Improving ergonomic value of product interface materials using numerical digital human models

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Abstract

Digital human models are usually constructed to study the human anatomical or topological features and its variance and to optimize the size and shape of various products and tasks. Therefore, most of the researchers focussed on developing accurate three-dimensional digital human models based on surface mesh using various methods and techniques. However, such models do not allow biomechanical and ergonomic analyses of product interface materials that are in direct contact with the user. Based on manual testing using various materials and analysing the subjective response of users, researchers have shown that product interface material has an important impact on the overall product safety, comfort and even performance. Basic ergonomic and biomechanical guidelines regarding the material choice were provided based on the findings, however detailed material choice and even material parameter determination has not been studied, evaluated, and discussed due to the complex biomechanical systems and lack of appropriate digital human models.

To overcome these limitations, numerical methods, especially the finite element method has been already used in the past by several authors. Finite element method allows calculating of various results in terms of internal stresses and contact pressure, deformations, and displacements, however it requires accurate development of numerical digital human models that accurately represent the anatomical, topological, material properties and boundary conditions.

In this paper we present theoretical background and provide methodology for successful development of numerical digital human models that can be used for biomechanical analyses and product material ergonomic improvement. This is presented with a case study of the development of a numerical digital human finger model for ergonomic improvement of the biomechanical response of a product handle deformable interface material. Based on the developed numerical model, a novel deformable interface material is analysed that reduces the resulting contact pressure during grasping and provides more uniform pressure distribution while still providing sufficient stability.

Keywords: finite element method, numerical model, biomechanics, product ergonomics, material properties.

Introduction

Digital human models are usually constructed to study the human anatomical or topological features and its variance and to optimize the size and shape of various products and tasks (Duffy, 2016). Therefore, most of the researchers focused on developing accurate three-dimensional digital human models based on surface mesh using various methods and techniques. However, such models do not allow biomechanical and ergonomic analyses of product interface materials that are in direct contact with the user (Harih, Borovinšek, Ren, & Dolšak, 2015). Based on manual testing using various materials and analyzing the subjective response of users, researchers have shown that product interface material has an important impact on the overall product safety, comfort and even performance (Wongsriruksa, Howes, Conreen, & Miodownik, 2012). Basic ergonomic and biomechanical guidelines regarding the material choice were provided based on the findings, however detailed material choice and even material parameter determination has not been studied, evaluated, and discussed due to the complex biomechanical systems and lack of appropriate digital human models.

Previous research has shown that soft tissue (skin, subcutaneous tissue, muscle, fascia, etc.) exhibits non-linear mechanical behaviour with low stiffness at small strains with a sudden increase of stiffness with higher strains. Therefore, also the resulting contact pressure when in contact with various products, equipment, etc results in high contact pressures, which leads to sudden increase in discomfort and pain (Hokari, Pramudita, Ito, Noda, & Tanabe, 2019).

Distinctive mechanical behaviour of soft tissue suggests the interface materials should be deformable to be able to reduce the resulting contact pressure and provide more uniform pressure distribution (Harih & Tada, 2015). Hence, companies tend to use foam materials in the areas of the products which are in direct contact with the user and result in high contact pressures. However authors did not optimize material properties of the interface foam material to improve ergonomics, which usually results in decreased ergonomic value with lower subjective comfort (Cupar, Kaljun, Dolšak, & Harih, 2020). Research has shown that foam rubber interface material provide more uniform contact pressure distribution, however it can also lead to excessive deformation of the foam resulting in the loss of control and stability feeling when grasping the product (Fellows & Freivalds, 1991).

Measurements of contact pressure at the contact regions are mostly impossible with existing measurement systems due to complex organic geometry of the anatomical parts that are in direct contact with the product. Hence, improvement of interface materials using conventional quantitative methods is not possible. Therefore, several researchers already developed numerical digital human models based on finite element method (FEM) for biomechanical and ergonomic analyses. Previous research has shown that FEM provides extensive results (stresses, deformations, displacements, contact pressure, etc), which can be used for quantitative biomechanical and ergonomic analyses and optimization (Tony & Alphin, 2019). Authors have shown that such technique require accurate development of numerical digital human models that accurately represent the anatomical, topological, material properties and boundary conditions to obtain results that are accurate.

