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FEMORAL VECTORING FOR HIP DYSPLASIA IN NEONATES

ORLANDO J. ARDILA[*'], KYLE G. SNETHEN['], EDUARDO DIVO[†]
FAISSAL MOSLEHY['], GEORGE T. RAB[‡], ALAIN J. KASSAB[']
CHARLES T. PRICE[•]

[*,'] Department of Mechanical and Aerospace Engineering
University of Central Florida
Orlando, FL 32816 USA

[†] Mechanical Engineering Department
Embry-Riddle Aeronautical University
Daytona Beach, FL 32114 USA

[‡] Department of Orthopaedic Surgery
University of California Davis
Sacramento, CA 95817 USA

[•] Department of Medical Education
College of Medicine
University of Central Florida
Orlando, 32827 FL USA

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Abstract. The biomechanical factors influencing the reduction of dislocated hips with the Pavlik harness in patients of developmental hip dysplasia (DDH) were studied and simulated using a three-dimensional Finite Element Method (FEM) computer model.

We identified five hip adductor muscles as key mediators in the prognosis of reduction for DDH, and determined the non-dimensional force contribution of each muscle in the direction necessary to achieve hip reduction for subluxated and fully dislocated hip joints.

Results indicate that the effects of the muscles studied are functions of the severity of DDH. For an abducted and flexed subluxated hip, the Pectineus, Adductor Brevis, proximal Adductor Magnus, and Adductor Longus muscles aid reduction, while the portions of the Adductor Magnus muscle with middle and distal femoral insertion contribute negatively. For a fully dislocated hip all muscles contribute detrimentally.

Consequently, our study points at the adductor muscles as the mediators of reductions of subluxated hips, and suggests the need for external traction to bring fully dislocated hips over the posterior acetabulum and labrum. Additionally, the reduction process of dysplastic hips was found to occur in two phases: (1) Release phase and (2) Reduction phase, and the muscles studied act distinctively in each phase. Moreover, we performed a cadaveric dissection to study the 3-dimensional orientation of the iliopsoas tendon in different hip configurations, and

found that in hip abduction and flexion this tendon is likely not an obstruction to DDH reductions.

We also report on the development of an improved three-dimensional anatomical computer model of the hip and femora of a 10-week old female infant for further study of hip dysplasia and other conditions of the hip using dynamic simulations and the Finite Element Method. This model was generated by combining CT-scans from four human subjects, as well as muscle positional data. It was segmented to encompass the distinct cartilaginous regions of infant anatomy, as well as the different regions of cortical and cancellous bone; these properties were retrieved from the literature.

This engineering computer model of an infant anatomy is being employed for (1) the development of an anatomy-based finite element and dynamics computer model for simulations of hip dysplasia reductions using novel treatment approaches, (2) the determination of a path of least resistance in reductions of hip dysplasia based on a minimum potential energy approach, (3) the study of the mechanics of hyperflexion of the hip as alternative treatment for late-presenting cases of hip dysplasia, and (4) a comprehensive investigation of the effects of femoral anteversion angle (AV) variations in reductions of hip dysplasia.

This study thus reports on an interdisciplinary effort between orthopedic surgeons and mechanical engineers to apply engineering fundamentals to solve medical problems. The results of this research are clinically relevant in pediatric orthopaedics.

1 INTRODUCTION

Hip dysplasia refers to an abnormal hip condition where misalignment, instability of the hip joint, or hip joint insufficiency without misalignment occurs, that if unsuccessfully treated, may lead to long term disability, as studies have found that as many as 76% of osteoarthritis cases are attributed to untreated hip dysplasia patients. This is in part the reason for which about 120,000 total hip replacements are performed yearly in the United States, and patients often require total hip replacement before the age of 50 [1].

This condition is typically discovered in infancy during physical examination and ultrasound [2, 3], and requires immediate treatment, for at this developmental stage ligaments are lax and the tissues surrounding the acetabulum have not yet ossified. It is thus crucial to diagnose hip dysplasia timely after birth and begin treatment immediately; The success of the treatment is inversely related to the age at which treatment is begun, with success rates remaining the highest when the treatment is begun immediately after birth or within the first month, and declining steeply after 9 months of age [2].

