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Medical Use of Finite Element Modeling of the Ankle and Foot

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ABSTRACT

Finite element modeling is a field of medicine with great potential future in experimental studies and in daily clinical practice as well. Computational modeling is currently used in several medical applications including orthopedics, cardiovascular surgery, and dentistry. In orthopedics, this method allows a proper understanding of joint behavior, as well as of more complex articular biomechanics that are encountered in several conditions such as ankle fractures or congenital clubfoot. Currently, there is little data on the development of a 3D finite element-defined model for congenital clubfoot. This paper aims to summarize the current status of knowledge and applications of finite element modeling of the foot and ankle.

Keywords: 3D finite elements, computational modeling, congenital clubfoot, foot and ankle models

INTRODUCTION

The use of finite element modeling in medicine was first introduced for those cases where animal or other mechanical models were not applicable. Along with the progression of computing techniques, this type of computer modeling became practically limitless in its development. Computational models have progressively evolved and can now almost perfectly reproduce the human body or distinct parts of it. Ten years ago, the number of elements required for a computational model was limited by the capacity of available computers. Currently, there are several possibilities for computational modeling, analysis, and testing, for any kind of bone and ligament structures. The most often used computational models in present are those applied in dental medicine and experimental orthopedics; however, several other applications in emerging fields such as cardiovascular surgery have also been introduced.[1–3]

This paper aims to summarize the current status on the use of finite elements for computational modeling in medicine and to highlight the types of elements recommended for creating a model for clubfoot and orthosis testing.

COMPUTATIONAL MODELS FOR ORTHOPEDIC PATIENTS

The most often modeled and tested part of the body is the lower limb; however, there is little published data on the use of models dedicated to clubfoot or complex foot models. Earlier reports described a three-dimensional computational model having this application, while finite elements were defined for the ankle, the distal tibia, talus, and some of the most important attached ligaments and muscles. However, the ankle model has not been entirely completed, the model being limited for testing the foot movements. Several researchers focused on the Achilles tendon, plantar flexion and deformation on the plantar flexion/extension.[4]

A team of Romanian researchers have analyzed the forces applied on the Calcaneus bone and Achilles tendon during running, using Altair Hyperworks for analysis of the applied force. This study aimed to measure the force and weight charging, and to analyze the deformations occurring due to force distribution. They measured forces between 0 and 40 Mpa, from no weight distributed on the foot to maximum load of forces, and practically created a model of a full-circle step during running. The group used this model to evaluate the forces that are impossible to measure in vivo or by other experimental methods.[5]

One of the best programs for the finite element analysis is the Abaqus program, which was first used in 1995 for the medical analysis of a prosthesis surface modeling in a total hip arthroplasty procedure.[6] In 1998, a group of researchers used the Abaqus program to compare the biomechanical properties of different biphasic soft tissues.[7] This program was also used by another team in 2013, in a comparative study based on finite element modeling. They created the model of an absolute normal ankle and one of an ankle with prosthesis. In order to increase precision as much as possible, they used one patient with prosthesis in the right ankle and normal left ankle. This group aimed to compare forces and tension distribution between the two lower limbs and also to analyze the differences that can be observed during motion and standing between the two legs, concluding that the proposed model can be used for designing new ankle prostheses.[8]

In the same period in which Abaqus was the main program used for model simulations of joint characteristics, another group conducted a study on the dynamic analysis of an ankle model that was created with finite elements, in which they calculated the forces and tensions in the bones during walking.[9] In 2014, Johnson *et al.* performed a study on the use of 3D finite elements on the foot and ankle and concluded that this could be a very useful tool in the simulation of force-displacement boundary conditions, which could be used to further evaluate the interaction between foot and orthesis.[10]

Shoe testing is another application of finite computational models, very similar to orthosis testing. Using tree different types of shoes, with different heights of the heel between 1.5 inches and 3.5 inches, Ahmady *et al.* observed and modeled their effects on tendons, bones, and aponeurosis in case of high heels. Their study evaluated the von Misses stresses, strain, and arch deformation on the foot during standing, proving that the smallest deformation and stretching forces regarding to plantar fascia were present in 2.5-inches high heels.[11] Some authors recommend the use of finite modeling elements even in treatment planning, for outcome prediction and follow-up. Another team of orthopedic surgeons compared four different ligament reconstruction techniques of the ankle with the use of modeled 3D finite elements.[12] They were able to evaluate ankle biomechanics using different methods, thus being able to determine which of the method is most suitable in obtaining normal joint mechanics.[12] Wong *et al.* have reported the case of a 28-year-old female with a talus and calcaneus fracture, in which a 3D finite element model was created using magnetic resonance imaging, illustrating the effectiveness of such models in offering proper fracture management.[13]

These studies reflect the value of 3D finite element modeling and simulation in orthopedics, a technique that provides great advantages in both clinical and experimental circumstances, representing a relatively easy method for the development of computational models of various structures such as bones, cartilage, tendons, and joints. Furthermore, joint deformation, forces, and movements are quite easy to model, thus allowing a proper illustration of joint biomechanics.

COMPUTATIONAL FINITE ELEMENTS IN CONGENITAL CLUBFOOT

Three-dimensional computational models can also be used as tools for the analysis of congenital clubfoot, in cases where animal experiments are not feasible, during treatment planning, or for orthosis testing. There is little data in the current literature on the use of finite defined models for the analysis of congenital clubfoot.

