

Finite element analysis to assess the biomechanical behavior of a finger model gripping handles with different diameters

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Summary

Study aim: Interactions between the fingers and a handle can be analyzed using a finite element finger model. Hence, the bio-mechanical response of a hybrid human finger model during contact with varying diameter cylindrical handles was investigated numerically in the present study using ABAQUS/CAE.

Materials and methods: The finite element index finger model consists of three segments: the proximal, middle, and distal phalanges. The finger model comprises skin, bone, subcutaneous tissue and nail. The skin and subcutaneous tissues were assumed to be non-linearly elastic and linearly visco-elastic. The FE model was applied to predict the contact interaction between the fingers and a handle with 10 N, 20 N, 40 N and 50 N grip forces for four different diameter handles (30 mm, 40 mm, 44 mm and 50 mm). The model predictions projected the biomechanical response of the finger during the static gripping analysis with 200 incremental steps.

Results: The simulation results showed that the increase in contact area reduced the maximal compressive stress/strain and also the contact pressure on finger skin. It was hypothesized in this study that the diameter of the handle influences the stress/strain and contact pressure within the soft tissue during the contact interactions.

Conclusions: The present study may be useful to study the behavior of the finger model under the static gripping of hand-held power tools.

Keywords: Finger segments – 3D finger model – Finger deformations – Contact pressure – Maximal compressive stress

Introduction

The interaction between the hand and a physical object with the physical environment is one of the key functions of the hand grasp. In this aspect, powered and non-powered hand tools are effectively used for different work. Extended exposure of the hand and fingers to forces during industrial activities leads to musculoskeletal disorders [21]. Since the handle is an interface between the hand and the machine, an optimized handle design is a very important factor to consider in order to avoid such disorders, thereby improving the comfort. The high grip, push and pull forces and torque to the hand produce high contact pressure, which leads to cumulative trauma disorder (CTD) [11]. Operator's safety, grip strength and comfort depend on the diameter of the handles [20, 30], handle shape [21], operator's posture [12], handle surface materials [23], contact surface stiffness [25], and contact surface

friction [29]. Handle diameter plays a vital role in reducing the disorders caused due to tool handles. The injury potential can be reduced by using handles with suitable diameters. The grip strength of the handle is strongly dependent on the handle diameter [14, 20]. Hence the size of the power tool handle is considered largely by ergonomic designers to maximize the torque strength and gripping force, thereby minimizing the efforts during the power tool operations [1, 6, 16, 17].

Therefore, the finite element method has already been used by several researchers for modeling and simulating the hand, thereby determining its biomechanical behavior during different manual tasks, then evaluating the resulting loads. Stresses and deformations are an important aspect that are represented as results of the FE method within the field of ergonomics and biomechanics [15]. Numerous finger and hand models have been developed by researchers for simulating different problems. Wu *et al.* [34] developed a simplified two-dimensional (2D) finger tip model

and analyzed the biomechanical responses during various loading conditions on a flat surface. The response of the soft tissues within different depths during vibration exposure has also been predicted using the 2D FEA model [35]. Dynamic strains induced within the soft tissues and the skin layer during both low and high frequencies were evaluated by Wu *et al.* [37]. Using the same 2D fingertip FE model various hand-handle interface materials were used with a flat contact. Simulations were performed and it was found that the hyper-elastic material lowered the contact pressure developed due to deformations [34].

Two-dimensional (2D) FE finger tip models are used by several researchers because of their simplicity. But in recent studies 3D FE finger tip models, which can provide insights into all three dimensions with better accuracy, were used. A geometrically symmetrical and simplified 3D fingertip FE model was proposed by Wu *et al.* [36] for simulating the dynamic loading and its responses. An index finger biomechanical model was developed by Brook *et al.* [8] and the model was applied to evaluate the muscle forces in the pinch grip. Anatomically realistic muscle connections and musculoskeletal parameters were included along with the finger models by Valero-Cuevas *et al.* [31]. The effect of the handle diameter and the handle size on the fingertip contact force was investigated using the hand model developed by Freund *et al.* [13]. The whole-hand models developed were used to simulate the muscle loading for free movements and static gripping [26].

All these hand models and fingers are simulated using a linkage system composed of finger and joint segments connected with the muscle which does not contain skin/subcutaneous tissues. Therefore these models cannot be used to evaluate the contact between the objects and fingers. In order to overcome this, the hybrid finger model was developed by Wu *et al.* [33]. It includes three finger

segments, three joints and anatomical structures (nail, bone, and soft tissues). The hybrid finger model is used to investigate the effect of contact interaction between a finger and a cylinder handle coated with different soft material. The aim of this research is to develop a hybrid finger model and to simulate the contact interactions between finger models and handles with different diameters (30 mm, 40 mm, 45 mm, and 50 mm). The mechanical behavior of the finger model gripping with different diameter handles is evaluated as a result, in terms of contact pressure (CPRESS) and finger deformations.

