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A METHOD OF SIMULATING SEAT LOAD FOR NUMERICAL ANALYSIS OF WOOD CHAIR STRUCTURE

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ABSTRACT

This study aimed to investigate the characteristic values of the human-seat interface in a normal sitting posture, and to numerically mode the load on the chair seat for the structural design of chairs. The stress distributions and the characteristic values of seat were measured under normal sitting posture by using a human body pressure distribution measurement system considering the effects of gender and body mass index (BMI). The stress distribution on the seat was then numerically modeled using three modeling methods. The observed results and the numerical analysisresults were compared. The results showed that an inverted U-shaped pressure distribution was observed in normal sitting posture. The stress was concentrated on the ischial tuberosity with a maximum value of 0.066 MPa. The ratio of the load on the seat to the gravity of the human body weight was about 65.3%. The numerical model established using the body pressure mapping method was superior to those of the uniform load method and the standard loading pad method in terms of stress distribution, maximum stress, and contact area.

KEYWORDS:Chair, body pressure, finite element method, modeling method.

INTRODUCTION

Chairs are commonly used furniture in our daily lives and work, which not only affect work efficiency but also affect people's comfort and health. Designing high-strength and ergonomic furniture has been being a hot topic of many studies (Zhu and Niu 2022, Tang et al. 2022, Xiong et al. 2023, Xu et al. 2023, Zhu et al. 2024a,b,Lin et al. 2023, Qi et al. 2024, Zhou et al. 2022, Zou et al. 2024a,b). With the rise and development of computer-aided engineering technology, the finite element method (FEM) has been widely used in the structural strength and ergonomic design of furniture (Bai and Guan 2022, Miao et al. 2024, Xia et al. 2024). Modeling the human body and seat interface has become a hot topic. However, it is also a difficult task. In order to find an optimal method for modeling seat loading, the following literature review summarizes two aspects: the ergonomic design of the chair and the methods for modelling the human-seat interface.

Previous studies have done numerous investigations into the comfort and health of chairs, including the factors influencing body pressure distributions considering various parameters such as the seat height and the angle of the chair. Concerning the investigating subjects, these studies mainly focus on the domestic chair (Yu et al. 2023, Chen and Bian 2024, Deng et al. 2024a,b), educational and office chair (Naddeo et al. 2018, Sang et al. 2023), wheelchair (Bao et al. 2013, Zou et al. 2024c), and aircraft chair (Vink and Lips 2017, Liu et al. 2021). The factors investigated in these studies were seat depth and height (Liu et al. 2021), inclination angles of seat and back (Yu et al. 2023), and mattress firmness (Chao et al. 2021, Zhu et al. 2024c, Denes et al. 2022, Luo et al. 2023, Zhou et al. 2024). The aim of these studies was either to improve the comfort of chairs or to evaluate the consequences caused by long-term sitting on a chair, such as disease of the shoulder, neck, and lumbar, and then improve the design of the seat. Their attention was mainly focused on the comfort and health of humans, not on chair structure.