For infants afflicted with hip dysplasia, the Pavlik harness is the standard brace of treatment worldwide [2, 4]. This harness (Figure 1) consists of shoulder straps, a halter, anterior and posterior abduction straps, and stirrups. It is designed to maintain the hips of an infant in abduction and flexion simultaneously as this position has shown to direct the femurs to direct the femoral head toward the triradiate cartilage [4]. It is indicated for infants between one and nine months of age, with its maximum effectiveness achieved when worn shortly after birth[2], and apart from rare exceptions, it is appropriate for most children diagnosed with the condition[2, 5].

It is however a fact that in certain circumstances the Pavlik harness fails to achieve reduction of the dislocated hips, and if unrecognized early, this failure may bring adverse consequences for children, possibly leading to permanent disability later in life as a consequence of hip osteoarthritis, delayed acetabular development, failure to stretch the hip adductors, femoral nerve palsy, or inferior (obturator) dislocation among others [5, 6].

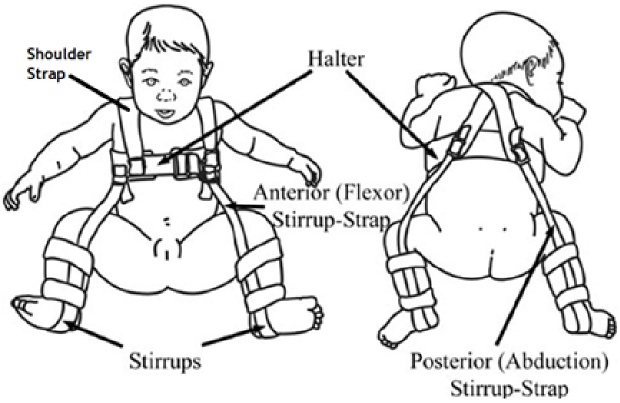

Figure 1: The Pavlik Harness (S.L. Weinstein, et al. J Bone Joint Surg Am 2003; 85:2024-35)

More alarming perhaps is the fact that often physicians cannot indicate whether hip dislocations are reducible during initial examination [5], because a conclusive parameter that indicates whether reduction will or will not occur does not exist. Successful treatment currently is therefore a matter of chance, and “the construction, application, and use of the Pavlik harness is guided by a few principles and practical techniques” and “with commercial production of the Pavlik harness, some of the principles of its construction have been violated” resulting in an inadequate harness [5], with inevitable surgical interventions as the end result.

It is known that 1/20 full-term babies have some type of hip instability, and 2-3 out of 1000 babies will require treatment [7]. Hence with over 4.13 million births in the United States for the year 2009, it is safe to predict that 8-12,000 babies will require treatment for hip dysplasia, of which nearly 15% will fail treatment [2, 5].

With these pressing figures we embarked in a study that used engineering fundamentals to determine the physical laws governing the operation of the Pavlik harness, in order to bring to light conclusive determinants to its mechanism of action, and in this way allow physicians to make better decisions during treatment, thereby decreasing the incidence of disability at cause of unsuccessful treatment of hip dysplasia.

As background, Suzuki and Iwasaki found that hip reductions with the Pavlik harness are due to passive mechanical factors, with no active movement involved, and that reductions occur only during muscle relaxation in deep sleep [8, 9].

Additionally Sten-Knudsen studied muscle fibers, Hill studied toad Sartorius whole muscles, and Magid studied frog semitendinosus muscles and all three studies agree that tension in response to elongation of muscles occurs in an exponential manner [10-13]. Furthermore, these studies and our clinical observations form the basis for our study.

This study thus uses computational methods to elucidate the dynamics of hip dysplasia reductions and to characterize the obstacles to the successful treatment of hip dysplasia. Furthermore, because no method has yet been found to reduce advanced degrees of hip dysplasia non-surgically, this study serves as a baseline to extend the frontiers of current knowledge and aim for the development of case-specific methods based on factual determinants obtained in Computed Tomography (CT) scan exam results, to actively vector the femoral head to its proper concentric position in the acetabulum using both active mechanical means, and/or passive methods that employ possible paths of minimum potential energy that can be used to relocate the femur to its physiological position.