Material and methods

FE model

The static gripping interaction responses among different diameter handles (30 mm, 40 mm, 45 mm, 50 mm) and the index finger model were analyzed using a three-dimensional (3D) hybrid finger [33] finite element model. The FE finger model gripping with various diameter handles is shown in Figure 1. Abaqus (version 6.14) commercial software package was used for the construction of FE models. The FE index finger model consists of three segments: the proximal, middle, and distal phalanges. Each finger segment model along with the skin, subcutaneous tissues, bone and the nail were connected to the distal segment. The proximal and middle phalanges were conical frustums, whereas the distal phalanx was considered as a conical frustum connected with a hemisphere-like fingertip. Each finger segment was considered to be rotationally symmetrical.

The dimensions of the bony – segment were adopted from experimental studies [28], and the average of the scaled measurements from the subjects were used for

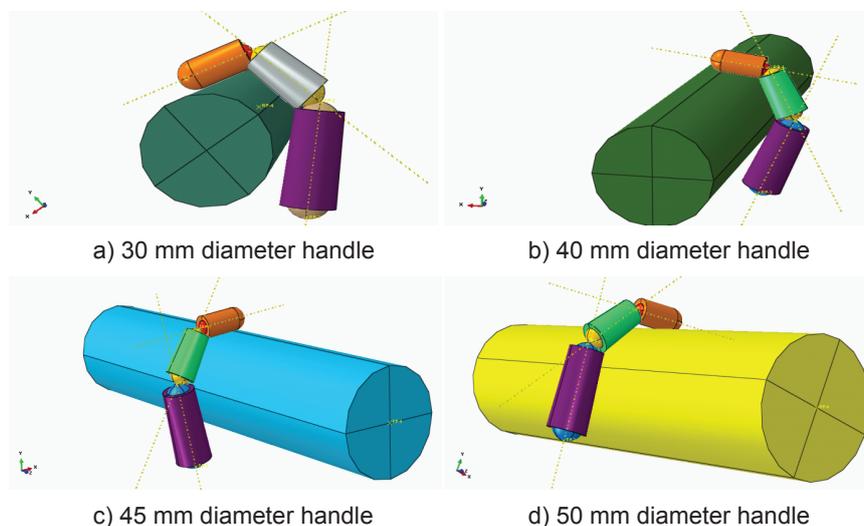


Fig. 1. Finger model gripping different diameter handles (a) 30 mm diameter handle, (b) 40 mm diameter handle, (c) 45 mm diameter handle, (d) 50 mm diameter handle

Table 1. External measurements of human phalanges from 25 subjects [28]

Phalanx		Length [mm]	Diameters					
			Frontal			Sagittal		
			PM	MS	DM	PM	MS	DM
Proximal	Mean	45.98	17.39	10.40	12.80	13.29	7.58	8.95
	±SD	2.45	1.13	0.83	1.00	0.95	0.60	0.65
Middle	Mean	30.44	14.66	9.47	11.22	10.24	5.86	6.85
	±SD	1.61	1.00	0.70	0.85	0.70	0.53	0.55
Distal	Mean	19.37	11.35	6.06	8.15	7.32	7.27	4.40
	±SD	1.51	1.47	0.66	1.55	0.72	0.56	0.62

PM – Proximal metaphysis; MS – Mid shaft; DM – Distal metaphysis; SD – Standard deviation.

Table 2. Internal measurements of human phalanges from 25 subjects [28]

Phalanx		Length [mm]			Midshaft width					
					Frontal			Sagittal		
		PM	MC	DM	UCX	RCX	MC	VCX	DCX	MC
Proximal	Mean	8.76	27.83	8.09	2.16	1.96	6.62	1.53	1.84	4.23
	±SD	2.49	3.34	1.17	0.44	0.67	1.27	0.30	0.39	0.91
Middle	Mean	7.53	15.56	6.10	1.84	1.81	5.32	1.21	1.62	3.00
	±SD	1.12	2.51	1.16	0.58	0.62	1.48	0.29	0.43	0.70
Distal	Mean	5.43	7.90	5.45	1.01	1.10	3.95	1.13	0.89	2.33
	±SD	1.29	1.88	1.24	0.33	0.30	0.84	0.39	0.28	0.50

PM – Proximal metaphysis; MC – Medullary canal; DM – Distal metaphysis; UCX – Ulnar cortex; RCX – Radial cortex; VCX – Volar cortex; DCX – Dorsal cortex, SD – Standard deviation.

finger segments [33]. Table 1 and Table 2 show the internal and external measurements of human phalanges which are obtained from 25 subjects. The metacarpophalangeal joint (MCP), proximal interphalangeal joint (PIP), and distal interphalangeal joint (DIP) were used to link the proximal, middle and distal segments of the index finger model. The moment of the finger was given by each finger segment. A universal joint was modeled for the MCP joint and hinges were modeled for the PIP and DIP joints.

