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Finite-element-based 3D computer modeling for personalized treatment planning in clubfoot deformity

Case report with technique description

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Abstract

Rationale: In clubfoot deformity, planning of corrective treatment requires a complex understanding of the foot anatomy, as well as of the geometry and distribution of altered mechanical forces acting at the level of the deformed foot. At the same time, treatment success depends largely on the selection of the most appropriate shape and angles of the customized orthesis developed for foot correction. Therefore, a complex assessment of the intensity and distribution of the mechanical forces at this site is mandatory prior to initiation of any corrective therapy.

Patient concerns: We present here the case of a 3-year-old male child with clubfoot deformity, weighting 20 kg, with no other congenital malformations, in whom finite element modeling (FEM) technology associated with a newly developed technique of three-dimensional (3D) computational simulation was applied for personalized treatment planning.

Interventions: The FEM-based computational 3D simulation technique allowed selection of the corrective treatment associated with the most physiologic pattern of force distribution at the level of the foot.

Outcomes: The proposed technique led to selection of the most appropriate therapy that successfully corrected the foot deformity. After 3D computer simulations, the elongations recorded were 2.71 cm for Achilles tendon, 1.69 cm for anterior tibialis tendon, 1.35 cm for the long flexor of the toes, and 1.69 cm for the long flexor of the hallux. The Von Mises equivalent stress distribution was $\sigma = 4.26$ MPa, not exceeding the elastic capacity of the bones, therefore the residual deformations were minimal. The customized treatment selected in this way was highly appropriate for the child, and led to complete recovery of the deformity in three months.

Lessons: This case is the first one in which FEM-based computational 3D modeling was applied for selection of treatment strategy in a child with clubfoot. The case reported here illustrates the role of advanced medical computer technology, based on complex image processing, FEM and 3D simulations, in providing an effective clinical decision support tool for personalized treatment selection in children with clubfoot deformity.

Abbreviations: 3D = three-dimensional, CT = computed tomography, FEM = finite element modelling.

Keywords: clubfoot, computational simulation, finite element modeling, imaging

1. Introduction

Clubfoot, also known as Congenital Talipes Equinovarus, represents a frequent pediatric congenital deformity of the foot, occurring 1 in 1.000 live births.[1]

The deformity of the baby‘s foot is present at birth and is characterized by a severe malalignment of the foot structures, the tendons being shorter than usual and the foot being twisted out of the normal shape or position.[2] Untreated, this deformity will

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seriously limit the mobility and walking capability of the child, thus impacting his growth and natural development. Therefore, many attempts have been made to improve the techniques available for correction of this deformity. Nowadays, it is considered that the best long term treatment option of these cases is represented by application of a dedicated orthesis that will lead in time to correction of the deformity.

However, the success of this therapy depends largely on the selection of the most appropriate shape and angles of the customized orthesis developed for correction of the foot. At the same time, treatment planning for clubfoot correction requires a complex understanding of the clubfoot anatomy, as well as of the geometry and distribution of altered mechanical forces acting at the level of the deformed foot. Therefore, a complex assessment of the intensity and distribution of the mechanical forces acting at this level is mandatory prior to initiation of any corrective treatment.

A major advance in the field of clubfoot assessment has been brought by the recent development of complex techniques of computational simulations, using sophisticated technologies based on complex image processing combined with modeling of finite elements.

The finite element modeling (FEM) is an emerging technological field with high potential for applications in medicine, allowing the development of numerical simulations in various medical fields, in order to propose new models or experimental methods for treatment of several diseases.[3,4] This technology is based on finite elements that can render mechanical behavior according to reality, as well as the corresponding properties of the materials, reducing the experimental costs and the working time needed to develop the new treatment models.[5,6]

In the case of clubfoot deformity, FEM of bones, ligaments and tendons can be used to obtain the required information about the deformation and tension state of the target elements, such as bones, tendons and ligaments. In order to obtain the finite element model, multiple imaging datasets are subsequently processed to obtain the three-dimensional image that is imported into a finite element special software.

We present here the case of a 3-year-old male child with clubfoot deformity, in whom FEM was applied for treatment planning, using a new developed technique of three-dimensional (3D) computational simulation that allowed selection of the corrective treatment associated with the most physiologic pattern of force distribution at this level. The FEM-based technique has been applied for the first time in this child and led to application of the most appropriate personalized therapy that successfully corrected the foot deformity.

1.1. Consent

The present study was approved by the ethics committee of the institution where the patient was treated. There was no need to obtain informed consent from the patient because all the data were collected and analyzed anonymously.

