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Finite Element Digital Human Hand Model – Case Study of Grasping a Cylindrical Handle

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Abstract

Products are becoming increasingly complex, therefore designers are faced with a challenging task to incorporate new or improved functionality, higher performance and optimal shape design. Traditional user-centered design techniques such as designing with anthropometric data do not incorporate enough user data to design better products for the target population. Measurements of contact pressure and contact area using traditional methods are time consuming and require actual product prototype and expensive measurement systems. In order to overcome these limitations, several researchers already proposed the use of computer simulations using finite element (FE) method. Therefore the aim of this research was to develop an anatomically accurate and numerically feasible and stable finite element digital human hand model with bio-mechanically accurate hand movement and grasping, which would allow virtual analyses of stresses on the soft tissue. The usability of the developed model is presented on a case study grasping a cylindrical handle.

Keywords: Product design; Digital human model; Reverse engineering; Finite element method; Human hand

Introduction

Product designers have to consider ergonomics to increase the human-product performance, comfort, and lower the risk of cumulative trauma disorders (CTD) [1]. Traditional user-centered design techniques such as designing with recommendations, designing based on anthropometric data and derived mathematical models do not incorporate enough subject specific data to improve the human-product interaction. To overcome limitations of traditional design, there has been an increase in use of multidisciplinary methods to reverse engineer human anatomical parts or whole body to incorporate them into the design process of workplaces and products. Using these so called virtual or digital human models (DHM), design process can be performed without physical prototypes [2]. Based on the analyses, safety and performance can be predicted inside computer environment and thereby design flaws can be identified and corrected in an early stage of development, where they are still quite cheap. Few authors also developed stand-alone anatomically-accurate Digital Human Hand Models (DHHM) for ergonomic evaluation of hand-held products [3,4]. Despite this, most of the ergonomic analyses of products and hand tools are still done using physical prototypes and costly measurement systems and therefore iterative design process, which increases development time and cost.

The mechanical behaviour of the biological materials of human hand is crucial since forces and moments are transferred from grasped object to anatomical structures [5-7]. The nature of the human hand and complex surfaces of the grasped objects usually prevent the direct measurements of stresses, strains and contact pressure on the hand, therefore it has been already shown that the one of the most viable methods in virtual environment are computer simulations using finite element (FE) method [8-10]. Using these methods, not only hand movement and tissue deformations are obtainable, but also stresses, strains and contact pressures on the hand, which can provide crucial insight into the hand bio-mechanics, injury development and product shape optimization.

The aim was to develop a finite element digital human hand model (FE-DHHM), which would allow simultaneous studying of bio-mechanics of human hand movement and grasping, analyses of biological tissue deformations, contact area and pressure.

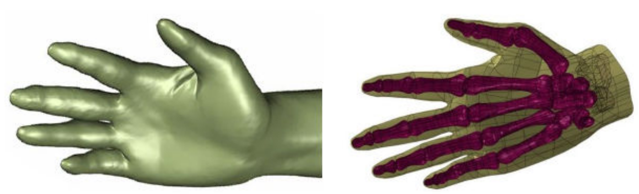

Figure 1: CAD model of skin (left) and final assembly of all reconstructed parts (right).

Methodology

Three dimensional data acquisition

Therefore, for the development of the proposed FE-DHHM CT medical imaging has been undertaken. The optimal posture for the generation of the FE model was determined to obtain undeformed soft tissue of the hand. Obtained images were manually segmented into bones (phalanxes, metacarpal bones, carpal bones, radius and ulna) and skin in medical imaging software ITK-SNAP [11]. Obtained models of the anatomical structures were then exported in STL file format and water-tight IGES models have been generated in Geomagic software. Afterwards all anatomical structures were imported into the Abaqus FE software for the appropriate definition of the FE model (Figure 1).

Finite element model definition–boundary conditions and mesh

Based on the joint link structure of a real human hand, our FE-DHHM is joint angle driven. Therefore, the joint movement is simulated using the connectors connecting two adjacent bones into one joint. The rotation of the joint is specified in the manner of degree of rotation (Figure 2).

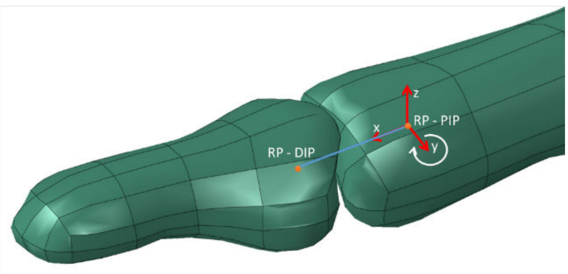

Figure 2: Geometry definition based on medical imaging and the definition of the joint. In order to be able to perform numerical tests, we created a mesh using 326427 4-node linear tetrahedral elements (C3D4) as shown in Figure 4.

Finite element model definition – material properties

Fingertip bone and nail were assumed to be linear elastic with isotropic material parameters with Young´s modulus of 17GPa and 170MPa respectively, with a Poisson ratio of 0.3 [12]. The material parameters for soft tissue were extracted from a uniaxial tensile test, and were fitted to the Ogden hyper-elastic material model [6]. Same material properties have been used by us in our previous research and showed great correspondence to experiments [9,10].

