is left of the model.

Demonstrated in the figure above is the stress distribution developed within the acetabulum of 387L with 15 degrees of adduction. As the stresses are displayed within the figure, there is a stress concentration on the posterior inferior portion of the acetabulum as well as on the superior anterior portion of the acetabulum. The first of these stress concentrations displays some minor impingement due to the force pushing the femur into the socket. However, it is more important to note the proper distribution of stresses along the superior and anterior portion of the acetabulum as this represents proper contact between the femur and the acetabulum in most positions within a healthy joint. This distribution coincides with previous studies for healthy joints. As we move to the anatomical position as seen in figure 20 below, it is important to note the continued trend of proper stress distribution within the acetabulum.

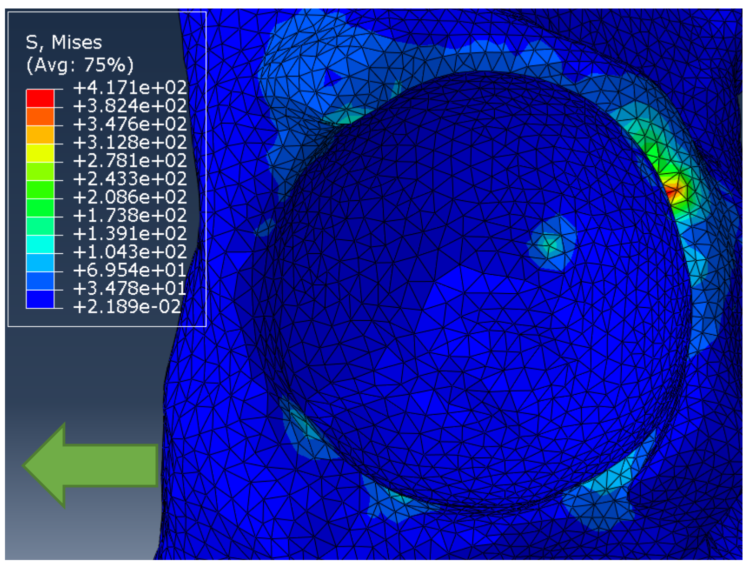

Figure 20: 387L in the anatomical position. Anterior is left of the model.

From the figure above it is once again demonstrated that within a hip joint, with limited to no dysplasia, there is a stress concentration in the superior posterior portion of the acetabulum coinciding with previous FEA of normal hips. The force placed on the femur created a pivoting motion at the femoral head that then causes an even distribution of stress around the rim of the acetabulum with some small pockets of stress showing up at the inferior rim as well as a small pocket of stress within the center of the acetabulum. This trend then continues within 387L with 15 degrees of abduction as seen below.

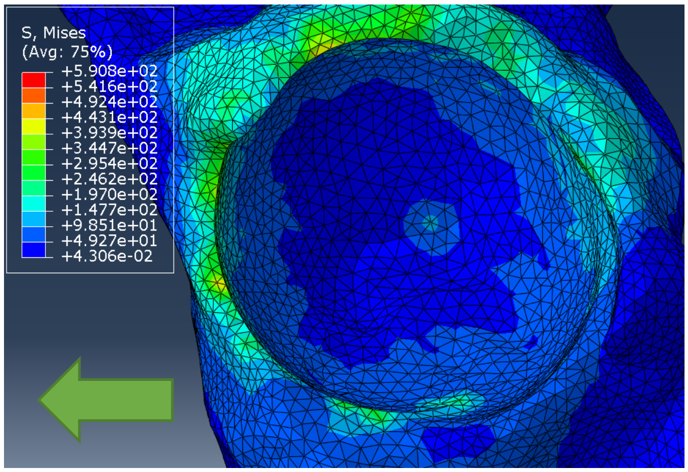

Figure 21: 387L 15 degrees of abduction. Anterior is left of the model.

Within the figure above there is a noticeable increase not only in the stress values but also in the distribution of the stress. It is important to note however, that even with the contracture, the stress distribution primarily remains on the superior portion of the acetabulum. There is also a small shift towards the anterior portion of the acetabulum in regards to stress distribution, although a concentration still remains in the superior posterior portion of the acetabulum. This distribution of stress remains similar within 387L with 30 degrees of abduction as seen below.

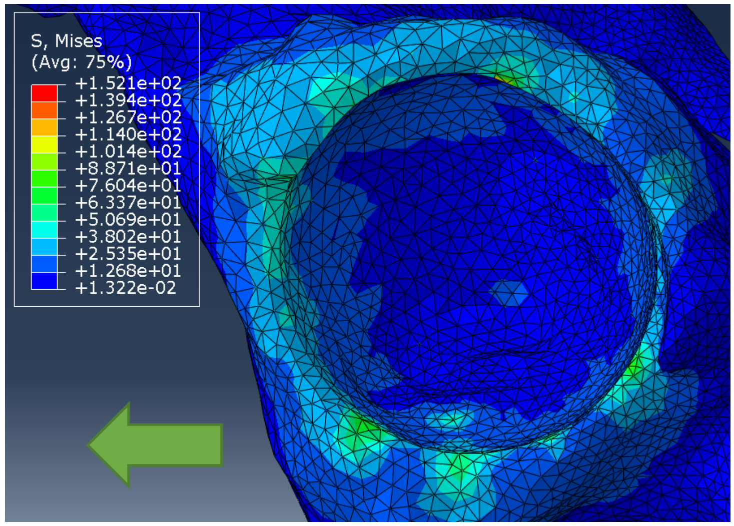

Figure 22: 387L at 30 degrees of abduction. Anterior is left of the model.

At 30 degrees of abduction the model not only has an overall reduction in stress but also has a distribution of stress that spreads continuously throughout the acetabulum with few stress concentrations. In addition, while there are a growing number of concentrations in the inferior portion of the acetabulum there still remains some concentration within the superior anterior portion of the acetabulum. However, when looking at 387L at 45 degrees of abduction there is a noticeable change in stress location as seen below.

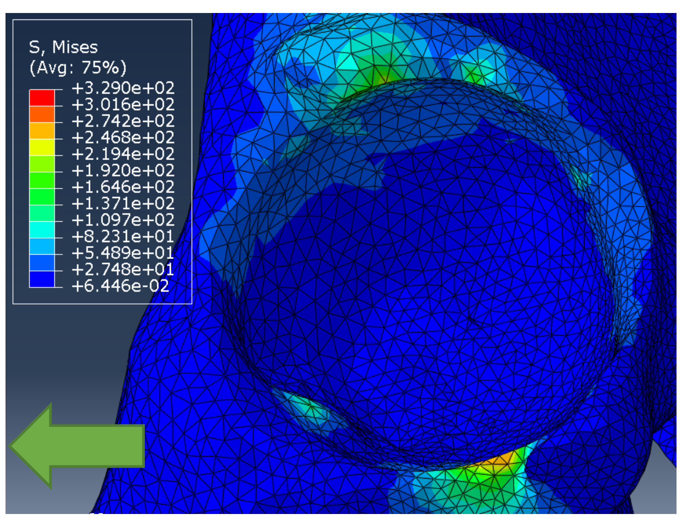

Figure 23: 387L at 45 degrees of abduction. Anterior is left of the model.

In the figure above it is clear that there is a large shift in terms of where the stress concentrations are located. However, it is also important to note that the acetabulum appears to be retaining the femoral head in a partially uniform way. There are still concentrations at the superior portion of the acetabulum and the stress is also partially distributed throughout the superior portion of the acetabulum. This is further demonstrated in a comparison between each of the five positions when the stress is normalized between the five models by setting the stress upper limit to the lowest maximum stress of the group. In the case of the 387L group, the lowest stress maximum was 152 megapascals. The value was rounded down to 150 mega pascals and the group can be seen in the figure below.

