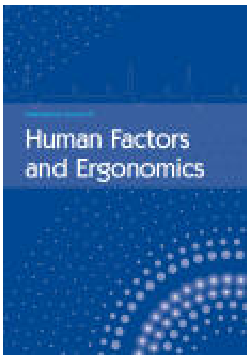

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Development of a gripping comfort evaluation method based on numerical simulations using individual hand finite element models

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Abstract: In this study, three individual hand finite element models with different dimensions were developed to perform grasping simulations. The performance of the three models was assessed by comparing the simulation results with experimental results in terms of gripping posture, contact pressure, and gripping comfort score. Results indicate that gripping comfort scores can be evaluated with sufficient precision by the grasping simulation. A contact pressure distribution dataset was then obtained by conducting grasping simulations under different conditions. Furthermore, a gripping comfort score dataset was generated by assigning the normalised contact pressures into a regression equation developed in a previous study (Hokari et al., 2019a). Consequently, gripping comfort can be evaluated more easily using a regression equation that predicts the gripping comfort score from the hand length and position of the thumb. The proposed evaluation method will allow designers to easily and quickly develop products with better gripping comfort.

Keywords: grasping simulation; hand finite element model; hand dimension; gripping posture; contact pressure; gripping comfort score; dataset; regression equation; hand length; evaluation method.

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1 Introduction

In recent years, it has become necessary to design products that are easy and comfortable to use and manipulate, thus stimulating the consumers' feelings of comfort. Nagamachi (1995) established Kansei engineering, a novel product development method for ergonomic human-centred design. Since then, Kansei engineering has been applied to products that include cars, houses, and office chairs. Furthermore, some methodologies have developed packages of ergonomically designed products for easy and safe use (Bonfim et al., 2016; Bošnjaković and Vladić, 2020).

In daily life, grasping is frequently used in various situations to hold and manipulate objects (Gracia-Ibáñez et al., 2018). Additionally, it was reported that factors such as 'good fit in hand' and 'handle feels comfortable' are associated with comfort when using hand tools (Kuijt-Evers et al., 2004, 2007a). Therefore, an evaluation of gripping comfort is important for developing and designing products that are easy and comfortable to use and manipulate.

Generally, gripping comfort is subjectively evaluated using a questionnaire in a human subject experiment. In one experiment, subjects were asked to evaluate comfort while gripping real-sized physical models (mock-ups). However, it is difficult to evaluate gripping comfort from an engineering perspective in an experiment due to the subjective nature of the evaluation. Therefore, products are usually designed using the subjects' feelings and the designer's experience. Additionally, it is very time- and cost-intensive to conduct repeated human subject experiments because the recruitment of subjects and creation of mock-ups are required to conduct each experiment.

To overcome the disadvantages of the conventional evaluation method, a regression equation that predicts the gripping comfort score by assigning normalised contact pressures on five regions of the palm when gripping an object was proposed in a previous study (Hokari et al., 2019a). Moreover, the finite element (FE) method was used to develop a hand FE model and grasping simulation method to calculate contact pressure when gripping a cylindrical object (Hokari et al., 2020). Gripping comfort was evaluated on a computer by combining the regression equation and the grasping simulation method. However, the evaluation method requires experimental data, FE analysis software, and calculation time. Therefore, a method that easily and quickly evaluates gripping comfort is required to speed up the development of new products in the design process. The acquisition of gripping comfort score datasets under varying conditions, such as human body dimensions and sizes of gripped objects, is crucial to reduce the number of candidate products in the design process, thus leading to faster product development.

The gripping comfort for different cylinder diameters was investigated by conducting subjective comfort evaluations (Kong and Lowe, 2005; Yakou et al., 1997). Additionally, subjective assessments of hand tools including screwdrivers, handsaws, and masons' trowels with different shapes were conducted in human subject experiments with specific tasks (Dianat et al., 2015; Kong et al., 2012; Mirka et al., 2009). The effect of the hand tools' material composition on the comfort rating has also been considered (Chang et al., 1999; Cupar et al., 2021; Kong et al., 2012). As mentioned previously, it is possible to collect data on gripping comfort using a questionnaire in a human subject experiment. However, the acquisition of large amounts of data in this way requires more time and cost to recruit more subjects and conduct the experiments. In addition, this method of evaluating gripping comfort is subjective. Because it is easier to simulate grasping under various conditions and obtain datasets of a physical parameter that quantitatively evaluates gripping comfort in a virtual experiment, a computational method is the most effective solution. Recently, hand FE models and grasping simulations have been developed in some studies (Chamoret et al., 2016; Harih et al., 2021; Hokari et al., 2020; Wei et al., 2020; Wu et al., 2017). A grasping simulation method using hand FE models facilitates the quantitative evaluation of gripping comfort based on a physical parameter. A dataset of gripping comfort scores is then efficiently obtained via a regression equation (Hokari et al., 2019a).

Some studies have reported that subjective comfort during grasping is affected by object size, and hand size (Kong and Lowe, 2005; Yakou et al., 1997). Additionally, the effects of object size (Mühldorfer-Fodor et al., 2017; Tony and Alphin, 2019; Yun et al., 1997), individual posture (Hokari et al., 2019a), and finger posture (Hokari et al., 2021) on contact pressure and grip force distributions have been reported in previous studies. Therefore, these factors should be included as parameters when creating a dataset of gripping comfort scores.

