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ORIGINAL ARTICLE

Finite element analysis evaluation of hypothetical alternative treatment scenarios for neglected developmental dysplasia of the hip

Evaluación mediante análisis de elementos finitos de escenarios hipotéticos de tratamiento alternativo para la displasia del desarrollo de cadera desatendida

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Abstract

Objective: *The study aimed to evaluate three different degrees of correction in the surgical treatment of neglected developmental dysplasia of the hip (DDH) using finite element models based on computed tomography.* **Method:** *Three tridimensional FEA models of hypothetical post-operative (PO) outcomes were developed, based on three tridimensional CT of a pediatric patient diagnosed with luxated neglected DDH: One with the acetabular index of the contralateral hip (CLAT); another based on a theoretical Bombelli biomechanical model (BMB); and another recreating the patient's actual PO.* **Results:** *The stresses in the affected hip were greater than those in the unaffected hip. CLAT showed the greatest stress and the smallest loading zone (LZ). In contrast, BMB showed the smallest stress and the biggest LZs.* **Conclusions:** *The approach based on the BMB gave the best results in terms of the distribution of the stresses over the hip, whereas the worst was CLAT. Qualitatively, estimating the stability and range of movement of the hip, the PO case was considered the best.*

Keywords: *Neglected developmental dysplasia of the hip. Dega acetabuloplasty. Finite element analysis. Biomechanics.*

Resumen

Objetivo: *Evaluar tres diferentes grados de corrección en el tratamiento quirúrgico de la displasia del desarrollo de la cadera (DDH) inveterada mediante modelos de elementos finitos basados en tomografía computarizada.* **Método:** *Se desarrollaron tres modelos tridimensionales de elementos finitos de resultados posoperatorios hipotéticos, basados en tres tomografías computarizadas tridimensionales de un paciente pediátrico diagnosticado de displasia del desarrollo de la cadera luxada inveterada: uno con el índice acetabular de la cadera contralateral (CLAT), otro basado en un modelo biomecánico teórico de Bombelli (BMB) y otro recreando el posoperatorio real (PO) del paciente.* **Resultados***: Los esfuerzos en la cadera afectada fueron mayores que en la cadera no afectada. El CLAT mostró el mayor esfuerzo y la menor zona de carga. Por el contrario, el BMB mostró el menor esfuerzo y las mayores zonas de carga.* **Conclusiones:** *La propuesta basada en el BMB dio los*

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mejores resultados en cuanto a la distribución de los esfuerzos sobre la cadera, mientras que la peor fue el CLAT. Cualitativamente, estimando la estabilidad y la amplitud de movimiento de la cadera, el caso PO se consideró el mejor.

Palabras clave: *Displasia del desarrollo de la cadera inveterada. Acetabuloplastía tipo Dega. Análisis por elementos finitos. Biomecánica.*

Introduction

Developmental dysplasia of the hip (DDH) is one of the main afflictions in pediatric orthopedics and a common cause of disability[1,2]. Diagnosis and treatment during the first 9 months of age generally result in a very positive prognosis[3].

Neglected cases are those in which the condition has remained undiagnosed and untreated for a very long time, even years, which unfortunately is still prevalent in mid- and low-income countries. In such cases, the severity of the dysplasia is greater, the treatment is more aggressive, and the outcome is less predictable[4]. The consequences of neglected DDH include early joint degeneration during adulthood[5,6]. The relationship between clinical and biomechanical parameters is currently being investigated to predict the long-term performance of a DDH-affected hip[7-10].

Neglected DDH is treated with open reduction, pelvic, and femoral osteotomies to correct the characteristic deformities of the condition (complete luxation, shallow and steep acetabulum, femoral anteversion, and valgus) and to restore congruence and function to the joint. For a better outcome, the hip should be reduced and well-oriented with conservative treatment before the surgical procedure, but in neglected cases, the surgeon cannot wait for this pre-requisite, so the reduction and reorientation are carried out in a single surgical procedure. Pediatric pelvic osteotomies represent one of the most technically challenging surgeries. Despite this difficulty, on many occasions, the surgical planning and clinical follow-up are carried out using plain radiographies (RX), due to its low cost and radiation dose, compared to other types of imaging studies, such as computed tomography (CT)[3,11,12].