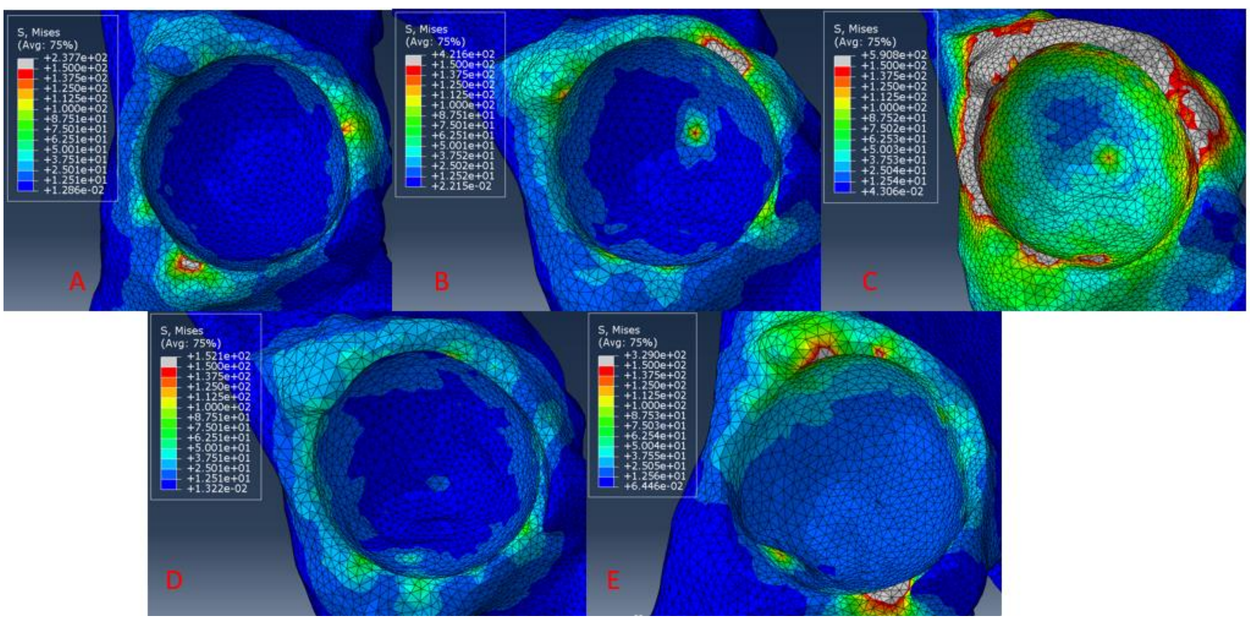

Figure 24: Comparison of all 387L stresses. (A) 387L 15 Degrees Adduction, (B) 387L Anatomical Position, (C) 387L 15 Degrees Abduction, (D) 387L 30 Degrees Abduction, (E) 387L 45 Degrees Abduction

As seen above there are several key results to compare between the models. Primarily, there is a consistent loading of the superior portion of the acetabulum. Throughout the models the stress concentrations also remain consistent in location with noticeable stress differences within 15 and 45 degrees of abduction.

Specimen 387 Right Hip – Grade B

Specimen 387 Right Hip (387R) is the model with a dysplasia rating of B. It therefore likely had some subluxation within the hip joint or possibly had the chance of lower levels of dislocation. This model provides a comparison point for the relatively healthy hip joint with an abduction contracture and can provide some insight into instabilities role in stress distribution within the acetabulum when paired with an abduction contracture. 387R at 15 degrees of adduction and its varied stress distribution is shown in the figure below.

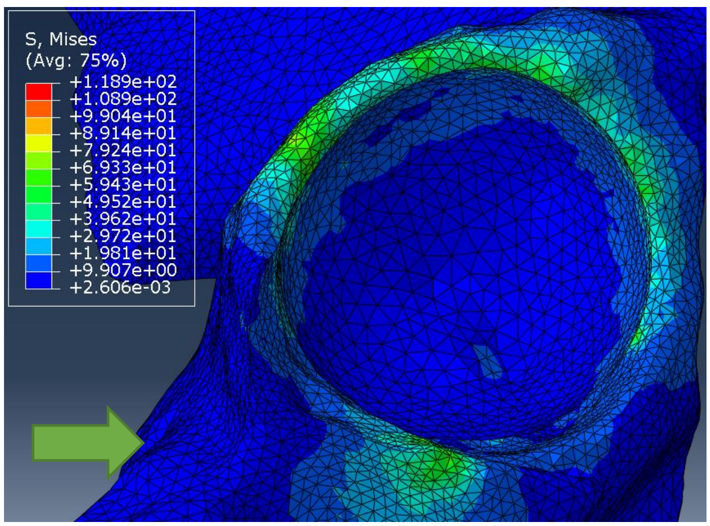

Figure 25: 387R with 15 degrees of adduction. Anterior is right of the model.

At 15 degrees of adduction 387R has stress concentrations primarily location in the superior anterior and the superior posterior portions of the acetabulum. In addition to the stress concentrations along the top of the acetabulum there is an additional concentration located at the inferior portion of the acetabulum. This acetabulum, while differing from normal distributions, does still contain a superior posterior stress concentration. However, when observing 387R in the anatomical position, seen below, the concentrations begin to differ.

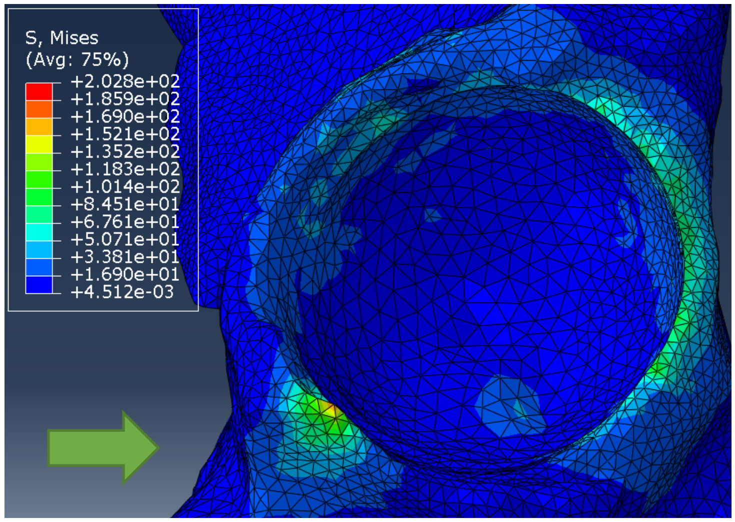

Figure 26: 387R in the Anatomical position. Anterior is right of the model.

For model 387R in the anatomical position the stress concentrations begin to vary heavily from a normal hip joint. The concentrations are now in the anterior portion of the acetabulum reaching from the superior to the inferior portion with an additional concentration lying in the posterior inferior portion. While this varies from what is typical of healthy hips there still remains some stress in the superior posterior portion of the acetabulum. However, when we begin to look at 387R at 15 degrees of abduction, seen below, large stress concentrations begin to appear.

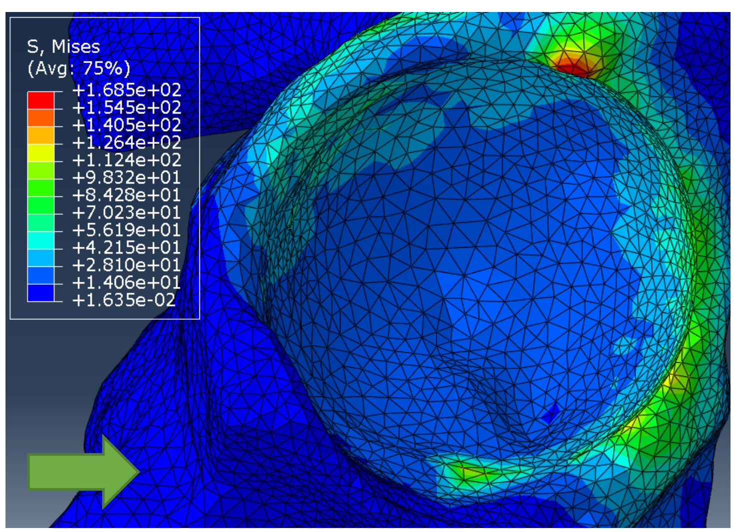

Figure 27: 387R with 15 Degrees of abduction. Anterior is to the right of the model.

When observing 387R with 15 degrees of abduction we begin to see large deviations from a healthy hip joint. In particular there is a concentration in the superior anterior portion of the hip joint. In addition to the location of this particular stress concentration the overall distribution of stress has shifted towards the anterior of the acetabulum. This trend in stress distribution continues in model 387R with 30 degrees of abduction as seen below.