In this study, we developed three individual hand FE models to perform a grasping simulation considering the effect of differences in hand dimensions. Then, the individual hand FE models were tested to confirm the accuracy of the grasping simulation. Additionally, we obtained a dataset of contact pressure distribution by conducting grasping simulations under varying conditions (i.e., different sizes of grasped objects, hand dimensions, joint torques, and gripping postures). Furthermore, a dataset of gripping comfort scores was generated by assigning the normalised contact pressures into the regression equation. Based on this dataset, we focused on the proposal of a gripping comfort evaluation method to efficiently design and develop products with better gripping comfort.

2 Materials and methods

2.1 Establishment of grasping simulation

2.1.1 Construction of individual hand FE models

A specific hand FE model developed in a previous study (Hokari et al., 2020) was used to construct individual FE hand models with different dimensions. In brief, the outer surfaces of the skin and bones that served as the base of the original hand FE model were extracted from the human model database using the computer graphics software Poser 9 (Smith Micro Software Inc., Aliso Viejo, CA, USA), and converted from OBJ to STL file format using the computer-aided design software Rhinoceros (Robert McNeel & Associates, Seattle, WA, USA). The surface models were then meshed using the FE modeling software HyperMesh (Altair Engineering Inc., Troy, MI, USA). The original hand FE model mainly consists of skin, subcutaneous soft tissue, and bones. Boundary nodes between the skin and subcutaneous soft tissue, as well as between subcutaneous soft tissue and bones, were shared. Further details regarding the construction of the original hand FE model are described in the associated study (Hokari et al., 2020).

In this study, three individual hand FE models with dimensions of the 5th, 50th, and 95th percentiles of Japanese adult men were constructed to perform grasping simulations. The model dimensions were calculated using hand dimension data of 54 adult men (age: 41.1 ± 10.3 years) from the Human Hand Dimensions Data for Ergonomic Design 2010 Dataset (Research Institute of Human Engineering for Quality Life, 2010). The P^{th} percentile values L of each region shown in Figure 1 that were reflected in the hand models were calculated using equation (1).

$$L = D_q + \left(D_{q+1} - D_q\right) \times r \tag{1}$$

where D_q denotes the dimension value of the q^{th} in ascending order, q denotes the integer component of $(n+1)\times\frac{P}{100}$, r denotes the decimal component of $(n+1)\times\frac{P}{100}$, and n denotes the number of data values. Calculated percentile values of the three regions are listed in Table 1.

Table 1 Three dimensions reflected in individual hand FE models

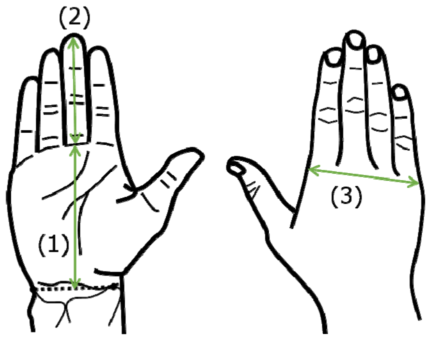
Part		*Percentile*		
		5th percentile	*50th percentile*	*95th percentile*
1	Palm length [mm]	102.0	113.0	125.0
2	Middle finger length [mm]	70.8	79.1	90.1
3	Hand breadth [mm]	77.3	84.0	94.3

Table 2 Numbers of elements and nodes as well as shapes of elements used in three individual hand FE models with different dimensions

Hand model	*Component*	*Number*		
		Elements	*Nodes*	*Element type*
5th percentile	Skin	5,052	2,543	Triangular shell
	Subcutaneous fat tissue	34,689	8,997	Tetrahedron solid
	Bones	16,550	5,422	Tetrahedron solid
50th percentile	Skin	5,472	2,749	Triangular shell
	Subcutaneous fat tissue	36,801	9,456	Tetrahedron solid
	Bones	17,667	5,800	Tetrahedron solid
95th percentile	Skin	5,880	2,953	Triangular shell
	Subcutaneous fat tissue	42,040	10,686	Tetrahedron solid
	Bones	19,118	6,028	Tetrahedron solid

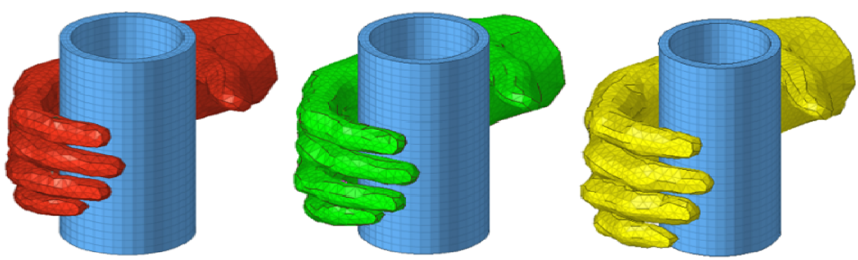
Three individual hand FE models with 5th, 50th, and 95th percentile dimensions were constructed by scaling the specific hand FE model based on the hand dimensions shown in Table 1. A mesh size of 5 mm was determined according to the results of a mesh sensitivity study based on contact pressure (Hokari et al., 2020). The object grasped to assess the individual hand FE models was a cylinder with a diameter of 60 mm and height of 131 mm, which was also modelled in the aforementioned study. The individual hand FE models are shown in Figure 2. The numbers of elements and nodes as well as element types for each component are listed in Table 2.