Expanding on these possibilities, we present the results of a study of the biomechanics of different severities of hip dysplasia, conducted using a simplified dynamics model. Additionally, we expand with a description of the four additional, simultaneous studies that are being carried out in our laboratory; namely (1) the development of a complete finite element and dynamics computer model for simulations of hip dysplasia reductions using novel treatment approaches, (2) the determination of a path of least resistance in reductions of hip dysplasia based on minimum potential energy, (3) the study of the mechanics of hyperflexion of the hip as alternative treatment for late-presenting cases of hip dysplasia, and (4) a comprehensive investigation of the effects of femoral anteversion angle (AV) variations in reductions of hip dysplasia.

This study was based on a through literary review in both the technical and clinical areas relevant to hip dysplasia, as well as the professional expertise and active participation of a group of orthopaedic surgeons.

2 METHODS

2.1 Development of a Simplified Dynamics Computer Model

We constructed a simplified three-dimensional (3D) dynamical computer model of an infant hip utilizing SolidWorks (Dassault Systèmes Simulia Corp., Providence, RI, USA). This model consists of the anatomical features that correspond to the hip bone, right femur, and five muscles of relevance to the biomechanics of DDH (Pectineus, Adductor Longus, Adductor Brevis, Adductor Magnus, Gracilis). Because the geometry of the Adductor Magnus can be regarded as a triangular sheet, we divided it into three components (*Adductor Minimus, Middle, and Posterior)* [14]. Our computational model thus results in seven distinct muscle entities. This model is capable of simulating spontaneous reductions by the Pavlik harness, as it was observed that these reductions occur passively during muscle relaxation in deep sleep [8, 9]. To create this model we employed the medical segmentation software Mimics (Materialise Inc, Plymouth, MI) to measure the anatomical features of the hip of a 6-month old female infant, and used these measurements to generate the 3D model of a simplified hip and leg (Figure 2). We constrained the leg to the degrees of freedom required to simulate a dislocated, and a reduced hip, in abduction and flexion. Furthermore, we restricted translation of the leg in the Y-direction, and restricted rotation about the Z-axis to account for the motion restrictions imposed by the Pavlik harness.

The simulated hip-leg assembly model is driven by gravitational loads and constrained to respond in the spatial envelope determined by the Pavlik Harness. It is supported by adductor muscles which were modeled following the constitutive model for passive muscle tension-elongation response introduced by Magid and Hill [10-12]. Their model was calibrated to fit the requirements of our model. The final model is presented in Equation 1.

$$T_{calib} = CA\frac{E_0}{\alpha}(e^{\alpha(\lambda-1)} - 1) \tag{1}$$

In Equation 1, T_{calib} is the tension in the muscles, C is a calibration constant obtained, A is the cross-sectional area of the muscles, E_0 is an initial elastic modulus, α is a an empirical constant, and λ is muscle stretch.