Hence, in this paper we present theoretical background and provide methodology for successful development of numerical digital human models that can be used for biomechanical analyses and product material ergonomic improvement. Additionally, a case study of the development of a numerical digital human finger model and numerical analysis and ergonomic improvement of a product handle with deformable material is studied.

Methods

Finite element method software Ansys was used to develop the numerical model and simulate the mechanical behavior of the biomechanical system.

Numerical model – geometry determination

Obtaining accurate geometrical information of the studied part is crucial for obtaining accurate results. Hence, most of the researchers utilize medical imaging for the determination of the accurate geometry since it allows to obtain geometrical information of internal anatomical structures as well. However, specific geometry based on imaged subject results also in specific geometry of the subject, which can differ from the average size and shape of the studied anatomical part of the target population. When developing numerical models, simplifications need to be chosen carefully to describe the studied biomechanical system accurately enough and maintain numerical stability.

In the case study of the numerical digital human finger model development, the geometry of the finger has been obtained by medical imaging (CT) and later with reverse engineering technology. Average sized human finger has been considered according to anthropometric measurements. The handle interface material has been modelled as a half cylinder resembling a product handle as seen in Figure 1.

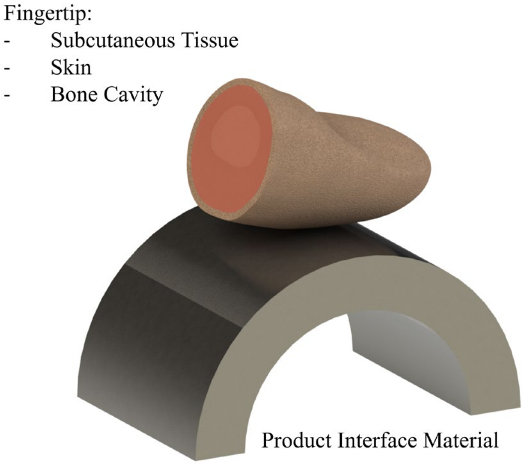

Figure 1. Geometry of the finger with product interface material.

Numerical model – material properties

Biological soft tissue shows highly non-linear mechanical behavior; therefore, it is crucial to include this behavior in the numerical simulations with appropriate numerical models to obtain accurate results. Simplifications by utilizing linear material models have shown to oversimplify the mechanical behavior and can be only used for simplified biomechanical analyses. Hyper-elastic material models should be used to include the actual mechanical behavior of the given soft tissue structure.

Therefore, in our case soft tissue was numerically modelled with Ogden hyper-elastic material model, which has been validated by us in previous research (Harih & Tada, 2019). We considered homogenous material and isotropic material behavior due to limited experimental data and to provide improved numerical stability. Bone was considered rigid since it is it is magnitudes stiffer than soft tissue and is not an anatomical part of interest in terms of results.

For the evaluation and comparison of the interface materials we considered two common materials that can be found with products, namely steel and rubber. Additionally for the biomechanical analysis and ergonomic evaluation we performed also numerical simulation using cellular meta-material that has already shown improved comfort with subjective testing (Cupar et al., 2020). Material properties of the numerical digital human finger model and interface materials are presented in Table 1.

Table 1. Material properties

Material	Material model	Parameters
Subcutaneous tissue	Ogden 3rd order	MU1 = -0,04895 MPa A1 = 5,511 MU2 = 0,00989 MPa A2 = 6,571 MU3 = 0,03964 A3 = 5,262 D1 = -4,2267 MPa^{-1} D2 = 20,92 MPa^{-1} D3 = 5,2194 MPa^{-1}
Skin	Ogden 3rd order	MU1 = -0,07594 MPa A1 = 4,941 MU2 = 0,01138 MPa A2 = 6,425 MU3 = 0,06572 A3 = 4,712 D1 = -2,7245 MPa^{-1} D2 = 18,181 MPa^{-1} D3 = 3,1482 MPa^{-1}
Steel	Linear-elastic	2100000 MPa $\nu = 0,3$
Rubber	Linear-elastic	E = 33,7 MPa $\nu = 0,49$
Cellular meta-material	Segmentially linear	$\sigma_1 = 0,23$ MPa $\varepsilon_1 = 0,1$ $\sigma_2 = 0,28$ MPa $\varepsilon_2 = 0,4$ $\sigma_3 = 0,65$ MPa $\varepsilon_3 = 0,53$ $\nu = 0,4$