The end of the handle is a constraint (fixed) and the grip force was applied to the bones of each segment (distal, middle and proximal). In the current study 10 N, 20 N, 40 N and 50 N grip forces were applied as a body force to each segment of the finger and static analysis was performed to evaluate the contact pressure and finger deformations while gripping handles of different diameters. Sensitivity analysis was performed on the model to determine the effects of varying material properties. The model

parameters were estimated by least-squares fitting (using MATLAB's `fminsearch`). Different loads were applied to the FE model to analyze the surface magnitude and strain between the heterogeneous and homogeneous model. The sensitivity analysis parameters are in good agreement with the previous research studies' material parameters. Table 3 displays the mechanical properties which are adapted from the previous research studies from several authors [2, 4, 5, 9, 32, 33, 38]. In the present study, linear hexahedron mesh and element type C3D8R is used for all the models.

Simulation procedure

Three-dimensional finite element simulations were performed to evaluate the bio-mechanical behavior of the hybrid finger model and its contact interaction while gripping cylindrical handles of various diameters. In this study, 10 N, 20 N, 40 N and 50 N grip forces were applied in the hybrid finger model and analysis was performed to simulate the quasi-static gripping. The entire loading of

Table 3. Material properties of biological components used in the FE finger model

Material	Property	Applied
ABS (Handle material)	Young's modulus	2500 MPa
	Poisson's ratio	0.35
	Density	$1.07 \cdot 10^{-6} \text{ kg/mm}^3$
Bone	Young's modulus	17500 MPa
	Poisson's ratio	0.3
	Density	$2 \cdot 10^{-6} \text{ kg/mm}^3$
Nail	Young's modulus	20000 MPa
	Poisson's ratio	0.3
	Density	$2 \cdot 10^{-6} \text{ kg/mm}^3$
Soft tissues distal	Hyper-elastic material coefficients	$C_{10} = 0.001704 \text{ MPa}$ $C_{11} = 0.00816 \text{ MPa}$ $D_1 = 1 \cdot 10^{-9} \text{ MPa}^{-1}$ $D_2 = 1 \cdot 10^{-9} \text{ MPa}^{-1}$
	Visco-elastic parameters	$g_1 = 0.25, g_2 = 0.13, g_3 = 0.20$ $\hat{\delta}_1 = 0.01, \hat{\delta}_2 = 0.40$ $\hat{\delta}_3 = 2.00\text{s}$
	Density	$2 \cdot 10^{-6} \text{ kg/mm}^3$
Soft tissues middle	Hyper-elastic material coefficients	$C_{10} = 0.001278 \text{ MPa}$ $C_{11} = 0.00612 \text{ MPa}$ $D_1 = 1 \cdot 10^{-9} \text{ MPa}^{-1}$ $D_2 = 1 \cdot 10^{-9} \text{ MPa}^{-1}$
	Visco-elastic parameters	$g_1 = 0.25, g_2 = 0.13, g_3 = 0.20$ $\hat{\delta}_1 = 0.01, \hat{\delta}_2 = 0.40$ $\hat{\delta}_3 = 2.00\text{s}$
	Density	$1.5 \cdot 10^{-6} \text{ kg/mm}^3$
Soft tissues proximal	Hyper-elastic material coefficients	$C_{10} = 0.001278 \text{ MPa}$ $C_{11} = 0.00612 \text{ MPa}$ $D_1 = 1 \cdot 10^{-9} \text{ MPa}^{-1}$ $D_2 = 1 \cdot 10^{-9} \text{ MPa}^{-1}$
	Visco-elastic parameters	$g_1 = 0.25, g_2 = 0.13, g_3 = 0.20$ $\hat{\delta}_1 = 0.01, \hat{\delta}_2 = 0.40$ $\hat{\delta}_3 = 2.00\text{s}$
	Density	$4 \cdot 10^{-6} \text{ kg/mm}^3$

10 N, 20 N, 40 N and 50 N was accomplished over 200 incremental steps. During the static pre-loading, joint moments were increased proportionally as a function of time. The coefficient of friction between the finger and the handle (contact interface) was considered to be 0.3 [27]. The deformations on the finger model were calculated using the static gripping of various diameter handles. The contact between the various diameter handles and the biological components (bone, skin, soft tissues) was considered. The computations for the static gripping were performed in time-domain computations.

Results

The static gripping analysis (200 incremental steps) was performed by gripping (10 N, 20 N, 40 N and 50 N grip forces) cylindrical handles of various diameters (30 mm, 40 mm, 44 mm and 50 mm) using the hybrid finger FE model. The finger deformations, maximum compressive stress, maximum compressive strain and the contact pressure distributions were calculated using static simulations. Figure 2 shows the maximal compressive stress in the soft

