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Mechanics of Hip-Dysplasia Reduction in Infants Using the Pavlik Harness: A Physics-Based Computational Model

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Abstract

The biomechanical factors influencing reduction of dislocated hips by the Pavlik harness in patients of Developmental Dysplasia of the Hip (DDH) were studied using a three-dimensional dynamic computer model capable of simulating hip reductions in (1) subluxated and (2) fully dislocated hip joints. Eight hip adductor muscles were identified as key mediators in the prognosis of hip dysplasia and the non-dimensional force contribution of each in the direction necessary to achieve concentric hip reductions was determined. Results point to the adductor muscles as the mediators of the reduction of
subluxated hips, as their mechanical action is a function of the degree of hip dislocation.

For subluxated hips in abduction and flexion, the Pectineus, Adductor Brevis, Adductor Longus, and proximal Adductor Magnus contribute positively to reduction, while the rest of the Adductor Magnus contributes negatively. Furthermore, in full dislocations all muscles contribute detrimentally to reduction, elucidating the need for traction to reduce Graf IV type of dislocations. Reduction of dysplastic hips was found to occur in two distinct phases in which the muscles act distinctively: (I) release phase and (II) reduction phase. This is the first study that uses dynamic computer simulations to understand hip dysplasia reductions by the Pavlik harness, bringing to light conclusive findings that may be used to predict successful vs. unsuccessful treatments, allowing physicians to make better treatment decisions.

**Key words:** Pavlik Harness, hip dysplasia, dynamical analysis, passive reduction, non-linear muscle model.

1. **Introduction**

Developmental Dysplasia of the Hip (DDH) is an abnormal condition where hip joint dislocation, instability or mal-alignment is present. As many as 1/20 infants will need evaluation or treatment of hip dysplasia, while 6 out of 1000 babies are treated for the condition (Bialik et al., 1998). DDH is typically discovered in infancy during physical examination or by ultrasound examination (Clarke et al., 1985; Weinstein et al., 2003). The Pavlik harness (Figure 1) is a standard non-surgical treatment method for DDH (Ramsey et al., 1976; Weinstein et al., 2003), and it is designed to maintain the hips in
abduction and flexion simultaneously, as this position directs the femoral head toward the triradiate cartilage at the center of the acetabulum. (Ramsey et al., 1976).

Treatment success is inversely related to the age at which treatment begins and the severity of the initial dislocation (Graf, 2006). For newborns with dislocated hips, the Pavlik harness fails in approximately 15% of cases (Mubarak et al., 1981; Weistein et al., 2003) and more than doubles when treatment begins after six weeks of age (Harding et al., 1997; Lerman et al., 2001). Prolonged Pavlik harness treatment of an inadequately reduced hip may damage the acetabulum, or contribute to delayed acetabular development, femoral nerve palsy, or inferior (obturator) dislocation (Mubarak et al., 1981; Rombouts and Kaelin, 1992). Accurate reduction in a reasonable time period is associated with improved outcomes for infants with hip DDH and should be the goal of Pavlik harness treatment.

We report on our study that utilizes engineering fundamentals and physics-based computer simulations to elucidate hip dysplasia reduction dynamics in the Pavlik harness with the purpose to explore the mechanics of the Pavlik harness and to determine factors that differentiate successful vs. unsuccessful treatment. The results from this study may help physicians make better treatment decisions in the Pavlik harness treatment of DDH.

2. Methods

A three-dimensional computer model of an infant hip was developed utilizing SolidWorks (Dassault Systèmes Simulia Corp., Providence, RI, USA) to simulate anatomical features corresponding to the hip bone, femora, and muscles relevant to hip
dysplasia biomechanics. We used CT-scans of a 14 year-old female and the medical segmentation and anatomical landmark measurement software Mimics (Materialise Inc, Plymouth, MI), to generate a 3D model consisting of a simplified hip and a complete leg constrained to the degrees of freedom required to simulate a dislocated, as well as a reduced hip, in abduction and flexion, with the origin located at the center of the right acetabulum (Figure 2). This dynamical model is driven by gravitational loads, and is supported by adductor muscles.