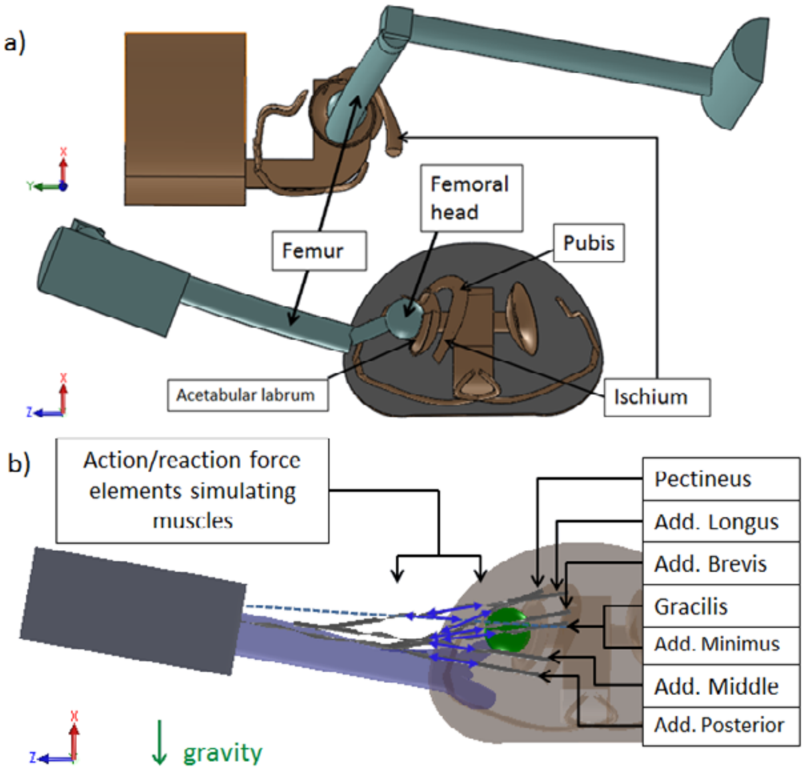

Figure 2: Three-dimensional dynamic computer model for simulations of hip dysplasia reductions. a) Hip and right leg assembly viewed laterally (topmost) and axially (middle). b) Hip and right leg assembly viewed axially, displaying modeled musculature.

This model was then used to study two severities of DDH:

(1) Graf III: subluxated hip in which the center of the femoral head lies on the posterior rim of the acetabulum.

(2) Graf IV: fully dislocated hip in which the femoral head is located posterior to the acetabulum.

Initial conditions for (1) and (2) were imposed by dislocating the femoral head and placing it in the locations corresponding to each severity. The differential equations of motion defined by Newton's second law were then solved using the GSTIFF integrator embedded in the SolidWorks software package until equilibrium was reached. We defined successful reductions as conditions in which the femoral head slid into the acetabulum, and concentric reduction was maintained throughout the solution until reaching equilibrium. Furthermore, we calculated the directional cosines of muscle tension necessary to affect reduction for each DDH severity studied.

2.2 Development of an anatomy-based FEM and dynamics computer model

For additional studies of conditions of the hip, we developed an anatomy-based FEM and dynamics computer model consisting of the hip and femora of a 10-week old female infant. For its development we combined CT-scan data and muscle positional data from four different human subjects:

(1) 10-week old female infant
(2) 14-year old female
(3) 38-year old male (Visible Human Project, The National Library of Medicine)
(4)Adult Male of unknown age [14].

Various important regions of the infant hip are conformed of cartilage, and thus are difficult to visualize in CT-scans. For this reason we performed a 3-dimensional reconstruction of the CT-scans of a 14-year old female (2), and scaled it anisotropically to match the anatomical proportions of the 10-week old infant (1). Our scaling was performed by superposition of anatomical landmarks, namely anterior superior and posterior superior iliac spines, and acetabuli. Upon scaling the pubic and ischial rami of the scaled 14 year old female hip was found to trace a wider arc while all other landmarks matched well. This arc was manually modified to closely match the trace of the infant hip arc; we attribute the observed variation to the possible widening of female hips at puberty. Our resulting scaling factors were 0.35, 0.32, and 0.32 in the X, Y, and Z directions respectively.

To generate the right femur, CT-data from the Visible Human Project (3) was scaled anisotropically to match the femur size of the 10-week old female (1), according Standards in Pediatric Orthopedics [15]. We used femoral head diameter and length between epiphyseal plates as scaling criteria. This procedure yielded scaling factors of and 0.22, 0.25 and 0.23 in the X, Y and Z directions. Making use of symmetry, the right femur was mirrored to create a model for the left femur.

Locations of origins and insertions of muscles were assigned by scaling adult male data (4) [14] isotropically to match the proportions of the 6-month old infant, using the distances between acetabular centers as scaling parameters. The resulting scaling factor was 0.39. The scaled muscle origin and insertion points matched the expected anatomical landmarks accurately, except in the X-direction at the insertions. In this location some muscles were found to lie slightly off the linea aspera. These muscles were manually adjusted to match the linea aspera, and this procedure is not expected to cause significant error in the results as the moment variation due to the modified moment arms is not believed to be significant.

