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Rigid body dynamics

\textbf{A B S T R A C T}

A physics-based computational model of neonatal Developmental Dysplasia of the Hip (DDH) following treatment with the Pavlik Harness (PV) was developed to obtain muscle force contribution in order to elucidate biomechanical factors influencing the reduction of dislocated hips. Clinical observation suggests that reduction occurs in deep sleep involving passive muscle action. Consequently, a set of five (5) adductor muscles were identified as mediators of reduction using the PV. A Fung/Hill-type model was used to characterize muscle response. Four grades (1–4) of dislocation were considered, with one (1) being a low subluxation and four (4) a severe dislocation. A three-dimensional model of the pelvis–femur lower limb of a representative 10 week-old female was generated based on CT-scans with the aid of anthropomorphic scaling of anatomical landmarks. The model was calibrated to achieve equilibrium at 90° flexion and 80° abduction. The hip was computationally dislocated according to the grade under investigation, the femur was restrained to move in an envelope consistent with PV restraints, and the dynamic response under passive muscle action and the effect of gravity was resolved.

Model results with an anteversion angle of 50° show successful reduction Grades 1–3, while Grade 4 failed to reduce with the PV. These results are consistent with a previous study based on a simplified anatomically-consistent synthetic model and clinical reports of very low success of the PV for Grade 4. However our model indicated that it is possible to achieve reduction of Grade 4 dislocation by hyperflexion and the resultant external rotation.

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1. Introduction

Developmental Dysplasia of the Hip (DDH) is an abnormal condition where hip joint dislocation, misalignment, or instability is present in infants. According to Bialik et al. (1999), “Congenital dislocation of the hip represents one of the most important and challenging congenital abnormalities of the musculoskeletal system”. It has been reported that in 20 cases per 1000 births, babies have some instability (USPSTF, 2006) and 6 out of every 1000 will require treatment (Bialik et al., 1999). Studies had also shown that DDH was responsible for 29% of primary hip replacements in people up to age 60 years (Furnes et al., 2001). There are four grades (1–4) of dislocation with Grade 4 being most severe as specified by the International Hip Dysplasia Institute (IHDI) (Narayanan et al., 2000). The grade classification of the IHDI has been adopted in this paper to characterize dislocations for DDH because it is applicable to infants and to older children. The IHDI Classification has also been found more reliable than earlier classifications (Fig. 1a). The Pavlik Harness (PH) (Fig. 1b) is a standard non-surgical treatment for DDH (Ramsey et al., 1976; Weinstein et al., 2003) that is designed to maintain the hips in abduction and flexion to bring the femoral head back into the acetabulum (reduction). Clinical reports and previous research indicate very low success of the PH for more severe

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grades of hip dislocation (Ardila et al., 2013; Atalar et al., 2007; Uras et al., 2014). Also, the incidence of failure doubles when treatment begins after three weeks of age (Harding et al., 1997).

It has been found that PH treatment fails in approximately 15% of cases when initiated shortly after birth (Kitoh et al., 2009; Mubarak et al., 1981; Viere et al., 1990; Weinstein et al., 2003). Statistically it has been shown that for severity Grades 1–3, successful reduction rate is 92% while for Grade 4 the successful reduction rate is approximately 2% (Grill et al., 1988). Therefore, special attention is needed for the fully dislocated hip described by a Grade 4. This paper uses a rigid body dynamics model constructed from MRIs and Ct-scans to quantify the force and moment generation of the adductor muscles when the PH is used. Specifically, the interest is to explore the unsuccessful reduction of Grade 4 and explore alternatives for reduction of this severe dislocation.

2. Methods and materials

In order to study the complex biomechanics of DDH treatment with the PH, a Rigid Body Dynamics (RBD) model has been developed. A 3D model of the pelvis-femur-lower limb assembly of a representative 10-week old female infant (TWOFI) was generated based on a composite of Ct-scans and MRIs of a 6-month and 14-year old female as well as the Visible Human Project with the aid of anthropomorphic scaling of anatomical landmarks. Five adductor muscles were considered as mediators of reduction. A Fung-type muscle model was calibrated to achieve equilibrium at 90° flexion and 80° abduction. The hip was computationally dislocated according to the grade under investigation, the femur was constrained to move in an envelope.

Fig. 1. (a) DDH dislocation grades (Narayanan et al., 2000) for a representative 10 week old anatomy (ossified regions are enclosed by solid lines), (b) typical Pavlik harness configuration.