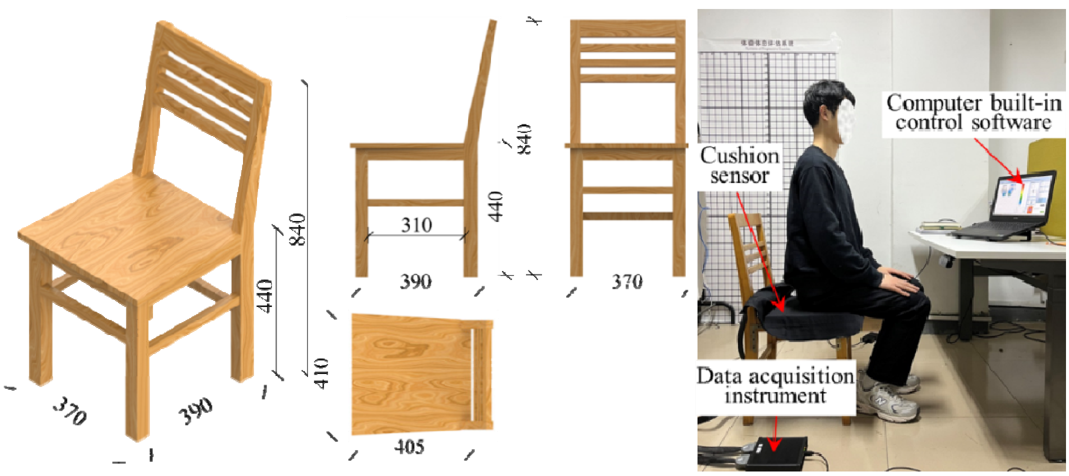
The finite element method (FEM) has become a versatile method widely used in various fields of engineering without exception for biomechanics and furniture structures. The FEM is commonly regarded as a supplement to experimental tests to reduce costs and predict trends. Therefore, the accuracy of FEM is a prerequisite. Previous studies have studied the strength of furniture and body pressure on seats separately. Some researchers model the load on a seat with a uniform load, which is undoubtedly a simple method to realize the aim. Yu et al. (2021) investigated the mechanical behavior of a traditional Chinese wooden chair using ANSYS. They created the FE model by applying a uniform load on the seat to study the stress distribution of the chair frame. Some researchers studied the loading-carrying capacity using FEM by applying the load directly to the four stretchers with concentrated loads (Ceylan et al. 2021, Hitka et al. 2022). However, unfortunately, the contact stress between the human body and the seat is not available. Meanwhile, the load on the seat is not suitable for evaluating the chair frame.Others tried to model the load on the seat through the loading mold according to the method described in CNS GB/T 10357.3 (2013). Smardzewski et al. (2010) studied the contact pressure between the human body and the seat cushion using hard and soft loading pads when modeling the FE model. Compared to the method described in the standard with a hard loading pad, it is obvious that modeling with a soft loading pad is more suitable as it is closer to the human tissue. Although the loading method is identical to the standard, the loading pad provided in the standard cannot, to a certain extent, reflect the real conditions at the interface between the human and the seat. To improve the accuracy of the FE model, the focus came on how to accurately model the human body (Alawneh et al. 2022, Deng et al. 2024c). Verver et al. (2004) proposed an FE model for the buttocks that includes a bony structure, human tissue, and skin, to investigate the pressure between the buttocks-seat interfaces for comfort analysis. In addition, some researchers have created a whole-body human FE model to study and evaluate the human-seat interface (Paul et al. 2012, Huang et al. 2015, Yadav et al. 2021). Among these studies, Grujicic et al. (2009) created a fine FE model that includes a skeletal model and a detailed soft tissue model. Although fine modeling of the human body is a direct way to improve the accuracy of the FE model, the cost of modeling and computation increased too much.

Previous studies have focused on modeling seat pressure distributions by attempting to reconstruct the human body to investigate the human-seat interface. These studies mainly focused on the comfort of the human body's contact with the seat. However, the main objective of this study is to investigate the effects of the seat load modeling method on the chair frames for further structure design. To achieve this goal, first, the load on the chair seat was experimentally investigated using a body pressure distribution system considering gender and body mass index (BMI) to obtain the characteristic parameters for the numerical model. Numerical models were then created and compared using three methods.

MATERIAL AND METHODS

Materials and configurations of chair

Fig. 1a shows the wood chair made of beech used in this study. The outline dimensions of the chair are 840×370×390 mm (height × width × depth). The seat of the chair measured 410×405×18 mm (width × depth × thickness). The cross-sections of the chair legs and stretcher are 40×40 mm, and 25×25 mm, respectively.



(a) *(b)*

Fig. 1: (a) Wood chair, (b)setup for measuring characteristic values of human-seat interface.

