GRIP FORCE ANALYSIS IN A 3D HAND PROSTHESIS MODEL

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Abstract. *Hand prostheses are artificial devices that replace the loss of hand trying to mimic as much as possible the appearance and function of a natural hand. While many models have limited mobility, advances in technology have made it possible to create a hand prosthesis that is capable of gripping objects with adequate forces. In the literature there are many studies dealing with forces acting on the hand during the objects grip. Many authors perform experiments in human hands to find out contact forces on the hand surface and forces to necessary accomplish most tasks. Some experimental tests present limitations to measure load in many points of hand because both of the positioning of sensors and limited space on the hand. Nowadays, the use of computational tools has been most widely used in biomechanical designs. The finite element method (FEM) has become the prevalent technique used for analyzing structural behavior. For biomechanics, the FEM has also received considerable advancements mainly to analysis forces and torques in biomechanical models in order to develop more ergonomic devices. The FEM is a useful method because one can use it to find out facts or study the process in a way that no other tool can accomplish.This work aims to develop a 3D biomechanical model of a hand prosthesis in order to investigate forces acting on fingers during the grasp. The 3D geometry model of the hand prosthesis was based on a prototype of a prosthetic hand built in the Bioengineering Laboratory (LabBio) at UFMG. The model developed in the SolidWorks Software was imported into Abaqus Software in order to perform the biomechanical analysis. These geometries were considered as deformable bodies and mechanical properties of the materials used in the building of the prototype were applied. After, meshes were created using tetrahedral elements (C3D4). Coupling forces between surface of the hand and the object were measure for different cylindrical objects of various sizes. The simulation allowed analyzing loads to implement a force control in the future and choose an adequate actuator in order to provide the necessary load grip.*

Keywords*: hand prosthesis, FEM, force analysis, biomechanical model*

1. INTRODUCTION

The human hand plays a very important role in social interaction and body image besides being a tool extremely necessary to execute the tasks in daily life such as eating, dressing and even operating machines. The loss of the limb has both a profound effect on the amputee's body image and self-esteem as also reducing the ability to perform many tasks causing functional and psychological trouble [Pillet et al., 2001]. Hand prostheses are artificial devices that replace the loss of hand and they are designed to restore as much as possible the function of a natural hand and its appearance thus reducing the problems.

In the last 30 years very innovative prosthetic hands have been developed. While many models have limited mobility, advances in technology have made it possible to create hand prostheses that are capable of gripping objects with adequate loads. In the literature there are many studies dealing coupling forces acting on the hand during objects grip[Reidel, 1995; Kaulbars, 1996; ISO-5349-1, 2001; ISO/WD-15230, 2000]. Many authors perform experiments on human hands to find out contact forces on the hand surface and forces to necessary accomplish most tasks. However, few studies deal with force analysis on hand prostheses. Some experimental tests present limitations to measure load in many points of hand because both of the positioning of sensors and limited space on the hand.

The finite element method (FEM), an advanced computer technique of structural behavior analysis developed in engineering mechanics, has been utilized in the biomechanical and biomedical areas such as orthopedics, orthodontics, cardiovascular in order to evaluate forces and torques in human bones and teeth, fracture fixation devices, behavior of soft tissues, lesions caused by impacts and as well as to improve the development of more ergonomic devices. The application of FEM is also a very suitable technique for structural studies in prosthesis because the analysis of these structures is developed in a way similar to evaluate mechanical structures with respect to forces and deformations.

Forces analysis in mechanical structures can be obtained by two (2D) or three (3D) dimensional models. The 3D models are feasible to analyze the structure completely and allow observing simultaneously the distribution of forces in each component of the prosthesis or the interaction among them [Hayasaki and Capello *et al*, 2006].

In this work, the structural behavior of a finger of hand prosthesis is analyzed by the FEM. The 3D biomechanical model of a prosthetic finger is developed in order to investigate forces acting on phalanges when the finger is submitted to the action of gripping an object. The dimensions and configuration of phalanges and the position of the contact points will determine the distribution of forces between the phalanges and the grasped object.

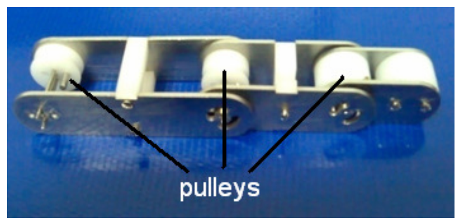
2. MATERIAL AND METHODS

2.1. 3D Geometry Model of the Hand

The 3D geometry model of the prosthetic finger was based on a prototype of a prosthetic hand built in the Bioengineering Laboratory (LabBio) at UFMG. The prosthesis hand has an underactuated mechanism, where three degrees of freedom of each finger are driven by a single actuator.