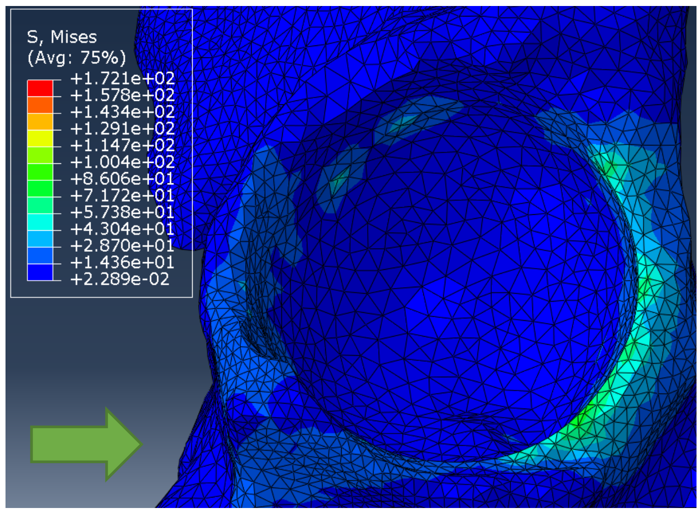

Figure 28: 387R with 30 Degrees of abduction. Anterior is to the right of the model.

The stress distribution within 387R with 30 degrees of abduction continues the previous trend of concentrating the stresses within the acetabulum on the anterior rim. It is important to recognize that while there is a concentration on the anterior portion there is also very little stress distributed throughout the rest of the acetabulum. This lack of distribution continues within 387R with 45 degrees of abduction as shown below.

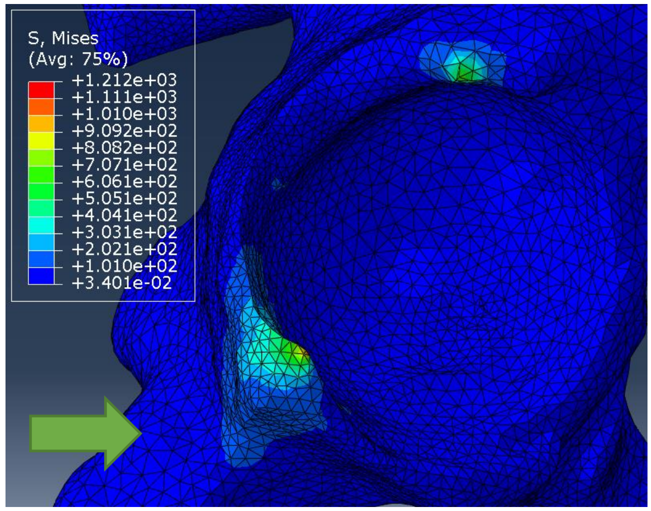

Figure 29: 387R with 45 degrees of abduction. Anterior is to the right of the model

Within 387R with 45 degrees of abduction there is a large shift in the location of the stresses within the model. They move from the anterior portion of the acetabulum to the superior and inferior crests that exist within the specimen specific geometry. These stress concentrations are significant due to not only their location but also their overall magnitude. The stresses appear to be many times larger than those of the previous models and due to the limited contact of the femoral head within the acetabulum as well as the severity of the abduction. With the stresses normalized, as seen in the figure below, it becomes apparent that the morphological changes within the acetabulum play a large part in maintaining proper stress distribution during a contracture.

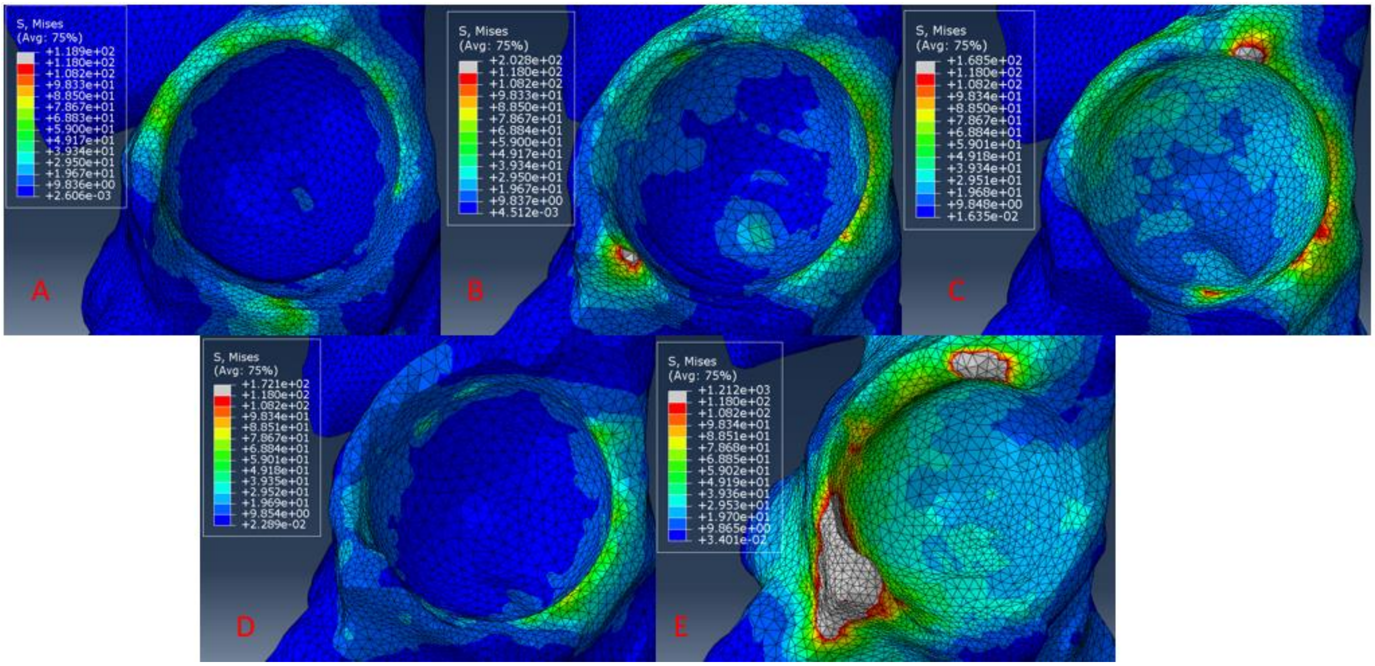

Figure 30: Comparison of all 387R stresses. (A) 387R 15 Degrees Adduction, (B) 387R Anatomical Position, (C) 387R 15 Degrees Abduction, (D) 387R 30 Degrees Abduction, (E) 387R 45 Degrees Abduction

The hip stresses were normalized, as with the previous group, to the lowest maximum stress concentration calculated within the models. In the 387L group the stresses were normalized to 118 megapascals. This stress level reveals not only the high levels of stress put on the acetabulum, but also important stress concentrations such as the consistent stress on the anterior portion of the acetabulum as well as the concentrations that form at the two outcroppings in the acetabular geometry at both 15 and 45 degrees.

Specimen 30 Right Hip – Grade C

The Specimen 30 Right Hip (30R) model has a dysplasia rating of C. Meaning that there is not only instability but it is also likely that the femoral head was able to dislocate from the acetabulum. Within the figure below, 30R is at 15 degrees of adduction, and, due to the nature of the geometry, has a variety of concentrations around the rim.

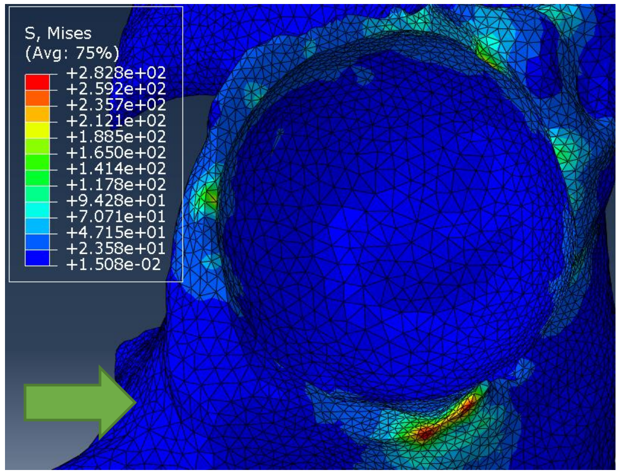

Figure 31: 30R at 15 degrees of adduction. Anterior is to the right of the model.

30R has a noticeable stress concentration at the inferior portion of the acetabulum as well as some concentrations distributed throughout the superior rim. However, there is a lack of a stress concentration at the superior posterior portion of the acetabulum. Therefore, denoting that with the grade c dysplasia geometry a possible problem is already present. This trend continues with 30R at the anatomical position as seen below.