2.1. Dynamic simulation of hip reductions with the Pavlik Harness

2.1.1. Non-linear Muscle modeling

A total of 8 muscles were considered (Table 1). Data from the Dostal and Andrews (1981) study of hip musculature were scaled isotropically to 0.39 to match reference infant proportions using interacetabular distances as scaling parameters to define coordinates of the origin and insertion of the Iliopsoas, Pectineus, Adductor Brevis, Adductor Longus, Adductor Magnus, and Gracilis muscles. Following (Dostal and Andrews, 1981), the Adductor Magnus was divided into three segments: Adductor minimus, middle, and posterior, according to proximal, middle and distal femoral insertion respectively. Muscle insertion and origin points scaled using this method matched expected anatomical landmarks accurately. (Hill, 1949) studied toad Sartorius muscles and found they are 25-40% pre-stretched in their natural position. We defined this natural position in our study as zero abduction, zero flexion, and zero rotation.

Suzuki and Iwasaki reported clinical observations that reduction occurred passively with the Pavlik harness during muscle relaxation in deep sleep (Iwasaki, 1983; Suzuki,
Thus our model considers only the passive component in reduction of DDH. The passive response of muscles to elongation, $\varepsilon_s$, is exponential (Hill, 1949; 1952; Magid and Law, 1985; Sten-Knudsen, 1953), and the model introduced by Magid and Hill in Eq. (1), with constants in Table 2 was initially adopted to simulate the tensile force of the adductor muscles in response to their stretching due to the weight of the leg.

$$\sigma = \frac{E_0}{\alpha} (e^{\alpha\varepsilon_s} - 1)$$  \hspace{1cm} (1)

To obtain muscle-specific force from Eq. (1), effective cross-sectional areas were approximated based on the scaled Adductor Brevis from the CT-scan and (a) approximating the cross-sectional area as an ellipse taken at ¾ of muscle length, and (b) by dividing muscle volume by its length, yielding an average value of $A=41 \text{ mm}^2$. This represents an intermediate value between that of the Pectineus and Adductor Longus, and, given that the Adductor Magnus was discretized into three discrete muscles, the cross-sectional area of the Adductor Brevis was then used as representative value for all the modeled muscles.

Clinical observation shows that healthy (non-dysplastic) infant hips are maintained in static equilibrium when placed in the Pavlik harness if slight infero-superior support is provided to the leg to maintain flexion. The healthy hip in the Pavlik harness was adopted as the reference configuration for our simulations and serves as muscle model calibration baseline.

With these inputs, additional tension in the musculature was necessary to replicate equilibrium in the reference hip configuration, and the muscle model was calibrated by
introducing a constant, $C$, into Eq. (1) to increase stiffness. The unknown muscle tensions in seven pre-stretched muscles were related as ratios to tension in the Adductor Brevis which experiences the largest elongation ratio in the Pavlik harness (Table 3). The FEM commercial software NX Nastran (Siemens AG, Munich, Germany) was employed to obtain the tension in the Adductor Brevis muscle and simultaneously finding the tensions of each of the remaining muscles (Table 3), necessary to guarantee static equilibrium in the reference hip configuration. From these results, a calibration constant of $C=5.5$ was obtained (Figure 3), attributed to possible leg-supporting structures not accounted for in the model, a difference in the density of elastic muscle fibers between the studied muscles, a difference in mechanical behavior between human and amphibian muscles from which the muscle models originated, or a combination of the three. The calibrated muscle tension $(T)$ model used in this study is

$$ T = CA \frac{E_0}{\alpha} (e^{\alpha \varepsilon} - 1) $$

(2)

2.1.2. Anatomical Definitions

A three-dimensional solid model of a six-month old infant hip including right femur, was generated using a reconstructed CT-scan data study belonging to a 14 year-old female, scaled anisotropically to match the anatomical proportions of a female infant for who CT-scan data was also available. This helped visualize cartilaginous structures invisible in infant CT studies. The model accounted for anatomical structures of the acetabulum, pubis and ischium, as well as the femoral head, neck and shaft respectively (Figure 4). Moreover, a solid model of the right calf and right foot were
incorporated into the leg model and assembled using frictionless pins. The right leg alone was considered due to symmetry.