Fig. 2. (a) Superposition of a solid model of FYOF rendered from a CT-scan (left) with a solid model rendered from a Ct-scan of SMOFI (right), (b) spherical femoral head in neonates: computational model (left) and dissection (right) (Ortolani and Ortolani), (c) illustration of 50° anteversion angle in a 3D solid model (left) and a dissected femur showing anteversion angle (right) (Ortolani and Ortolani).

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consistent with PH restraints, and the dynamic response under passive muscle action and under the effect of gravity was resolved using the Adams solver in Solidworks (Dassault Systemes, Concord, MA). Hyperflexion was also investigated for severe dislocations using this model.

2.1. Three-dimensional anatomical solid model of a 10-week old female infant

Anatomical lower limbs models representative of a TWOFI were constructed using a combination of CT-scans from several human subjects and the use of medical segmentation packages: Mimics and 3-matic (Materialise Inc., Plymouth, MI). The lower extremity was composed of the hip, femur, tibia, fibula, and foot. It must be mentioned that symmetry was assumed along the sagittal plane, which divides the body into right and left portions (x-y plane). Thus only the right lower limb was modeled.

Due to the presence of large cartilaginous zones, the MRIs of a neonate offer a challenge in reconstruction of the complete anatomy based on medical segmentation software alone. Moreover, retrospective MRIs and CT-scans of subjects with DDH focus mainly on hip region and therefore do not provide the required geometric information of the rest of the anatomy. As such, a model was constructed from a composite of CT-scans of a 6-month and 14-year old female as well as the Visible Human Project with the aid of anthropomorphic scaling of anatomical landmarks in order to assemble the TWOFI model. It is also known that bone growth is not proportional in all directions, thus, anisotropic parameters will be used for all the lower limb bones.

For hip reconstruction, the starting point was to obtain rough bone geometry contours from CT-scan of a six month old female infant (SMOFI) and then superimpose it on well-defined bone geometry obtained from high quality CT-scan data of a fourteen year old female (FYOF). Both the SMOFI and the FYOF models were superimposed so the iliac spines and acetabuli were aligned (Fig. 2a).

This accounts for the hip widening that occurs in females during puberty. Once the geometry was obtained, the SMOFI was scaled to a TWOFI by matching infant

![Fig. 3. (a) Reconstructed lower limb from infant and VHP CT-scans and MRIs, (b) adductor muscles origin and insertion points, (c) healthy hip (Left), Grade 3 (Center), and Grade 4 (Right).](image_url)

Table 1

Lower extremity mass distribution and scaled TWOFI PCSAs using shape adductor brevis factor (f) (Friederich and Brand, 1990).

<table>
<thead>
<tr>
<th>Total body mass (BM)</th>
<th>Limb</th>
<th>Thigh</th>
<th>Leg</th>
<th>Foot</th>
<th>Full leg</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.26 kg</td>
<td>9.45</td>
<td>0.69</td>
<td>4.2</td>
<td>1.35</td>
<td>1.09</td>
</tr>
<tr>
<td>f = 0.036</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pectineus</td>
<td>9.03</td>
<td>11.52</td>
<td>22.73</td>
<td>25.52</td>
<td>18.35</td>
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<td></td>
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<td>Adductor magnus</td>
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<td></td>
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<td>Adductor magnus min</td>
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<td></td>
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<tr>
<td>Adductor magnus middle</td>
<td>16.95</td>
<td>0.603</td>
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<tr>
<td>Adductor magnus</td>
<td>3.73</td>
<td>0.133</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1

Lower extremity mass distribution and scaled TWOFI PCSAs using shape adductor brevis factor (f) (Friederich and Brand, 1990).

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orthopedic data found in Hensinger (1986)’s Standards in Pediatric Orthopedics. The final hip anisotropic scaling factors were determined to be: 0.35 in the x-direction, 0.3 in the y-direction, and 0.35 in the z-direction. The acetabulum depth was approximately 7.9 mm, the acetabular depth-width ratio (ADR) was 45%, and the acetabulum diameter was approximately 17.5 mm.

High-quality CT-scans and MRIs from the visible human project (VHP) (NIH, 2009) were used to reconstruct the femur, tibia, fibula, and foot. The geometry was reconstructed using the superposition approach used for the hip. Scaling parameters for all the other bones of the lower extremity are found to be: 0.23 in the x-direction, 0.22 in the y-direction, and 0.25 in the z-direction. The femoral head had a diameter of 14 mm and was assumed to be perfectly spherical as observed during infant dissections (Fig. 2b).