Figure 1 Hand dimensions used for scaling hand FE model as obtained from the HQL Japanese hand dimensions database (see online version for colours)



Source: Research Institute of Human Engineering for Quality Life (2010)

Figure 2 Individual hand FE models with different hand dimensions, (a) 5th percentile (b) 50th percentile (c) 95th percentile (see online version for colours)



(a) (b) (c)

2.1.2 Material properties

The material properties were defined using the FE analysis software called Radioss (Altair Engineering Inc., Troy, MI, USA). The material model of the skin is linearly elastic. The subcutaneous soft tissue was modelled using the Ogden hyperelastic material model, which was expected to accurately simulate the deformation behaviour of subcutaneous soft tissue. Bones were defined as rigid bodies because bone deformation is minimal compared to that of subcutaneous soft tissue. The cylindrical FE model is composed of acrylonitrile butadiene styrene (ABS) resin with linear elastic characteristics, as used in the original experiment (Hokari et al., 2019a). The density, Young's modulus, and Poisson's ratio of each component were defined based on extant studies (Maeno et al., 1998; Pramudita et al., 2017; Saga et al., 2013), as shown in Table 3. Additionally, the material parameters of the Ogden hyperelastic material model for subcutaneous soft tissue were identified from the results of compression tests using porcine fat tissue (Ito, 2017), as shown in Table 4. The Young's modulus and Poisson's ratio of each component and the material parameters of the Ogden hyperelastic material model were equal to those used in the previous study (Hokari et al., 2020).

Table 3 Material properties of each component used in the hand FE models and cylindrical FE model

	Density [kg/mm³]	*Young's modulus [GPa]*	*Poisson's ratio*
Skin	0.90×10^{-6}	8.00×10^{-5}	0.48
Subcutaneous fat tissue	0.90×10^{-6}	-	0.48
Bones	1.80×10^{-6}	-	-
Cylindrical object	1.04×10^{-6}	2.00	0.39

Table 4 Material parameters of the Ogden hyperelastic material model for subcutaneous soft tissue used in this study

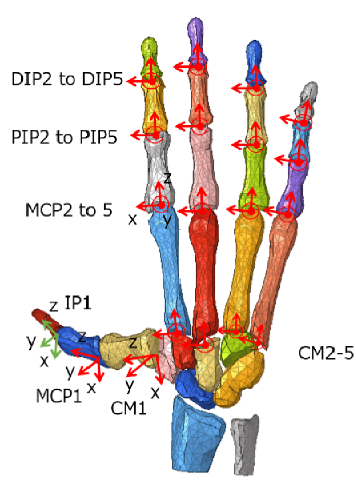
p	*1*	*2*	*3*	*4*
μ_p [GPa]	15.7	9.32	–15.7	–9.32
α_p	–1.21	9.34	–1.21	9.34

Interactions between skin and cylinder, and between skin and skin, were defined as surface-to-surface contact using the penalty method with a friction coefficient of 0.6 and 0.7, respectively (Asserin et al., 2000; Shao et al., 2009; Sivamani et al., 2003).

2.1.3 *Finger joints and joint torques for grasping motion*

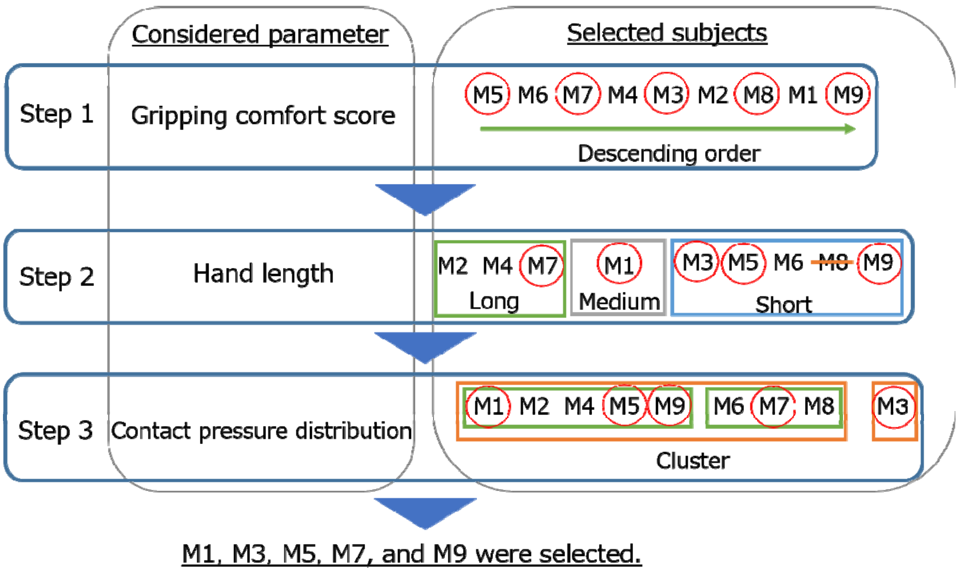
Finger joints were constructed to model the joints of the human hand and input joint torque to reproduce grasping motion. As shown in Figure 3, 19 finger joints of the hand FE model were constructed by incorporating each local coordinate system into the adjacent bone as a rigid body. Carpal bones were completely restrained.

Figure 3 Nineteen local coordinate systems constructed at finger joints of the hand FE model (see online version for colours)



Grasping motion was reproduced by inputting torque to the joints of the hand FE model. The joint torque was estimated by multiplying the contact pressure value on each region of the hand, contact area of each region, and moment arm from the proximal joint, assuming a static condition at the final gripping posture and the normal force associated with contact generated at the middle of the phalanx (Hokari et al., 2020).