The hip was scaled by matching the anterior superior and posterior superior iliac spines, as well as the acetabuli centers and this yielded scale factors of 0.35, 0.32, and 0.32 in the X, Y, and Z directions respectively. The pubic and ischial rami of the scaled-down 14 year-old female hip was found to trace a wider arc, possibly due to widening of female hips at puberty, while all other landmarks matched well. This arc was manually modified to exactly match the trace of the infant hip arc.

2.1.3. External Loads

Load input to the model was defined as the weight of the leg acting though its center of mass, directed in the (–X) direction, assuming a supine infant fitted with the Pavlik harness. We used 7.26kg. based on the weight of a 6-month old female infant at the 50th length-for-age percentile (CDC, 2009). The leg was modeled by three separate segments - thigh, calf, and foot, and the weight and center of mass of each segment (Table 4) was calculated from anthropometric studies (Clauser et al., 1969; Dempster, 1955; Drillis and Contini, 1966; Osterkamp, 1995).

2.1.4. Boundary conditions

The model was constrained to define the necessary degrees of freedom that resemble both, a reduced and a dislocated hip, restricted by the Pavlik harness to the inherent narrow envelop of motion in abduction and flexion. A frictionless slip condition was defined for the hip/femoral head surface interaction. The hip configuration at 90° of
flexion and 80° of abduction (Figure 2) is referred hereon as “Pavlik Harness configuration”. Rotation of the leg assembly about the $x$-axis was restricted to precisely account for the flexion maintained by the Pavlik harness. Rotation about the $z$-axis was restricted to account principally for the restriction to this component of rotation imposed by the Pavlik harness with its below-knee attachment, but, in part, to account for reaction moment components about this axis possibly imposed by anatomical structures not included to reduce model complexity. The femoral head was restricted to move in space in the antero-posterior direction only, as the model accounts for an infant already fitted with the harness. The leg assembly was allowed to rotate freely about the $y$-axis, allowing it to abduct in response to the combination of external loads and internal muscle reactions.

2.1.5. Reduction Dynamic Simulations.

Hip muscles were simulated using action/reaction force elements defined by the non-linear constitutive Equation (2) positioned between points of origin and insertion of each muscle. Inertial properties of anatomical components were defined per section 2.1.2. The equations of motion were solved numerically in SolidWorks using GSTIFF integration as the femoral head and hip models remained in contact during the full solution. The Jacobian was updated at each time-step, 25 iterations were taken per time-step and the initial, minimum, and maximum integrator step sizes were set to $1.0 \times 10^{-8}$, $1.0 \times 10^{-7}$, and $1.0 \times 10^{-2}$.

Two independent dysplastic conditions were analyzed and simulated:
(1) Graf III subluxated hip: the center of the femoral head lies on the posterior rim of the acetabulum (Figure 5b).

(2) Graf IV fully dislocated hip: the femoral head is located posterior to the acetabulum, and obstructed by the labrum (Figure 5a).

The magnitude and direction of forces developed in each muscle were analyzed separately. First, we compared directional cosines of the lines of action of each muscle with those of the resultant forces necessary to induce motion towards reduction. To evaluate condition (1), a subluxation was induced while maintaining the length of the Pectineus muscle constant, and the equations of motion were solved numerically with the dislocation as initial condition. Additionally we evaluated the contributive components of muscle force in the direction necessary to affect reduction for 43°, 52°, 60°, 70°, and 80° and reported findings as percentage contributions in that direction. To evaluate condition (2) a full Graf IV type dislocation was digitally induced while maintaining the length of the Pectineus constant and the equations of motion were solved numerically with the dislocation as initial condition. Additionally we evaluated the contributive components of muscle force in the direction necessary to affect reduction for 56.3° and 70° of abduction.