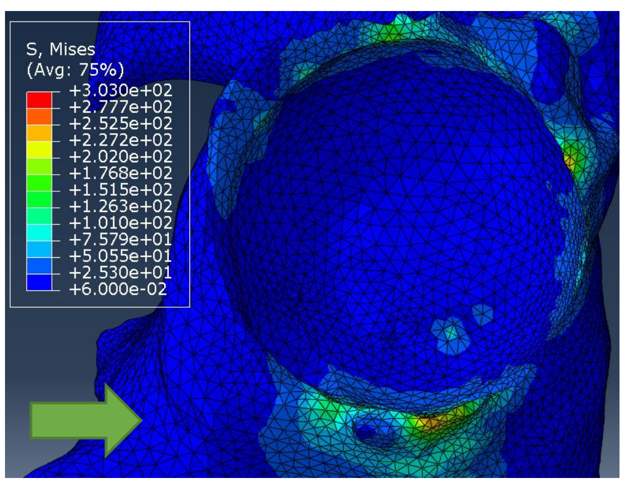

Figure 32: 30R in the anatomical position. Anterior is to the right of the model.

30R in the anatomical position, as seen above, has a stress concentration that occurs at the inferior portion of the acetabulum and thereby coincides with the previous position. Two other key stress concentrations then occur within the acetabulum with the first being in the superior portion on the acetabulum and the second occurring in the superior anterior portion of the acetabulum. These concentration locations show some distribution of the load but varies heavily from the traditional loading locations of a healthy hip joint. This distribution then takes a drastic change as seen in 30R at 15 degrees of abduction in the figure below.

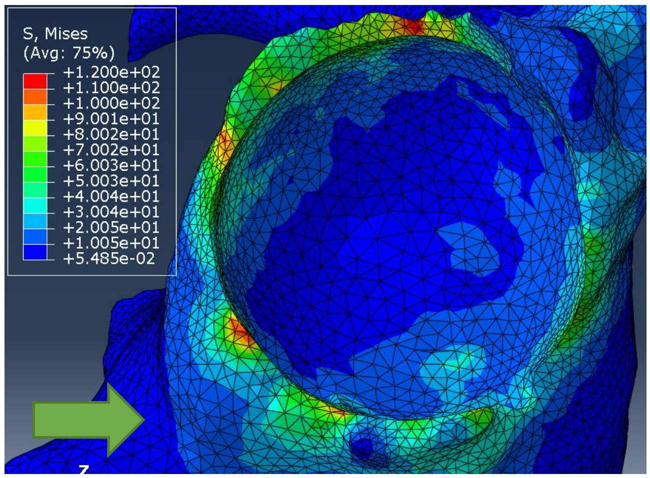

Figure 33: 30R at 15 degrees of abduction. Anterior is to the right of the model.

Within 30R at 15 degrees of abduction the stress is heavily distributed throughout the entirety of the acetabular rim. This distribution does contain several concentrations with higher levels being focused in the superior portion of the acetabulum as well as the inferior posterior portion of the acetabulum. This maintains that the socket is attempting to hold the femoral head in place, but due to the underdeveloped nature of the acetabulum there are more concentrations in sections where there may be impingement or an overall lack of material. 30R at 30 degrees of abduction, seen in the figure below, displays a similar set of results with the distribution being along the outer rim of the acetabulum.

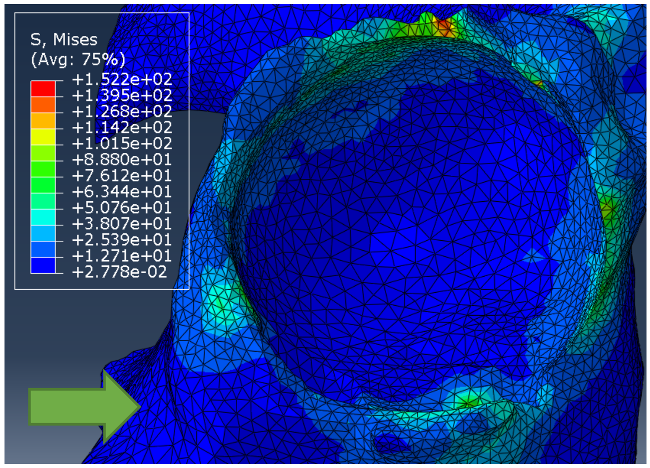

Figure 34: 30R at 30 degrees of abduction. Anterior is to the right of the model.

While the distribution is similar at 15 degrees of abduction it is important to note that there is less stress distribution throughout the entirety of the acetabulum and that there is now a shift towards isolated pockets of stress concentration. In particular the concentrations are focused in the anterior, anterior superior, inferior, and the posterior portions of the acetabulum. Showing that while there is some distribution, the system is starting to rely more on the far rim to help keep the femoral head in contact. This is again shown within 30R at 45 degrees of abduction in the figure below.

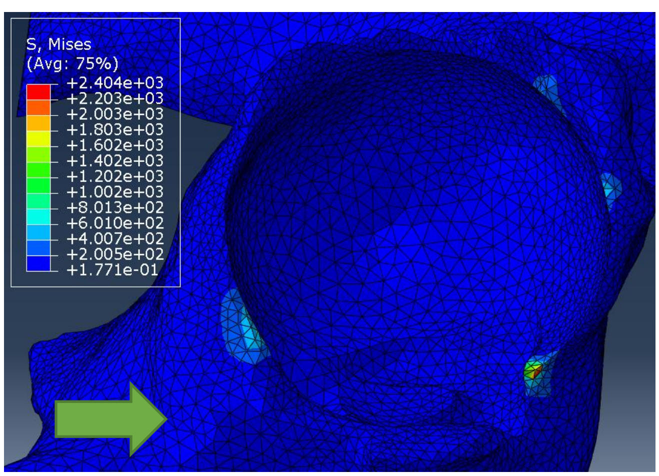

Figure 35: 30R at 45 degrees of abduction. Anterior is to the right of the model.

30R at 45 degrees displays the lack of overall contact and support that the femoral head is receiving during the abduction contracture. Once the adduction force is fully applied to the femur, stress concentrations only occur at the inferior anterior and posterior portions of the acetabulum. It is also important to note that the stress level within this final model is well above the rest within 30R. This increase in stress is seen within the normalized group comparison below.

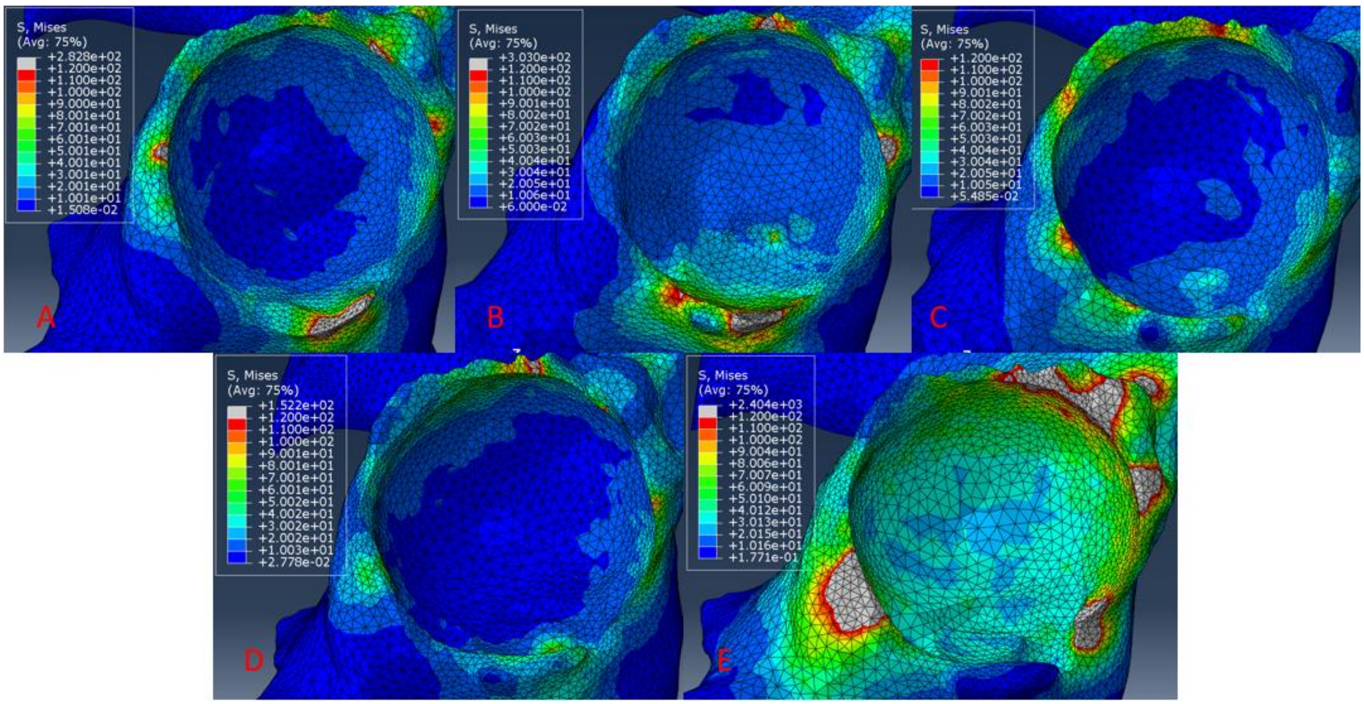

Figure 36: Comparison of all 30R stresses. (A) 30R 15 Degrees Adduction, (B) 30R Anatomical Position, (C) 30R 15 Degrees Abduction, (D) 30R 30 Degrees Abduction, (E) 30R 45 Degrees Abduction

As with the previous groups the stress has been normalized to the lowest maximum stress in the group to display the changes in stress concentrations and distributions between each of the models. It is important to note that the largest change in both concentrations and stress as a whole occurs within the 45-degree abduction contracture. The concentrations not only show the locations of possible deformity within the hip joint but also displays the extreme load the acetabulum would then be enduring.