2. Case report

A 3-year-old male child weighting 20 kg was evaluated for correction of a congenital clubfoot. There were no other malformations or genetical defects associated in this patient.

A computed tomographic (CT) scan of the leg with deformity was performed using a 64 slices CT Somatom Sensation equipment (Siemens Healthcare, Erlangen, Germany). A three-dimensional model of the foot was built and used to investigate the forces involved in the inferior limb. Further, this model was than subjected to a simulation-based postprocessing, using a process similar to the one used for evaluation of the forces pressing on the structural components of a building.

The concept of simulation-based treatment in this case started from the assumption that the forces acting on the foot are directly related to the angles between different structures, and correction of these angles would result in a better distribution of forces and vice-versa. Therefore, using computerized simulations for selection of different angles of an orthesis (or those resulting from a surgical intervention), and measuring the resulting forces associated to each angle configuration, would allow selection of the most appropriate angle configuration, the one that correspond to the most favorable force distribution.

To achieve this goal, the following technique for FEM based 3D computer simulation was developed and applied for the first time in this case.

2.1. Finite-element-based 3D computer modeling-technique description

The 3D model of the clubfoot was achieved using the 3D Slicer software (3D Slicer, Cambridge, MA) to extract bone content from the CT scan and generate 3D images from 2D images, and the 3D Studio Max software (Autodesk Media and Entertainment, San Rafael, CA) for modeling. The definition of properties and forces in the final analysis were performed using ABAQUS 6.11-1 software (Dassault Systenes, Waltham, MA).

After loading the Digital Imaging and Communications in Medicine file into the 3D Slicer software (Fig. 1A), it automatically generated the 3 planar views, along axial, sagittal, and coronal axes, allowing to visualize all the sections of the CT scan. Similar to a radiograph, the images were represented in black and white, where each black-and-white shade corresponded to a different biological tissue. Thus, the bones had a lighter shade, while soft tissues appeared darker. Using a pipette-type instrument (similar to the one used in photo editing programs to select a color from an image), a selection was made on the lightest area corresponding to the bony tissue. After this area had been selected, the function that generates a topology using all CT images from the 3 anatomical planes was used to produce a three-dimensional model that highlighted each bone in part (Fig. 1B).

Resistance calculation on the 3D model requires a well-defined volume of polygons. As in our technique, the volume obtained by rendering from the 3D Slicer software was inconsistent, a 3D modeling program was required for defining each bone as accurately as possible, which in our case was provided by the 3D Studio Max software (Fig. 1C and D).

For FEM, the Abaqus 6.11-1 commercial software (Dassault Systenes, Waltham, MA) was used. After obtaining the 3D model, this was imported by elements in *.sat format (Fig. 1B).

Material laws have been created for both bones and tendons, each having assigned elastic properties, with Young's modulus and Poisson's coefficient as the ones listed in Table 1.

The connection between the elements was made using beam connectors to simulate cartilage between bones, as well as the corresponding tendons and ligaments. The main elements used for development of the connection were the following: Achilles tendon; long flexor of the toes; long flexor of the hallux; and anterior tibial. Solid elements have been assembled in the model after being imported as presented in Figure 2B.