2.2. Role of the Iliopsoas in reductions of hip dysplasia

The possible interference to reductions by the psoas tendon was analyzed by studying the straight-line path of travel of the tendon as it departed from its last point of contact on the bony pelvis towards its insertion point in the femur, neglecting tendon volume. Various hip configurations were analyzed: (1) zero abduction, zero flexion and
zero rotation; (2) zero flexion, gradual abduction, and (3) 90° flexion, gradual abduction from 0° to 80° (Pavlik harness configuration). This was also studied in a cadaveric dissection.

3. Results

3.1. Obstruction to reduction by Psoas tendon

Given that the Pavlik harness maintains hips abducted and flexed, and that we approximated this position as 80° of abduction and 90° of flexion, we found that:

(1) The psoas tendon is relaxed and is not an obstruction to reduction for any abduction angle while the hips are flexed to 90°. This includes the Pavlik harness hip configuration and both Graf III and Graf IV dislocations.

(2) An obstruction to hip reduction by the psoas tendon is only present when the hip is extended beyond approximately 45° based on cadaveric dissection observations. Upon extension, the tendon tightens, and its straight line path interferes with the femoral head; the exact flexion angle at which obstruction onset was not determined due unavailability of data on tendon volume.

3.2. Simulation - Reduction of subluxated hips by the Pavlik harness & Role of the Pectineus muscle

Inducing a Graf III type of dislocation, while maintaining the length of the Pectineus muscle constant, resulted in a reduction of 28° in abduction angle, which agrees with our clinical observations and those of (Iwasaki, 1983; Suzuki, 1994), providing a validation of our model. A successful dynamic reduction simulation was carried out.
indicating that Graf III initial dislocations can be reduced by the Pavlik harness, and for insight into the mechanisms of reduction we considered (a) the magnitudes and (b) directions of muscle tensions. The magnitudes of the tensions are functions of the elongation ratio of the muscles (Figure 3), but care must be taken at evaluating these as (1) uncertainty in cross sectional areas translates directly to uncertainty in tension values, and (2) muscles are pre-stretched by 25-40% in the natural position in the body (Hill, 1949). The unstretched lengths ($L_0$) found to best suit the model at the reference configuration were found to be $0.60 \times L_i$ for Pectineus, Adductor Brevis and Adductor Longus, and $0.675 \times L_i$ for the Adductor Minimus, Middle, and Posterior, and for the Gracilis, where $L_i$ is the length of each muscle at the natural position (Sec. 2.1.1). Although these are parameters employed in our study, pre-stretches of 25-40% may also induce uncertainty in calculated tensions.

Within the limitations of our model, further insight is gained by comparing elongation ratios of hip muscles with those observed in dysplastic hips of Graf III, and Graf IV reported in Table 5. While all muscles are stretched, the Adductor Brevis, incurs the largest elongation ratio, hence the largest tension, closely followed by the Adductor Longus and Adductor Minimus (Sec 2.1.1) depending of the severity of dysplasia. Naturally, given uncertainty inherent from pre-stretch, the largest elongation ratio can vary between these muscles if the pre-stretch percentage is varied within that range.

Examination of directional components of muscle tension upon inducing dislocation reveals that the Gracilis, as well as portions of the Adductor Magnus that insert in the distal femur, contribute negatively to the reduction with the Pavlik harness (Table 6), and that the percent constructive contribution of the studied muscles increase in direct
proportion with abduction angle (Figure 6) which may explain observations by different authors of reductions occurring during loss of muscle tone while in deep sleep (Iwasaki, 1983; Suzuki, 1994).