3 RESULTS

3.1 Dynamic Simulation of reductions of DDH, grades Graf III and Graf IV.

A successful dynamic reduction simulation was carried out indicating that Graf III subluxations can be reduced by the Pavlik harness. For further insight we considered (a) the magnitudes and (b) directions of muscle tensions. We found that the Gracilis, *Adductor*

Middle, and *Adductor Posterior* contribute negatively to the reduction with use of the Pavlik harness (Figure 3, Table 1), and that the percent constructive contribution of the muscles studied increases in direct proportion with abduction angle.

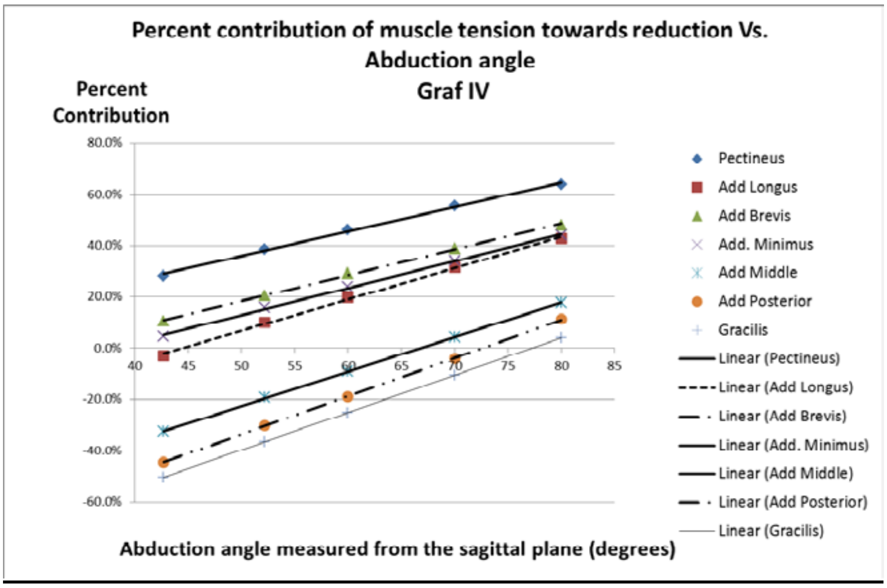

Figure 3: Percent contribution of muscle tension towards reduction vs. abduction angle - Graf III.

Table 1 - Percent directional contributions of muscle tensions in the direction of reduction - Graf III.

Percent directional contributions of muscle tensions - Graf III						
	Abduction Range (degrees, measured from sagittal)					contribution order
	42.7	52.2	60	70	80	
Pectineus	28.1%	38.7%	46.3%	55.5%	63.9%	1
Add Longus	-3.0%	10.1%	19.7%	31.6%	42.8%	4
Add Brevis	10.6%	20.4%	29.1%	38.9%	48.2%	2
Add Minimus	4.7%	15.7%	23.9%	34.2%	44.0%	3
Add Middle	-32.6%	-19.3%	-9.1%	4.4%	17.8%	5
Add Posterior	-44.6%	-30.2%	-19.0%	-3.9%	11.3%	6
Gracilis	-50.32%	-36.60%	-25.18%	-10.60%	4.00%	7

Simulation results of hip dysplasia of grade Graf IV indicate that reductions of hip dysplasia of this severity are unlikely to occur by Pavlik harness treatment. In this severity, and while the infant wears the Pavlik Harness, the tensions of all muscles contribute negatively to the direction of the motion necessary for reduction.

