Optimisation of Product's Hand-Handle Interface Material Parameters for Improved Ergonomics

Gregor Harih[1(✉)], Matej Borovinšek[2], and Zoran Ren[2]

[1] Laboratory for Intelligent CAD Systems, Faculty of Mechanical Engineering, University of Maribor, Smetanova ulica 17, 2000 Maribor, Slovenia
gregor.harih@um.si

[2] Laboratory for Advanced Computational Engineering, Faculty of Mechanical Engineering, University of Maribor, Smetanova ulica 17, 2000 Maribor, Slovenia
{matej.borovinsek,zoran.ren}@um.si

Abstract. Most authors have focused on the sizes and the shapes of the product handles, but neglected those interface materials of the handles, which could further improve the ergonomics of the product. Therefore we utilized optimisation method to determine optimal interface material properties of a product for optimal mechanical response of the system using numerical simulations of a fingertip model grasping a product's handle. Objective function was set to find material parameters in such way that the interface material of the product stays firm during low grasping forces to provide stability of the product in hands and deforms when a critical contact pressure is reached to provide higher contact area. This increases comfort and lowers the contact pressure on the hand and thereby the risk of injury development.

Keywords: Tool handle · Material design · Optimisation · Ergonomics · Finite element analysis · Contact pressure · Grasp simulation · Hyper-elastic foams

1 Introduction

Correct design of handheld products is crucial for preventing upper extremity acute trauma disorders (ATD) and cumulative trauma disorders (CTD), such as blisters, carpal tunnel syndrome, hand-arm vibration syndrome, tendonitis, etc. [1]. In order to prevent this, authors have provided guidelines and mathematical models for determining the sizes and shapes of the product handles to maximize finger-force exertion, comfort, contact area, thus minimizing the chances to develop ATD and CTD [2–5].

The mechanical properties of the skin and subcutaneous tissue are very important during grasping tasks as they are in direct contact and the forces and moments are transferred from the product to the whole hand-arm system. It has been shown that skin and subcutaneous tissue have non-linear viscoelastic properties, where the skin is stiffer than the subcutaneous tissue [6, 7]. Both have low stiffness regions at small strains followed by a substantial increase in the stiffness when the strain increases.

A power grasp can yield a contact pressure of the fingertip of 80 kPa or over, which has been shown as excessive loading for skin and subcutaneous tissue [8]. Authors also

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provided rough guidelines of pressure discomfort (PDT) and also pressure-pain threshold (PPT). Values between 100 kPa and almost 200 kPa have been reported [9, 10]. Handheld products which require high grip, push, pull or torque exertion on the handle produce high contact pressures, which is known to be one of the primary factors for the ATD and also CTD development [11]. In order to maintain the desired user performance, the designer has to design tool-handles, which distributes contact pressure more evenly and do not exceed the provided limits [9].

Most authors have focused on the sizes and the shapes of the product handles, but neglected those interface materials of the handles that are in direct contact with the user's hand. Authors provided basic guidelines regarding the material choice, but did not investigate and consider the mechanical behaviour of the skin and soft tissue whilst grasping handles of different materials [12].

It has already been shown that cellular materials can be characterised to meet specific mechanical behaviour [13]. Within such context we have already proposed a composite hyper-elastic foam material that can lower the contact pressure whilst keeping the low deformation rate of the product handle material to maintain a sufficient stability rate when using the product [14].

Due to high complexity of the simulated system of the fingertip and hyper-elastic foam with non-linear materials, it is difficult to propose a foam material with optimal material properties for optimal mechanical behaviour of the system.

In this regard we utilized optimisation to find the optimal material parameters of the interface hyper-elastic foam material. The optimisation was set to determine material parameters of the interface material which stays firm during low grasping forces to provide stability of the product in hands and deforms when a critical contact pressure is reached to provide higher contact area. This lowers the contact pressure on the hand and thereby increases comfort and lowers the risk of ATD and CTD development.