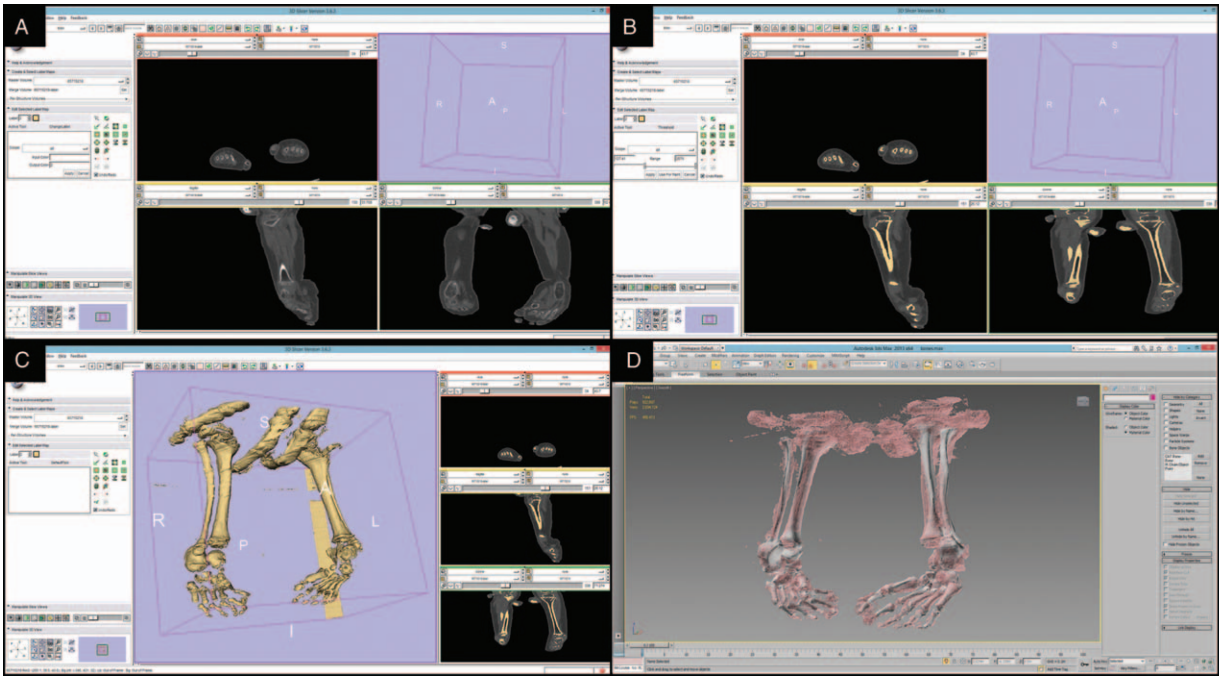

Figure 1. Generation of the 3D model for computer modeling. (A) Introduction of DICOM model from CT imaging data using 3D Slicer processing tool; (B) processing of DICOM files; (C) 3D Studio Max processing. DICOM = Digital Imaging and Communications in Medicine.

In the next step, reference points were introduced and connected with all the nodes for each bone. Connectors have been assigned different behavioral laws depending on the modeled element and on the particular elastic properties. Thus, the force–displacement curves, calculated previously using the elastic properties, were obtained for each type of tendon.

2.2. Computational simulation of mechanical forces

The following components have been introduced in the simulation program: the beam connectors (axial), the constituent laws for connectors, the connector type elements, the tendon type elements, material properties, and bearings.

The upper part of the tibia and the bones that allowed the patient to touch the ground were used to simulate the bearing conditions. Load conditions were introduced considering half the weight of the patient (10 kg) distributed as pressure on the 3 fingers of the foot that were not considered in the bearing. Since the finite element 3D model contains a number of 75,987 nodes, a linear static analysis leads to a very high computational time (about 480 hours). For this reason, a quasi-static analysis was proposed, using a “mass scaling” technique that leads to a much lower computational time (about 3 hours). The last step was the definition of the quasi-static analysis type and the simulations.

After importing the 3D model, application of the loads and establishment of the bearing conditions, a number of factors had to be considered for determining the final finite element model. Possible “distortions” caused by some finite elements considered to have inappropriate dimensions have been eliminated following a mesh-convergence study. The results were obtained after loading the model with half the weight of the patient, and monitoring both displacements and stresses.

Finally, computational simulation was used to estimate the effect of the proposed therapy, via measuring the differences between the initial deformations and the final deformations after the proposed corrective treatment.

2.3. Clinical results of FEM-based 3D simulation

The difference between initial deformity and the final deformity after applying the simulated model is presented in Figure 3. Simulated treatment model led to a better distribution of forces as compared to the initial one, in parallel with a significant reduction in the deformation. At the same time, finite element analysis of displacements and related stresses revealed, as expected, the largest displacements for the Achilles tendon (Fig. 4), followed by the anterior tibialis (Fig. 5), long flexor of the hallux, and long flexor of the toes (Fig. 6).

Table 1

Elastic properties of the elements used for computational simulation.

Element	Element type (Abaqus)	Young’s modulus, MPa, Poisson’s coefficient	Reference
Bones	C3D4, tetrahedron with 4 nodes	7300; 0.3	Nakamura et al[24]
Cartilage	2 nodes, connector	1.01; 0.4	Athanasiou et al[25]
Ligament	2 nodes, connector	260; 0.4	Siegler et al[26]
Achilles tendon	C3D4, tetrahedron with 4 nodes	816; 0.3	Wren et al[27]
Flexor (tendons)	2 nodes, connector	450; 0.3	Garcia-Gonzalez et al[28]

Figure 2. Steps for computational simulation. (A) Importing of 3D elements in *.sat format; (B) assembling of solid elements; (C and D) introducing of connectors and tendon-type elements in the system.