Figure 4 Procedure to select subjects for calculation of joint torques (see online version for colours)



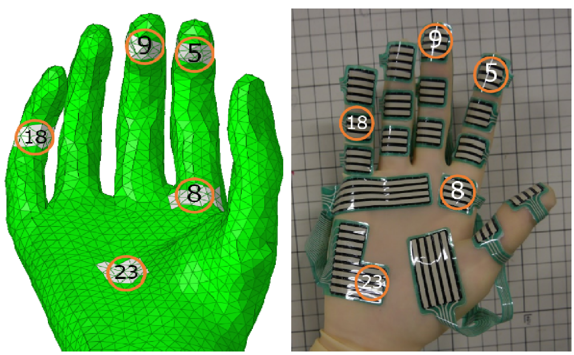
In this study, five contact pressure data and contact areas of nine male subjects (Hokari et al., 2019a) were extracted to calculate joint torques that were then inputted into the joints of the FE models. Five subjects were selected based on the gripping comfort score, hand length, and contact pressure distribution obtained from the experiment, as shown in Figure 4. To consider the differences in gripping comfort scores between subjects, five tentative subjects who were first (subject M5), third (M7), fifth (M3), seventh (M8), and ninth (M9) in descending order of gripping comfort scores were chosen. Subsequently, the tentative subjects' hand lengths were confirmed to consider their effect on contact pressure (Hokari et al., 2019b). Hand lengths (palm plus middle finger length) were divided into three groups ('long': longer than 200.9 mm, 'medium': 185.0–200.9 mm, and 'short': shorter than 185.0 mm) based on Table 1. There were no subjects in the 'medium' group. Therefore, subject M1 in 'medium' was selected instead of subject M8 because the gripping comfort scores (1: good comfort; –1: bad comfort) of subjects M1 (–0.02) and M8 (0.00) were extremely close. Finally, contact pressure distributions of the selected subjects while gripping a cylinder were checked based on the results of cluster analysis (Hokari et al., 2021) to consider the effect of contact pressure distribution on gripping comfort score. As a result, subjects were distributed into each cluster. From the above, male subjects M1, M3, M5, M7, and M9 (age: 22.2 ± 0.4 years, hand length: 188.2 ± 12.2 mm) were eventually chosen, and their contact pressure data were used to calculate joint torques. When conducting grasping motion simulations, the 'long', 'medium', and 'short' groups correspond to 95th (M7), 50th (M1), and 5th (M3, M5, and

M9) percentile FE models, respectively. Simulations were performed using the Radioss software.

2.2 Validation of grasping simulation

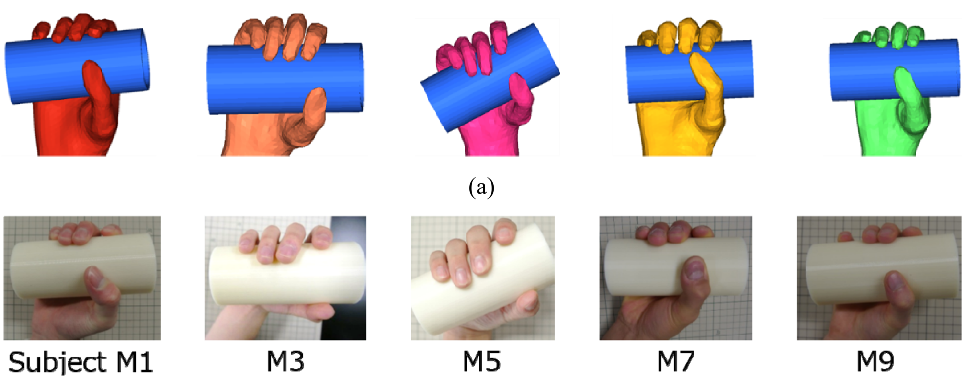
The grasping simulation using the individual hand FE models was assessed in terms of gripping posture, contact pressure value, and gripping comfort score. When comparing contact pressure values between the simulation and the experiment, values in five regions (labelled 5, 8, 9, 18, and 23 shown in Figure 5) used to predict gripping comfort scores using a regression equation (Hokari et al., 2019a) were validated. The experimental data of contact pressure were measured using a pressure-sensor sheet (Grip System, Tekscan, Inc., MA, USA) custom-made for the palm in the previous study (Hokari et al., 2019a).

Figure 5 Five regions used for assessment of contact pressure value, (a) hand FE model (b) experiment (see online version for colours)



(a) (b)

Figure 6 Comparison of final gripping postures between (a) FE simulation results and (b) experimental results during the gripping of a cylinder (see online version for colours)



(a)

(b)

Comparisons of gripping postures, contact pressure values, and gripping comfort scores are shown in Figure 6 and Table 5. When comparing gripping posture, it was confirmed that the simulation reproduced the gripping postures of the experiment. In particular, the relative locations of the thumb and four fingers between the simulation and experiment are a sufficient match. Comparing the contact pressure values in the five regions of the simulation with those of the experiment, the smallest difference is 0 kPa in region 18 of subjects M5 and M9, and on region 23 of all subjects, whereas the largest difference is 34 kPa in region 8 of subject M3. Table 5 illustrates the effect of contact pressure on gripping comfort scores, as the normalised contact pressures obtained from each simulation were assigned to the regression equation (Hokari et al., 2019a). The smallest difference in gripping comfort score between the simulation and the experiment is 0.06 for subjects M5 and M7, whereas the largest difference is 0.38 for subject M1. Gripping comfort scores were measured using the visual analogue scale (VAS) method and ranged from 1 (good comfort) to –1 (bad comfort). The average ± standard deviation of the residual of the regression equation for gripping comfort evaluation using contact pressure was 0.264 ± 0.202 (Hokari et al., 2019a). Therefore, the differences in this study were within a standard deviation of the average (0.466). This result indicates that the gripping comfort scores of subjects can be evaluated with sufficient precision via grasping simulations using the individual hand FE models.

