BIOMECHANICAL ANALYSIS OF THE EFFECTS OF SPRING-ASSISTED CRANIAL DISTRACTION IN CHILDREN IN CRITICAL PHASES OF DEVELOPMENT

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The aim of this study was to numerically analyze the biomechanical discrepancies occurring during the simulation of spring-assisted distraction. The analysis was conducted on three-dimensional models of infant skulls at 3, 6, and 12 months of age, generated from computed tomography (CT) data. Following surface mesh processing in Geomagic Design X and MeshMixer, the models underwent virtual surgical planning with a predefined osteotomy width of 16 mm. The placement of distraction springs was evaluated according to standard neurosurgical procedures, i.e., at a distance of 25 mm from the coronal suture and 55 mm from the lambdoid suture. In the ANSYS environment, spring loads of 4.8 N, 8 N, and 13.2 N were simulated, accounting for a physiological intracranial pressure of 2666.4 Pa, which continuously drives the outward displacement of the released bone flaps.

The models assumed isotropic, linear-elastic material properties for the bone, with mechanical parameters increasing proportionally to the patient's age. Young's modulus (E) was defined as 350 MPa for the 3-month-old, 700 MPa for the 6-month-old, and 1400 MPa for the 12-month-old models. Cranial sutures were modeled using Bonded contact relationships with increasing absolute stiffness, reflecting the macroscopic phenomenon of bone mineralization and interlocking. The joint stiffness was determined according to a simplified relationship, where the equivalent normal contact stiffness (k) for the analyzed age groups was 45 N/mm³, 75 N/mm³, and 120 N/mm³, respectively. To evaluate material failure, criteria suitable for flexible and poorly mineralized infant bones were employed: maximum principal strain (ε_1) and maximum principal stress (σ_1).

The numerical simulation results demonstrated significant variations in the mechanical response of the skeletal system to the applied forces. In the 3-month-old model, which is in the phase of highest susceptibility to deformation, all applied forces (4.8 – 13.2 N) exceeded the safe limits; maximum strains ranged from 15.5% to 28.9%, and maximum principal stresses (σ_1) ranged from 40.53 to 82.59 MPa. This results in a high probability of localized bone tissue failure.

In the 6-month-old skull model, an increase in stiffness was observed; the application of a 4.8 N force induced a principal strain of 7.2%, which falls within the safe limit (6% – 9%). Nevertheless, higher forces (8 N and 13.2 N) still generated critical loads, with stresses exceeding bone strength and reaching up to 78.75 MPa.

Conversely, the 12-month-old skull model exhibited by far the lowest susceptibility to deflection. Although the principal strains (3.3% – 6.4%) remained within safe limits for all tested forces, the high stiffness of the bone resulted in very large, localized stress concentrations (up to 76.65 MPa for 13.2 N), located primarily at the contact points between the springs and the tissue.

In conclusion, the use of a standard, widely available spring placement configuration may be associated with a significant risk of complications, including fractures and plastic deformation, particularly in patients up to 3 months of age. These findings demonstrate the necessity for preoperative personalization of surgical treatment and highlight the utility of virtual planning based on biomechanical Finite Element Analysis (FEA) for each pediatric patient undergoing surgery.

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