The elongations recorded were 2.71 cm for Achilles tendon, 1.69 cm for anterior tibialis tendon, 1.35 cm for the long flexor of the toes, and 1.69 cm for the long flexor of the hallux. The Von Mises equivalent stress distribution was $\sigma = 4.26$ MPa, not exceeding the elastic capacity of the bones, therefore the residual deformations were minimal (Fig. 7).

The customized treatment selected in this way was highly appropriate for the child, and led to complete recovery of the deformity in three months.

3. Discussions

Through the advances of technology, the computer has come to play a pivotal role in the advancement of scientific fields. In medicine, it became nowadays an instrument as indispensable as a scalpel to save lives and help patients. Technology has led, by its evolution, to the continued exponential expansion of potential and new breakthroughs in various fields including medicine.

The technique described in this case illustrates the role of advanced computer technology in modern healthcare, being able to generate effective tools for supporting personalized medical decision. Our technique generated a 3D model of the foot and of the mechanical forces acting at the site of the foot deformity, while 3D computer simulation allowed selection of the therapy that led to the most physiological possible model of the foot.

The application of FEM in the orthopedic field started as early as in 1972, in an attempt to analyze the mechanical behavior of human skeletal bones, being regarded as a viable way to solve mechanical equations and to obtain coherent results.[3] A vast description of the use of FEM in orthopedics was done by Mackerle,[4,5] detailing the ways to obtain biomechanical information about the musculoskeletal tissues, the design and

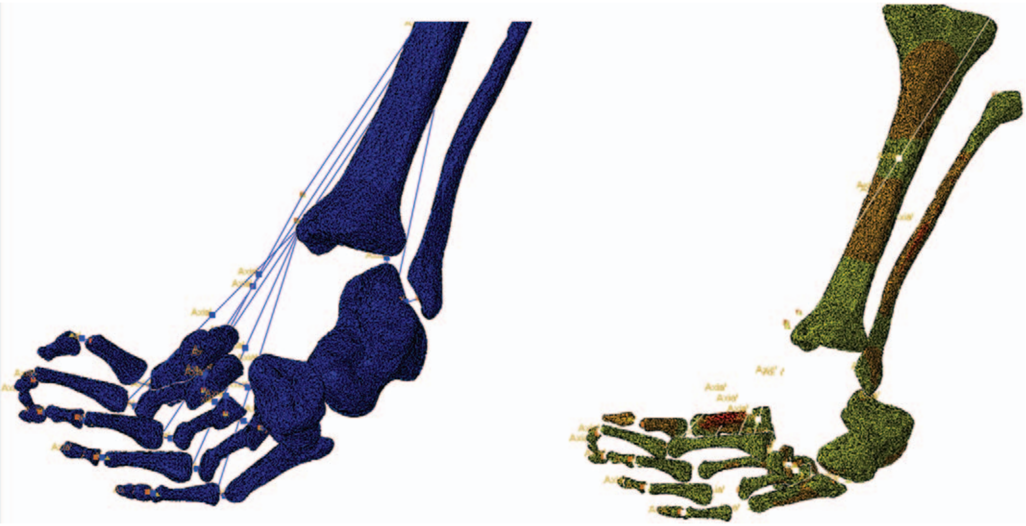

Figure 3. Improvement of clubfoot deformation after applying computational modeling for treatment selection. (A) initial deformation; and (B) final deformation.

preclinical analysis of endoprostheses, as well as about the study of the adaptation processes of tissues over time.

Currently, the literature has a wide range of research on bone structure of the lower limbs using FEM; however, there are no reports so far on using FEM for studying clubfoot deformity. According to author‘s knowledge, this is the first report on FEM-based computational simulation for complex 3D characterization of clubfoot deformity.

Studies of pressure on the sole of the foot as a result the action of the patient’s own weight were also undertaken by several groups.[6–12] Lemmon et al developed numerical models for numerical studies on the influence of the thickness of the therapeutic footwear on the tissue, reporting an accuracy of 5.9% compared to the experimental ones.[13,14] Gefen[15,16] developed 2D finite-element models useful for target surgery in a leg in vertical position. At the same time, Cheung et al[17,18] used three-dimensional models of a leg, corresponding to a vertical position, and investigated the effects of changes in rigidity, as well as those of force changes in the Achilles tendon, using forces between 0 and 700 N. Using FEM, Johnson and Haihua[19] also showed that general rigidity of the foot and of the plantar aponeurosis are strongly influenced by the ankle bearing and attachment conditions.