Results in Table 6 indicate that the Pectineus, although less tense than other muscles in the Pavlik harness position, exhibits the highest component of pull in the direction of reduction (towards the center of the acetabulum) based on the line of action of its force, and thus significantly helps effect and maintain reduction. This was later confirmed with a dynamic numerical simulation which successfully reduced the dislocation. Reduction was not achieved upon numerically suppressing the Pectineus,

3.2. Reduction of greater severities of hip dysplasia by the Pavlik harness.

Inducing a Graf IV type dislocation, while maintaining the length of the Pectineus muscle constant, resulted in a decrease in abduction of 13.7°. A smaller decrease in abduction resulted when inducing a Graf IV dislocation because for dysplasia of lesser severity the length of muscles that would otherwise be available to allow the leg to further abduct must account for the thickness of the posterior acetabular protrusion. This effect is mitigated once the femoral head has crossed the labrum posteriorly.

Simulation results indicate that reductions from dislocations of type Graf IV are unlikely to occur by Pavlik harness treatment, since the tensions of all the muscles contribute components that oppose the direction of the motion necessary for reduction (Table 7).

Given the exponential behavior of passive muscle tension in response to elongation, muscles tend to shorten when their equilibrium length is increased. This shortening
while the femoral head is located posterior to the acetabulum leads to displacement directed further posterior to the acetabulum, implying that energy to overcome tension in muscles is necessary to bring the femoral head over the posterior labrum to achieve reduction. Furthermore, for high severity types of dysplasia, the directional contributions of the muscles also increased in direct proportion with increasing abduction angle (Figure 7). However, with the femoral head in this location, abduction was insufficient to turn the detrimental directional cosines of the tensions into beneficial components, hence reduction did not occur.

4. Discussion

4.1 Role of the Psoas tendon in reductions of hip dysplasia

Our findings indicate that the psoas tendon does not obstruct reduction when the hip is in flexion, which is the position of reduction in the Pavlik harness and during closed reduction with cast application. However, this tendon tightens and crosses anterior to the hip capsule when the hip is extended. In the extended position the psoas is an obstruction to reduction. Releasing this tendon may only be necessary when a reduction is sought by managing the hips in an extended position, as is customary following open surgical procedures. Some support for this observation is provided by the medial approach for open reduction of the hip. When the hip is in the extended position, the iliopsoas muscle is taut and is released in order to gain greater surgical visibility of the joint capsule. Conversely, the position recommended for closed reductions is that of flexion and slight abduction - the “human” position, in which the iliopsoas tendon is shown to be relaxed. (Eberhardt et al., 2012) reported arthroscopic reduction of
dislocated hips in infants and did not perform release of the iliopsoas for visualization or for reduction when the hip was held in the “human” position.

4.2 Role of the Pectineus and adductor muscles in hip dysplasia reductions

Although the Pectineus is significantly less taught than other adductors when the hip is in the Pavlik harness configuration, it was found to have a significant effect due to having the most favorable line of action towards reduction. Conversely, the portion of the Adductor Magnus of distal femoral insertion, defined as Adductor Middle and Posterior (sec. 2.1.1) develop components of tension that oppose the direction desired for reduction. When the femoral head lies posterior to the acetabulum as in higher degrees of dysplasia, these muscles pull the femoral head further posterior to the acetabulum trapping it in this location. This may help explain the “Pavlik Disease” where the femoral head erodes the posterior wall of the acetabulum when the harness is used for prolonged periods in instances where the hip is inadequately reduced. This further implies that traction is necessary to overpower the detrimental components of tension of these muscles when the hip is fully dislocated (Graf IV). Another avenue to overcome this could be the surgical release of these muscles, or alternative methods for closed management (Papadimitriou et al., 2007). Hence, novel procedures that combine various techniques, in addition to the possible artificial activation of the Pectineus muscle, may enhance treatment and contribute to successful reductions for dysplastic hips that are irreducible with the Pavlik harness.