However, as some adult and older children hip dysplasia studies have shown[7,13], the 3D models built from CT images, and its integration with biomechanical finite element analysis (FEA), make this technology a better alternative to conventional RX for the study, planning, and evaluation of treatment of the dysplastic hip, regardless of the increased cost and radiation dose[3,12]. Although the majority of examples in the literature are about adult dysplasia, the treatment for pediatric neglected DDH patients could also benefit from the CT capacities for visualization and FEA integration.

Surgical planning assistance by means of biomechanical models could improve the neglected DDH treatment effectiveness, because it could allow predicting the behavior of the hip under different possible osteotomy approaches, each leading to a distinct post-operative (PO) outcome, and then choosing the scenario that offers the best biomechanical performance.

There exist different criteria for the ideal approach to dysplastic hip treatment. One criterion establishes as a PO goal an acetabular index (AI) value normal for the patient's age; for a unilateral DDH case, the contralateral control hip should have such a normal AI value (CLAT approach). In contrast, another criterion establishes that, for a unilateral, completely dislocated DDH case, the best option is to produce a configuration that avoids a re-dislocation, even if that implies an over-correction, this option corresponds to the real post-operatory outcome with the patient (PO)[4]. A third criterion developed by Bombelli and based on 2D biomechanical models, suggested that the best hip joint configuration is one that has a horizontal loading zone (LZ) in the acetabular roof, right above the femoral head (Bombelli biomechanical model [BMB])[14]. Each of these criteria is optimized by following each of the three different approaches (CLAT, PO, and BMB, respectively).

The objective of this study is to develop CT-based biomechanical finite element models from a single patient to determine which osteotomy approach, each optimizing one of the aforementioned criteria, is the one that produces the best outcome, in terms of the mechanical stresses and LZs over the joint surfaces, as well as how this relates with clinical practice.

Methods

This research work was approved by the research committee of our institute. The patient's parents signed the informed consent form.

The modeling was based on a 6-year-old female patient, diagnosed with unilateral neglected luxated

DDH on the right hip, and with no record of previous treatment. The contralateral hip was considered the control and the dislocated one was the case. A CT scan (LighSpeed® VCT 64, General Electric, Fairfield, CT, USA) of the patient was obtained with 0.625 mm slices from the vertebral body of L5 to the proximal third section of the femur. The modeling was based on this CT scan, and institutional guidelines for patient data protection and privacy were followed. The patient presented a complete hip dislocation and hip dysplasia grade IV for the DDH IHDI classification[15], with AI values of 43° and 28° on the affected and non-affected side, respectively, as well as severe deformity of the acetabulum and proximal femur. One month after the CT scan, the patient was treated with one-stage open reduction and a Dega acetabuloplasty, and a derotational and shortening femoral osteotomy, postoperatively immobilized with a fiberglass pelvic cast for 12 weeks and then managed with physical therapy and rehabilitation for a further 12 weeks. Diagnosis, CT scan, and treatment were performed in our institution following standard clinical practice.

3D models of the pelvis and femur were built after the segmentation of the CT images. Posteriorly, those 3D models were used to generate tetrahedral meshes. Segmentation and reconstruction of the models were done using the InVesalius 3.1.1 (CTI Renato Archer, Campinas, SP, Brazil) and Autodesk Meshmixer (Autodesk, Inc., San Rafael, CA, USA).

Three hypothetical models were generated: CLAT, with the same AI value (28°) that in the contralateral hip; BMB, with an AI value of 0°, based on the theoretical model of Bombelli; and PO, that reproduces the post-operatory outcome (AI = 7°), based on an AP RX projection taken at the end of the surgery (Fig. 1).

Since the starting position was a complete dislocation, the femur 3D model was translated and rotated to simulate the femoral derotational and shortening osteotomy. In all the scenarios, the inter-articular space was set to be the same as the one measured in the unaffected hip.

To transmit the loads during the FEA, similarly to the articular cartilage in the actual joints, interface volumes between the articular surfaces were generated. The generated meshes were composed of around 270,000 ten-noded tetrahedral elements (TET10). FEA was performed using ANSYS Mechanical APDL v14.5 (ANSYS Inc., Canonsburg, PA, USA).

All bones and interface volumes were considered to be linear elastic homogeneous isotropic solids, described by these mechanical properties: 17,000 MPa and 0.3 for the elastic modulus and Poisson coefficient of the bone, respectively; and 15 MPa and 0.45 for the elastic modulus and Poisson coefficient of the cartilage, respectively[13].