Testing method

Fig. 1b shows the setup for measuring the distribution of body stress when subjects sit on a wooden chair without leaning on the chair back, using the TACTILUS human body pressure distribution measurement system (MATS, SPI, USA). The cushion of the system was placed flat on the seat. It consists of a piezo-resistive fabric sensor with a measurable area of 480×480 mm. The output data was analyzed by the supporting data collection software also called TACTILUS. The test procedure consisted of subjects slowly sitting down on the seat and remaining seated for 5 s to allow the data collection software to obtain stable data. The data was processed by the software and the following characteristic values were output, such as an image of the body stress distribution, the contact area (CA), the average contact stress (ACS), and the maximum and minimum stress. Then the weight on the seat (WOS) was calculated using Eq. 1. The ratio of WOS to the weight of the test subjects (RWOSW) is:

$$W_s = P\ x\ S \tag{1}$$

where: W_s is the weight on the seat (kg); P is the average contact pressure (kg.cm^{-2}); S is the contact area (cm^2).

Experimental designs

The experiment consisted of two parts. The first consisted of measuring the characteristic values of the test subjects when they were sitting on the chair without leaning against the backrest. The second part was to numerically model sitting on the chair using different methods to find the optimal modeling method. In the first part, 10 volunteers, including 5 males and 5 females aged 23-25 years, were selected to perform the tests using the method described in the testing method section. All subjects were in good health and had no muscle or ossicular disease. Each subject repeated the tests 3 times, and their means were calculated as results. Therefore, a total of 30 data sets were collected.

Numerical modeling

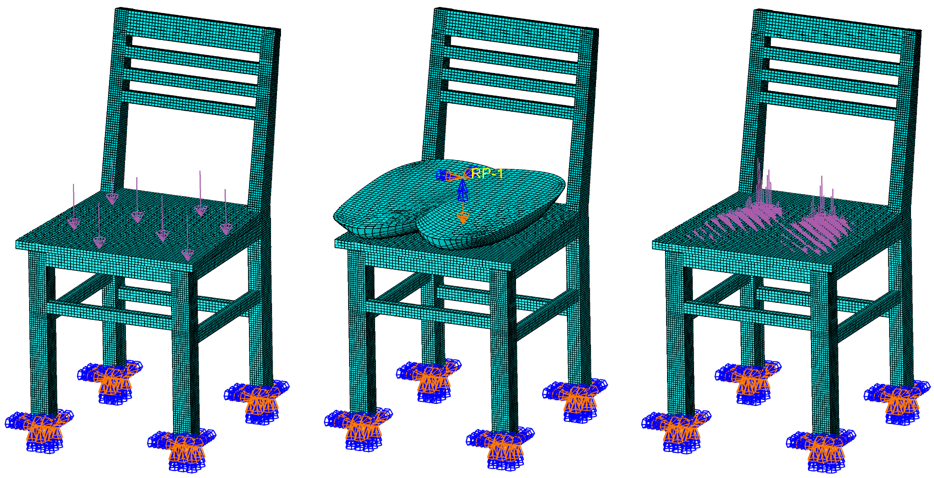
The numerical models were established based on the finite element method using ABAQUS (version 2021, Dassault, USA). The main procedure included the following steps: *1)* the geometric model of the chair was created using Solidworks (version 2020, Dassault, USA) according to the dimensions shown in Fig. 1; *2)* and then it was im-ported into ABAQUS for pre-processing; *3)* the beech wood was considered as an orthotropic material (Hu et al. 2021) and the soft tissue (Akyildiz et al. 2014) of the human as an isotropic material with all the mechanical parameters shown in Tab. 1; *4)* the joints of all the chair members were tied since the main objective is to model the stress distribution on the seat.

Tab. 1: Mechanical properties of beech and soft tissue of human.

Materials	Elastic modulus (MPa)			Shear modulus (MPa)			Poison's ratio (Dimensionless)			Yield strength (MPa)	
	E_L	E_R	E_T	G_{LR}	G_{LT}	G_{RT}	ν_{RT}	ν_{LR}	ν_{LT}	σ_L	σ_R
Beech (Hu et al. 2021)	12205	1858	774	899	595	195	0.502	0.705	0.526	53.62	12
Soft tissue (Akyildiz et al. 2014)	0.0648						0.49				

Note: L, R, and T mean the longitudinal, radial, and tangential grain orientations of beech, respectively.