The femoral anteverision angle also plays a critical role on hip reduction since it will affect muscle force and moment contribution while the PH is in use. This angle defines the difference between the axis of the femoral head and the transcondylar axis of the knee. This angle ranges typically from 30° to 40° at birth, but can reach up to 70°. The anteverision decreases in adulthood to about 15°. It has been shown that anteverision angles between 0° and 40° had relatively small effect on the isometric moment-generating capacity (Delp et al., 1994). Consequently, the present study considers an anteverision angle beyond 40°, specifically, the model under consideration will be based on a representative average (Sankar et al., 2009) anteverision angle of 50° (Fig. 2c).

Once solid models were completed for the hip, femur, tibia, fibula, and foot, Solidworks is used to assemble all the components (Fig. 3a). To assemble the femur to the pelvis origins and orientations in both bones were specified as defined by Dostal and Andrews (1981). The origin of the inertial Cartesian reference frame was located at the center of the acetabulum for the hip and at the center of the femoral head for the femur. Five adductor muscles were identified as mediating muscles during reduction with the PH: (1) Pectineus, (2) Adductor Brevis, (3) Adductor Longus, (4) Adductor Magnus, and (5) Gracilis. For this study, musculoskeletal geometry and posture similar to the fetal positioning for the newborns was induced to attain muscle relaxation, and, in flexion and abduction, towels adjusted to the appropriate height were placed under the knees to avoid forcible abduction and it was clinically observed that under mild sedation and in natural abduction and flexion, the spontaneous reduction with the PH is reproduced (Fukaiye et al., 2014). This further justifies the passive muscle model adopted in this study.

Well-known models (Hill, 1970; Fung, 1972) 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. A Hill-based model (Delp, 1990) had been proposed to estimate passive muscle force by normalizing it using a peak isometric muscle force (PIMF) as shown in Eq. (1):

\[ F = \frac{F_{PIMF}}{F_{PIMF}} \]

(1)

where \( F_{PIMF} \) is the normalized passive muscle force, \( F_{PIMF} \) is the PIMF, and \( F \) is the muscle force. Delp also reports peak isometric force is proportional to its physiologic cross sectional area (PCSA) as seen in Eq. (2):

\[ F_{PIMF} = C \times (\text{PCSA}) \]

(2)

where \( C \) has a value of 25 N/cm² (Delp, 1990) and was estimated to scale PCSAs that were measured on young adult cadavers to match moment curves measured on young subjects. Furthermore, Thelen (2003) reports that \( F_{PIMF} \) can be expressed as

\[ F_{PIMF} = \frac{K_{p}^{n} - 1}{K_{p}^{n} - 1} \times \lambda^{n} \]

(3)

where \( K_{p} \) is an exponential shape factor with a value of 4 obtained from OpenSim (Delp et al., 2007), \( e_{m}^{n} \) is the passive muscle strain with a value of 0.60 for young adults, and \( \lambda \) is the optimal muscle-fiber length (stretch). The stretch can be written as \( \lambda = L_{m} - L_{0} \) with \( L_{m} \) being the deformed length, and \( L_{0} \) being the initial muscle length at rest measured at 20° abduction and 120° flexion for newborns. This flexion and abduction ‘neutral’ configuration accounts for the fact newborns maintain a posture similar to the fetal positioning for the first few months after birth with the hips flexed in toward the belly and wide apart. This initial muscle length at rest is also multiplied by a specified muscle pre-stretch for the lower extremity muscles and is usually between 20 and 30%. By combining Eqs. (1)-(3), an expression can then be derived to obtain passive muscle force as function of stretch:

\[ F = \text{PCSA} \left[ \left( \frac{K_{p}^{n} - 1}{K_{p}^{n} - 1} \right) \right] \]

(4)

Using MRI data, a TOFWI PCSA of 0.41 cm² for the adductor brevis was estimated by measuring the volume of the muscle and dividing it by its average length. A shape factor was then defined, by using a PCSA of 11.52 cm² of an adult’s adductor brevis (Friederich and Brand, 1990), as the ratio between an adult PCSA and the TWOFI PCSA. The adductor brevis shape factor of 0.036 was then used to scale all of the other muscles measured by Friederich (Table 1).

2.3. Rigid body dynamics (RBD) model

Numerical RBD was carried out using the ADAMS dynamics motion analysis module in Solidworks. The governing differential equations of motion provided in

![Fig. 4.](image-url) (a) TWOFI passive force versus stretch for calibrated model, (b) adductor brevis force–stretch comparison between TWOFI and young adult models.