2 Methods

In order to perform numerical simulations we used finite element simulation software Abaqus/CAE 6.10 from Dassault Systems (France). The optimisation procedure has been performed using an in-house developed software called OptiMax.

2.1 Finite Element Model – Geometrical and Boundary Conditions

The FE model was constructed based on existing fingertip FE models [15]. We modelled a symmetrical model to lower the needed computational power for optimisation process. The product interface material has been modelled as a flat rectangle with two sections using 1 mm protection layer of EPDM rubber and 3 mm hyper-elastic foam layer for the appropriate deformation during grasping (Fig. 1).

The displacements and rotations of the rectangle representing the interface material of the product were fixed on the lower contour. The displacement and rotations of the fingertip were fixed, except for the displacement along the vertical axis. In order to simulate the grasping, we applied displacement of the fingertip $u_p = 5$ mm, which was applied on the vertical top point of the finger bone and is directed normal to the interface material surface. The fingertip and the product interface material were meshed using 5149 and 1920 CPE8 elements, respectively.

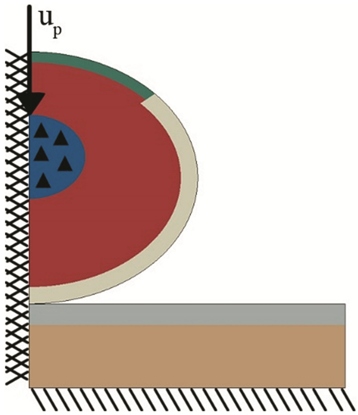

Fig. 1. Geometrical and boundary conditions

2.2 Finite Element Model – Material Properties

Fingertip bone and nail were assumed to be linear elastic with isotropic material parameters with Young´s modulus of 17 GPa and 170 MPa respectively, with a Poisson ratio of 0.3 [16]. The material parameters of skin and subcutaneous tissue were defined using the Ogden hyper-elastic material model (Table 1). Since skin and subcutaneous tissue are almost incompressible, the Poisson ratio was determined to be 0.4 [16].

Table 1. Material parameters determining hyper elasticity of skin and subcutaneous tissue

	Skin		Subcutaneous tissue	
N	μ_i	α_i	μ_i	α_i
1	−0.07594	4.941	−0.04895	5.511
2	0.01138	6.425	0.00989	6.571
3	0.06572	4.712	0.03964	5.262

Material parameters of the outer protective layer made of EPDM rubber were based on literature [14]. The material properties of the hyper-elastic foam (interface material) were not defined in advance but determined with the optimisation procedure.

2.3 Optimisation and Numerical Tests

In order to identify the interface hyper-elastic foam material with optimal material properties a single-objective optimisation problem was formulated. Since the investigated problem is highly nonlinear, more than one local optima of the objective function was expected and because the problem also includes discretized geometry with contacts, which could cause the occurrence of noise in the objective function, a non-gradient based optimisation method was used.

A genetic algorithm with elitism and selection based on the biased roulette wheel scheme was chosen for the identification of material parameters. The genetic algorithm is a well-known meta-heuristic algorithm, which follows the natural evolution process. The inputs of the algorithm are control parameters, design variables and an objective function. The control parameters define the populations size, number of generations and the rate of crossover and mutation operations. The design variables were the material parameters of the foam and the objective function will be described in the next chapters.

According to the literature we defined the limit contact pressure p_{lim} as 100 kPa, which should not be exceeded in order to prevent injuries. But if the limit pressure is reached and exceeded during product usage, the pressure should rise as slow as possible in regard to the fingertip displacement. On the other side, larger deformations of the product handle interface material decrease the users' product stability and therefore control. Figure 2 presents the typical contact pressure response when hyper-elastic foam material is used for the product handle. The response curve has a characteristic plateau region with a prominent plateau point P and a corresponding plateau slope, where the stiffness of the handle decreases and the contact pressure rises slower.