4.3 Mechanism of reduction
Based on our findings, reduction of higher degrees of dysplasia can be considered to take place as two distinct, consecutive events (Figure 8):

(a) Release phase: the femoral head is released from external resistances or factors constraining its movement, such as it being trapped behind the acetabulum, the Piriformis muscle resisting its movement, or other resistive factors.

(b) Reduction phase: follows the release phase and the femoral head has now overcome its initial barriers to reduction and can now be found somewhere over the perimeter of the labrum, as if it were only subluxated.

Reductions of subluxated hips (Graf III) may only require reduction phase, when there are no muscle contractures that require gradual release. Otherwise, gradual muscle relaxation is required and the muscles act distinctively in each phase. Following reduction, the Pectineus, due to its directional advantage, and the adductors, primarily the Adductor Brevis, are able to take over and pull the femoral head into the acetabulum, aided by the geometry of the acetabulum and the compressive components of tension of the portion of Adductor Magnus of distal femoral insertion, maintaining concentric reduction.

Suzuki (1994) describes three degrees of hip dysplasia and states that the greatest severity which places the femoral head center posterior to the labrum of the acetabulum requires traction for reduction. This is supported by our computational model: traction, referred to by Suzuki, is a method to free the femoral head from constraints, hence manually executing a release phase. Our findings, which correlate with previous observations, lead us to conclude that for hip dysplasia of greater severity (Graf IV), the
release phase is highly unlikely via the Pavlik harness alone. Traction, surgical release of the distal adductors and/or a different treatment avenue is therefore required.

5. Conclusions

We created a three-dimensional computer model to simulate the dynamics of hip dysplasia reductions when treated with the Pavlik harness. We identified eight hip adductor muscles as the key mediators in the prognosis of hip dysplasia (Pectineus, Adductor Longus, Adductor Brevis, Adductor Magnus, Psoas Major, Gracilis), and found that reductions occur in two distinct phases: (a) the release phase and (b) the reduction phase. Results indicate that muscles studied act distinctively in each phase and the mechanical effects of muscles vary with degree of hip dislocation. For subluxated hips in abduction and flexion, the Pectineus, Adductor Brevis, proximal Adductor Magnus, and Adductor Longus contribute positively to reduction, while the portions of the Adductor Magnus muscle with middle and distal femoral insertion contribute negatively. Conversely, for a fully dislocated hip, all muscles contribute detrimentally to reduction elucidating the need for traction to reduce Graf IV type of dislocations.

For the first time, dynamic computer simulations were used to study the mechanism of action of the Pavlik harness and our model is consistent with clinical observations reported by previous authors. It may provide methods for valid simulations to estimate modifications for treatment that could lead to new insights for non-surgical management of DDH by passive reduction with the Pavlik harness or similar devices. It may additionally prove useful in the training of physicians as correct or incorrect forces may be easily evaluated.
Conflict of interest statement
The authors have no conflicts of interest to disclose.

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The sponsors had not role in the study design, in the collection, analysis and interpretation of data; in the writing of the manuscript; and in the decision to submit the manuscript for publication.
List of figures included in the manuscript listed in order of appearance.

Figure 2. Solid model of the Pavlik Harness: (a) CT-based three-dimensional hip reconstruction. (b) Simplified solid model with musculature. Right-hand coordinate system. Y-axis normal to the page. Both models viewed in the infero-superior direction, on the axial plane.
Figure 3. Original muscle model (Magid and Law, 1985) and calibrated model.
Figure 4. Three-dimensional dynamic CAD 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.
Figure 5. Hip dislocation cases modeled: (a) subluxated hip (Graf IV) with femoral head position over posterior acetabular labrum, (b) full dislocation (Graf III) with femoral head located posterior to acetabulum and (c) reduced hip.
Figure 6. Percent contribution of muscle tension towards reduction vs. abduction angle - Graf III.
Figure 7. Percent contribution of muscle tension towards reduction vs. Abduction angle - Graf IV.
Figure 8. Simplified model depicting the directions of necessary motion to complete the (I.) Release and (II.) Reduction phases of the mechanism of reduction of hip dysplasia.
List of tables included in the manuscript listed in order of appearance.

