DEVELOPMENT OF 3D BIOMECHANICAL MODEL OF THE HUMAN HAND USING FEM

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Abstract. *The human hand is responsible for a significant part of daily activities, becoming one of the most important tools of the human body. Hand injuries caused by different pathologies, by trauma or by the use of manual instruments with low ergonomics are pointed as the cause of social problems affecting individuals with limited capacity of using their hands. Designs of more ergonomic instruments are an important step to obtain comfortable and useful instruments to prevent hand injuries. Information about the pressure in the palm of the hand and the acting forces in the tendons of the fingers and wrist are useful to study. The discomfort, pain, muscle-skeletal and tendon injuries are consequences of using non-ergonomic instruments. The utilization of 3D models of the human hand has become a valuable tool, aiding the studies for the design of artificial members with more accurate controls and design of ergonomic instruments. The aim of this work is to create a 3D finite element model of the human hand, characterize the constitutive tissues (bones, skin and ligaments) and perform the simulation of the index finger's flexion. The devised numerical model was successfully implemented leading to stable and easily converged results, showing that the 3D biomechanical model of human hand is robust.*

Keywords*: Finite Elements Method, Human Hand, Biomechanical, 3D Model*

1. INTRODUCTION

The human hand is responsible for a significant part of daily activities, becoming one of the most important tools of the human body (Thompson *et al*, 1988). Some lesions of the upper limb, such as brachial plexus injury, can cause a partial or complete loss of upper limb movements. In Brazil, most patients with brachial plexus injury are young, male, victims of accidents with motorcycle (Bertelli and Ghizoni, 2005). Hand injuries caused by pathologies, accidents or by use of objects with low ergonomics (objects poorly adjusted for the destined work) are the cause of social problems affecting individuals (Wu *et al*, 2008).

In order to minimize the effects of these lesions and restore functionality, artificial limbs can be used. Some studies are also done to construct more ergonomic equipment, preventing future injuries on users. Studies use methods to determine maximum values of pressure in the palm of the hand and the forces on the tendons when objects are being grasped. The results allow studying the discomfort, pain, muscle-skeletal injuries and tendons rupture (Aldien *et al*, 2005; Vigouroux *et al*, 2006).

Recent biomechanical studies underline the importance of the ability to grasp objects, as well as the way of how this movement is accomplished (Cunha *et al*, 2000). Many authors create different methods for biomechanical studies of the human hand. Among those, the majority implicate in the use of 3D analysis through capture of images, becoming a high cost method (Nagem *et al*, 2007).

The use of 3D human hand models has become extremely important for the design of artificial limbs with a control more accurate and for studies of ergonomic equipment (Sancho-Bru *et al*, 2001). Many authors have used advanced techniques to capture images for the generation of 3D models. These authors use imagiologic examinations such as computed tomography (CT) and magnetic resonance images (MRI) to acquire images. The images are imported into programs of computer aided design (CAD) to create the geometries of 3D models (Alexandre *et al*, 2006; Pimenta *et al*, 2006).

The aim of this paper is to present a methodology for the development of a finite element model of a 3D hand. In order to analyse the behavior of the model, an experiment of flexion movements of the index finger was performed as a first biomechanical study of the model.

2. METHODOLOGY

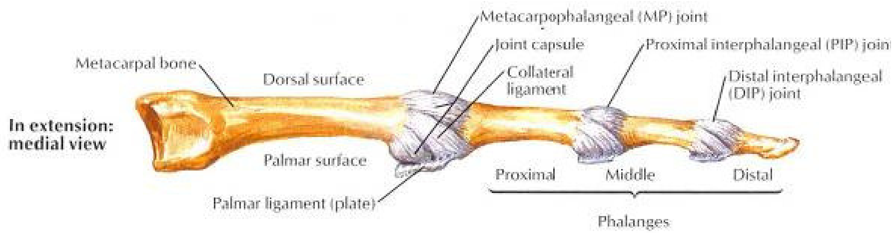
The human hand is a very complex tool, its structure is constituted by 27 bones and innumerable muscles, tendons and ligaments. The set is responsible for 23 degrees of freedom. Given the great complexity of the human hand, it was initially proposed, in this work, the creation of a simplified model for the hand. The model developed is composed of 16 bones of the fingers - 4 metacarpals and 12 phalanges.