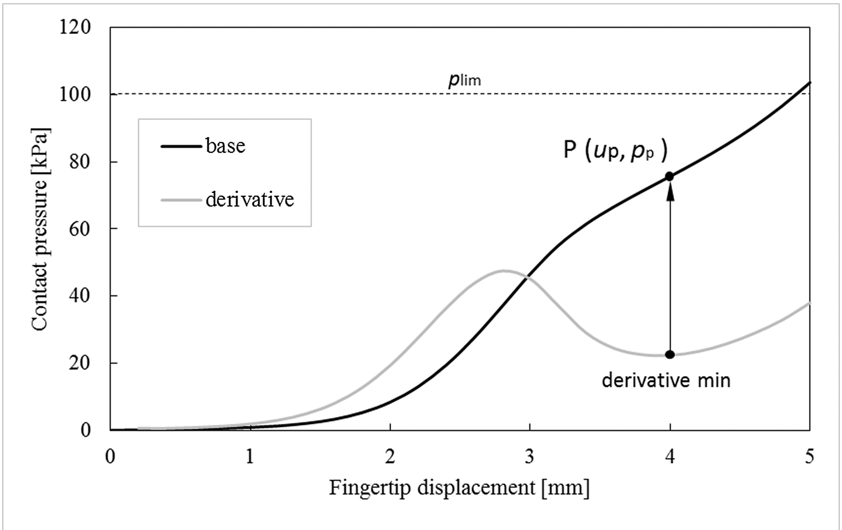

Fig. 2. Typical contact pressure vs fingertip displacement curve (black) and its derivative (grey) (Color figure online)

The plateau point is the point where the contact pressure rises the slowest so the plateau point pressure p_p should be as close to the limit contact pressure of 100 kPa as possible. At the same time the plateau angle and the fingertip displacement u_p at the plateau point should be as small as possible.

Based on these observations a single-objective function was formed. It was comprised from the difference between the plateau point pressure and the limiting pressure, plateau point angle and plateau point fingertip displacement where $\boldsymbol{x}$ represents the design variables and w represents weights of single objective functions (Eq. 1).

$$f(\boldsymbol{x}) = w_1 \cdot abs\left(p_p - p_{\text{lim}}\right) + w_2 \cdot \left(u_p - 3\right) + w_3 \cdot \left(\frac{\mathrm{d}p}{\mathrm{d}u}\right)_P \tag{1}$$

The weights were determined with preliminary simulations in such a way that the values of all objective function parts were approximately the same. They were set to $w_1 = 0.1$, $w_2 = 0.\bar{3}$ and $w_3 = 0.01$. The plateau point angle was replaced with the slope of the contact pressure curve which was determined with the derivative of the contact pressure curve at the plateau point.

In order to determine the plateau point on the contact pressure versus displacement curve, first its derivative was computed (Fig. 2). Then the last local minimum of the derivative curve was found. The fingertip displacement at derivative minimum was then taken as the plateau point fingertip displacement. Then the plateau point pressure was determined from it.

The design variables $\boldsymbol{x}$ were the material parameters of the foam material. The foam material was modelled with a hyper-foam constitutive model defined with uni-axial test data. The test data was approximated with a three-linear curve in order to reduce the number of design variables (Fig. 3). The three-linear curve is determined with four data points T_i where their coordinates correspond to the strains ε_i and stresses σ_i respectively. The first data point T_1 was fixed at (0, 0) while the strain value of the fourth data point T_4 was fixed to $\varepsilon_4 = 0.9$. All five other coordinates were taken as design variables with values within interval bounds given in Table 2.