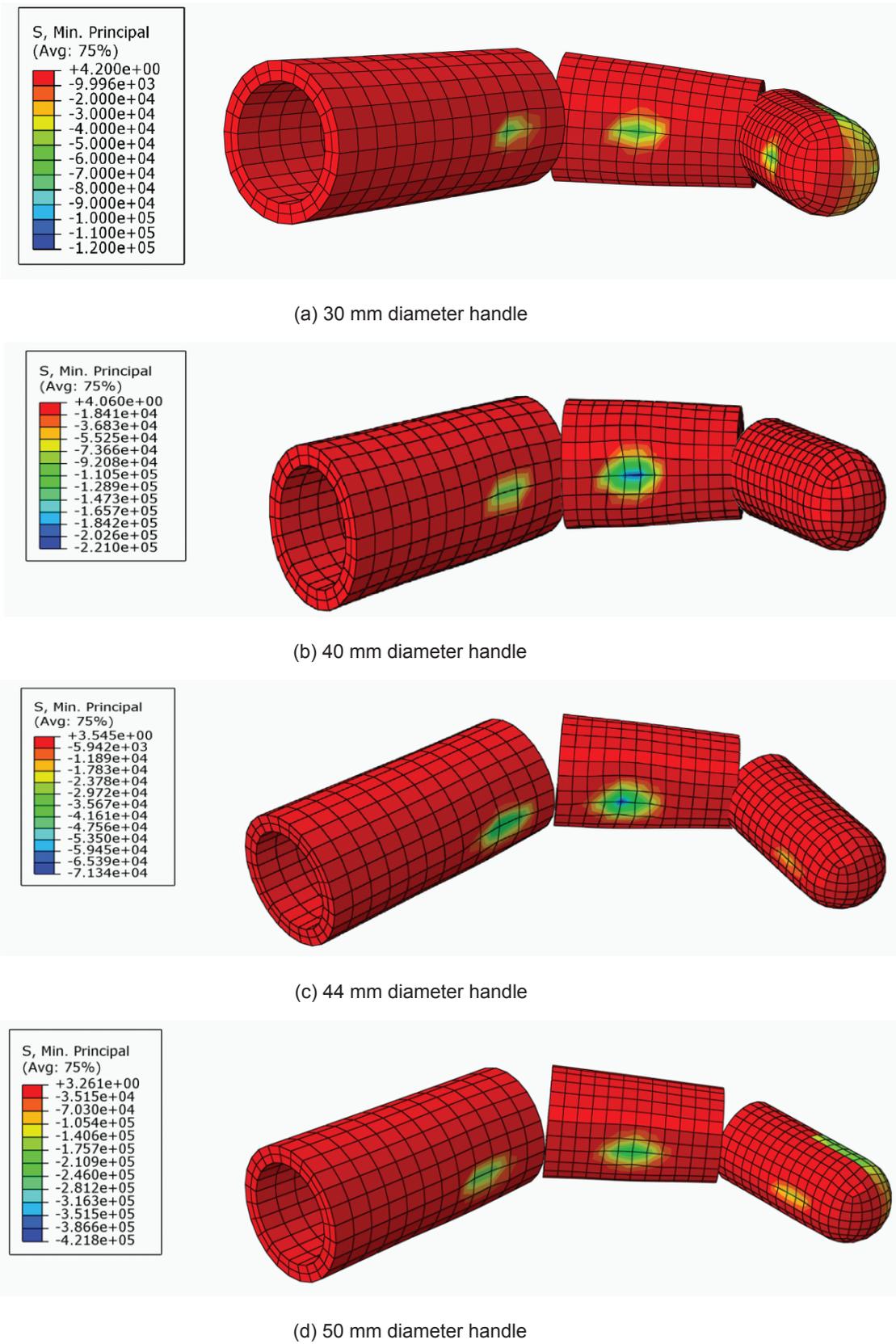


Fig. 2. Maximal compressive stresses in soft skin for various diameters handle with 10N grip force (a) 30mm diameter handle, (b) 40mm diameter handle, (c) 44mm diameter handle, (d) 50mm diameter handle

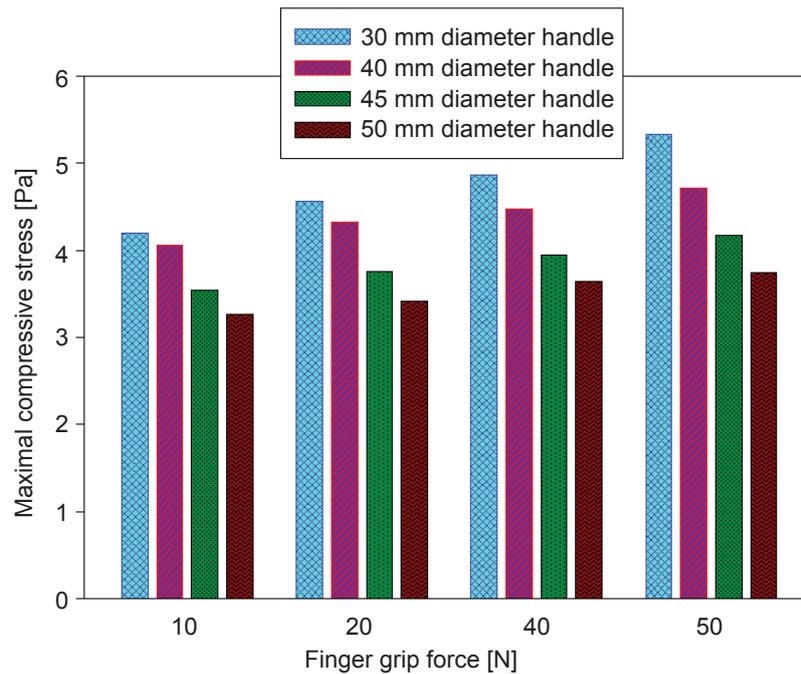


Fig. 3. Maximal compressive stresses on the soft skin while gripping various diameter handles with different grip force (Pa)

skin of the finger gripping handles of various diameters. It is seen that the maximal compressive stresses decreased with increasing handle diameter (Fig. 2). Stresses were observed in all the three segments (proximal, middle and distal) during the hybrid finger model gripping at 30 mm, 44 mm and 50 mm diameter handles.