Table 5 Differences in contact pressure on each region and absolute values of differences in gripping comfort scores between simulation results and experimental results

Subject	*Differences of contact pressures on each region [kPa]*					*Gripping comfort score*		
	Area 5	*Area 8*	*Area 9*	*Area 18*	*Area 23*	*Analysis*	*Experiment*	*Difference*
M1	0.8	16.5	–10.8	–1.0	0	–0.40	–0.02	0.38
M3	–12.9	34	5.6	–26.3	0	0.27	0.44	0.17
M5	8.5	25.2	12.4	0	0	0.65	0.71	0.06
M7	–6.8	–12.6	–28.4	–25.6	0	0.44	0.50	0.06
M9	–18.3	12.6	–20.5	0	0	–0.03	–0.24	0.21

2.3 Compiling a dataset of gripping comfort score using individual hand FE models

2.3.1 Selection of parameters for dataset

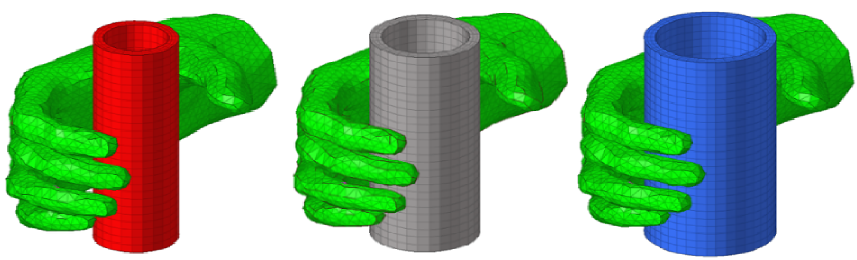
In this study, grasping simulations under conditions with three parameters (i.e., sizes of grasped object, hand dimensions and joint torques, and different gripping postures) were conducted to generate a dataset of gripping comfort scores predicted by the regression equation. The grasped object used to generate the dataset was cylindrical in order to compare this study's results with those of associated studies that also used a cylindrical object (Sancho-Bru et al., 2003; Seo and Armstrong, 2008; Yakou et al., 1997).

The diameter of the cylinder was chosen as a parameter because it was reported to affect gripping comfort (Kong and Lowe, 2005; Yakou et al., 1997). Contact pressure distributions when gripping cylinders with diameters of 40, 50, and 60 mm were obtained via the grasping simulation. The cylinder FE model with a diameter of 60 mm was the same as that used in Subsection 2.1. Cylinder models with diameters of 40 and 50 mm were constructed using hexahedral solid elements. The models are shown in Figure 7. The number of elements and nodes, as well as element type for each cylinder model, are listed in Table 6. It was difficult to estimate joint torques in order to reproduce grasping for cylinders with diameters of 40 and 50 mm because contact pressure data were not measured for these cylinders. Therefore, the corresponding simulations were performed by inputting 1.25–3.00-times magnified joint torques due to the greater flection of finger joints required for gripping smaller objects (Lee and Jung, 2016). The force of the palm on the cylinder tends to increase as the cylinder's diameter decreases (Kong and Lowe, 2005).

Table 6 Numbers of elements and nodes, as well as types of elements, used in the cylinder FE models with different diameters

Diameter	*Number*		
	Elements	*Nodes*	*Element type*
40 mm	1,950	2,700	Hexahedron solid
50 mm	2,418	3,348	Hexahedron solid
60 mm	3,198	4,428	Hexahedron solid

Figure 7 Cylinder FE models with different diameters, (a) 40 mm (b) 50 mm (c) 60 mm (see online version for colours)



(a) (b) (c)

Because hand length has been reported to affect gripping comfort (Kong and Lowe, 2005), hand length was selected as a parameter. Gripping comfort was also reported to be affected by differences in the contact pressure distribution caused by the varying joint torque among the subjects (Hokari et al., 2019a); therefore, joint torque was also chosen as a parameter. The hand dimensions used as parameters are the percentile values described in Subsection 2.1, whereas the joint torques are those estimated from the contact pressure data of five subjects as described in Subsection 2.1.3.

Changes in contact pressure distribution caused by differences in gripping posture were also considered; therefore, the position of the thumb was adopted as the parameter of gripping posture. A significant difference in thumb position between two clusters with different contact pressure distributions was found (Hokari et al., 2021). In this study, thumb positions relative to the four fingers were classified into four groups: radial side, index, index and middle, and middle (see Figure 8). It is noted that the joint torques around the y- and z-axes of the carpometacarpal (CM) joint of the thumb were adjusted to change the thumb's position when conducting the simulations, as they could not be estimated using the experimental data.

Figure 8 Four positions of the thumb in grasping postures used as parameters, (a) radial side (b) index (c) index and middle (d) middle (see online version for colours)

(a) (b) (c) (d)

In summary, simulations under 60 conditions (three cylinder models with different diameters × five hand dimensions and joint torques × four positions of the thumb) were conducted to generate a dataset of gripping comfort scores.

2.3.2 Statistical analysis method

Statistical analysis was performed using the JMP statistical software (SAS Institute Inc., NC, USA).

The Steel-Dwass test was used to investigate the differences in the gripping comfort scores between the four positions of the thumb and the three diameters of the cylinder FE model.