The correlation between the local forces and deformity has also been demonstrated by Ahmady et al[20], who investigated the

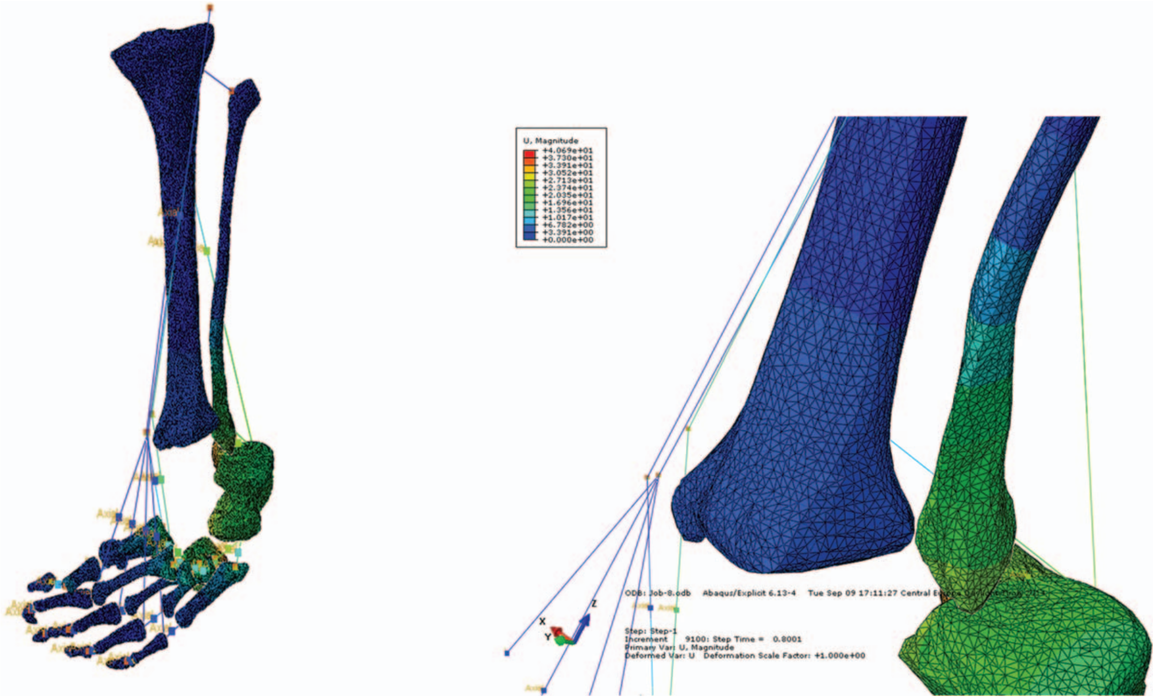

Figure 4. Elongation of Achilles tendon after computational simulation, l = 2.71 cm.