The geometric model was defined as a struture that represents the soft tissue, bones, capsule and cartilages.

2.1. Geometrical Model

A base geometric model from Anatomium 3D was used for the creation of the geometry (Anatomiun 3D, 2009). This model was created by medical images. Since the base model is only illustrative, was necessary to create a new geometrical model.

The geometries of bones, cartilages and capsules from the base geometric model were imported to SolidWorks software. Reference points were created in each geometry and then interconnected by smoothing curves called splines. The curves were interconnected and thus new solids geometries were generated. Anatomical images from atlas (Netter, 2006) (Fig. 1a) were used to assembly the new fingers model using the new solids geometries of bones, cartilages and capsules (Fig. 2b). Joints were created in order to connect the bone: Metacarpophalangeal (MCP), Proximal Interphalangeal (PIP) and Distal Interphalangeal (DIP). The joints are basically composed by an articular capsule and cartilages that are fixed at the end of the bones (Fig. 1c).



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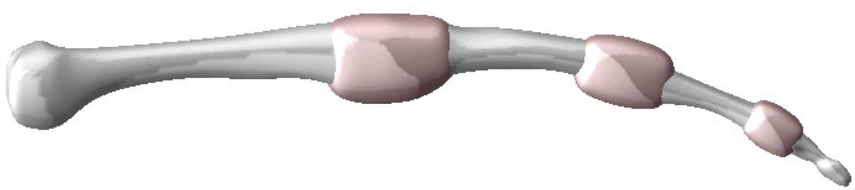

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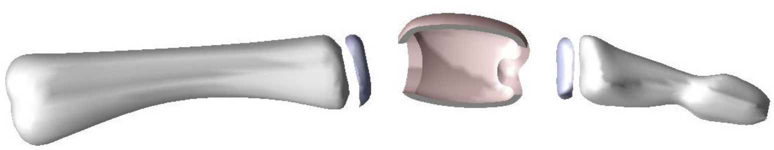
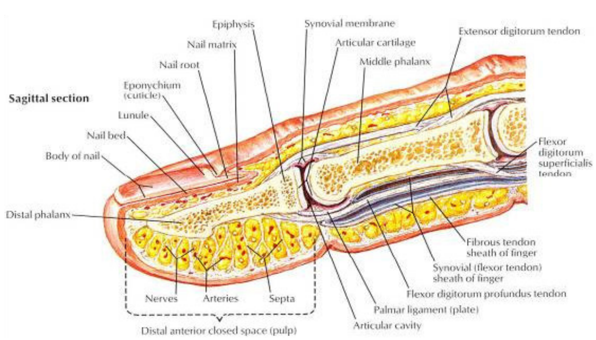


(c)

Figure 1. (a) Representative image (Netter, 2006); (b) Assembly of the index finger geometry; (c) The Distal Interphalangeal

The skin tissue was created by the union of several sketches located in cross section along the fingers assembly. Reference points were created around the cross section and these points were displaced outside, according to thickness of soft tissue values based on literature, Fig. 2b (Netter, 2006; Wu et al, 2006). Splines linked the new points originating the skin tissue (Fig 2b).



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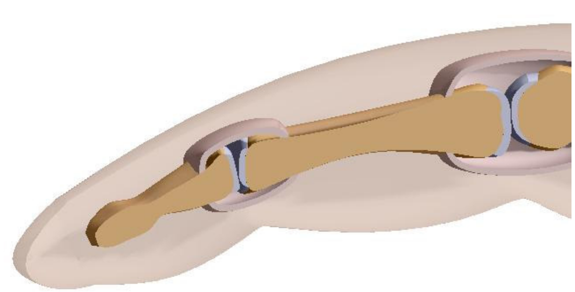


(b)

Figure 2. (a) Representing of soft tissue (Netter, 2006); (b) Skin tissue generated

2.2. FEM Model

The new geometry model of the hand was imported into Abaqus in order to create the model using Finite Element Method (FEM) and perform a biomechanical analysis.

To characterize the capsules, the mechanical properties of the medial collateral ligament of the knee were applied using a Neo-Hooke hyper-elastic material, with constant C1 = 6.43 MPa (Peña et al, 2005).