Multiple regression analyses for each diameter were conducted to obtain regression equations that estimate gripping comfort scores from the hand length and position of the thumb. Equation (2) shows the regression equation that relates the gripping comfort score with the parameters.

$$\begin{aligned} y = {} & a_1 x_{5th\ percentile} + a_2 x_{50th\ percentile} + a_3 x_{radial\ side} \\ & + a_4 x_{index} + a_5 x_{index\ and\ middle} + b \end{aligned} \tag{2}$$

where the objective variable y denotes the gripping comfort score (ranging from 1 to –1) estimated from the simulation results, the explanatory variable x denotes the hand dimension and the position of the thumb, a denotes the regression coefficients, and b denotes the intercept. In the regression equations, each explanatory variable was converted into a dummy variable because the three hand lengths (‘long’, ‘medium’ and ‘short’) were discrete values, and the four positions of the thumb (radial side, index, index and middle, and middle) were qualitative variables. The dummy variable has a value of 1 or 0. For instance, under the conditions of ‘short’ in the parameter of hand length and radial side in the parameter of thumb position, $x_{5th\ percentile}$ and $x_{radial\ side}$ in the regression equation correspond to 1 because the terms are relevant to the conditions, whereas other x correspond to 0 as they are not relevant.

3 Results

Final gripping postures of subject M3 are shown in Figure 9 as an example.

The gripping comfort scores of each thumb position for the 60 mm cylinder FE model are shown in Figure 10. The Steel-Dwass test demonstrated that there were no significant differences ($p < 0.05$) in gripping comfort scores between positions of the thumb.

Moreover, Figure 10 also shows how many experimental gripping comfort scores of nine Japanese male subjects (Hokari et al., 2019a) are within a standard deviation of the average score for each position. According to Figure 10, one standard deviation of the simulation results encompasses 66.7% of the experimental data. Therefore, the simulation results represent 66.7% of the relationships between experimental gripping comfort scores and thumb positions.

Figure 9 Representative examples of final gripping posture with different positions of the thumb when gripping cylinder FE models with different diameters (subject M3) (see online version for colours)

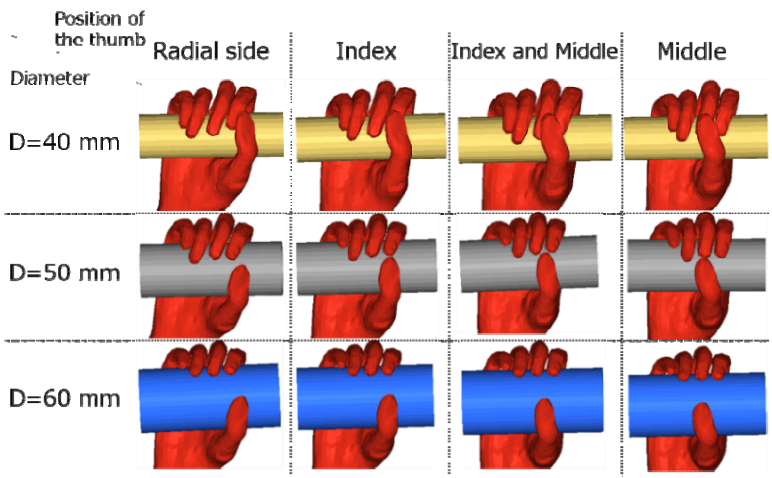
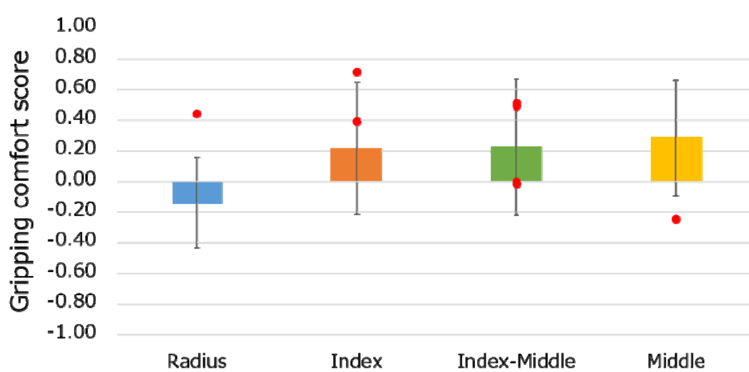


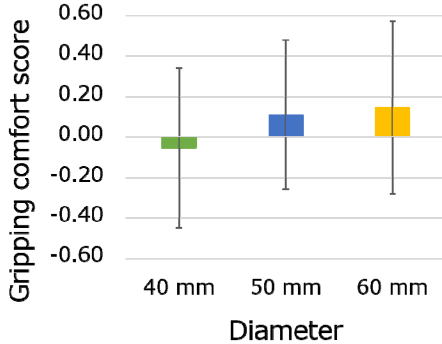
Figure 10 Comparison of gripping comfort scores between four positions of the thumb when gripping cylinder FE model with a diameter of 60 mm, between the simulation and experimental results (see online version for colours)



Percentage of experimental gripping comfort scores within the average ± SD of the simulation results				Total
0% (0/1)	50% (1/2)	100% (5/5)	0% (0/1)	66.7%

Note: Bars denote simulation results and dots denote experimental results.

Figure 11 Comparison of gripping comfort scores among three cylinders with different diameters (see online version for colours)



The gripping comfort scores for each cylinder FE model are shown in Figure 11. The Steel-Dwass test demonstrated that there were no significant differences ($p < 0.05$) in gripping comfort scores between cylinders with different diameters.

The relationship between gripping comfort score and hand dimension with subject for the estimation of the input joint torque is shown in Figure 12. The results indicate that the gripping comfort scores of the 50th percentile model (subject M1) were low, whereas those of the 95th percentile model (M7) were high. Additionally, the scores of M5 were high, whereas those of M9 were concentrated near 0.