Chapter 5

Discussion

Having completed each of the simulations and recorded the data it is then important to understand the impact the stresses and stress concentrations would have on the acetabulum over time. In comparison with previous studies it is important to note that in most cases the dysplastic models (387R and 30R) had stress concentrations that often times did not appear in healthy locations. The lack of stress concentrations on the superior posterior wall of the acetabulum shows that not only did the dysplasia have an effect on where the stress would appear, but also where the stress concentrations would appear. In particular, 30R showed high levels of stress in locations that were not ideal. In the following figures, the stresses have again been normalized according to the lowest maximum stress level in the group. In the 15 degrees of adduction set of models that stress level is 118 megapascals. In Figure 37 below, the stress locations varied greatly while the level of stress at 15 degrees of adduction remained consistent.

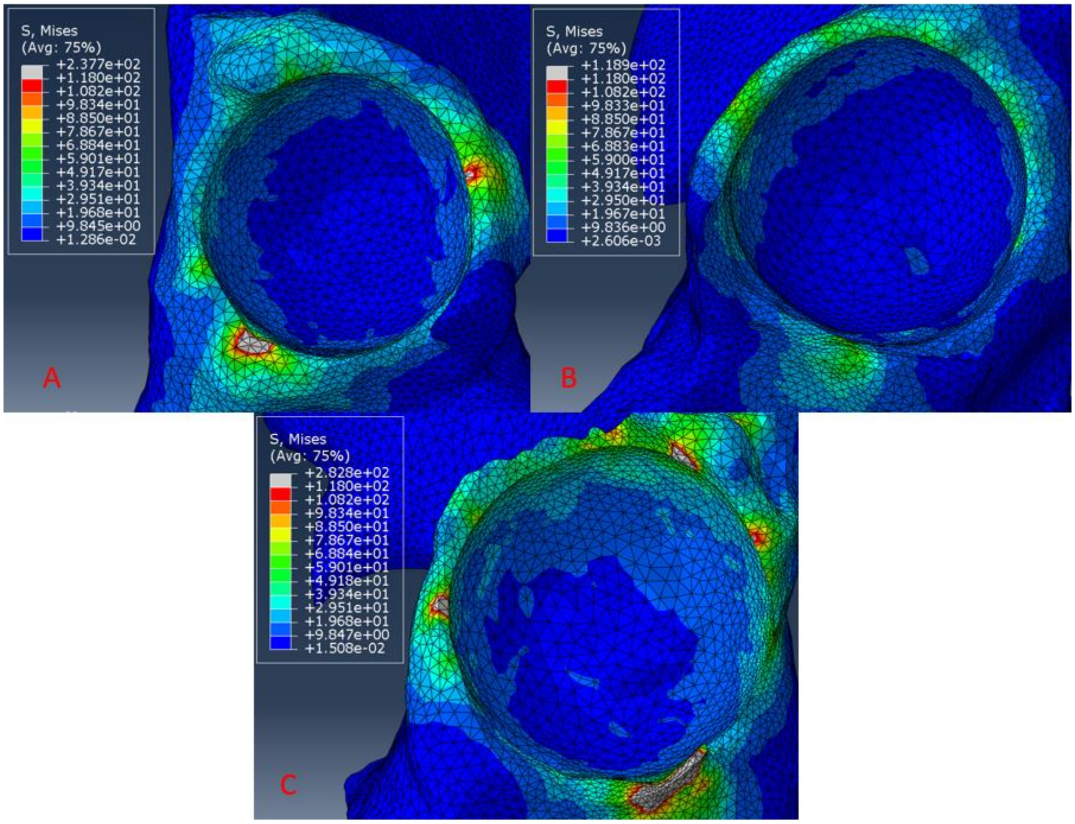

Figure 37: Comparison of all 15 Degrees of Adduction stresses: (A) 387L (B) 387R (C) 30R

It is important to note that while the lowest level of stress appeared in 387R the stresses were distributed along the upper portion of the acetabulum and there was a lack of concentration in the superior posterior portion of the model. When comparing both 387L and 387R to 30R there is not only an increase in the stresses due to the abduction contracture but there is also a lack of healthy stress distribution. The lack of healthy distributions within the dysplastic hip in particular creates concern for continued negative morphological changes in the hip joint. This trend continues in the comparison between each of the models in the anatomical position as seen in Figure 38 below.

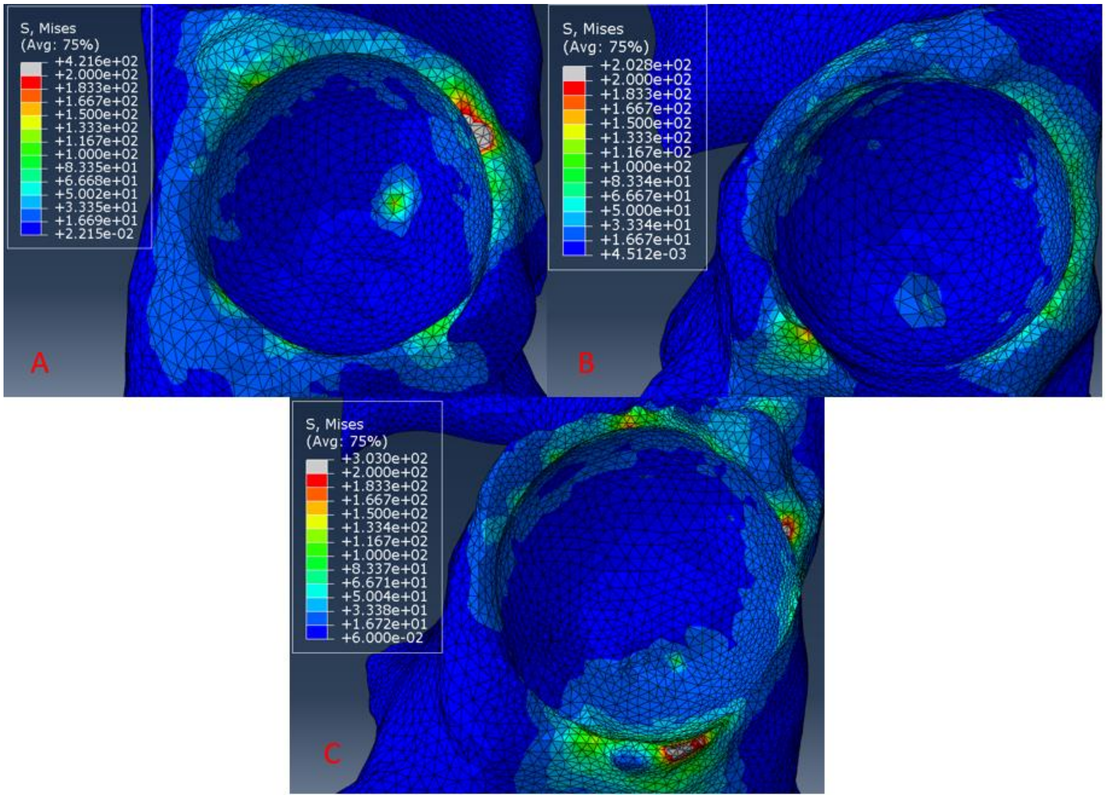

Figure 38: Comparison of all anatomical position stresses: (A) 387L (B) 387R (C) 30R

The stress distributions in the normalized models now vary to a greater degree within the models above. In particular we begin to see a divergence from a healthy distribution in 387R. In addition to the divergence from healthy distributions we also begin to see the appearance of stress concentrations in areas of the acetabulum that can, over time, cause malformations within the acetabulum and could possibly exacerbate the effects of dysplasia. The group of models with a 15-degree abduction contracture begin to show a reduction in stresses but also show a possible inability for the dysplastic acetabula to contain the femoral head as it attempts to adduct. In addition, the stress concentrations are not in healthy positions as seen in the figure below.