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Eq. (5):
\[
\mathbf{M} \dot{q} + \beta \mathbf{F}(q, \dot{q}) = \mathbf{A}^T \mathbf{F}(q, \dot{q}) = 0
\]
are numerically solved subject to the natural constraints \( \phi(q, \dot{q}) = 0 \). The system mass matrix is \( \mathbf{M} \), the vector of generalized coordinates for the displacements is \( \dot{q} \), the Lagrange multiplier adjoining the gradient constraints \( \phi \) is \( \beta \), the set of configuration and applied motion constraints is denoted by \( \mathbf{F}(q, \dot{q}) \), projects the applied forces in the \( \dot{q} \) direction, and \( \mathbf{A} \) is the vector of applied forces. The governing equations of dynamics described in Eq. (5) are Newton’s laws of motion augmented via a Lagrange multiplier by constraints. The Force vector is in general a function of displacement, linear in the case of a Hookean solid or non-linear as in our case as in Eq. (5), and a function of time-derivative of the displacements in case of the presence of damping. In this study, the Gear Stiff (GSTIFF) integrator was used, the Jacobian was updated at each time-step, 25 sub-level iterations were taken per time-step, and the initial, minimum, and maximum integrator step sizes were set to \( 1 \times 10^{-2}, 1 \times 10^{-2}, \) and \( 1 \times 10^{-2} \). The hip joint is a multi-axial ball and socket joint and physiologically considered a synovial joint on which the bone ends are covered by a slippery tissue called articular cartilage to create a frictionless bearing point. Therefore, the contact between surfaces was assumed to be frictionless using a restitution coefficient of zero. Moreover, the constraints serve to restrain the motion within the envelope realized with the PH during Grade 1–4 studies and to constrain the knees in a hyperflexed configuration for Grade 4 studies. Custom functions were written in Solidworks for each of the muscles studied using the model described in Eq. (4) with their respective PCSAs.

2.4. Equilibrium reference for model calibration
Since the passive muscle model developed previously was for a young adult, the constants \( a \) and \( b \) in Eq. (4) needed to be recalibrated for a TWOFI and also to stiffen the exponential function to account for ligaments that start acting at the limit of ranges of motion, namely, the iliofemoral, pubofemoral and ischiofemoral ligaments which help to stabilize the hip joint. The muscle model was calibrated by calculating the factors that allowed to precisely replicate the clinical observation that equilibrium is attained when infants are supine and the hips are placed in abduction at 80° and 90° flexion. That is, in this position, the passive action of the muscles holds the legs in place. Constants \( a \) and \( b \) were tuned in this model until the equilibrium configuration was achieved by only using muscle passive tensions. Constant \( a \) was found to be 0.0337 N/cm² and \( b \) was found to be 13.95. It is important to mention that there is no unique set of values for \( a \) and \( b \). However there is a minimum value requirement for \( b \), which is needed to stiffen the curve in order to achieve physically realistic equilibrium at 80° abduction. The constants \( a \) and \( b \) are inversely related; while \( b \) needs a minimum value to allow the model to achieve realistic muscle behavior, \( a \), which is used to find final equilibrium, is found through iteration once \( b \) has been established. The passive force behavior of our calibrated muscle model is presented in Fig. 4a where it is observed that the exponential behavior becomes very pronounced after a lambda (λ) value of about 1.35. Our equilibrium model stiffens significantly after this value due to the previously mentioned hip ligaments that prevent any further abduction of the legs past an angle of 80°. Fig. 4b also shows a comparison of the force-stretch behavior between our TWOFI calibrated model and the young adult of the adductor brevis where it is clearly seen our calibrated model stiffens faster once it gets close to the limits of ranges of motion as expected. After a close comparison between all the adductor muscles, it is found that all muscles display the same behavior as the brevis.

Fig. 5a and b provide the x-y and x-z views at equilibrium with reaction force (s) imparted at the contact(s) of the femoral head and the acetabulum shown as single headed (yellow) arrows whose magnitude is proportional to the size of the arrow. Muscle force and moment contribution at equilibrium clearly show that the Pectineus and the Adductor Brevis are the main muscle contributors (Table 2).

2.5. Anatomical dislocation configuration
The TWOFI model was dislocated as previously explained to investigate dislocations Grades 1–4. Subtle dislocations are modeled for Grades 1 and 2 as described by the HDI (Fig. 6a and b), for Grade 3, ossification center is at the level of the superolateral margin of the acetabulum. The femoral head was placed at the rim of the acetabulum (Fig. 6c) and the center of the femoral head was placed at \( x = -3.44 \text{ mm}, y = 1.14 \text{ mm}, z = 6.59 \text{ mm} \) relative to the origin located at the center of the acetabulum. For Grade 4, ossification center is above the level of the superolateral margin of the acetabulum. The femoral head was fully dislocated and positioned on the posterior wall of the acetabulum. Specifically, the center of the femoral head was placed at \( x = -10.05 \text{ mm}, y = 12.69 \text{ mm}, z = -1.87 \text{ mm} \) relative to the origin located at the center of the acetabulum (Fig. 7a).