Table 2. The design space of the design variables

Design variable	Lower bound	Upper bound
ε_2 [/]	0.01	0.08
ε_3 [/]	0.21	0.58
σ_2 [MPa]	0.01	0.08
σ_3 [MPa]	0.02	0.18
σ_3 [MPa]	0.42	1.18

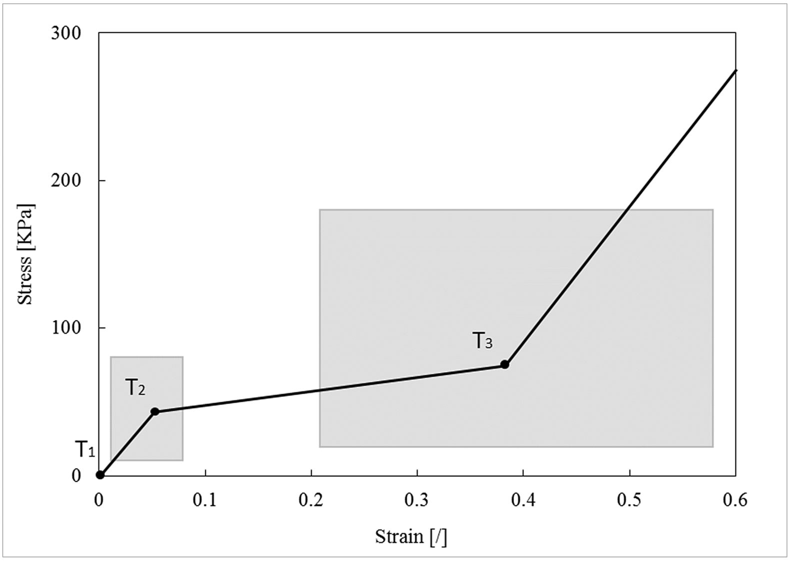

Fig. 3. The design space of the uni-axial test data of the foam material

The genetic algorithm was run using 100 samples in a generation for 50 generations. The crossover parameter was set to 0.80 and the mutation parameter to 0.05. A personal computer was used to run the optimisation procedure in parallel and a high performance cluster was used to compute the simulations. Each simulation was run on 4 cpu-cores resulting in execution time of about one minute. In total 5000 simulations were done to find the result.

3 Results

In our previous research we verified and validated the 2D FE model in regard to existing FE models and to experimental data, since it showed great correspondence between results [14].

The optimisation procedure finished after 50 generations. From the convergence curve we could observe that the best solution was quickly improved in the first five generations and then only slightly changed in the following generations. The last improvement of the solution occurred at 45th generation.

The best solution after optimisation are the following foam material parameters $\varepsilon_2 = 0.053$, $\varepsilon_3 = 0.383$, $\sigma_2 = 0.043$, $\sigma_3 = 0.075$ and $\sigma_4 = 0.796$. The deformation of the fingertip and foam with these material parameters is shown in Fig. 4. In the first stages of the simulation only skin and the soft tissue deform, where they are in contact with the foam. As the fingertip displacement increases the deformation of the foam becomes visible.

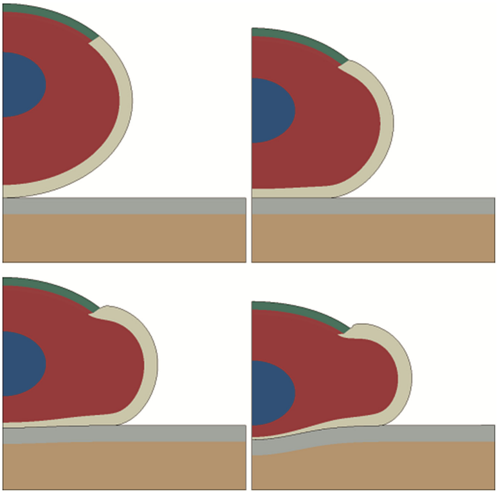

Fig. 4. The deformation of the fingertip and "foam" at the fingertip displacement of 0, 1.67, 3.33 and 5 mm.