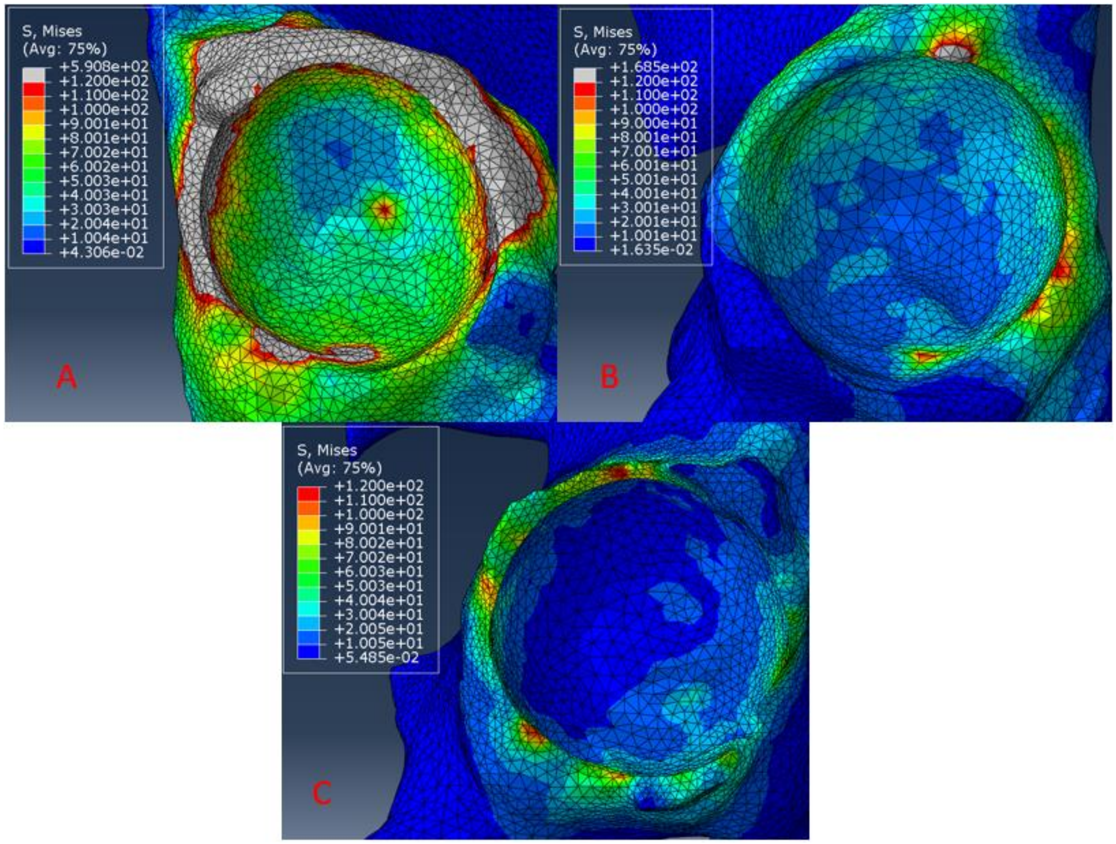

Figure 39: Comparison of all 15 Degrees of Abduction stresses: (A) 387L (B) 387R (C) 30R

As seen in the figure above there is a large increase in stress within 387L. However, a key point to that increase in stress it the acetabulum's ability to evenly distribute the stress throughout the entire structure. Whereas in 387R there is some distribution of the stress but the primary concentration of stresses lie either within the inferior anterior portion of the acetabulum or the small morphological outcropping in the superior portion of the acetabulum. When comparing both 387L and 387R to 30R there is less of a concern with the level of stress concentration in the rim but instead it is the underdeveloped and thin nature of the rim that is bearing the stresses that raises the possibility of morphological changes or possible dislocation over time. This concern continues within the next abduction contracture group with the largest shift in stress concentration locations being within 387R as seen below.

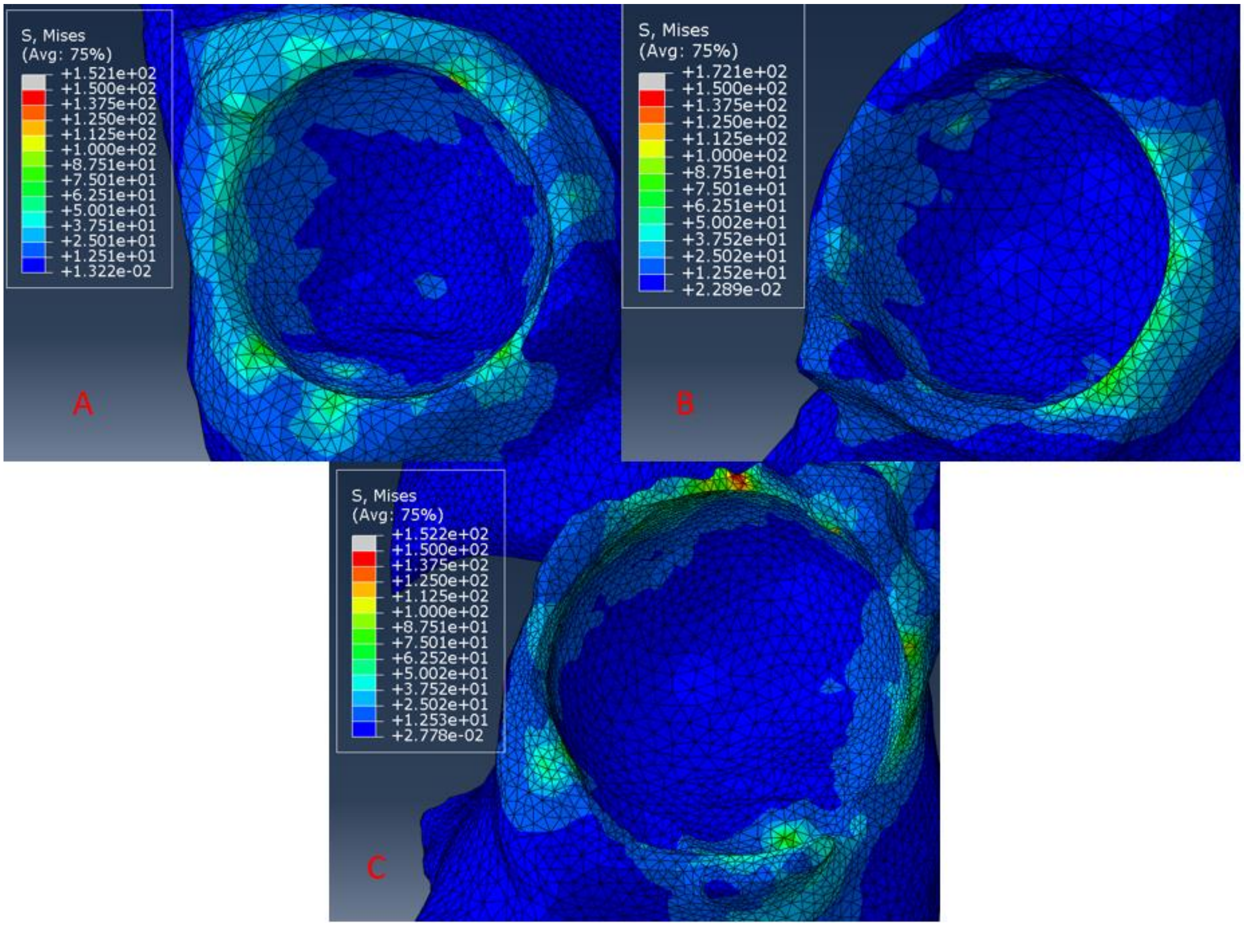

Figure 40: Comparison of all 30 Degrees of Abduction stresses: (A) 387L (B) 387R (C) 30R

Overall, there is a reduction in stress distributions within each model. However, a key stress point continues to make itself evident within 30R. This being the stress concentration in the superior portion of the acetabulum. This stress concentration remains consistent throughout each of the 30R models and is a point of concern due to the thin nature of the acetabulum. In addition, when looking at the stress distributions between the three models, 387L still maintains consistent levels of contact and stress due to the encapsulating nature of the healthy acetabulum. Model 387R however, displays a reliance on the anterior wall of the acetabulum to ensure contact within the system. These trends however, shift drastically when comparing the 45-degree abduction contractures in the figure below.