The approach to modeling people sitting on the chair is a critical point that directly determines the accuracy of the model. In this work, three methods for modeling the load acting on the seat were developed and compared (Fig. 2). Fig. 2a shows the first method where the load on the seat is modeled by uniformly loading the entire surface of the seat. The load value on the seat was measured using the test method described in the testing method section. Fig. 2b shows the second method, in which the load was applied by a hip-shaped mold according to the test method presented in GB/T 10357.3 (2013) and previous study (Smardzewski et al. 2010). The contact relationship between the mold and the seat was modeled as hard surface-to-surface. The value of the load applied to the mold is identical to that of the experimental tests. Fig. 2c models the load on the seat by mapping the body pressure data set determined in the experimental tests using the analytical mapping field built in ABAQUS. It enables the import of body pressure data into ABAQUS in coordinate format. In the meantime, all other settings in these three models were identical. Element C3D8 was used to mesh the model. All degrees of freedom of the four legs were restricted.



(a) (b) (c)

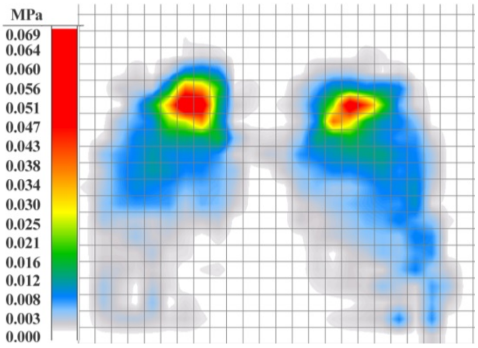
Fig. 2: Finite element models modeled by different loading methods: (a) uniform loading method, (b) standard loading pad method, and (c) body pressure mapping method.

RESULTS AND DISCUSSION

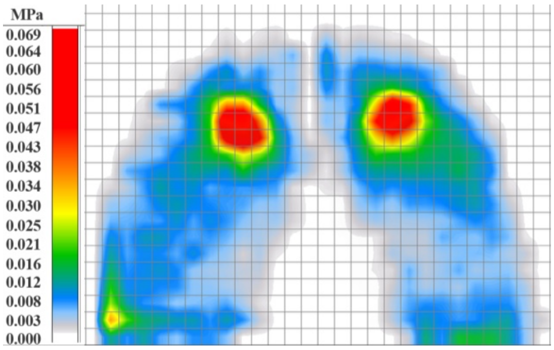
Distribution of body stress

Fig. 3 shows a typical distribution of the body stress when the test subjects are seated in a normal sitting posture. Although the average contact pressure was higher in the male than in the female, the distributions were almost identical and tended towards an inverted U-shape.

The maximum pressure was concentrated on the ischial tuberosity and gradually decreased around it until it disappeared.



(a)



(b)

Fig. 3: Typical body pressure distributions of subjects: (a) female, and (b) male.

Characteristic values of human-seat contact

Tab. 2 summarizes all observed results when subjects are seated in normal conditions. This includes information about the subjects, such as gender, height, weight, and BMI, and characteristic values of body pressure such as contact area (CA), average contact stress (ACS), weight on seat (WS), and the ratio of WS to weight (RWSW). It shows that the mean values of CA, ACS, WS, and RWSW are 616.8 mm^2, 0.070 MPa, 43.06 kg, and 65.3%, respectively. The RWSW is very close to the ratio of body segments to total weight, which is calculated based on the human body configuration (Pan 1982).

Tab. 2: Characteristic values of subjects and their body stress.