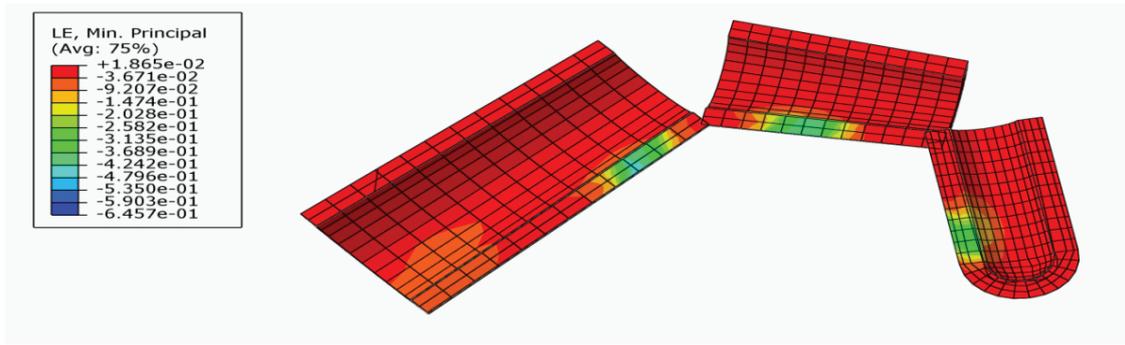
The maximal compressive stress for 10N grip force was found to be 4.2 Pa, 4.06 Pa, 3.5 Pa and 3.2 Pa for 30 mm, 40 mm, 44 mm and 50 mm diameter cylinders, respectively, as shown in Figure 3. However, the distribution of maximal compressive stress was not found in the distal segment during 10 N grip force applied on the 40 mm diameter handle. For 20 N grip force the maximal compressive stress was found to be 4.56 Pa, 4.321 Pa, 3.76 Pa and 3.41 Pa for respective cylindrical diameter handles. Similarly, the maximal compressive stress on the soft skin of the finger response is shown in Figure 3 for 40 N and 50 N grip forces. The results indicate that the compressive stress increases with respect to the grip force and at the same time the results suggest that the stresses in the soft tissues can be reduced by considering the handle diameter. The contact area between the finger and handles increases, and thereby the compressive stress decreases. The obtained results were in good agreement with the previous results obtained by Wu *et al.* [33] for a hybrid finger model gripping various stiffness materials with various grip forces.

The simulation results of maximal compressive strain on the soft tissues, when the finger model is subjected to 10 N grip force of various diameters, are shown in Fig. 4

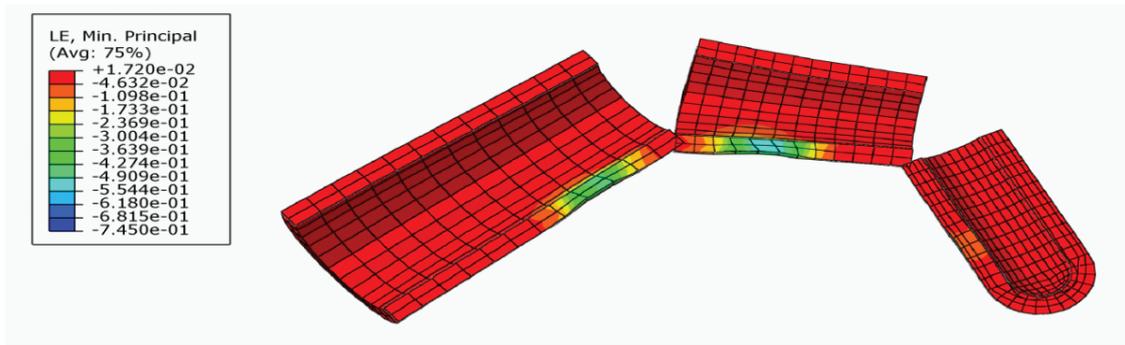
(a, b, c, d). The maximal compressive strain varies with respect to the handle diameter similar to the compressive stress. From Figure 5, the maximal compressive strain for 10 N was found to be 0.018, 0.017, 0.014 and 0.012 for 30 mm, 40 mm, 44 mm and 50 mm diameter cylinders respectively. Similarly the maximal compressive strain on the soft skin of the finger response is shown in Figure 5 for 20 N, 40 N and 50 N grip forces. Similar to the compressive stress, the compressive strain also decreased with the increase in the handle diameters due to the increase in the contact area between the finger and the handles. Also, the simulation results recommend that the compressive strain increases with respect to the increase in grip forces. The highest magnitude of stresses and strains is indicated with blue in the figures.