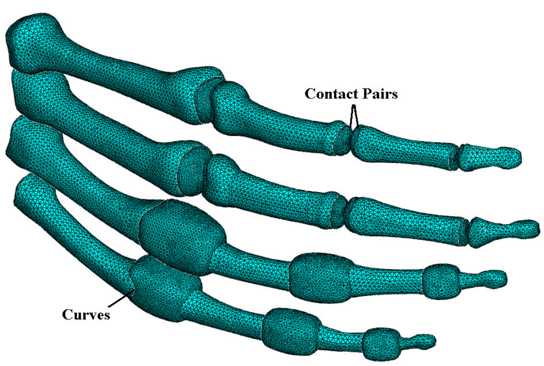
In this work two simulations were conducted. In each simulation, different mechanical properties were applied for the skin tissue. In the first simulation a Mooney-Rivlin hyperelastic material was applied, with constants C10=9,4kPa and C11=82kPa [Hendriks, 2003]. In the second simulation the same constitutive model was used, with constants C10=1,7kPa and C11=1kPa [Cox, 2007].

The use of FEM in simulations implicates a discretization of the geometric model. The discretization was performed through the creation of a mesh for each of the bodies (bones, cartilages, capsules and skin tissue).

Since bones and cartilages don't deform during flexion and extension of fingers, they were considered as rigid bodies; this made the model simpler in a computational point of view. For these rigid bodies shell elements of triangular shape (R3D3) were used. Considering that the capsules and skin tissue have a lower stiffness and vary its geometry during flexion and extension of fingers, they were considered as deformable bodies. For these bodies, solid hybrid elements of tetrahedral shape (C3D4H) were used.

To a correct biomechanical representation of the model was necessary to create contact pairs and the tie between the bodies. The contact pairs limit the penetration of nodes of slave surface in the master surface. These contact pairs were used between the cartilages to allow sliding between them, considering sliding without friction. Other contact pairs were established between the bones and capsules to ensure that each capsule involves the bones during the simulation. The tie (connection between the solids) was used to ensure that the bodies remain united during the simulation. The established tie surfaces received properties of displacement restrictions, i.e., the nodes of slave surface assume the same displacements of nodes of master surface. On the model a tie between the capsules and bones was used, and also between the cartilages and bones. The option for initial adjust of the nodes was applied in tie surfaces to adjusts the spacing and penetration between them automatically.

The size of elements were limited according to: *representative geometry* - The larger the level of detail of the geometry, such as curves and thicknesses, the smaller the size of elements; *contact pairs* – The size of slave surface elements were defined as half the size of master surface elements in order to ensure a lower penetration of bodies involved in contact; *region of interest* - To obtain a better analysis of the results, the region of interest had theirs elements reduced. It´s possible to verify, in Fig. 3a, the difference on the size of several bodies elements (bones, capsules and cartilages) due to their geometries and contact pairs that they are submitted. Figure 3b shows that the elements of the fingers are smaller than the elements of the wrist, since the purpose of this study is the biomechanical analysis of the fingers.



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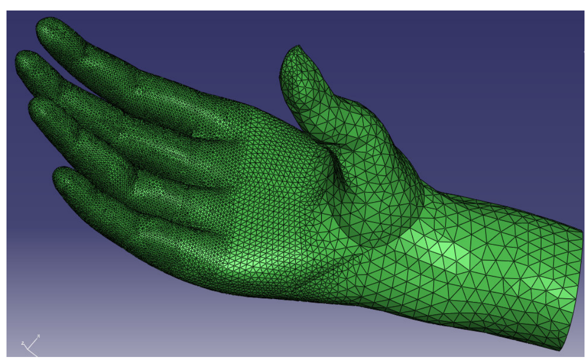

(b)

Figure 3. (a) Mesh of bones, cartilages and capsules; (b) Skin tissue mesh.

2.3. Simulation

A biomechanical experiment was proposed, where the flexion of the index finger of the 3D human hand model was performed.