Table 7 Regression coefficients and standardised regression coefficients obtained from the multiple regression analyses for each diameter

Explanatory variable		*a_1 (5th percentile)*	*a_2 (50th percentile)*	*a_3 (radius)*	*a_4 (index)*	*a_5 (index and middle)*	*b*
D = 40 mm	Regression coefficient	–0.470	–0.814	–0.462	–0.273	–0.164	0.617
	Standardised regression coefficient	–0.584	–0.824	–0.507	–0.299	–0.180	-
D = 50 mm	Regression coefficient	–0.169	–0.932	–0.159	–0.049	0.037	0.440
	Standardised regression coefficient	–0.225	–1.013	–0.187	–0.058	0.043	-
D = 60 mm	Regression coefficient	–0.046	–0.751	–0.425	–0.069	–0.058	0.462
	Standardised regression coefficient	–0.053	–0.706	–0.432	–0.071	–0.059	-

The regression coefficients and the standardised regression coefficients for each diameter are listed in Table 7. Additionally, the coefficient of determination R^2, adjusted coefficient of determination R_f^2, and differences between the predicted gripping comfort scores estimated from the regression equation and actual gripping comfort scores evaluated in the experiment (Hokari et al., 2019a) are shown in Table 8. R^2 generally tends to increase with an increase in the number of explanatory variables. Therefore, R_f^2, which accounts for the number of explanatory variables, is also shown. Moreover, the absolute value of the difference between predictive and experimental gripping comfort scores was considered. We note that because cylindrical objects with diameters of 40 and 50 mm were not utilised in the experiment, only results for the 60 mm diameter cylinder were compared.

Table 8 Coefficients of determination and absolute error between predicted gripping comfort scores and experimental results

	R^2	R_f^2	*Absolute error*	
			Average ± SD	*0.4 or below*
D = 40 mm	0.612	0.473	-	-
D = 50 mm	0.838	0.780	-	-
D = 60 mm	0.611	0.472	0.276 ± 0.200	77.8%

4 Discussion

There were no significant differences ($p < 0.05$) in the gripping comfort scores between thumb positions. A comparison of contact pressure distributions between thumb positions for subject M7 is shown in Figure 13. According to the figure, the contact pressure distribution varied with the change in thumb position, especially when comparing the radial side with the others. Nevertheless, significant differences in gripping comfort scores based on thumb position could not be found. For the above reasons, although differences in joint angles of the thumb between object sizes (Lee and Jung, 2016) and individuals (Hokari et al., 2021) during gripping were reported, it was suggested that the gripping comfort score was not significantly affected by the difference in contact pressure distribution caused by the position of the thumb.

According to Figure 11, the simulation results indicate that gripping comfort score decreases with the diameter of the cylinder FE model. These results agree with those of a previous study using a finger FE model (Tony and Alphin, 2019), which suggested that the concentration of contact pressure on the finger can be reduced by increasing the diameter of a handle. In contrast, in an experiment investigating the optimal diameter for gripping (Yakou et al., 1997), it was reported via subjective evaluation that the optimal diameter corresponds to 27–40 mm. Other studies found that the optimal diameter corresponds to 33 (Sancho-Bru et al., 2003) and 40 (Seo and Armstrong, 2008) mm in terms of gripping force. The difference between our results and those of previous studies may be attributed to differences in gripping styles. Our study adopted ‘power grip (gripping posture as rapping an object by whole hand)’ (Napier, 1956; Lee and Jung, 2014), which may differ from previously used gripping methods. In fact, the number of fingers used for gripping an object and the gripping style tend to vary according to the object’s diameter (Lee and Jung, 2014). Therefore, a grasping simulation method that can change the gripping style depending on object size is required to extend the applicable range of the simulation method.

Figure 12 Relationship between gripping comfort score and hand dimension with subject for estimation of input joint torque (see online version for colours)