The simulation results of contact pressures for the finger model subject to grip with 10 N force of various diameters are shown in Figure 6. The pressure distribution on the cylindrical handle by the proximal, middle and distal phalanges is shown in the below Figures 6. The results from the CPRESS provide the peak contact pressure of the finger model.

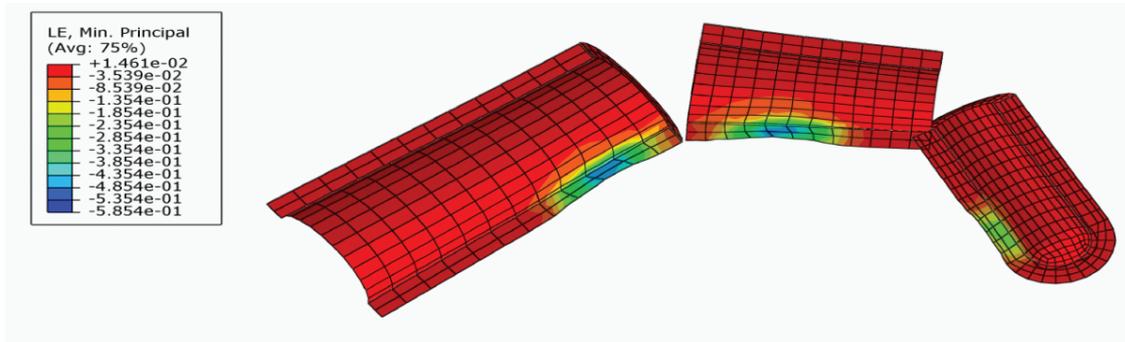
The contact pressure varies with respect to the diameter of the handles. The simulation results suggest that the maximal contact pressure was obtained at the middle segment. From Figure 7, it can be seen that the contact pressure was reduced from $2.126e + 05$ Pa to $1.562e + 05$ Pa for the 30 mm diameter handle to the 50 mm diameter handle respectively. Similarly, the contact pressure on the soft skin of the finger response is shown in Figure 7 for 20 N,



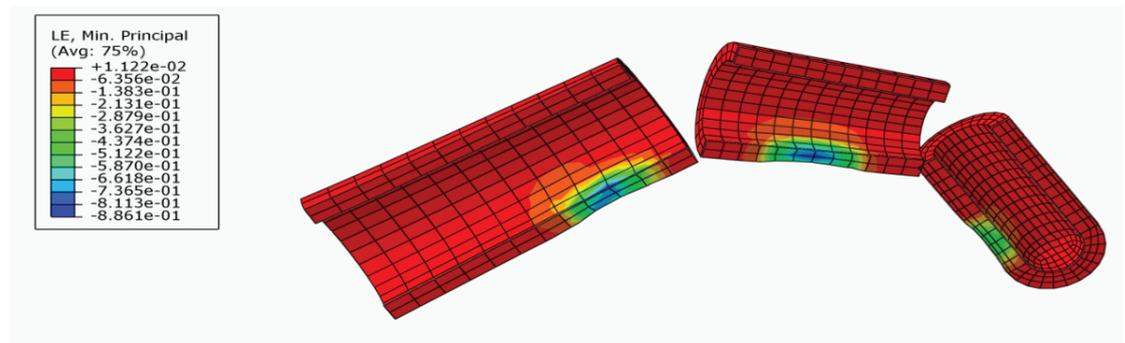
(a) 30 mm diameter handle



(b) 40 mm diameter handle



(c) 44 mm diameter handle



(d) 50 mm diameter handle

Fig. 4. Maximal compressive strains in soft skin for various diameters handle with 10N grip force. (a) 30mm diameter handle, (b) 40mm diameter handle, (c) 44mm diameter handle, (d) 50mm diameter handle

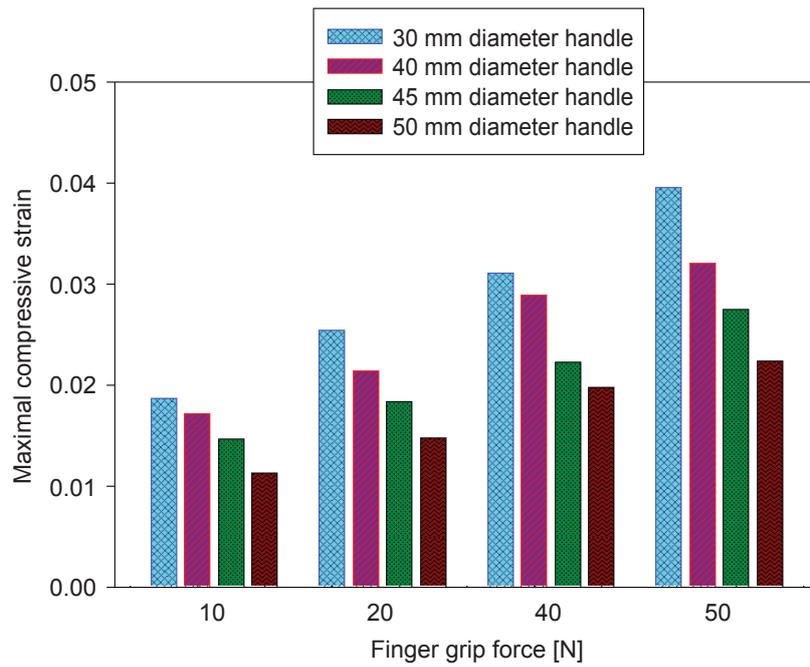


Fig. 5. Maximal compressive strain on the soft skin while gripping various diameter handles with different grip force