Table 1: Coordinates of muscle origins and insertions scaled to fit 6-mo old Female infant (Dostal and Andrews, 1981). Hip configuration: Zero abduction, zero flexion, zero rotation.

<table>
<thead>
<tr>
<th>Muscle origin and insertion coordinates scaled to fit 6-mo. old infant in natural position</th>
<th>Origin on Pelvis (mm)</th>
<th>Femoral insertions (mm)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale: 0.4</td>
<td>X</td>
<td>Y</td>
<td>Z</td>
</tr>
<tr>
<td>1. Iliopsoas</td>
<td>11.1</td>
<td>9.5</td>
<td>-2.0</td>
</tr>
<tr>
<td>2. Pectineus</td>
<td>17.4</td>
<td>1.2</td>
<td>-15.0</td>
</tr>
<tr>
<td>3. Adductor Longus</td>
<td>16.2</td>
<td>-12.3</td>
<td>-25.7</td>
</tr>
<tr>
<td>4. Adductor Brevis</td>
<td>8.3</td>
<td>-17.8</td>
<td>-26.5</td>
</tr>
<tr>
<td>5. Adductor Minimus</td>
<td>2.8</td>
<td>-19.4</td>
<td>-24.2</td>
</tr>
<tr>
<td>6. Adduct Mag (Middle)</td>
<td>-12.3</td>
<td>-24.2</td>
<td>-17.4</td>
</tr>
<tr>
<td>7. Adduct Mag (Posterior)</td>
<td>-19.0</td>
<td>-23.4</td>
<td>-13.5</td>
</tr>
<tr>
<td>8. Gracilis</td>
<td>-4.0</td>
<td>-19.4</td>
<td>-26.9</td>
</tr>
</tbody>
</table>
Table 2: Parameters for Eq. (2). Values $\alpha$ and $E_0$ as defined by Magid (Magid and Law, 1985).

<table>
<thead>
<tr>
<th>Variables in Eq. (2)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>4.28±0.19</td>
</tr>
<tr>
<td>$E_0$</td>
<td>2.6±0.25 ($\times 10^3 , N/m^2$)</td>
</tr>
<tr>
<td>$A$</td>
<td>41 mm$^2$</td>
</tr>
<tr>
<td>$\varepsilon_s$</td>
<td>Elongation ratio $(L/L_0 - 1)$</td>
</tr>
</tbody>
</table>
Table 3: Muscle tensions that maintain a reduced hip in static equilibrium at 80° abduction and 90° flexion. Li refers to the length of the muscles in the natural position in the body.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Initial muscle length**</th>
<th>Elongation Ratio at 80° abduction, 90° flexion (L/Lo - 1)</th>
<th>Tension (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pectineus</td>
<td>0.6 x Lo</td>
<td>0.96</td>
<td>8.9</td>
</tr>
<tr>
<td>Adductor Longus</td>
<td>0.6 x Lo</td>
<td>1.32</td>
<td>38.2</td>
</tr>
<tr>
<td>Adductor Brevis</td>
<td>0.6 x Lo</td>
<td>1.54</td>
<td>97.8</td>
</tr>
<tr>
<td>Adductor Minimus</td>
<td>0.675 x Lo</td>
<td>1.31</td>
<td>21.3</td>
</tr>
<tr>
<td>Add. Magnus (Middle)</td>
<td>0.675 x Lo</td>
<td>1.28</td>
<td>23.6</td>
</tr>
<tr>
<td>Add. Magnus (Posterior)</td>
<td>0.675 x Lo</td>
<td>0.92</td>
<td>26.7</td>
</tr>
</tbody>
</table>

** per Hill muscles are 25-40% stretched in their natural position in the body (Hill, 1949).
Table 4: Weights of leg segments relative to total body weight (Drillis and Contini, 1966).