The finite element model was linear static, simulating a biped stance, applying the following loading conditions: 56% of the patient's body weight, in the vertical direction, over the S1 superior vertebral body surface, representing the body weight above the waistline; 63% of the patient's body weight over the greater trochanter and ilium wing (insertion zones of the abductor muscles), with force directions resembling the abductor muscle fibers; total movement restriction in the distal end of the proximal femur; rotational restriction on the pelvic bone. Loading conditions were formulated as previously described by other researchers[13,16].

Maximum von Mises stresses (SMAX) and LZs over the articular surfaces of the acetabular roofs were registered. A LZ was arbitrarily defined as that in which the top 20% of the stresses were concentrated. For clarity, the LZ is presented as a percentage of the total articular surface. Quantitative and qualitative comparisons of the stress distributions in the acetabular roofs were made. As is standard practice, we considered that the lesser the SMAX the better, and the greater the LZ the better. The qualitative assessment involved the evaluation of joint congruency, location of stress peak values and bone protuberances, and an impression of dislocation risk by the medical team.

Results

In the three analyzed alternatives, the stresses in the affected hip were greater than those in the unaffected hip. Stress magnitude and distribution in the control hip (SMAX of 30.3 MPa, and LZ of 20.7% of the total articular surface in the acetabular roof) did not seem affected by the configuration of the affected osteotomy-treated hip. Stress magnitude and distribution in the affected hip, however, did change considerably between scenarios (Fig. 2).

CLAT showed the greatest SMAX, 65.45 MPa, and an LZ of 9.9%, the smallest found (Figs. 3 and 4). Qualitatively, the instability of the setup and the disposition to redislocation were noticeable. Furthermore, the stresses are concentrated on the anterior flank, thereby increasing the risk of arthrosis.

In contrast, BMB showed the smallest SMAX of the affected hips, 33.99 MPa, and the biggest LZ, 62.7%. However, this scenario also showed a clear

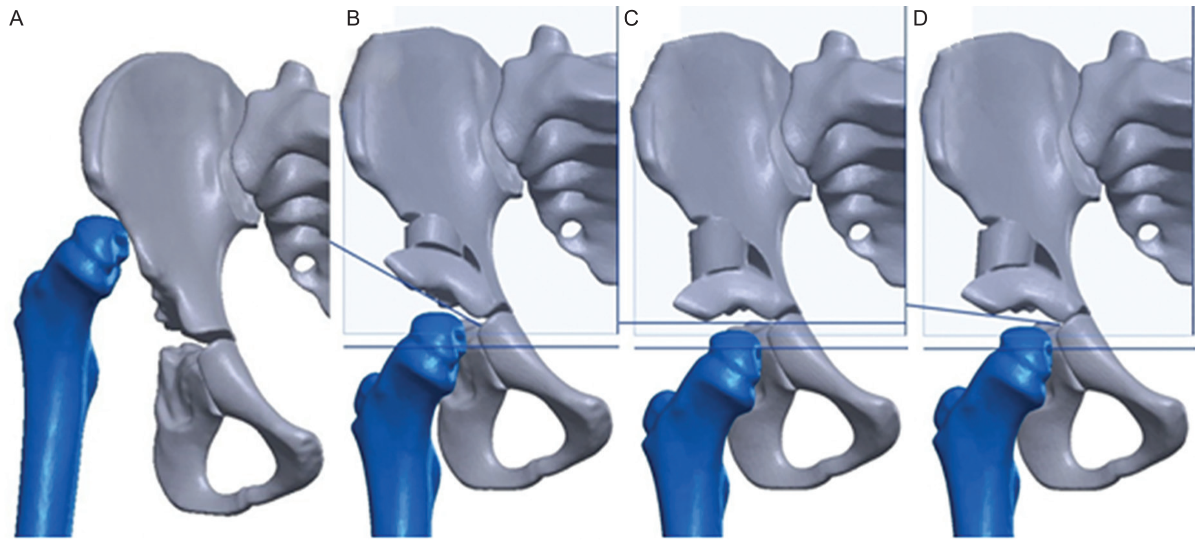

Figure 1. *CT 3D models of the neglected developmental dysplasia of the hip-affected hip.* **A:** *pre-operatory state showing an IHDI grade IV dysplasia.* **B:** *CLAT with acetabular index (AI) = 28°.* **C:** *bombelli biomechanical model scenario with AI = 0°.* **D:** *PO with AI = 7°.*