Congenital clubfoot is a frequently encountered malformation of the joints; therefore, the use of an experimental model can be very useful for a proper management of these patients. Prior to the development of a finite element, it is essential to determine the type of elements that can be used to model the foot or clubfoot. Different connectors

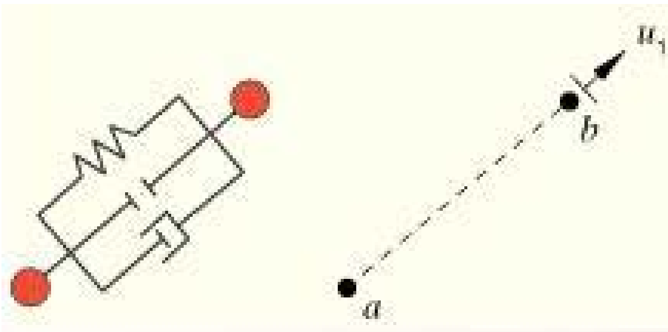

FIGURE 1. Axial connector used for computational development of a foot model

are used to model ligaments, tendons, and solid-type elements for the bone, hence the need to determine material properties and to analyze the type of foot modeling. Figures 1–4 represent illustrations of the technique and materials required for creation of a foot model.

MATERIALS REQUIRED FOR CREATING FOOT MODELS

Connectors

The connector elements can be used for two- or three-dimensional analyses, in order to create a connection between two nodes of different part instances. There are two types of connectors that can be used, beam connectors and axial connectors, respectively. The beam connectors are used to connect the bones between two reference points, giving the two parts a rigid type of connection. The axial connectors are used for tendons. A precise analysis of a minimum of four main ligaments is highly recommended: the Achilles tendon, long flexor of the toes, long flexor of the hallux, and the anterior tibial ligament. For each axial

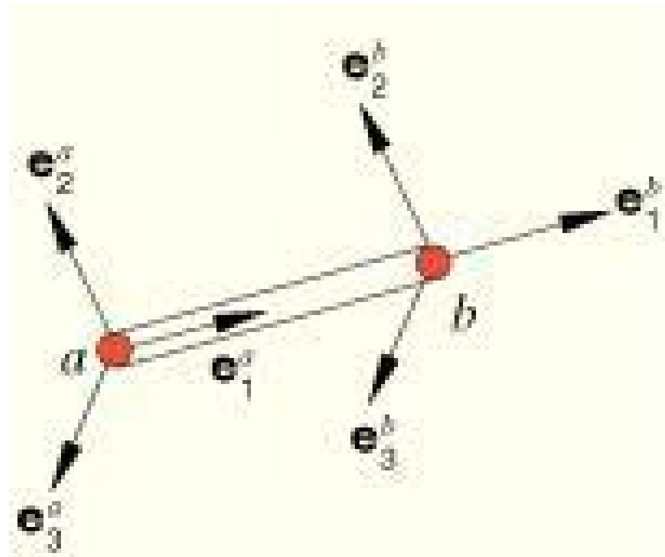

FIGURE 2. Beam connector used for computational development of a foot model

FIGURE 3. Bones, tendons and ligaments reproduced using computational models

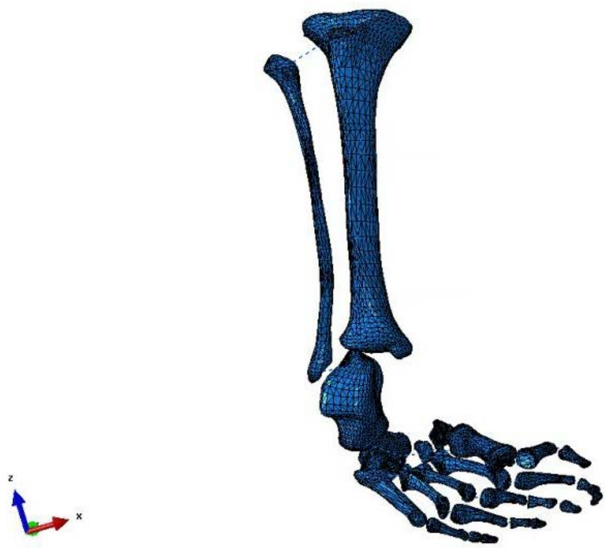

FIGURE 4. Bones reproduced using computational models

connector, a different property has to be assigned in order to simulate the elements' elasticity using a force-displacement curve based on Young's modulus and Poisson's coefficient.[14]

Bones

The bones can be modeled by using 3D solid-type C3D4 elements (4 linear nodes of tetrahedron). This is a generally used method, easily applied, and compatible with a lot of programs and analyses. The method is based on a limb model; however, it is the simplest one when it comes to its properties.

Material properties and laws

An elastic behavior should to be assumed for the bone material; consequently, elasticity is defined by using the Elasticity material law in terms of Young's modulus and Poisson coefficient. No laboratory measurements are required, as all the data can be obtained from the literature. However, a nonlinear behavior of the bones requires a full description of the stress-strain relation from compression and tensile tests.[15]

Analysis

A linear static analysis of the full foot model leads to a computational time of approximately 480 hours because of the large number of estimated nodes (75.000) that the model contains and also because of the interaction given by the connectors, which adds extra equations. An explicit dynamic analysis with the use of a mass scaling technique can lead to a lower computational time of 3 hours on a supercomputer.

CONCLUSIONS

The use of three-dimensional computational models for the simulation of various conditions, from orthopedics to cardiology and cardiovascular surgery, has started to emerge as an adjuvant method to guide treatment and patient management. The efficacy of finite models for joints and bones has been proved by several preclinical and clinical studies and has also been demonstrated in cases of fractures. However, their use in congenital clubfoot has yet to be established. Due to the increased frequency of patients with congenital clubfoot, further developments are required in the field of computational modeling and finite element analysis in order to provide more insights on the individual biomechanics of this disorder.

CONFLICT OF INTEREST

Nothing to declare.

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