The prototype of the finger was designed based on anatomical characteristics of the human index finger, according to Bundhoo e Park (2005). The phalanges: proximal, middle and distal have lengths equal to 4.5, 3.0 e 2.4 cm, respectively (Fig. 1a). Phalanges are connected by pulleys so that each pulley is rigidly connected at the proximal part of each phalange and can rotate freely around the axis fixed on the distal part of the previous phalange (Fig. 1b). A non-elastic wire (tendon) is fixed on each pulley and they are connected to a differential mechanism. This same configuration was installed on the finger in an opposite and parallel way, using the same pulleys. Thus, when each pulley rotates forward or backward the phalange flexes or extends.

(a)



(b)

Figure 1. Finger prototype: (a) Finger with anatomical characteristics; (b) Pulleys

In order to act on all the tendons using a single actuator, a differential mechanism system capable of controlling multiple DOFs with a single input was built by combining several differentials. The system is composed of two differentials (it has one input and two output) so that the output of one is connected to the input of other, allowing the system has one input and three outputs. So, each tendon is connected at each output of the differential mechanism. This mechanism allows that even if one phalange of the finger is restricted by an object the others continue moving so that at the end of the movement, the phalanges adapt themselves to the shape of the object allowing a good grasp. More details of the differential mechanism are not described here because it is not the focus of this work and only finger structure is important for now.

Since the thumb is important to provide a grasp movement, a static finger was added to the prototype as can be view in the Fig. 2.

Figure 2. Grasp prototype

The 3D model was built in the SolidWorks 2009 software (Fig. 3). The model is composed by the index finger, which mechanism is described previously, connected to a thumb. The thumb is important to provide a grasp movement besides being used to position all objects with the same pattern. The metacarpus was also built in the prototype in order to be used as a support for the finger. Both the metacarpus and thumb are statics.

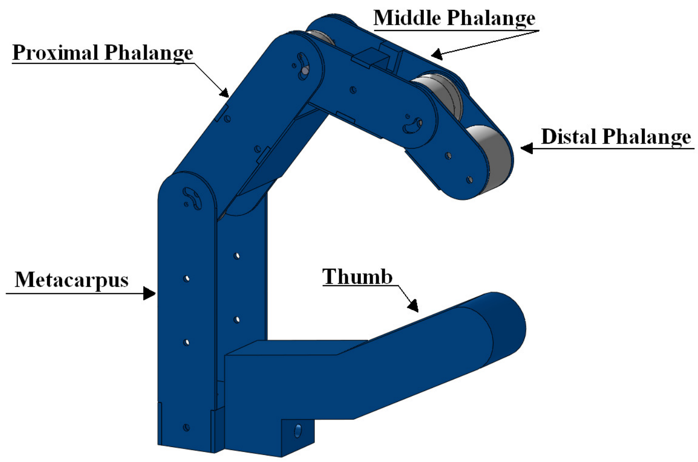
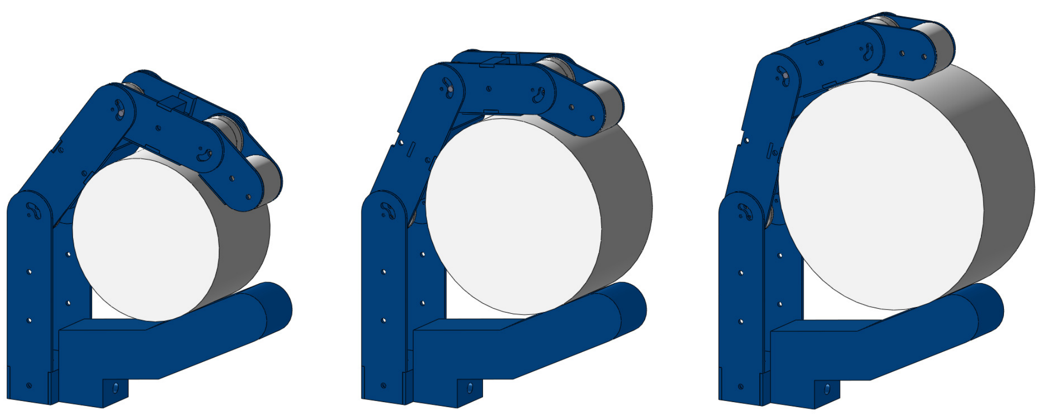


Figure 3. 3D model of the finger

Cylindrical objects of different diameters (50mm, 60mm and 70mm) were inserted in the 3D model and positioned in such a way that the object touches the thumb.