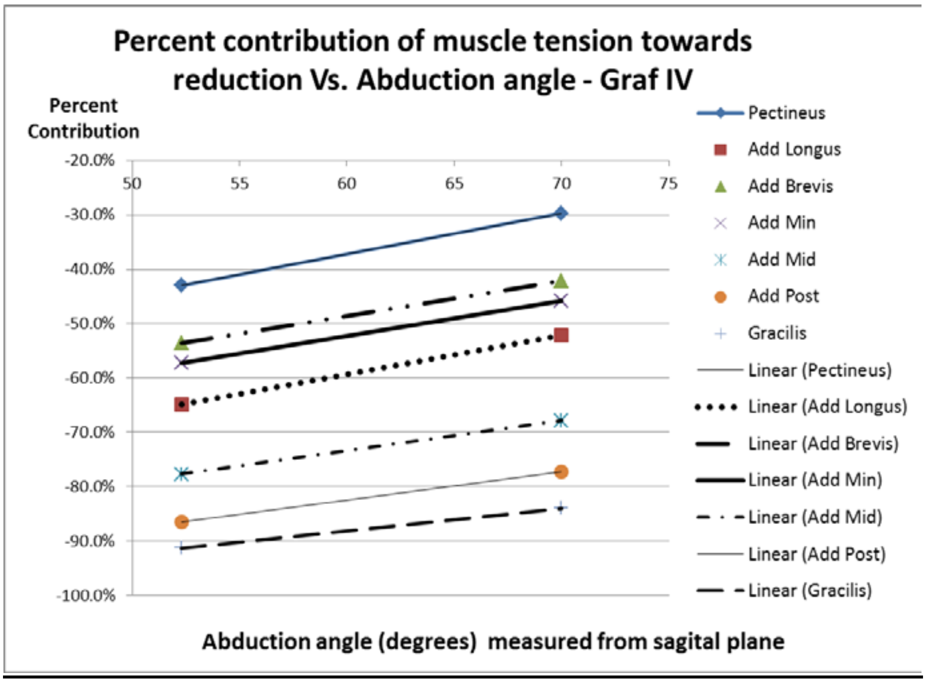

Figure 4: Percent contribution of muscle tension towards reduction vs. Abduction angle - Graf IV.

Table 2 - Percent contribution of muscle tensions in the direction of reduction - Graf IV.

Percent directional contribution of tensions - Graf IV			
	Abduction angle		Contribution
	52.3°	70°	order
Pectineus	-42.9%	-29.7%	1
Add Longus	-64.8%	-52.2%	4
Addr Brevis	-53.5%	-42.1%	2
Add Minimus	-57.3%	-45.7%	3
Add Middle	-77.7%	-67.9%	5
Add Posterior	-86.5%	-77.3%	6
Gracilis	-91.3%	-84.0%	7

3.2 Resultant anatomy-based computer model

Converging and scaling CT-scan and muscle positional data from four human subjects resulted in a 3-dimensional anatomical computer model of an infant hip and femora corresponding to the size of a 10-week old female infant. This model was segmented to account for the different regions of cortical and cancellous bone, as well as for the distinct regions of cartilage observed in infant anatomy. Properties of the different bone tissues and cartilage were obtained from the literature and assigned to the model.

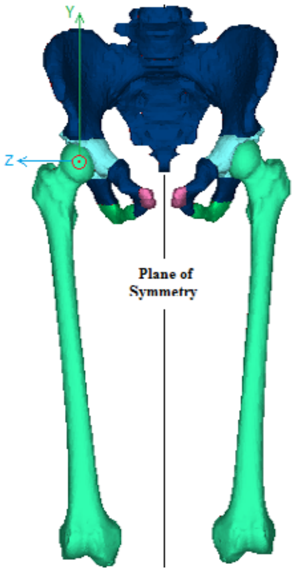

Figure 5: Three dimensional anatomy-based model of human hip and femor

The method developed to create this infant anatomical computer model may be used to generate Computer Aided Design models of various different components of the human anatomy with different dimensional requirements, by combining various sets of data into a single model. The resulting models may then be used to study various conditions in orthopaedics.

The 10-week old female anatomical model that we generated is being used in our laboratory to carry out four parallel investigations:

(1) Development of a finite element and dynamics computer model for simulations of hip dysplasia reductions: This model includes adductor muscles that follow physiological geometries to account for the moment arms that simplified and straight-line muscle models cannot model properly.
(2) Determination of a path of least resistance for reductions of hip dysplasia: With this model (Figure 6) we make use of the anatomical geometry around the acetabulum, gravitational potential energy, and strain energy in the muscles, to find a path of minimum potential energy which can be used to vector the femoral head to the acetabulum.
(3) Study the mechanics involved in hyperflexion of the hip: This study (Figure 7) aims to determine the mechanics of hyperflexion as alternative treatment for late-presenting cases of hip dysplasia.
(4) Effects of femoral anteversion angle (AV) variations in reductions of hip dysplasia: We performed artificial derrotation osteotomies to a femur (Figure 8) to evaluate the mechanical implications of AV variations in the treatment of hip dysplasia. We aim to determine if femoral anteversion may be used as determining factor for reducible or irreducible hips.

