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Design of grippers for laparoscopic surgery and optimization of experimental parameters for maximum tissue weight holding capacity

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Abstract. Grippers are routinely used to hold, lift and move organs in laparoscopic operations. They are generally toothed to prevent organs from slipping during retention. Organs held by grippers are always at risk of being damaged by the clamping force. In this study, noncontact grippers working with the Bernoulli principle and using air pressure were developed, and vacuum performance was compared in terms of maximum tissue weight holding capacity. For this purpose, Taguchi method was employed for experimental design and optimization, and Taguchi L_{16} orthogonal array was selected for experimental design. The experimental parameters were 4 gripper types, 4 air-pressure levels (3.5, 4.5, 5, and 5.5 bar), 4 flow rates $(2.2, 2.6, 2.8 \text{ and } 3 \text{ m}^3/\text{h})$ and two animal tissue types (ventriculus/gizzard and skin). Values from the experimental procedures were evaluated using signal-to-noise ratio, analysis of variance and three-dimension graphs. An equation was obtained by using 3rd-order polynomial regression model for weight values. Optimization reliability was tested by validation tests and the revealed test results were within the estimated confidence interval. The results obtained from this study are important for future studies in terms of organ injury prevention due to traditional grippers in laparoscopic surgery.

Key words: Laparoscopic gripper, noncontact gripper, tissue type, Taguchi method, optimization.

1. Introduction

Due to the advantages presented to the patients, laparoscopic surgery (closed surgery) is rapidly growing [1]. In laparoscopic surgery, small incisions are made for the placement of surgical tools without large incisions in the human body. Performance of the small incisions provides faster healing and causes less pain compare to the open surgery. This advantage for patients limits the holding capacity of tissues for the surgeon. Human tissue is difficult to hold due to its flexible, wet, and delicate structure. The present holders used for that purpose are grippers with the long and toothed structure. It is necessary to compress the tissues sufficiently to prevent them from slipping. This raises the risk of tissue damage. Although various grippers have been developed, toothed grippers are used in most laparoscopic surgical procedures [2]. Existing grippers are still inadequate to hold and move internal organs without harming them [3–5]. In order to transport the flexible products, Erzincanlı et al. developed an air-operated noncontact gripper with the Bernoulli principle. A 45° deflector was installed in the center of the gripper to prevent direct contact of air with the object to be removed. They successfully lifted jelly block, animal flesh, sliced bread, sponge, and cloth in their experiments [6]. Özçelik and Erzincanlı developed a gripper working with the Bernoulli principle in order to be able to remove the delicate and woven fabrics in a noncontact manner [7, 8]. Davis et al. used Bernoulli principle and developed a noncontact holder for lifting sliced vegetables and fruits commonly used in the food industry [9]. Sam and Buniyamin used Bernoulli principle to develop a gripper for the transport of unpacked food products of variable shape, size, and weight. The experimental results showed that the food with different structures and shapes can successfully be lifted by noncontact grippers [10]. Dini et al. successfully lifted the skin layers, which had delicate surfaces, without any contact with grippers of various retaining surfaces and deflector angles [11]. The Taguchi method is widely used in many areas of the scientific literature to reduce the number of experiments and to optimize test parameters and employed for the similar purposes in the present study [12–21]. When literature is examined, it is seen that different types of grippers are used especially in medical robots. On the other hand, it is known that grippers are used in robotic applications. Consequently, the gripper design has an important place, especially for medical applications [22, 23].

The aim of the current study was to design and produce grippers so as to prevent tissue damage caused by the toothed grippers while holding the tissues during laparoscopic surgery. An experimental setting was formed to test the performance of the grippers designed and produced. Taguchi method was used for experimental design and optimization. For the experimental parameters, 4 different types of grippers, 4 different air pressure levels, 4 different flow rates, and two different animal tissue types were used. Taguchi L16 orthogonal array was employed to reduce the number of the experiments and maximum tissue weight holding capacity was measured. The results of the experimental procedures were evaluated using signal-to-noise ratio (S/N), analysis of variance (ANOVA).

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Three-dimension graphs and regression method was applied to obtain the mathematical equation for the model. Moreover, three different confirmation tests were applied to test the accuracy of the optimizations.

2. Design and experimental details

In this study, four different laparoscopic grippers were designed and produced using air force with Bernoulli principle. The selected grippers for the experimental evaluations are shown in Fig. 1. The grippers were produced from bio-compatible liquid resin using 32-micron precision on the 3D Projet 3510 HD Plus printer. Wax was used as support material (Fig. 1). The grippers are composed of two parts as the retaining surface and the deflector. The outer diameter is 14 mm, the hole diameter is 6 mm, the length is 20 mm and the retaining surface area is 154 mm^2. In the gripper designs, a deflector is placed in the center of the holding surface in order to refract the compressed air coming from the center of the gripper to