No. of subject	Gender	Height (mm)	Weight (kg)	BMI	CA (mm^2)	ACS (MPa)	WS (kg)	RWSW (%)
1	Female	1600	53	20.70	465.59	0.074	34.52	65.13
2	Female	1700	55	20.76	660.41	0.067	44.84	74.73
3	Female	1700	55	19.03	583.75	0.057	33.34	60.62
4	Female	1650	57	20.94	654.08	0.062	40.52	71.08
5	Female	1650	60	22.04	554.91	0.066	36.41	60.68
6	Male	1900	92	25.48	714.57	0.077	55.07	59.86
7	Male	1710	71	24.28	691.36	0.077	53.37	75.17
8	Male	1800	65	20.06	481.77	0.072	34.70	53.39
9	Male	1680	73	25.86	738.48	0.070	51.71	70.84
10	Male	1800	75	23.15	623.14	0.074	46.09	61.45
Mean		172	66	22.23	616.81	0.070	43.06	65.30
COV (%)		5.0	18	10.6	15.22	9.54	19.36	11.18

Note: CA - contact area, ACS - average contact stress, WS - weight on seat, RWSW - ratio of WS to weight.

Mean comparison of characteristic values

Tab. 3 shows the results of the two-way ANOVA for the effects of gender, BMI, and their interaction on the characteristic values of the human-seat interface when sit-ting on the chair. It indicates that gender has a significant effect on ACS and WS (Chao et al. 2021). However, the effect of gender on RWSW is not significant. BMI has a significant effect on WS and CA, while no significant effect on RWSW. This could be due to the fact that BMI is an indicator that reflects the body shape of the subjects (Naddeo et al. 2018). In contrast, the value of

RWSW also indicates the body shape of subjects. Therefore, BMI has no significant effect on RWSW. However, the interaction of gender and BMI has a significant effect on CA. Therefore, further mean comparisons were performed using the least square difference.

Tab. 3: Two-way ANOVA of load pressures considering effects of factors.

Factor	CA		ACS		WS		RWSW	
	F	p	F	p	F	p	F	p
Gender	2.50	0.125	4.99	0.03372*	7.98	0.00863*	0.01	0.92204
BMI	14.96	$4.6e^{-7}$*	1.11	0.41012	4.59	0.0022*	1.45	0.23401
Gender × BMI	5.49	0.005*	1.16	0.38179	1.78	0.18007	2.87	0.05267

* Means that the factor has a significant effect on load pressure.

Tab. 4 shows that the BMI, ACS, and WS of males are significantly higher than those of females. However, CA and RWSW between males and females do not show significant differences. Both ACS and WS increased with the increase in BMI. However, neither CA nor RWSW in males showed significant differences from those in females.

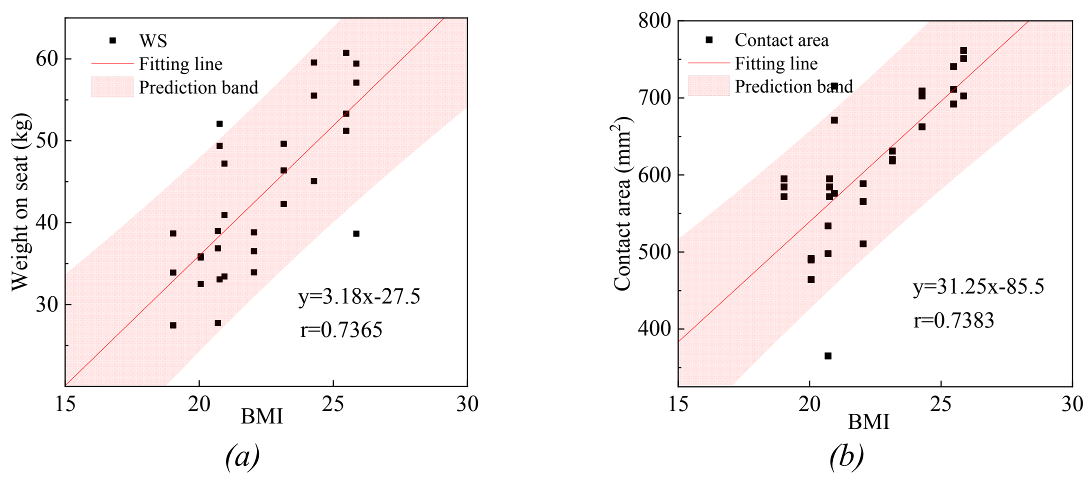
Tab. 4: Mean comparison of characteristic parameters of subjects for gender.