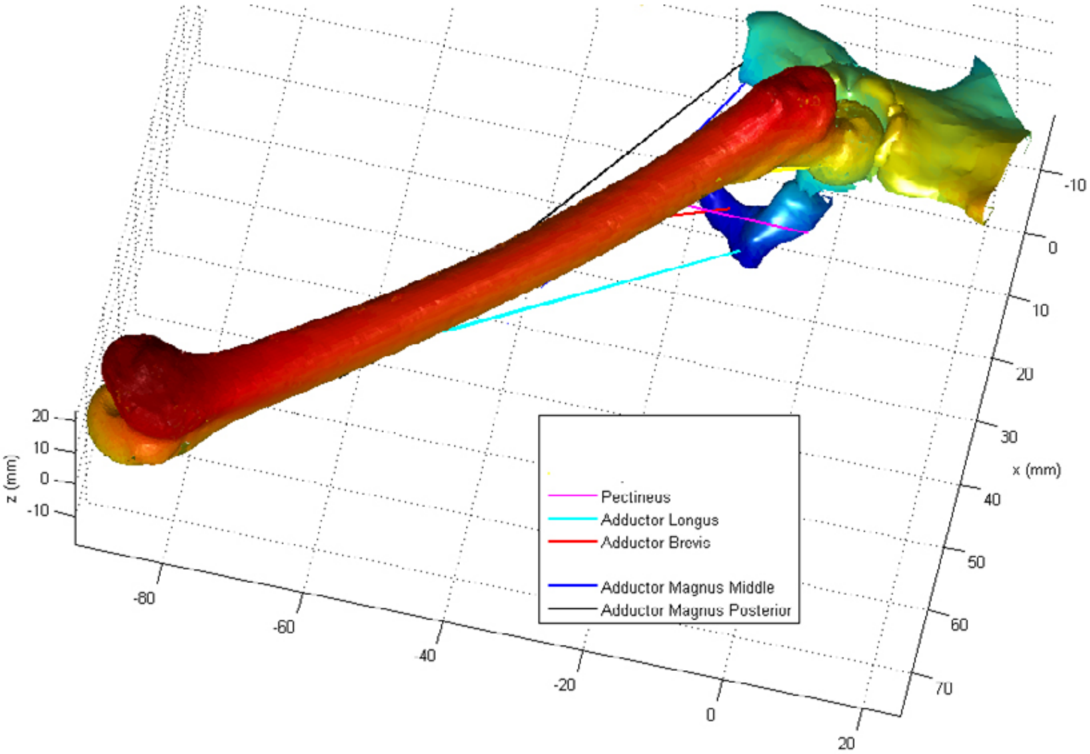

Figure 6: MATLAB rendering of femur and acetabulum for minimum potential energy analysis. Color gradient represents depth in Z direction.

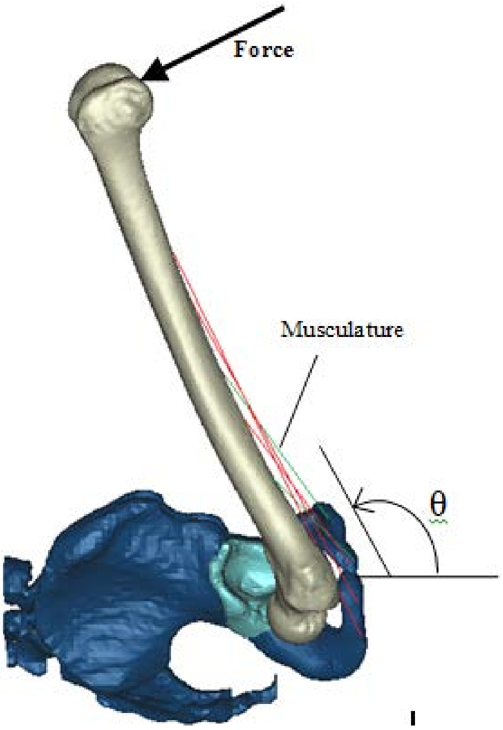

Figure 7: Development of model to evaluate hyperflexion of the hip as alternative treatment approach