Phalanges of the finger have relative displacement between them, their displacements were simulated and the final configuration was obtained to analyzing contact forces between the object and phalanges. Figure 4 shows the final configuration of the finger when it flexes and get in contact with the object.



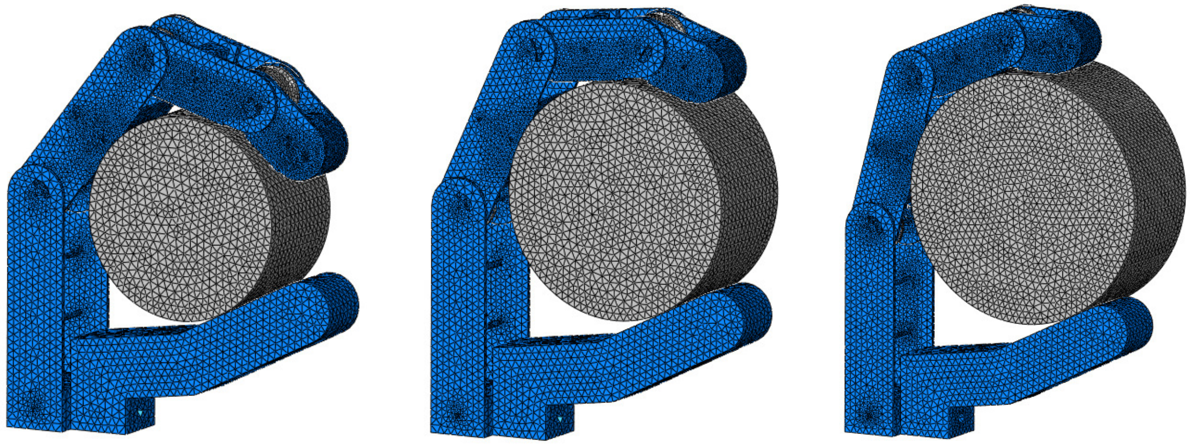
(a) (b) (c)

Figure 4. Final configuration of the finger for each cylindrical object: (a) 50 mm; (b) 60mm; (c) 70mm

2.2. Finite Element Model

The structural analysis of the prosthesis through FEM was realized into the Abaqus 6.9.3 software. Representative geometries of 3D model were imported into the software with the aim to create a finite element model, where loads analysis was performed.

An initial step of the FEM for numerical computation is discretize the model by a mesh generation in finite elements (Fig. 5). Phalanges, metacarpus and thumb were considered as 3D deformable bodies, so their meshes were composed by tetrahedral elements (C3D4). Deformations of the pulleys and object were despised, so geometries were considered as rigid bodies. Their meshes were composed by 3D triangular elements (R3D3).



(a) (b) (c)

Figure 5. Mesh of finite element model for each simulation: (a) 50 mm; (b) 60mm; (c) 70mm

The phalanges of the prosthesis were built in steel material while pulleys and cylindrical objects were built in polypropylene. The phalanges material was considered linear elastic with Modulus of Elasticity (E) and Poisson Coefficient (ν) equal to 200 GPa and 0.3, respectively. Because the pulleys and grasped object were considered to be rigid bodies there was no need to apply mechanical properties.

The simulation consisted to analyzing the variation of coupling load between finger and objects of different diameters. Here, forces were analysed only in points where the prosthesis got in contact with the object, i.e, only contact points of the prosthesis with objects were analysed. The contact force measure in each phalange represents the mean of reaction forces on all surface elements of each phalange, using surface-to-surface contact analysis. As initial condition, all degrees of freedom of the metacarpus, thumb and object were restricted since they do not move. Subsequently, torques were applied (M1, M2 and M3) on pulleys representing the actuation of the motor and thus resulting in the grip of the object (Fig. 6). The applied torque values varied from 0 to 0.9 Nm since the torque of actuator used in the prototype has its maximum value equal to about 0.9 Nm.

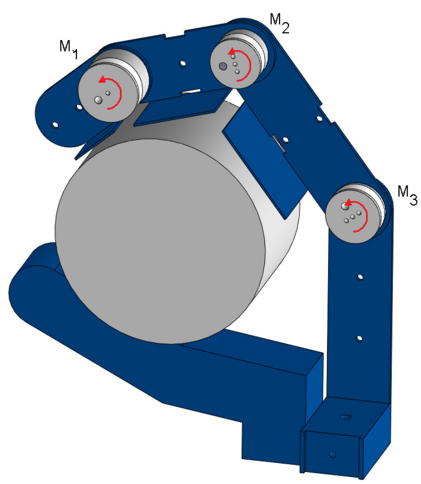


Figure 6. Torques applied (M1, M2 and M3) on each pulley

3. RESULTS AND DISCUSSION

Simulations were performed using three different sizes of cylindrical objects. Different torques values (from 0 to 0.9 Nm) were applied in each pulley of the finger, at the same time, when the finger achieved its final configuration. During the simulations coupling load between phalanges and object were recorded. Figure 7 shows lines those relate contact forces of each phalange (distal, proximal and middle) and torque applied on pulleys during the simulation of grip with an object of diameter equal to 50 mm. It is noticed that, in all phalanges, coupling forces are increased according to the intensity of applied torque and their relationship is linear. The distal phalange was the most requested in this simulation.