Numerical tests

In initial numerical test each joint has been prescribed with 1 radian (57.3°C) of rotation. In this manner rotations at each joint could be observed under same boundary conditions.

Additionally, to demonstrate the usefulness of the developed model, it has been coupled to motion capture system where joint angles of hand movements from real life grasping a cylindrical handle have been extracted and feed into the developed FE model.

Results and Discussion

The soft tissue deformation of the FE-DHHM during simulation is a consequence of the bone link structure movement prescribed by the boundary conditions. Therefore, bone movement has been carefully investigated, which is defined with the joint definitions. It has been shown that joint definitions were defined correctly, since each bone showed correct bio-mechanical movement (Figure 3).

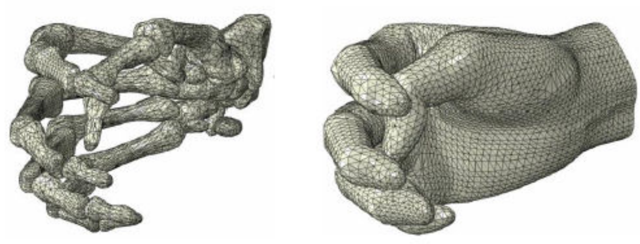

Figure 3: Bone structure responsible for the deformation of soft tissue.

Since the presented FE-DHHM is one of the first full hand finite element models we introduced several simplifications in terms of anatomical structures, material models and joint definitions. Based on our previous research, we have shown that such simplifications are reasonable and allow maintaining high level of accuracy of the simulated system.

Using the motion capture system realistic hand posture and grasping pattern was obtained during grasping a cylindrical handle with 60mm diameter. The result is contact area and resulting contact pressure (Figure 4).

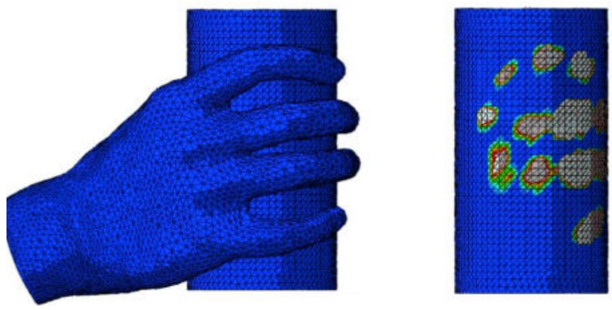

Figure 4: FE-DHHM grasping a cylindrical handle and resulting contact area/pressure.

In order to validate the results in terms of contact area, we compared the results from the simulation to the result from experiment a subject grasping a cylindrical handle. Results have shown there is good correspondence between both results, which shows that the developed FE-DHHM produces similar contact area size and shape for the given grasping scenario (Figure 5).

Real-world grasping is very complex and is also depends on the psychophysical, psychological and comfort factors of the user, therefore this kind of evaluation can be unreliable. It is therefore necessary to incorporate this aspect of product evaluation during the design phase, which is usually still not possible with modern DHMs.

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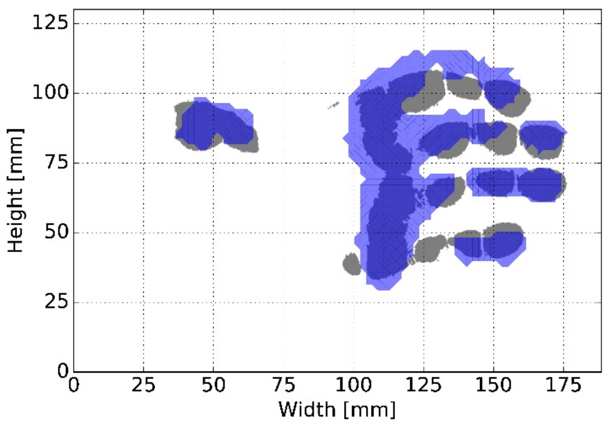

Figure 5: Comparison of contact area between an experiment (gray) and FE-DHHM (blue).

In this regards future work should include throughout process of verification and validation of the developed FE-DHHM in terms of contact area, pressure, stresses and deformations of anatomical structures. Future FE-DHHM should also include more anatomical structures (skin, subcutaneous tissue, nail, capsules, synovial fluid, and cartilage) and more realistic joint definitions to obtain more realistic numerical results. Additionally, the physiological aspects of discomfort should be studied in detail to establish a link between numerical results and the subjective response of a user. This would allow direct evaluation of the product inside the virtual environment with the possibility of topological modifications of the product to improve the ergonomics and therefore lower the development times and costs. Safety and effectiveness of a product could be predicted and design mistakes could be eliminated in the development phase for increased performance, comfort and avoidance of cumulative trauma disorders.

Conclusion

We have shown that deformations and stresses that represent basic results of the structural analysis using FE method are also an important aspect in the field of ergonomics. In this manner finite element method has been successfully used to develop an angle driven full hand finite element human hand model. Initial simulations have shown that the FE-DHHM is numerically feasible and also stable, which presents a reasonable bio-mechanical movement and provides results in terms of contact area and pressure.

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