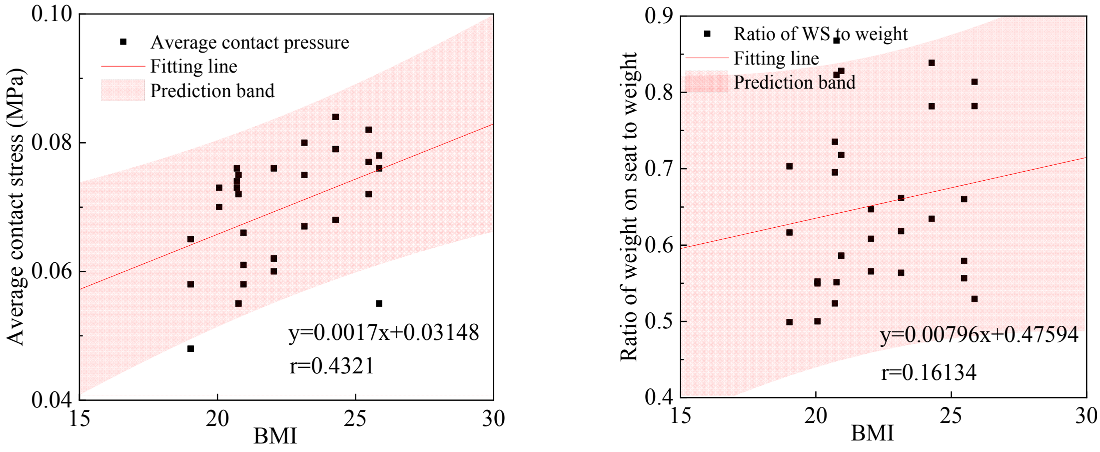
Gender	BMI	CA (mm^2)	ACS (kg/mm^2)	WS (kg)	RWSW (%)
Male	23.09(9.8) A	626.85(14.5) A	0.072(11.4) A	46.03(20.9) A	0.652(17.9) A
Female	20.22(5.1) B	567.81(17.82) A	0.064(14.2) B	36.12(17.5) B	0.656(16.4) A

Note: the values in the same column not followed by a common letter mean significantly different from the other at a 5% significance level.

Relationships between characteristic values

Fig. 4 shows the relationships between the characteristic values evaluated and BMI using a linear regression method. It indicates that the correlations between WS and BMI, as well as CA and BMI have a higher Pearson's ratio beyond 0.73 than those of ACS and RWSW relating to BMI. This also indirectly reflects that BMI has significant effects on WS and CA but not on ACS and RWSW. In other words, these parameters are more significantly influenced by BMI having higher correlations with BMI (Li et al. 2020).