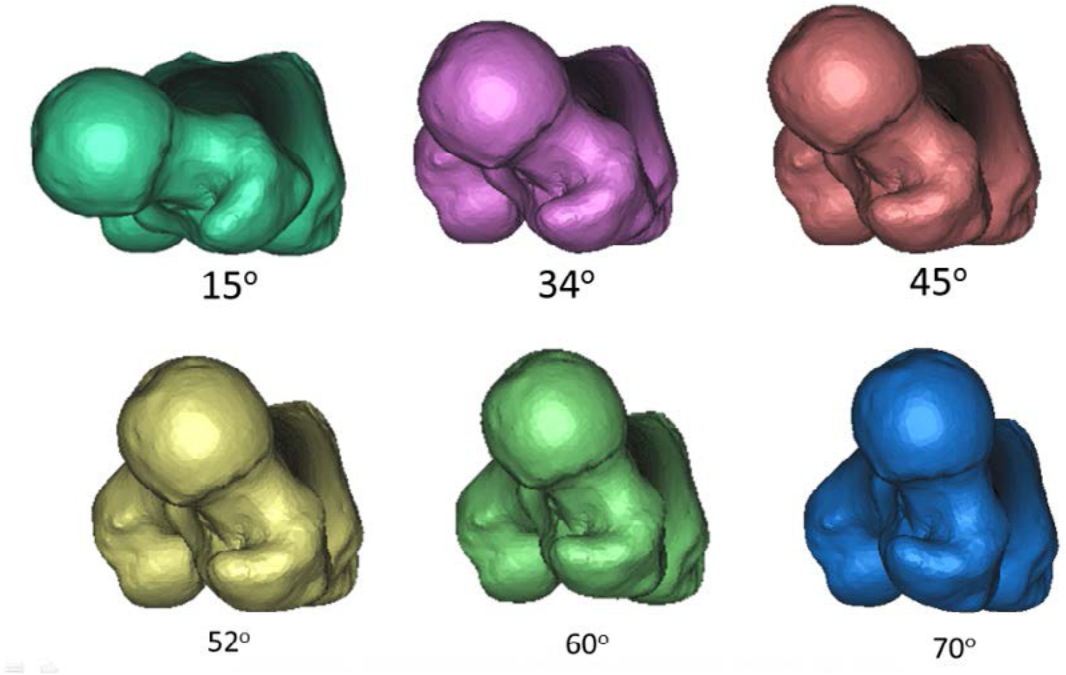

Figure 8 - Femur model with artificial derotation osteotomies to study the effects of AV angle variations in reductions of hip dysplasia

4 DISCUSION & CONCLUSIONS

We developed a simplified model of the anatomy of the human hip, and carried out simulations of reductions of hip dysplasia for the Graf III and Graf IV severities.

Our study aims to prevent treatment failures with the Pavlik harness, and we found that in hip subluxations (Graf III) the tension that develops in most muscles contributes to successful treatment; while in complete hip dislocations (Graf IV) the tension in most muscles contributes detrimentally to treatment. This implies that a treatment different from the Pavlik harness must be employed in greater severities of DDH.

Additionally we developed a method by which CT-scan data belonging to different human subjects may be combined into a single model, and scaled to meet different dimensional requirements. We employed this method to combine the CT-data and muscle positional data from four different human subjects, including adults, to engineer a comprehensive anatomy-based FEM and dynamics model of the lower anatomy of a 10-week old female infant. We are using this model for the study of the treatment for hip dysplasia.

Our findings are clinically relevant and directly applicable in the field of orthopaedics.

5 ACKNOWLEDGMENTS

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