3. Results
The TWOFI lower extremity model was used to quantify force and moment generation of the adductor muscles. Results provide insight of their contribution to reduction of DDH on severe Grade 3 and 4 dislocations whenever the PH is used and gravity is acting. It is known from clinical observation that reduction is successful whenever the PH is used on Grades 1 and 2 (Uras et al., 2014), thus these two grades were analyzed but values are not reported. Force and moment contribution of the adductor muscles while the PH is being used are reported for Grade 3 and Grade 4 (Table 3).

4. Discussion
As expected, Grades 1 and 2 were successfully reduced, which is consistent with our previous study based on a synthetic model (Ardila et al., 2013) as well as from clinical observation (Uras et al., 2014). Grade 3 was successfully reduced while Grade 4 dislocation was not. However, Grade 4 dislocation reduction was achieved by an external rotation of the lower extremity followed by a semi-circular path taken

Table 2

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Force (N m)</th>
<th>Moment (N m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pectineus</td>
<td>1.170</td>
<td>45.84</td>
</tr>
<tr>
<td>Adductor brevis</td>
<td>1.523</td>
<td>15.01</td>
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<td>Adductor longus</td>
<td>1.422</td>
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<td>1.392</td>
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</tr>
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<td>Adductor magnus posterior</td>
<td>1.229</td>
<td>0.33</td>
</tr>
<tr>
<td>Gracilis</td>
<td>1.357</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 5

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by the femoral head along the posterior wall of the acetabulum along the ischial plane, and the subsequent entrance into the acetabulum via the acetabular notch (Fig. 7b). This path of reduction is generally consistent with clinical studies performed to avoid surgical release of adductor muscles by Papadimitriou et al. (2007) where the reduction phase is divided in three sub-phases: (1) the femoral head travels from the grade 4 dislocated position arriving at the ischial tuberosity, (2) the femoral head rides over the ischial tuberosity to obturator
foramen, and (3) the femoral head departs from the obturator foramen and enters the acetabulum via the acetabular notch, achieving reduction. Papadimitriou studies showed successful reduction of severe dislocations by this alternative hyperflexion procedure using the Hoffmann–Daimler harness keeping the hip flexed at 120°.

In summary, a patient-derived geometry was successfully constructed to model the right lower extremity of a TWF. The model developed allows for the detailed study of the biomechanics of DDH treatment with the PH. Results suggest muscle force contributions on hip reduction are functions of severity of hip dislocation. Our findings also strongly indicate muscle tensions contribute to reduction with the harness for subluxated and intermediate dislocations (Grades 1–3). It is also notable that the Pectineus and Adductor Brevis muscle force contribution favors reduction significantly in Grades 1–3 while it disfavors reduction in Grade 4. The latter dislocations, which have been considered irreducible by most physicians, could be reduced by using a hyperflexion method. Further optimization of PH configuration may help improve DDH treatment effectiveness. This multi-physics computational approach is consistent with clinical observations reported in the literature and may potentially provide physicians means to determine modifications to evaluate treatment that could lead to new insights for non-surgical management of DDH by passive reduction with the PH or in combination with other orthosis. A limitation of this study is the absence of abductor muscles as well as a fixed anteverision angle of 50°, which may influence total force and moment contribution. Plans to include additional lower limb muscles, the effect of different anteverision angles, and the effect of cartilage deformation, are contemplated for future studies.

**Conflict of interest statement**

None.

**Acknowledgments**

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**References**


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Table 3
Muscle force and moment contribution on Grade 3 dislocation and Grade 4 dislocation.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Grade 3 dislocation</th>
<th>Grade 4 dislocation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>λ (Stretch)</td>
<td>Total force (N)</td>
</tr>
<tr>
<td>Pectineus</td>
<td>2.009</td>
<td>2967.04</td>
</tr>
<tr>
<td>Adductor brevis</td>
<td>1.658</td>
<td>105.68</td>
</tr>
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<td>Adductor longus</td>
<td>1.588</td>
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<td>Adductor magnus posterior</td>
<td>1.460</td>
<td>2.15</td>
</tr>
<tr>
<td>Gracilis</td>
<td>1.432</td>
<td>0.42</td>
</tr>
</tbody>
</table>


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