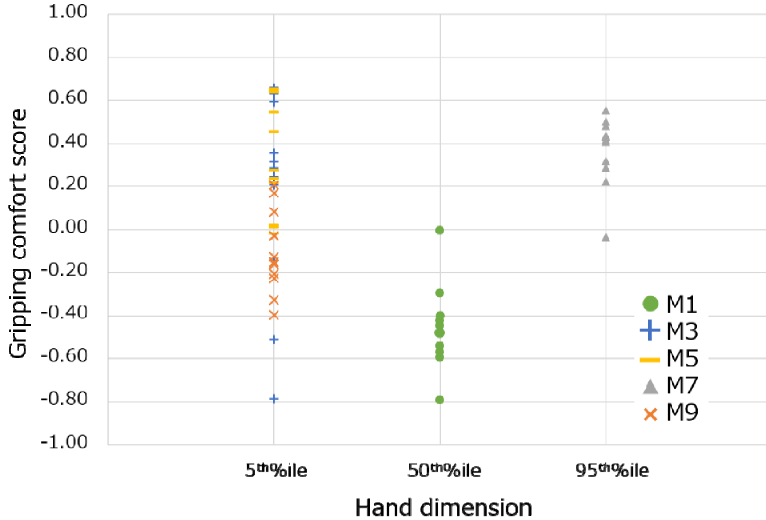
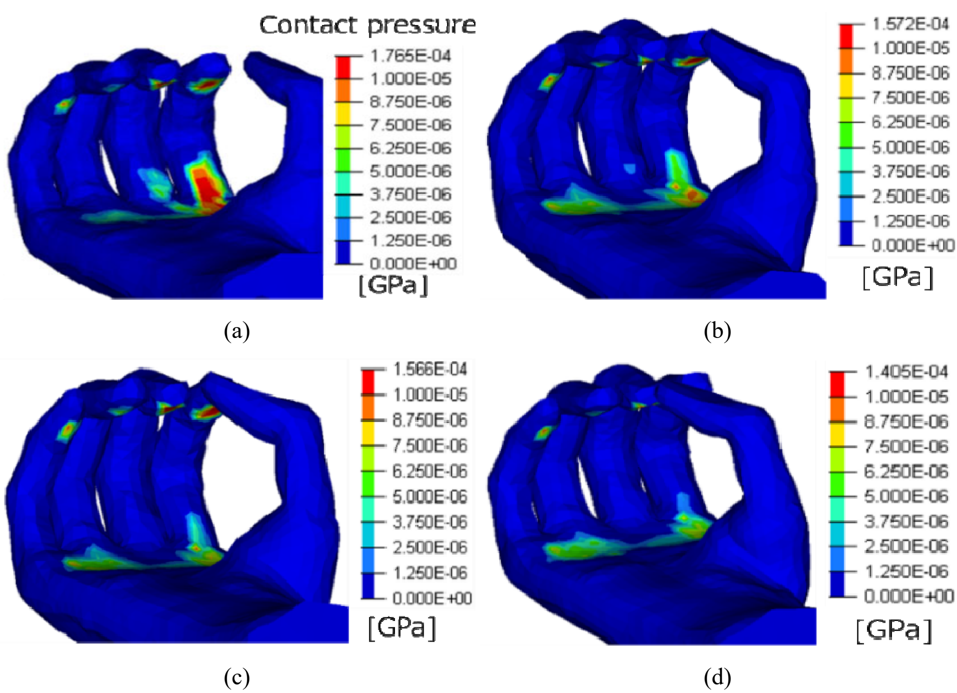


Figure 13 Comparison of contact pressure distributions between the positions of the thumb when gripping the cylinder FE model with a diameter of 60 mm as a representative example (subject M7), (a) radial side (b) index (c) index and middle (d) middle (see online version for colours)



As shown in Figure 12, the difference between the subjects for estimating the input joint torque was reflected in the gripping comfort score. Therefore, it is crucial to consider the contribution of each region (percentage of contact pressure distribution) on the hand during gripping when evaluating gripping comfort. In fact, the contribution of each finger during gripping differed in previous studies (Goislard De Monsabert et al., 2012; Hokari et al., 2021; Kong and Lowe., 2005; Nicholas et al., 2012; Rossi et al., 2012; Vigouroux et al., 2011).

According to Table 7, the signs of the coefficients were negative, with the exception of a_5 for a diameter of 50 mm. This indicates that gripping comfort is relatively low when the hand length and position of the thumb correspond to the 5th or 50th percentile and radial side, index, or index and middle, respectively. According to Table 8, R^2 (R_f^2) for diameters of 40, 50, and 60 mm corresponded to 0.612 (0.473), 0.838 (0.780), and 0.611 (0.472), respectively. Additionally, the average and standard deviation of the difference in gripping comfort scores between predictive and experimental values correspond to 0.276 ± 0.200. Moreover, 77.8% of all data exhibited a difference of 0.4 or less. Therefore, the construction of a gripping comfort evaluation method based on a dataset created by an individual grasping simulation is useful for easily evaluating gripping comfort. However, expanding the applicable range of the grasping simulation and increasing the amount of gripping comfort score data is required to increase the precision of the gripping comfort evaluation. Object shape (Hokari et al., 2019a; Kuijt-Evers et al., 2007b) and material (Chang et al., 1999; Cupar et al., 2021), which were reported to affect subjective ratings, could also be included as parameters in a future study. Additionally, as contribution of each region of the hand corresponds to individual joint torque as input to reproduce grasping in the simulation, it is important to expand the applicable range of this method.

This study had several limitations. Gripping comfort was evaluated based on contact pressure under a static condition (final gripping posture without any finger motion). However, many manufactured products such as hair dryers, shavers, and irons are used with hand motion in daily life. Hence, an evaluation method under a dynamic condition should be constructed by conducting other subjective evaluation such as ease of use and muscle fatigue as well as by measuring a muscle activity and hand motion. Additionally, the simulations reproduced grasping of young male subjects. Grasping simulation and dataset including female, child, and elderly are required to apply this method to various conditions.

5 Conclusions

In this study, we proposed a gripping comfort evaluation method based on a grasping simulation using individual hand FE models with different dimensions. The grasping simulation was verified via testing. The results indicate that gripping comfort scores can be evaluated with sufficient precision by conducting the simulation.

Additionally, a dataset of gripping comfort scores was created by conducting grasping simulations under various conditions. Furthermore, a method that easily evaluates gripping comfort was proposed based on the dataset of gripping comfort scores, and the usefulness of the evaluation method was validated. Consequently, the following findings were obtained from this study:

1 Gripping styles, such as 'power grip', should be considered to reproduce grasping of cylinders with various diameters.

2 The contribution of each finger joint during gripping as a human characteristic is important for evaluating the gripping comfort because the differences in individual joint torque affect the gripping comfort score.

3 Gripping comfort can be evaluated more easily using a regression equation that predicts gripping comfort from hand length and thumb position.

The results of this study indicate that an evaluation method for gripping comfort can be established using the individual hand FE models and a dataset of gripping comfort scores, which will allow designers and manufacturers to develop products with better gripping comfort easily and quickly.

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