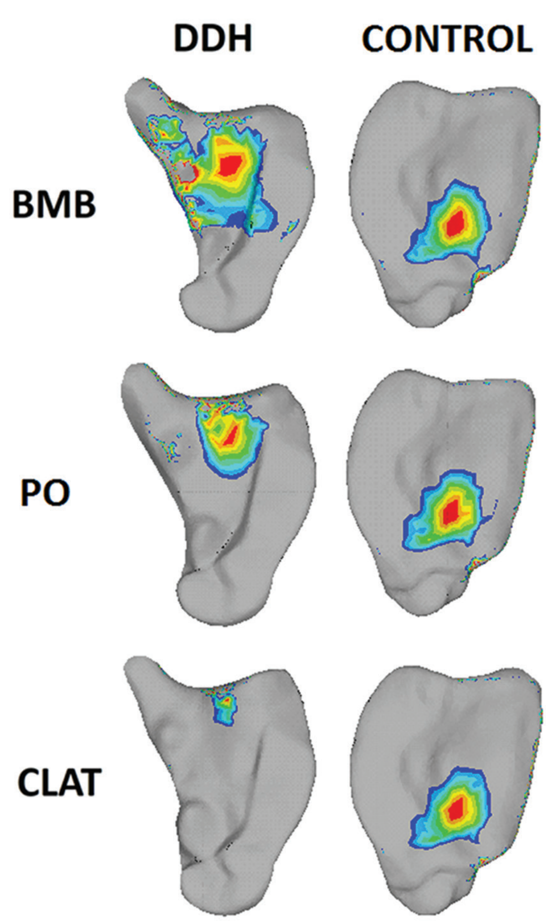

Figure 2. *Inferior view of the acetabular roofs showing loading zones on the simulated surgery analyzed both on control and affected hips. The scale was adjusted to show only the zones with von Mises stresses greater or equal to 80% of the maximum of each case.*

over-correction and limb shortening. On the contrary, it shows the best load distribution by concentrating the stresses in the central portion.

PO, a SMAX of 41.43 MPa and a LZ of 36% were found. It showed an apparent over-correction as well. In addition, the leading edge is tilted forward, which exerts excessive pressure on the femoral head.

Discussion

Based on our results, CLAT is the worst of the alternatives given that it showed considerable stress concentration on the articular surface and setup instability. Those characteristics, in an actual hip joint, are related to immediate post-operatory complications, such as avascular necrosis and re-dislocations[4,13,14].

Findings in CLAT also suggest that the AI, used on its own to evaluate a DDH-affected hip, could lead to an overestimation of the actual joint state. The AI offers only a measure of the steepness of the acetabular roof, and indirectly, assuming normal morphology, a measure of acetabular coverage or stability. Auxiliary radiological measurements, such as the Center-Edge or Wiberg angle, could help obtain a better estimate of acetabular coverage with RX images. Nevertheless, being plane projection measurements, it would be difficult to evaluate acetabular concavity, a determining characteristic of hip stability. Concavity is one of the most important reasons why the unaffected hip can be stable whereas the affected hip in the CLAT scenario is not, even if both hips have the same AI.

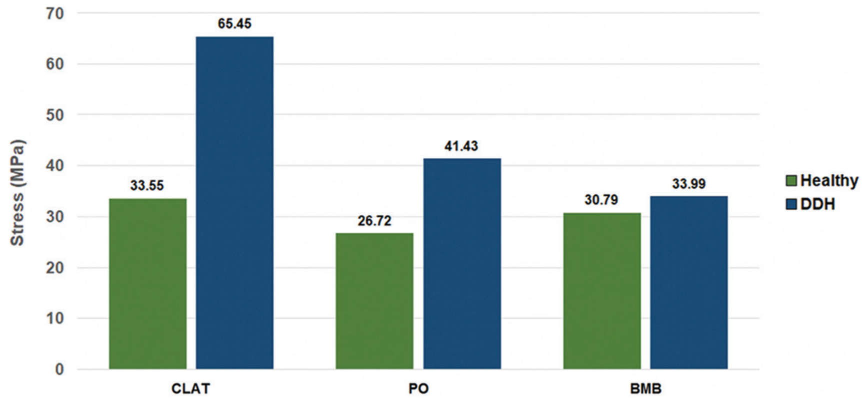

Figure 3. *Maximum stresses in the acetabular roof of control and developmental dysplasia of the hip affected hips, in the surgical simulation scenarios.*