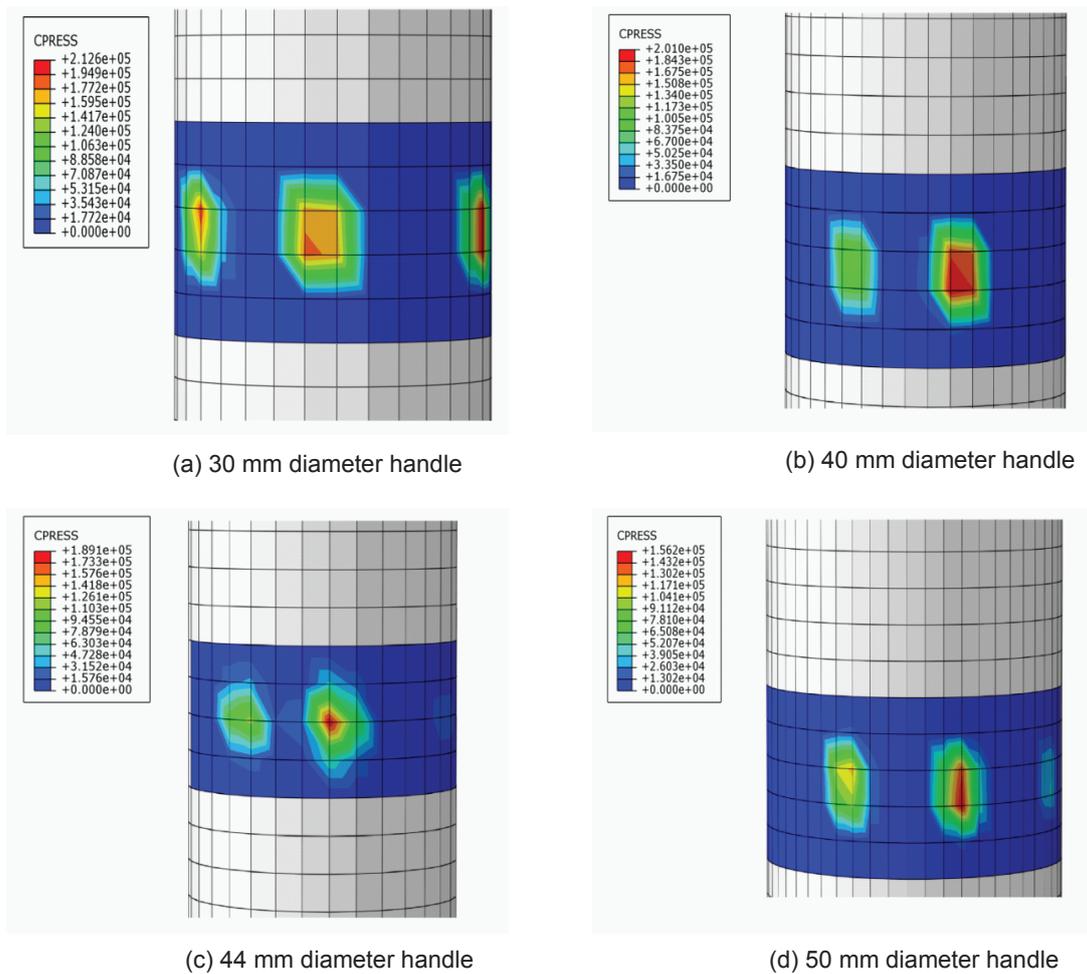


Fig. 6. Distribution of contact pressure on soft skin for various diameters handles with 10 N grip force

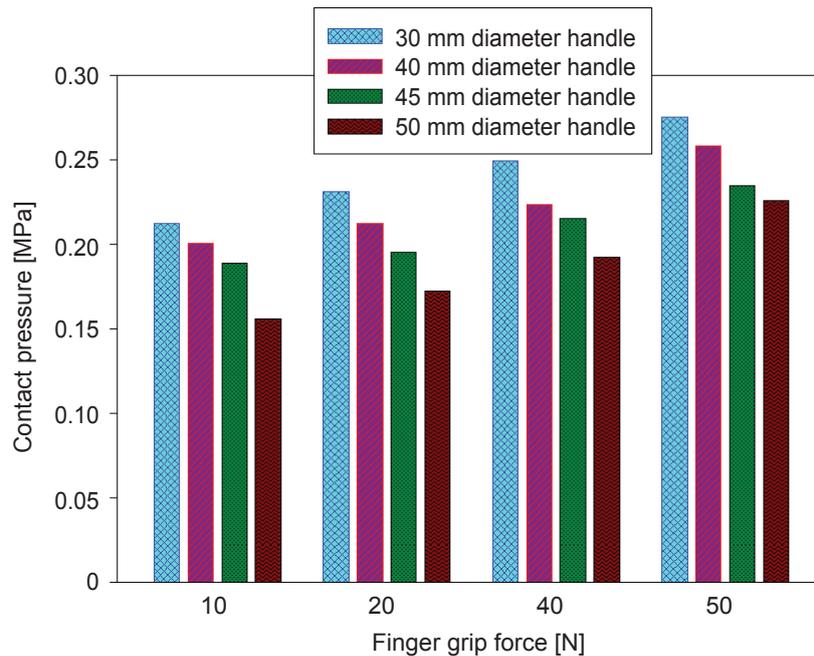


Fig. 7. Contact pressure on the soft skin while gripping various diameter handles with different grip force