<table>
<thead>
<tr>
<th>Weights of leg segments</th>
<th>Total Body Weight (BW)</th>
<th>7.26 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment</td>
<td>%BW</td>
<td>Weight</td>
</tr>
<tr>
<td>Thigh</td>
<td>9.46</td>
<td>0.69 kg</td>
</tr>
<tr>
<td>Calf</td>
<td>4.2</td>
<td>0.30 kg</td>
</tr>
<tr>
<td>Foot</td>
<td>1.35</td>
<td>0.10 kg</td>
</tr>
<tr>
<td>Full leg</td>
<td>15</td>
<td>1.09 kg</td>
</tr>
</tbody>
</table>
Table 5: Comparison of elongation ratios between reference hip configuration, Graf III, and Graf IV severities of hip dysplasia.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Reference configuration</th>
<th>Graf III</th>
<th>Graf IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pectineus</td>
<td>0.31</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>Adductor Longus</td>
<td>0.96</td>
<td>1.23</td>
<td>1.21</td>
</tr>
<tr>
<td>Adductor Brevis</td>
<td>1.54</td>
<td>1.58</td>
<td>1.55</td>
</tr>
<tr>
<td>Adductor Minimus</td>
<td>1.322</td>
<td>1.4</td>
<td>1.11</td>
</tr>
<tr>
<td>Add. Magnus (Middle)</td>
<td>1.31</td>
<td>1.36</td>
<td>1.05</td>
</tr>
<tr>
<td>Add. Magnus (Posterior)</td>
<td>1.28</td>
<td>0.98</td>
<td>0.73</td>
</tr>
<tr>
<td>Gracilis</td>
<td>0.91</td>
<td>0.85</td>
<td>0.68</td>
</tr>
</tbody>
</table>
Table 6: Percent muscle tensions directional contribution in the direction of reduction - Graf III.

<table>
<thead>
<tr>
<th>Abduction Range (degrees, measured from sagittal)</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>42.7</td>
<td>52.2</td>
</tr>
<tr>
<td>Pectineus</td>
<td>28.1%</td>
</tr>
<tr>
<td>Add Longus</td>
<td>-3.0%</td>
</tr>
<tr>
<td>Add Brevis</td>
<td>10.6%</td>
</tr>
<tr>
<td>Add/Mag/Min</td>
<td>4.7%</td>
</tr>
<tr>
<td>Add/Mag/Mid</td>
<td>-32.6%</td>
</tr>
<tr>
<td>Add/Mag/Post</td>
<td>-44.6%</td>
</tr>
<tr>
<td>Gracilis</td>
<td>-50.32%</td>
</tr>
</tbody>
</table>
Table 7: Percent contribution of muscle tensions in the direction of reduction - Graf IV.

<table>
<thead>
<tr>
<th>Percent directional contribution of tensions - Graf IV</th>
<th>Abduction angle</th>
<th>Contribution order</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>52.3°</td>
<td>70°</td>
</tr>
<tr>
<td>Pectineus</td>
<td>-42.9%</td>
<td>-29.7%</td>
</tr>
<tr>
<td>Add Longus</td>
<td>-64.8%</td>
<td>-52.2%</td>
</tr>
<tr>
<td>Addr Breviss</td>
<td>-53.5%</td>
<td>-42.1%</td>
</tr>
<tr>
<td>Add/Mag/Min</td>
<td>-57.3%</td>
<td>-45.7%</td>
</tr>
<tr>
<td>Add/Mag/Mid</td>
<td>-77.7%</td>
<td>-67.9%</td>
</tr>
<tr>
<td>Add/Mag/Post</td>
<td>-86.5%</td>
<td>-77.3%</td>
</tr>
<tr>
<td>Gracilis</td>
<td>-91.3%</td>
<td>-84.0%</td>
</tr>
</tbody>
</table>

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REFERENCES