In order to quantify the results of interface material parameter optimisation, we compared the response of the simulated system using optimised foam also to other product interface materials. Therefore we also provide the results for steel as quasi-rigid (Young's modulus of 210 Gpa and a Poisson ratio of 0.3) and a composite of EPDM rubber and PU foam as product's interface material proposed in one of our previous papers [14]. Material behaviour under uniaxial compression of the optimised

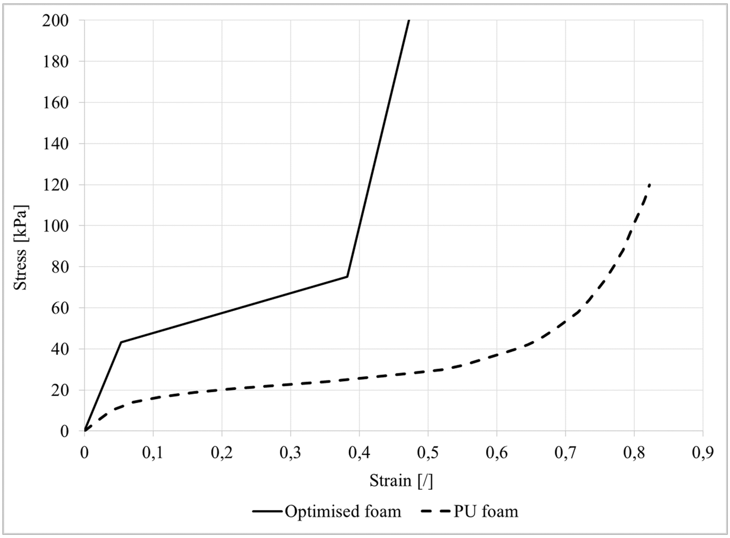

Fig. 5. Stress strain responses of PU foam and optimised foam under uniaxial compression

foam proposed in this paper and PU foam used by us in previous research can be seen in Fig. 5.

Since optimisation was performed in regard of contact pressure and displacement of fingertip and interface material, we plotted the results of the contact pressure in comparison to the combined vertical displacement of the fingertip and interface material (Fig. 6).

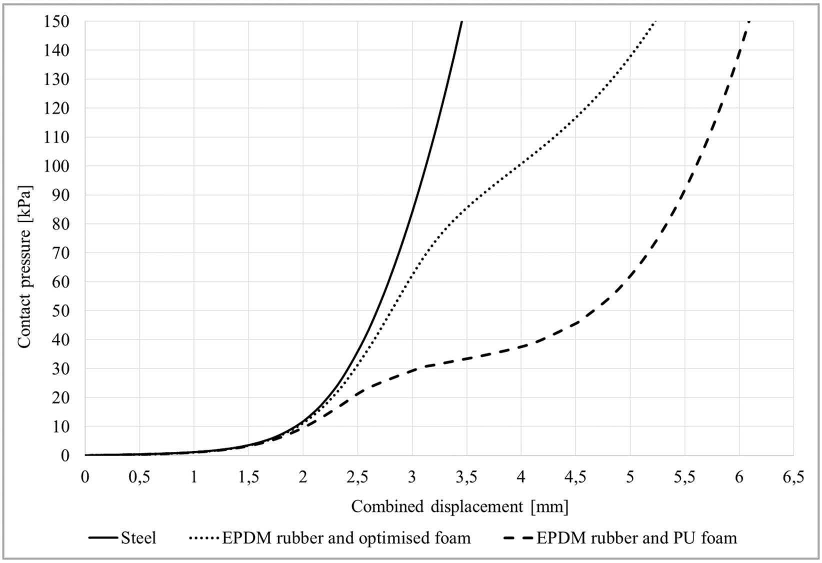

Fig. 6. Contact pressure vs combined displacement of the fingertip and interface material

Results show that all curves coincide to about vertical displacement of 1.7 mm. After that point every interface material show its unique behaviour. The steel shows the highest contact pressure for the given displacement. Contact pressure of 100 kPa is reached at the vertical displacement of 3.1 mm. The response from the interface material of EPDM rubber and PU foam shows reduction in contact pressure for the given vertical displacement in comparison to steel. Contact pressure of 100 kPa is reached at the vertical displacement of 5.6 mm. The optimized interface material of EPDM rubber and optimized foam shows contact pressure reduction, however less displacement compared to interface material of EPDM rubber and PU foam. In simulation of the optimized material the contact pressure of 100 kPa results in vertical displacement of 4 mm.