40 N and 50 N grip forces. It is perceived that the contact pressure decreases and contact area increases when the diameter of handles varies from 30 mm to 50 mm. The results show that the contact pressure varies depending on the design, size, material and diameter of the handles. The contact pressure analysis obtained is in good agreement with the experimental values [34]. The interaction between the finger model and handle plays a major role in the pressure development in each segment.

An increase in the grip force also may increase the contact pressure in all three segments. From the simulation results, the maximal compressive stress/strain and maximal contact pressure were observed in the middle segment, whereas the minimal compressive stress/strain and minimal contact pressure were observed in the distal segment.

Discussion

A handle is an interface between the hand and tools. It is important to consider the comfort of the operator to increase the efficiency of the work, thereby avoiding fatigue and injuries. The important factors that affect the interface between the hand and handle are the curvatures of the handles and the diameters of the handles. As shown by the experimental studies, handle diameter and curvature of the handle diameter influence the strength [13] of the grip and stability [19].

The maximal compressive stress on the finger skin was reduced by 23% during the 10 N grip force while the diameter of the handles varied from 30 mm to 50 mm.

Similarly, the compressive stress was reduced by 24.6%, 25% and 39.6%, while the diameter of the handles varied from 30 mm to 50 mm during 20 N, 40 N and 50 N respectively. Experimental work carried out by Alphin et al. [3] with various diameter handles showed that the minimum vibration transmissibility occurred at the wrist, elbow and shoulder for maximum diameter handles. But the trend varies, since an increase in grip force increases the compressive stress in the finger soft skin model. Maximal compressive stress was increased by 21% for the 30 mm diameter handle while the grip force was increased from 10 N to 50 N simultaneously. Likewise, the compressive stress was increased by 13%, 15% and 13% for 40 mm, 45 mm and 50 mm diameter handles, respectively, while the grip force was increased from 10 N to 50 N.

In the present analysis, the maximal compressive strain was influenced significantly by the diameter variations of the handles. Within a range of handle diameter from 30 mm to 50 mm the compressive strain decreased when the diameter of the handle increased. The maximal compressive strain on the finger skin decreased by 40%, 41.7%, 36% and 43.4%, while the diameter of the handle varied from 30 mm to 50 mm during 10 N, 20 N, 40 N and 50 N respectively. Similar to the compressive stress, compressive strain also decreased while the diameter of the handle increased. But the compressive strain increased with respect to the increase in the grip force for the same handle diameter. The maximal compressive strain was increased by 52.7%, 46%, 47% and 50%, while the grip force was increased from 10 N to 50 N for 30 mm, 40 mm, 45 mm and 50 mm handles diameters respectively.

Contact pressure on the finger model also has a similar response as like compressive stress and strain. Again, from the simulation results it is seen that the contact pressure decreases with the increase in the contact area. The increase in the contact area between the hand and handle reduces the contact pressure and prevents the excessive stress/strain transferred to the human hand-arm system [18]. The contact pressure was reduced by 26.5%, 25.4%, 22.8% and 18%, while the diameter increased from 30 mm to 50 mm during forces of 10 N, 20 N, 40 N and 50 N respectively. In all the cases, the typical contact pressure and contact area increased for the same diameter handle with an increase in the load. The contact pressure was increased by 22.8%, 22%, 19.4% and 30.8%, while the grip force was increased from 10 N to 50 N for 30 mm, 40 mm, 45 mm and 50 mm respectively. Several studies indicate that the discomfort in the hand is associated with interaction between the hand and the handle, and also the concentration of the contact pressure [7, 10, 24]. The present study recommends that the compressive stress, compressive strain and contact pressure on the finger can be reduced by considering the diameter of the handles. The simulation results imply that the comfort of the operator depends on the diameter of the handles.

Conclusions

In the present study, the contact interactions between the FE finger model and cylindrical handles with different diameters were analyzed using finite element analysis.

- The different diameter of the handles was found to influence the distributions of maximal compressive stress, maximal compressive strain and contact pressure within the FE finger model.
- Simulation results suggest that for the same grip force, increase in handle diameters reduces the maximal compressive stress/strain and contact pressure and at the same time, for the same diameter handle, increase in grip forces increases the maximal compressive stress/strain and contact pressure in the finger model.
- The simulation results from the present study will be useful for ergonomic designers to avoid risks for the hand, by reducing fatigue and increasing the comfort for the fingers.

Conflict of interest: Authors state no conflict of interest.

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