Numerical model –boundary conditions

Boundary conditions need to reflect the actual biomechanical behavior in terms of movement and external loading on the structure. Loading scenarios on a distinctive studied biomechanical structure can be complex, therefore appropriate simplifications need to be undertaken to obtain numerically stable model. Biomechanical movement presents additional challenge since biomechanical movement is usually complex and stochastic. Hence, motion capture systems should be used to obtain actual movement data for the given study.

In our case study of the numerical digital finger model, grasping has been simplified with a normal force of 35N on the distal phalange bone. Finger phalange bone was fixed in all directions, except the direction of the vertical force as seen in Figure 2. The value represents a typical power grasp scenario, where the object is firmly grasped for transferring of high loads and moments and to increase stability. All interface materials have been numerically tested and results can be observed in following section.

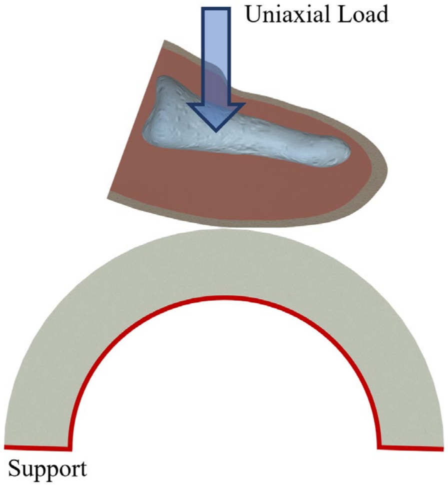

Figure 2. Boundary conditions of simplified grasping scenario.

Results

The developed numerical digital human model has been extensively validated in the past and results show comparable contact pressure, deformation, and displacements (Harih, Tada, & Dolšak, 2016). Therefore, the result is a numerically stable and feasible numerical digital human model that provides accurate biomechanical behavior and provides results in terms of stresses, strains, deformations, displacements, contact pressure, etc.

As presented, obtained results can be used to perform biomechanical analyses and product interface material ergonomic evaluation and improvement. Hence, results of contact pressure distribution for studied interface materials are provided in Figure 3 and maximum contact pressure for each interface material is provided in Figure 4. Additionally, stability is analyzed with results of displacement of finger and product interface material in lateral cross-section in Figure 5.

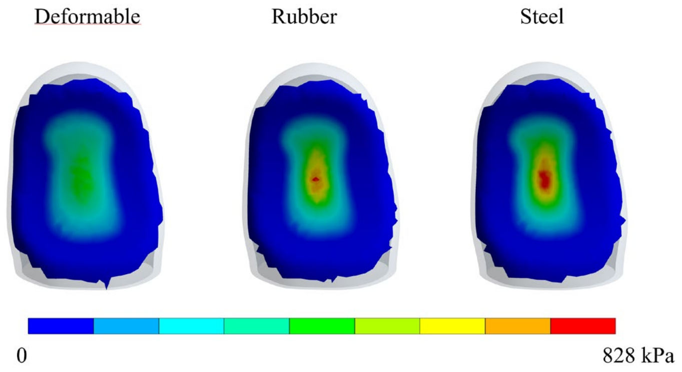

Figure 3. Contact pressure distribution for each infertface material.

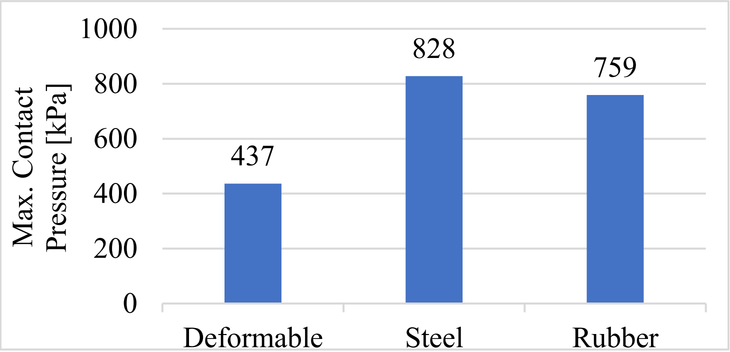

Figure 4. Maximum contact pressures for each interface material.