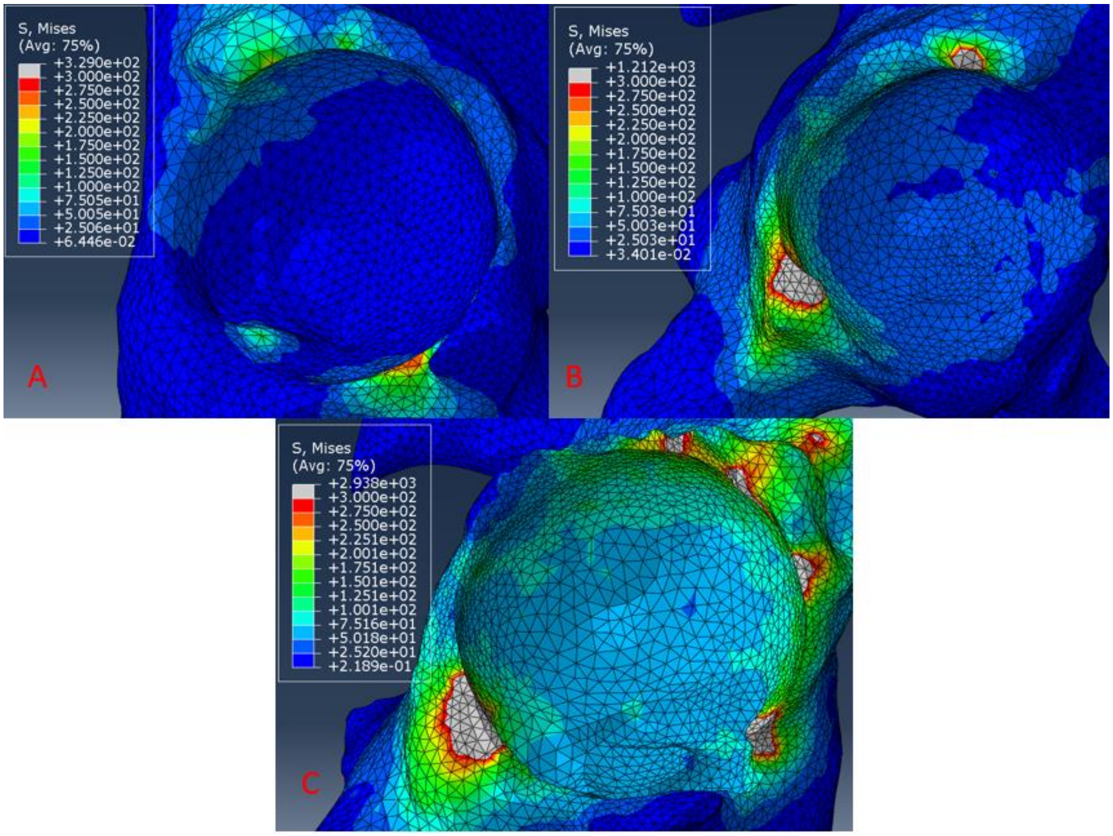

Figure 41: Comparison of all 45 Degrees of Abduction stresses: (A) 387L (B) 387R (C) 30R

The models with a 45-degree abduction contracture were normalized against the lowest maximum stress value in the group, which had a value of 300 megapascals. This particular comparison grants insight into the importance of the hip morphology and also allows conclusions to be drawn about how each of the hips are affected by the varying levels of dysplasia. In particular, when comparing 387L to both 387R and 30R there is a noticeable reduction in not only overall stress levels but also in the concentrations and their locations within the acetabulum. In particular, both 387R and 30R display stress concentrations on the outcroppings that exist on the rim of the acetabulum. In addition to those concentrations on the edge, they both appear to be receiving an incredible amount of stress throughout the entirety of the acetabulum. This stress distribution and level of stress concentration is problematic in a number of ways. Firstly, there is the distinct possibility of morphological changes over time, particularly at the areas of stress concentration in both 387R and 30R. Secondly there is the possibility of dislocation due to the limited concentrated contact on the rim of the acetabulum. Finally, there is also the distinct possibility that the femoral head could be damaged due to a possible crushing effect from the adduction force being applied with the abduction contracture.

Conclusion

The results from this study offer a few answers to the questions posed previously. Primarily, it offers insight into the effects an abduction contracture can have on an infant hip with varying levels of dysplasia. This insight being that when an adduction force is being applied to a stabilized hip joint with an abduction contracture, the stress concentrations developed within unhealthy hips have the capability of changing the morphology of the acetabulum and is therefore detrimental to the infant hip joint. In addition, it also shows that stress concentrations formed by healthy hips at greater levels of abduction have the possibility of being detrimental if left with a contracture for an extended period of time.

In addition to being detrimental to already dysplastic hips it is also possible that the abduction contracture may contribute to ipsilateral hip dysplasia in addition to increasing the risk of contralateral hip dysplasia. There are many circumstances in which the pelvis may be unable to skew in order to protect the ipsilateral hip from hip dysplasia causing forces such as swaddling. That inability to skew can force the femoral head under the abduction contracture to change the morphology of the hip due to the pliable and developing nature of immature hips.

There is also the distinct possibility that at extreme levels of abduction contracture, such as at 45-degrees, there may be compression of the femoral head that could lead to other complications such as avascular necrosis. Deformation of both the femoral head and the acetabulum can both lead to cases of dysplasia and due to the distinct possibility of development, it is then, based on this study, not recommended that exercises be performed to reduce hip abduction contractures that would place adduction forces on the leg of the infant. These contractures often resolve on their own over time throughout the development of the infant. It instead may be more beneficial to protect both hip joints through part time splinting or bracing to allow for proper hip development without stretching exercises. These same principles are also recommended following cast removal for hip reductions of hip dislocations. It may instead be more beneficial to the infant to allow for spontaneous or gradual improvement in order to prevent recurring dysplasia or dislocation. The implications of this study play a key role in understanding how abduction contractures can affect dysplastic hip joints and grant insight into how some practices to reduce the effects of an abduction contracture may in-turn increase the occurrence or recurrence of developmental dysplasia of the hip.

References:

Ardila, O. J., Divo, E. A., Moslehy, F. A., Rab, G. T., Kassab, A. J., & Price, C. T. (2013). Mechanics of hip dysplasia reductions in infants using the Pavlik harness: a physics-based computational model. *J Biomech, 46*(9), 1501-1507. doi:10.1016/j.jbiomech.2013.03.031

Aronsson, D. D., Goldberg, M. J., Kling, T. F., & Roy, D. R. (1994). Developmental Dysplasia of the Hip.

Atrey, A., & Katchburian, M. (2010). The creation of a Pavlik "hemi-harness" for a singly irreducible hip in bilateral dysplastic hips. *J Child Orthop, 4*(1), 81-84. doi:10.1007/s11832-009-0226-1

Bachtar, F., Chen, X., & Hisada, T. (2006). Finite element contact analysis of the hip joint. *Med Biol Eng Comput, 44*(8), 643-651. doi:10.1007/s11517-006-0074-9

Blemker, S. S., & Delp, S. L. (2005). Three-dimensional representation of complex muscle architectures and geometries. *Ann Biomed Eng, 33*(5), 661-673.

Chang, C. Y., Rupp, J. D., Kikuchi, N., & Schneider, L. W. (2008). Development of a finite element model to study the effects of muscle forces on knee-thigh-hip injuries in frontal crashes. *Stapp Car Crash J, 52*, 475-504.

Chegini, S., Beck, M., & Ferguson, S. J. (2009). The effects of impingement and dysplasia on stress distributions in the hip joint during sitting and walking: a finite element analysis. *J Orthop Res, 27*(2), 195-201. doi:10.1002/jor.20747

Clarke C., Taylor C., & J., J. (2016). Diagnosis and management of developmental hip dysplasia. In (pp. 252-257). Journal of Pediatrics and Child Health.

Clarke C., T. C., Judd J. (2016b). Diagnosis and management of developmental hip dysplasia. In (pp. 252-257). Journal of Pediatrics and Child Health.