Displacement restrictions in all directions (u1, u2 and u3) for the reference points of metacarpals bones were imposed as boundary conditions, so that during the simulation they were immobile. The displacement restrictions were imposed on the metacarpal bones, since its restriction implicates the stabilization of the wrist, allowing only the phalanges movements.

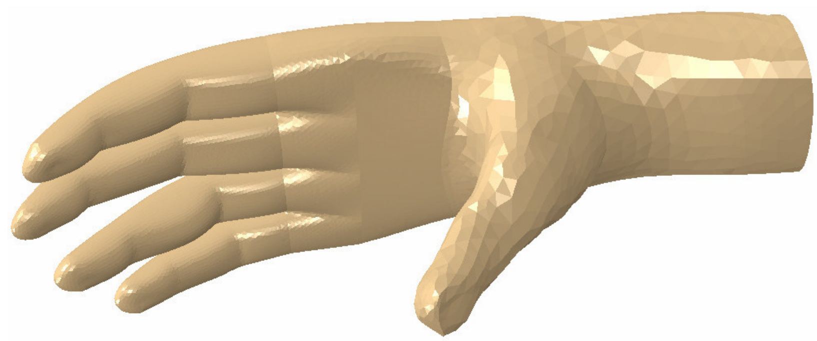
In order to simulate the flexion of the finger, it was applied as input a displacement of 20mm in the node contained in the index fingertip, in the direction of center of the hand palm.

Created the model that contains all geometry, interactions and their conditions, this was submited in a Cluster of high capacity for calculation in the solution of the problem. The Cluster of the IDMEC-Polo FEUP is composed by the following components: 2 main nodes with 2 AMD Opteron 280 processor (dual core 2.4GHz 64Bits) and 2 disks of 160 GB; 39 solver nodes with 2 AMD Opteron 280 processor (dual core 2.4GHz 64Bits) totalizing 156 parallel cores for simulations, 8GB memory and 160 GB disk; 1 net to store data with 11 disks of 300GB connected by optical fiber. Forty cores were used in parallel to solve the biomechanical simulation of index finger.

3. RESULTS AND DISCUSSION

The computational time was approximately 52 hours. The results showed that the final value of the simulation converged to the input. The biomechanical analysis of 3D human hand model was evaluated comparing the initial geometry (Fig. 4a) with the results obtained in the simulation (Fig. 4b).

(a)



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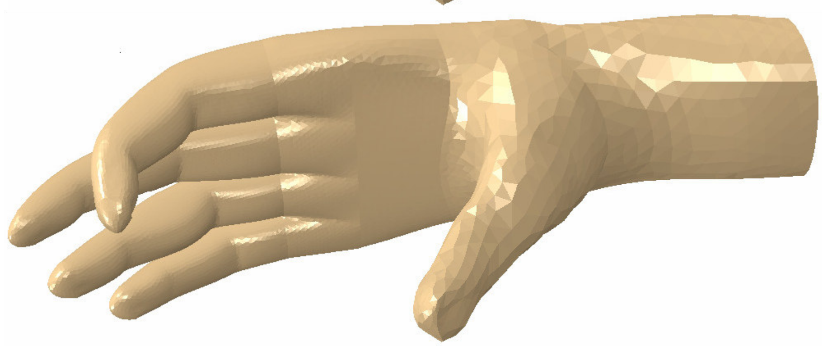

Figure 4. (a) Initial geometry; (b) Result obtained in the simulation

The applied displacement had as a result the flexion of index finger showing that the model presented physiological movement. The result obtained in the simulation demonstrated that the contact pairs were functional, since the bones and cartilage remained inside the capsules and allowed the slide between the cartilages.

The results of simulation showed different behaviors. The first simulation obtained a force of 0,97N, while in the second simulation a force of 0,19N was obtained. This difference occurred due to the distinct mechanical properties used in the skin.

4. CONCLUSIONS

The creation of a 3D human hand model was developed using a base geometric model and anatomical information. A biomechanical simulation was performed using the model created. The results obtained in the simulation showed that the applied displacement resulted in the flexion of the index finger.

The numerical simulations conducted resulted in different values for the force obtained due to the use of mechanical proprieties from different authors, which used different methodologies in their works. In both simulations the model converged, allowing the flexion of the index finger of the human hand.

5. ACKNOWLEDGEMENTS

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