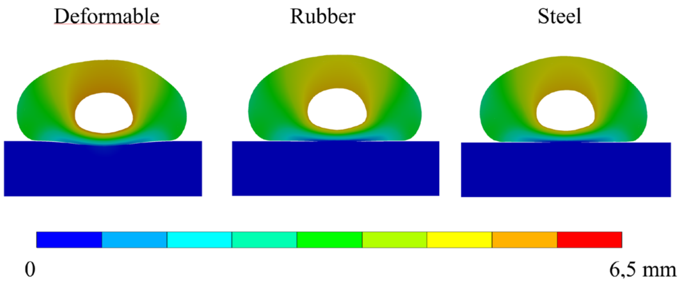

Figure 5. Displacement of finger and product interface material in lateral cross-section.

Discussion and Conclusions

When developing numerical digital human models, through validation of the model is needed for the later use of the model in terms of biomechanical analyses and ergonomic evaluations. Research has shown that validation of biomechanical systems is usually very complex and demanding due to simplifications that need to be incorporated into the numerical models. These simplifications usually need to be included due to limitations defining actual model geometry, material determination and definition and boundary conditions. This also influences the numerical stability and feasibility; hence an appropriate compromise needs to be set to obtain usable results with good numerical stability. Hence most of the numerical digital human models are best suited for relative comparison in terms of biomechanics and ergonomics.

Human grasping of various products usually requires high grasping forces, therefore also the resulting loads on the hand are high, which can lead to musculo-skeletal disorders. Most of the researchers focused on defining correct sizes and shapes of the product for the best fit with the user, however they rarely investigated the materials that are in direct contact. Development of digital human models in last years had increased substantially, however they are limited to geometrical data and statistical shape models that can be used for size and shape optimization. Product material choice and determination is usually defined based on product manufacturing requirements and limitations and also ergonomic recommendations. This leaves possibility for further ergonomic improvement as presented in this study.

Results have shown that steel is magnitudes stiffer than soft-tissue and hence all deformation can be attributed to the finger. This is also reflected in the results where numerical simulations with steel interface material produce the highest contact pressure and concentrated distribution. Rubber interface material can be found on many products, where manufacturers try to provide better human-product interaction. While stability is increased due to higher friction of the rubber, contact pressure is reduced just slightly as shown by results. Contact pressure distribution is similar to steel and hence rubber interface materials cannot be effectively used for contact pressure reduction and uniform contact pressure distribution. On the other hand, the proposed deformable interface material reduces the maximum contact pressure substantially (48%). Additionally, deformable interface material provides more uniform contact pressure distribution when compared to steel and rubber. When comparing the vertical displacement, all three biomechanical systems show similar results, hence stability of the product is maintained even with the deformable interface material.

We have shown that FEM can be successfully used for obtaining results in terms of stresses, contact pressure, displacements that can be used for ergonomic evaluation. In our case study we focused on novel deformable meta-material, that allows minimization of contact pressure with maintaining stability. This is achieved with inverse mechanical behavior to soft tissue, where the proposed deformable material stays quasi-stiff at low stresses and starts to deform when critical stress (contact pressure) is achieved to provide higher contact area and distribute contact pressure more uniformly. This behavior of the biomechanical system has been also confirmed by the results. Based on previous extensive subjective comfort rating measurement and evaluation we have shown that proposed deformable material provides increased comfort compared to quasi-stiff materials such has rubber, while providing same stability.

Using the FEM, the quantitative results that affect the comfort rating values have been evaluated in this study and have shown that they correspond well to results from subjective comfort rating evaluation. Hence, appropriately validated numerical digital human models can be successfully used for ergonomic analyses and evaluations, especially in the area of biomechanical behavior.

Acknowledgments

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