Delp, S., Anderson, F., Arnold, A., Loan, P., Habib, A., John, C., . . . Thelen, D. (2007). OpenSim: Open-Source Software to Create and Analyze Dynamic Simulations of Movement In (Vol. 54, pp. 1940-1950). IEEE Transactions on Biomedical Engineering: IEEE.

Delp, S., Loan, P., Hoy, M., Zajac, F., Topp, E., & Rosen, J. (1990). An Interactive Graphics-Based Model of the Lower Extremity to Study Orthopaedic Surgical Procedures. In (Vol. 37, pp. 757-767). IEEE Transactions on Biomedical Engineering: IEEE.

Developmental Dysplasia of the Hip - International Hip Dysplasia Institute. (2020). Retrieved from https://hipdysplasia.org/developmental-dysplasia-of-the-hip/

Dezateux, C., & Rosendahl, K. (2007). Developmental dysplasia of the hip. *The Lancet, 369*(9572), 1541-1552. doi:https://doi.org/10.1016/S0140-6736(07)60710-7

Duda, G. N., Brand, D., Freitag, S., Lierse, W., & Schneider, E. (1996). Variability of femoral muscle attachments. *J Biomech, 29*(9), 1185-1190.

Flack, N. A., Nicholson, H. D., & Woodley, S. J. (2012). A review of the anatomy of the hip abductor muscles, gluteus medius, gluteus minimus, and tensor fascia lata. *Clin Anat, 25*(6), 697-708. doi:10.1002/ca.22004

French, L. M., & Dietz, F. R. (1999). Screening for developmental dysplasia of the hip. *Am Fam Physician, 60*(1), 177-184, 187-178.

Giorgi, M., Carriero, A., Shefelbine, S. J., & Nowlan, N. C. (2015). Effects of normal and abnormal loading conditions on morphogenesis of the prenatal hip joint: application to hip dysplasia. *J Biomech, 48*(12), 3390-3397. doi:10.1016/j.jbiomech.2015.06.002

Girish, G. (2017). Computational Investigation of the Biomechanics of Babywearing in Regards to Developmental Dysplasia of the Hip.

Gottschalk, F., Kourosh, S., & Leveau, B. (1989). The Functional anatomy of tensor fasciae latae and gluteus medius and minimus In (pp. 179-189). Journal of Anatomy.

Graf, R. (1984). Fundamentals of sonographic diagnosis of infant hip dysplasia. *J Pediatr Orthop, 4*(6), 735-740.

Graham, S. M., Manara, J., Chokotho, L., & Harrison, W. J. (2015). Back-carrying infants to prevent developmental hip dysplasia and its sequelae: is a new public health initiative needed? *J Pediatr Orthop, 35*(1), 57-61. doi:10.1097/BPO.0000000000000234

Green, N., & Griffin, P. (1982). Hip Dysplasia Associated with Abduction Contracture of the Contralateral Hip. In (Vol. 64, pp. 1273-1281). Journal of Bone and Joint Surgery: Journal of Bone and Joint Surgery.

Halanski, M., & Noonan, K. J. (2008). Cast and splint immobilization: complications. *J Am Acad Orthop Surg, 16*(1), 30-40. doi:10.5435/00124635-200801000-00005

Henak, C. R., Ellis, B. J., Harris, M. D., Anderson, A. E., Peters, C. L., & Weiss, J. A. (2011). Role of the acetabular labrum in load support across the hip joint. *J Biomech, 44*(12), 2201-2206. doi:10.1016/j.jbiomech.2011.06.011

Huayamave, V., Rose, C., Serra, S., Jones, B., Divo, E., Moslehy, F., . . . Price, C. T. (2015). A patient-specific model of the biomechanics of hip reduction for neonatal Developmental Dysplasia of the Hip: Investigation of strategies for low to severe grades of Developmental Dysplasia of the Hip. *J Biomech, 48*(10), 2026-2033. doi:10.1016/j.jbiomech.2015.03.031

Kotlarsky, P., Haber, R., Bialik, V., & Eidelman, M. (2015). Developmental dysplasia of the hip: What has changed in the last 20 years? *World J Orthop, 6*(11), 886-901. doi:10.5312/wjo.v6.i11.886

Kumagai, M., Shiba, N., Higuchi, F., Nishimura, H., & Inoue, A. (1997). Functional Evaluation of Hip Abductor Muscles with use of Magnetic Resonance Imaging. In (Vol. 15, pp. 888-893). Journal of Orthopaedic Research.

Merchant, A. (1965). Hip Abductor Muscle Force. In (Vol. 47, pp. 462-476): Journal of Bone and Joint Surgery.

Michaeli, D. A., Murphy, S. B., & Hipp, J. A. (1997). Comparison of predicted and measured contact pressures in normal and dysplastic hips. *Med Eng Phys, 19*(2), 180-186.

Neumann, D. A. (2010). Kinesiology of the hip: a focus on muscular actions. *J Orthop Sports Phys Ther, 40*(2), 82-94. doi:10.2519/jospt.2010.3025

Proske, U., & Morgan, D. (2001). Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptation and clinical applications. In (pp. 333-345). Journal of Physiology.

Reed, C., Carroll, L., Baccari, S., & Shermont, H. (2011). Spica cast care: a collaborative staff-led education initiative for improved patient care. *Orthop Nurs, 30*(6), 353-358; quiz 359-360. doi:10.1097/NOR.0b013e318237105a

Retchford, T., Crossley, K., Grimaldi, A., Kemp, J., & Cowan, S. (2013). Can local muscles augment stability in the hip? A narrative literature review. In (Vol. 13, pp. 1-12). Journal of Musculoskeletal & Neuronal Interaction.

Robertson, W., Gardner, M., Barker, J., Boraiah, S., Lorich, D., & Kelly, B. (2008). Anatomy and Dimensions of the Gluteus Medius Tendon Insertion. In (Vol. 24, pp. 130-136). Arthoscopy: The Journal of Arthoscopic and Related Surgery.

Roper, A. (1976). Hip dysplasia in the African Bantu. *J Bone Joint Surg Br, 58*(2), 155-158.

Salter, R. B. (1968). Etiology, pathogenesis and possible prevention of congenital dislocation of the hip. *Can Med Assoc J, 98*(20), 933-945.

Sankar, W. N., Nduaguba, A., & Flynn, J. M. (2015). Ilfeld abduction orthosis is an effective second-line treatment after failure of Pavlik harness for infants with developmental dysplasia of the hip. *J Bone Joint Surg Am, 97*(4), 292-297. doi:10.2106/JBJS.N.00707

Shefelbine, S., & Carter, D. (2004). Mechanobiological predictions of growth front morphology in developmental hip dysplasia. In (Vol. 22, pp. 346-352). Journal of Orthopaedic Research.

Shen, Y.-S. (1975). Abduction Contracture of the Hip in Children. In (Vol. 57): Chung-Jen Orthopaedic hospital.

Singh, A. P. (2015). Hip Joint Anatomy | Bone and Spine.

Somerville, D., & Macnicol, M. Abductor Contracture of the Hip. In (Vol. 10, pp. 93-37). The Iowa Orthopaedic Journal.

Suzuki, S. (1994). Reduction of CDH by the Pavlik harness. Spontaneous reduction observed by ultrasound. *J Bone Joint Surg Br, 76*(3), 460-462.

Wilkinson, A. G., Sherlock, D. A., & Murray, G. D. (2002). The efficacy of the Pavlik harness, the Craig splint and the von Rosen splint in the management of neonatal dysplasia of the hip. A comparative study. *J Bone Joint Surg Br, 84*(5), 716-719.

Zou, Z., Chávez-Arreola, A., Mandal, P., Board, T. N., & Alonso-Rasgado, T. (2013). Optimization of the position of the acetabulum in a ganz periacetabular osteotomy by finite element analysis. *J Orthop Res, 31*(3), 472-479. doi:10.1002/jor.22245

Zwawi, M. A., Moslehy, F. A., Rose, C., Huayamave, V., Kassab, A. J., Divo, E., . . . Price, C. T. (2017). Developmental dysplasia of the hip: A computational biomechanical model of the path of least energy for closed reduction. *J Orthop Res, 35*(8), 1799-1805. doi:10.1002/jor.23461

Ömeroğlu, H., Köse, N., & Akceylan, A. (2016). Success of Pavlik Harness Treatment Decreases in Patients ≥ 4 Months and in Ultrasonographically Dislocated Hips in Developmental Dysplasia of the Hip. *Clin Orthop Relat Res, 474*(5), 1146-1152. doi:10.1007/s11999-015-4388-5