4 Discussion

Power grasps of various products can yield in high contact pressures for over 100 kPa, which has been shown to be the one of main reasons of ATD and CTD development. Therefore the designer of products has to consider ergonomics in order to develop sizes, shapes and interface materials, which distribute the contact pressures evenly and do not exceed the limits provided by the literature. Hence we investigated the peak contact pressure at the fingertip center line compared to the combined vertical displacement of the fingertip and interface material.

Results have shown that the least deformation of the fingertip and tool-handle material at any simulated contact pressure was achieved with steel as a quasi-rigid material (Fig. 6). This was to be expected, since the stress strain curve of the steel is much steeper and higher than the soft tissue, therefore almost all the deformation on the vertical axis could be addressed to the deformation of the fingertip. Since almost none deformation of the interface material was observed, we considered steel as a reference interface material to evaluate other interface materials.

From the results it is evident that all three interface materials (steel, EPDM rubber and PU foam, EPDM rubber and optimised foam) also showed almost the same contact pressure versus vertical deformation behaviour to a deformation of about 1.7 mm. This deformation can be accredited to the deformation of the fingertip, since the curve corresponds, to great extent, to the curve of steel, where almost no deformation of the product handle interface material was observed. After 1.7 mm of deformation, both composites of EPDM rubber and PU foam and EPDM rubber and optimised foam started to deform.

Due to the different stress strain behaviour and different plateau levels of both composites, the diagrams had different characteristic curves after the deformation of 1.7 mm. The lower and very prominent deformation plateau of the PU Foam accounted for "S" like shaped curve with extensive deformation of the foam when the plateau was reached. The low deformation plateau of this foam also accounts that the interface material starts to deform at around 30 kPa of contact pressure. According to literature contact pressure of 30 kPa is still safe and occurs during normal handling of products in hands. Therefore deformations of the interface material at these contact pressure are not preferred as this lowers the stability of the product in hands.

On the other hand the interface material using the optimised foam shows just slightly bigger deformations compared to the steel for the given contact pressure. The deformation plateau is reached at around 80 kPa. At this point the optimised foam starts to deform and thereby provides higher contact area and lowers the contact pressure.

According to the results, it can be seen that interface material parameters cannot be easily determined. Therefore optimisation is required, which enables the desired mechanical response of the simulated system. The optimisation was set to determine parameters in such way that the interface material did not deform at lower contact pressures, but deformed when high contact pressure was achieved, thus lowering the risk of ATD and CTD development. Using the objective function and appropriate weights the optimisation was set to produce low contact pressures and considering least additional deformation of the interface material in order to maintain high level of stability of the product when in the hand.

5 Conclusion

In this paper we have shown that due to high complexity of the simulated system of the fingertip grasping various interface materials of the product handle optimisation can be a viable method to propose a foam material with optimal material properties for optimal mechanical behaviour of the system. The success of the optimisation process is largely dependent on the correct determination of the objective function. Based on recommendations from literature and previous simulations performed by us the objective function was set to obtain optimal parameter data of the interface hyper-elastic foam material, which stays firm during low grasping forces to provide stability of the product in hands and starts to deforms only when the critical contact pressure is reached to provide higher contact area. This lowers the contact pressure on the hand, which can increase comfort and lower the risk of pressure-dependent ATD and CTD development.

Future work should further consider improving the objective function in regard of subjective responses from test users. The optimisation could also consider the thicknesses of the composite. Additionally dynamic simulations could be carried out to simulate the effect of vibration and foam damping and optimise those parameters. Three dimensional simulations should also be performed to consider a realistic geometry of a human fingertip and further improve the results.

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