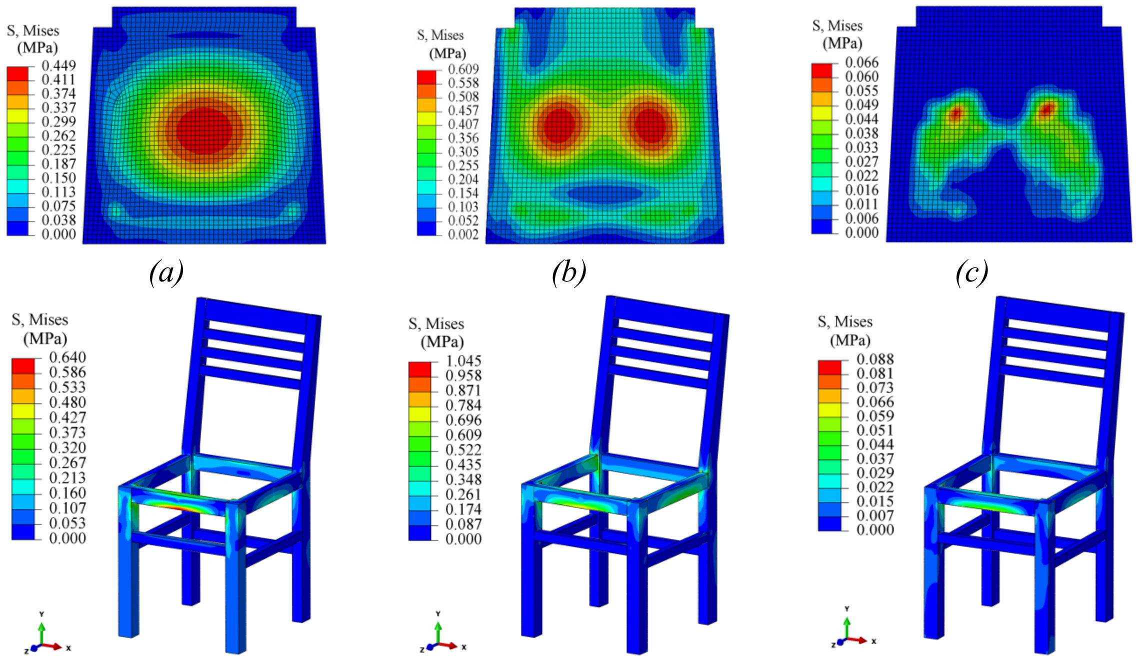


(c) *(d)*

Fig. 4: Relationships between BMI and characteristic values: weight on the seat (a), contact area (b), average contact stress (c), and the ratio of weight on the seat to weight (d).

Numerical analysis results

The experimental data of the No. 3 subject was randomly selected to input into the numerical models. Fig. 5 shows the results of the numerical analysis modeled with three methods. The stress distributions on the seat showed that the result of the body pressure mapping method (Fig. 5c) was more consistent with the observed results (Fig. 3) than those of the uniform loading method (Fig. 5a) and the standard loading pad method (Fig. 5b). Comparing the stress distribution on the chair frame (Figs. 5d,e,f), it can be seen that the maximum stresses of the three modeling methods were all in the middle of the front stretcher.



(a) *(b)* *(c)*

(d) *(e)* *(f)*

Fig. 5: Stress distributions on the seat and frame of the chair are modeled by different loading types: (a) and (d) uniform loading method, (b) and (e) standard loading pad method, and (c) and (f) body pressure mapping method.

Tab. 5 provides a quantitative comparison between the experimental tests and the three modeling methods. It indicates that the maximum stress on the seat and the contact area determined by the body pressure mapping method is identical to those of the experimental tests. However, the maximum stress and contact areas output by the standard loading pad method and the uniform loading method are much higher than those of the body pressure mapping method and the experiments. This may be due to the fact that the standard loading pad concentrates the load on the bottom of the mold, which has a hard contact in the geometric model (Huang et al. 2015, Yadav et al. 2021).

Tab. 5: Comparison of results obtained by numerical simulation with experimental test.

Method	Maximum stress on seat (MPa)	Contact area (mm^2)	Maximum stress on frame (MPa)
Uniform load	0.449	144940	0.714
Standard loading pad	0.609	26506	0.752
Body pressure mapping	0.066	59500	0.055
Observed	0.066	59500	*

*- not available.

From the synthesis of the qualitative stress distributions of the seat and frame of the chair and the quantitative maximum stress and contact area, it can therefore be concluded that the body pressure mapping method is the optimal method for modelling the load on the seat of the chair compared to the other two. It provides a sufficient method to simulate the mechanical behavior of the chair structure. In future work, experimental testing of the mechanical properties of chairs in normal sitting posture will be further investigated.

CONCLUSIONS

The pressure distributions on seats in a normal sitting posture were investigated experimentally and numerically. The following conclusions were drawn: *(1) a*n inverted U-shaped pressure distribution was observed with the maximum stress of 0.066 MPa concentrated on the ischial tuberosity;*(2)*although gender has a significant effect on the average contact stress and weight on the seat (WS), the ratio of WS to human body weight is 65.3% regardless of gender;*(3)*the numerical model established using the body pressure mapping method was superior to the uniform loading and standard loading pad methods in terms of stress distribution, maximum stress, and contact area.

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