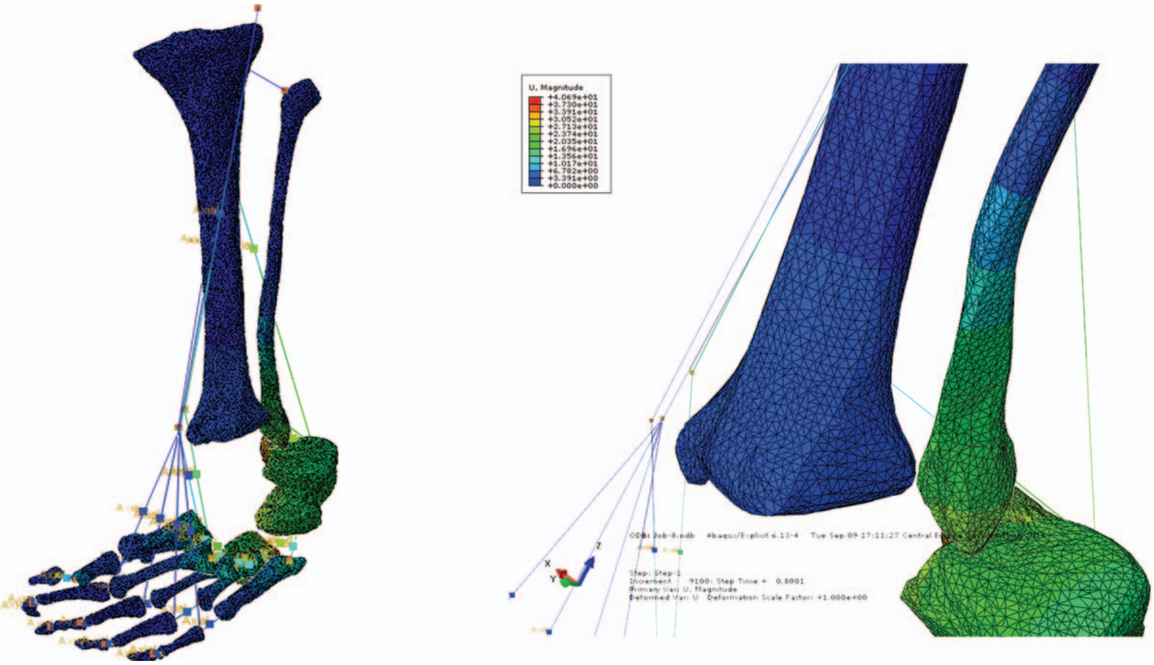

Figure 5. Elongation of anterior tibialis tendon after computational simulation, l = 1.69 cm.

effect of heeled footwear on the bones of the ankle, showing that increasing the height of the shoe leads to decreased deformation of the foot arch and to increased Von Mises equivalent stresses in the analyzed bones. At the same time, use of Altair Hyperworks for analysis of dynamic forces during movement was reported, achieving a complete modeling of a full circle of a step in running.[21]

The application of Abaqus for determination of the stress acting on the bones during locomotion has also been proposed by Qian *et al.*[22] Using the capabilities of the same Abaqus program, Ozen et al[23] modeled and analyzed the bone structure of a normal and a prosthetic ankle, in order to record the differences that occur in distribution of tensions under the action of different forces.

All these studies demonstrated not only the interrelation between mechanical forces, their anatomical distribution and morphologic deformities, but also the role of computer-assisted technology in the study of tension distribution in various orthopedic applications. However, this case is the first one in which FEM-based computer modeling was applied for selection of treatment strategy in a child with clubfoot.

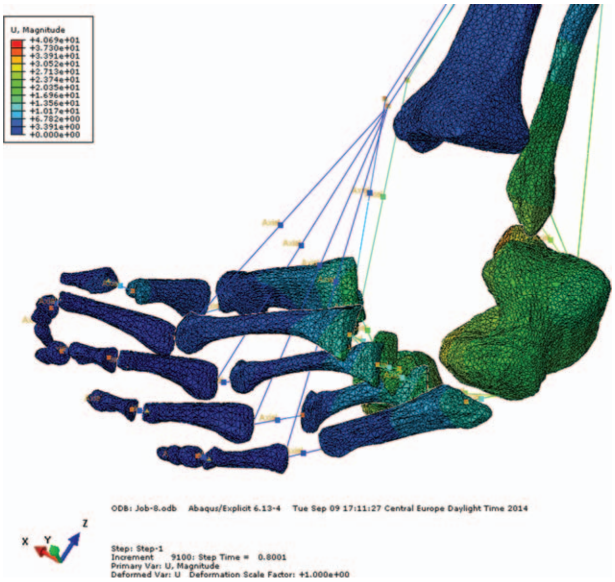

Figure 6. Elongation of the long flexor of the toes (l = 1.35 cm) and long flexor of the hallux (l = 1.69 cm) after computational simulation.

Figure 7. Von Mises equivalent stress distribution in the simulated foot.

In conclusion, this case shows how modern computer technology and FEM-based computational 3D modeling can be applied for selection of treatment strategy in children with clubfoot. This technique can be further extended to a large number of orthopedic applications. The case reported here illustrates the role of advanced medical computer technology, based on complex image processing, FEM and 3D simulations, in providing an effective clinical decision support tool for personalized treatment selection in clubfoot deformity and orthesis testing.

Author contributions

Conceptualization: Horea Gozar, Zoltan Derzsi.
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Investigation: Horea Gozar, Zoltan Derzsi.
Methodology: Horea Gozar, Zoltan Derzsi, Theodora Benedek.
Software: Zoltan Derzsi, Alexandru Chira.
Supervision: Horea Gozar.
Validation: Zoltan Derzsi, Ors Nagy.
Visualization: Ors Nagy.
Writing – original draft: Horea Gozar, Zoltan Derzsi, Theodora Benedek.
Writing – review & editing: Alexandru Chira, Ors Nagy, Theodora Benedek.

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