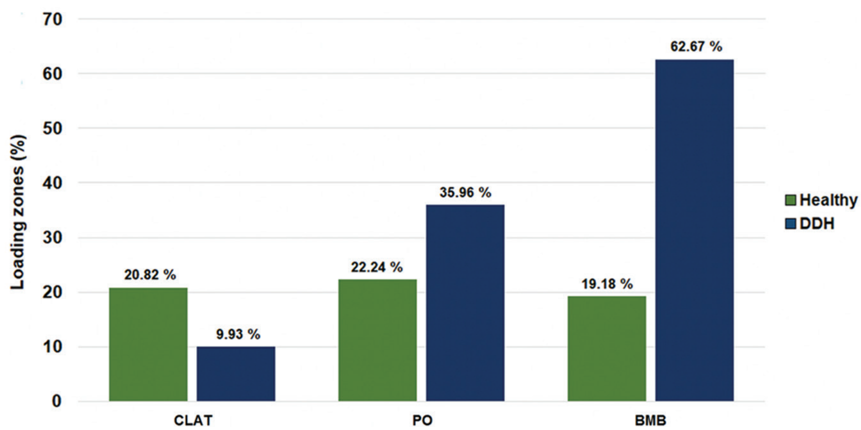

Figure 4. *Loading zones in the acetabular roof of control and developmental dysplasia of the hip affected hips, in terms of percentage of the total articular surface, on the surgical simulation scenarios.*

When comparing BMB and PO, it is clear that the quantitative results of BMB are better than those of PO, as suggested by Bombelli's theoretical point of view, both in terms of maximum stresses and in terms of LZs. Qualitatively, it can be seen that the results also favor BMB, given that the load is concentrated in the central region of the hip with DDH, as opposed to PO which locates the LZs at the anterior border, with the risk of redislocation. However, the overcorrection observed in BMB could have adverse consequences for the function of the hip joint, since its range of motion would be limited, producing a discrepancy in the length of the limb and possibly an impingement.

A limitation of this study is that the models do not consider the effect of bone remodeling. In an actual patient, the hip is immobilized for at least 3 months after surgery, before being allowed to be loaded with the body weight, and only then, the bone remodeling process is mechanically stimulated. Bone remodeling and resorption could generate concavity in shallow acetabular roofs and reduce bone protuberances that limit movement. It would be beneficial to perform a rigorous PO follow-up of neglected DDH patients to find out how the correction level achieved in the surgery and the bone remodeling relate to hip joint evolution in the short, medium, and long terms. Neglected DDH produces deformities that make each case unique, and so, it makes its treatment unique as well. Subsequent studies analogous to this one exploring additional patients would offer additional data.

The use of models similar to the ones used in this study could help achieve an optimal correction degree that maximizes stress distribution on joint surfaces and minimizes over-correction and its consequences. Clinical implementation of such models could improve treatment effectiveness and patient life quality, and potentially delay or avoid adulthood DDH sequelae.

In conclusion, even though obtained biomechanical results seem to indicate that a hip would have a better stress distribution as the acetabular roof gets more horizontal, the morphologic characteristics of the hip should not be dismissed, as these factors could indicate overcorrections and its harmful consequences: impingement, limb length discrepancy, and limited range of movement.

Caution must be taken when using the AI to plan and evaluate treatment for neglected DDH; if auxiliary measurements and images, such as the Center-Edge angle or 3D visualizations, were not to be available or used to assess acetabular coverage and joint congruency, the sole AI value could be overestimating the actual state of the hip joint.

More studies are needed to determine the ideal correction degree for the surgical treatment of neglected DDH, to work out the best means to reproduce virtual surgery scenarios in the actual surgery, and to investigate the long-term consequences of the treatment and its planning procedures.

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Conflicts of interest

The authors declare no conflicts of interest related to the present manuscript.

Ethical disclosures

Protection of human and animal subjects. The authors declare that the procedures followed were in accordance with the regulations of the relevant clinical research ethics committee and with those of the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Confidentiality of data. The authors declare that they have followed the protocols of their work center on the publication of patient data.

Right to privacy and informed consent. The authors have obtained the written informed consent of the patients or subjects mentioned in the article. The corresponding author is in possession of this document.

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