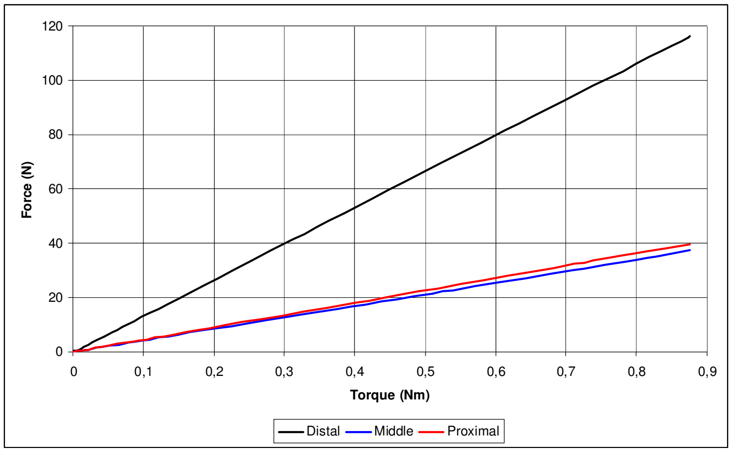


Figura 7. Relations between contact forces and applied torque for each phalange with a cylindrical object of diameter equal to 50 mm

Figure 8 shows the results of the coupling loads s in each phalange for cylindrical objects of different diameters when a torque of 0.9 Nm was applied on pulleys. The red line represents the variation of loads according to cylindrical objects of different diameter. It can be noticed that in this phalange occurred the highest contact forces values, for all diameter values, when it compared with contact forces of other phalanges. The maximum force obtained was 116.28 N for diameter of 50 mm. It can be also viewed that the force decreased to about 98 N with the increase of the diameter of the object. Forces related to the middle (green line) and the proximal (blue line) phalanges presented with similar values. However, the coupling force acting on the proximal phalange tends to decrease with increasing diameter, while coupling forces on the middle phalange presented an opposite behavior.

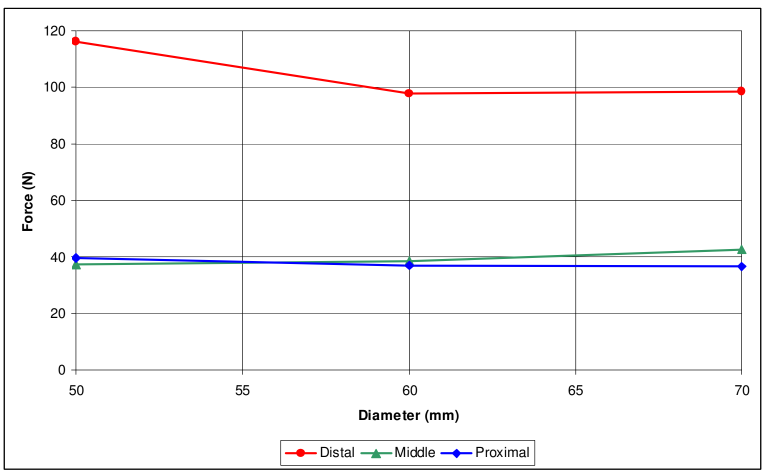


Figure 8. Coupling forces between finger and cylindrical objects of different diameters.

4. CONCLUSION

The simulation allowed analyzing coupling loads between finger and objects for different applied torque values. These results are useful to choose an adequate actuator that provides the necessary grip load for the final prototype.

It was noticed that coupling forces changes according to the object diameter. It means that coupling forces changes according to flexion angle of each phalange. In this way, if the flexion angle of each phalange and the actuator torque is known, the coupling force on each phalange can be calculated.

Since the mesh is well refined mesh test was not done. Here, applied loads does not cause contact geometry deformation and surface-to-surface contact analysis calculates automatically interactions on the entire surface of the element. Despite the facts of the simulation takes more time to be performed, mesh test was not needed to analyze the contact.

In the future, studies using objects of different shapes will be analyzed. Also, authors intend to compare results from simulations with data obtained from experiments.

5. ACKNOWLEDGEMENTS

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