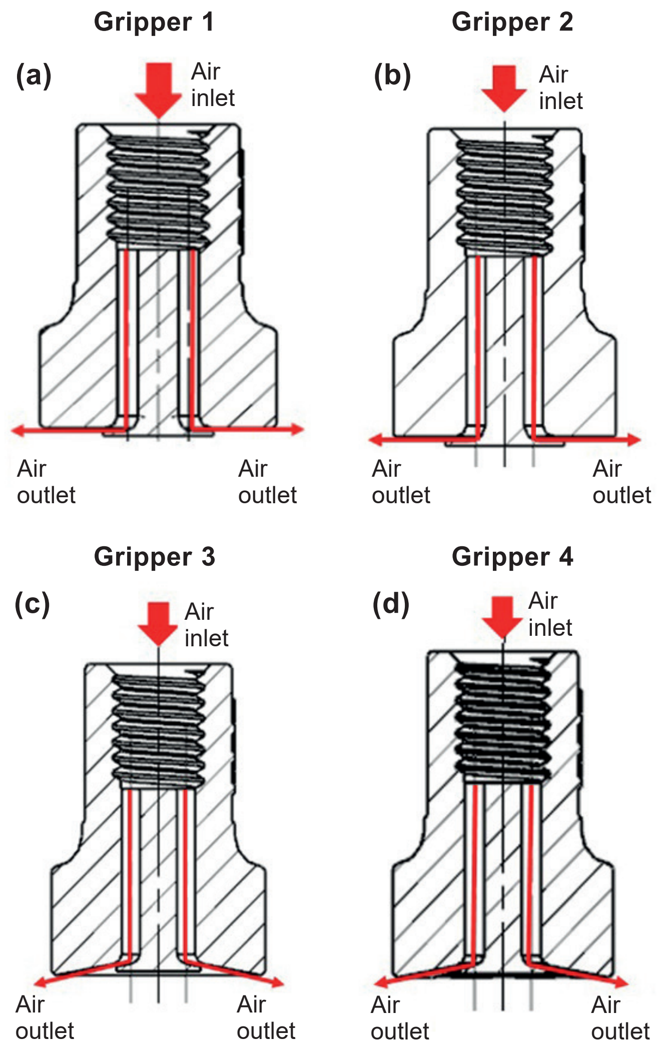

Fig. 1. CAD drawings of laparoscopic grippers

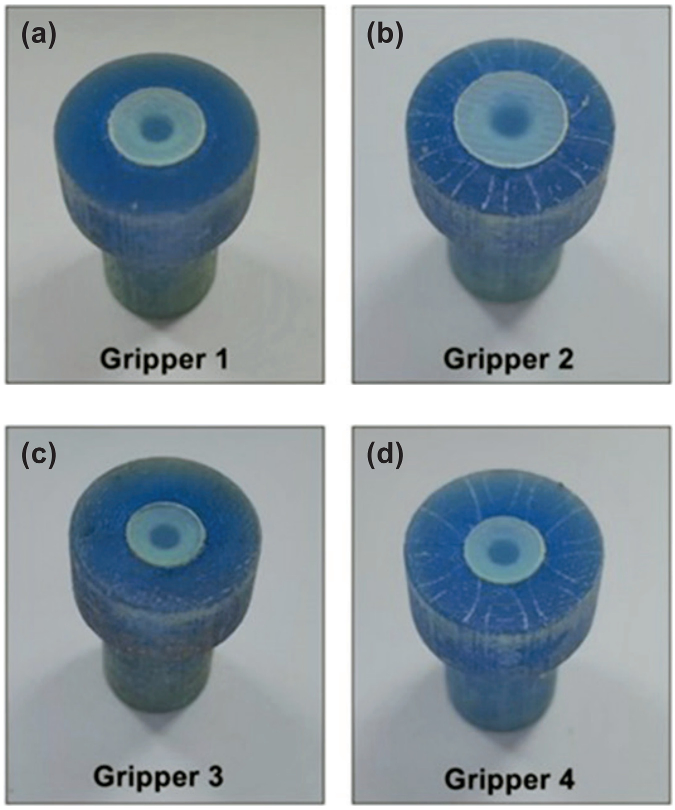

Fig. 2. Laparoscopic gripper models used in experiments

change direction without impacting on the delicate materials. Gripper 1 has a smooth surface without angle (Fig. 1a and Fig. 2a). There are 12 venturi channels on Gripper 2 (Fig. 1b and Fig. 2b). Gripper 3's holding surface and deflector have an angle of 10 degrees (Fig. 1c and Fig. 2c). The deflector and gripping surface of Gripper 4 has an angle of 10 degrees, and there are 12 venturi channels on it (Fig. 1d and Fig 2d). The reason for the installation of venturi channels was to increase the vacuum force, and the reason why the gripper surface was made at a 10-degree angle was to allow holding objects that did not have a smooth surface. Each gripper was operated by being connected to a manually controlled air gun. In order to test the maximum tissue weight that can be lifted with four holders produced and to check its applicability to laparoscopic surgery on different tissues, the experimental setup in Fig. 3 was established. In the experiments, 50 liters capacity air tank, maximum 8 bar pressure and 200 l/min flow capacity air compressor were used. The pressure of the air flowing into the system was measured by a manometer. The speed of the air flow is regulated by the one-way flow control valve and the flow rate by the flow meter.

The flowchart shown in Fig. 3 was used in the experiments and in this experimental setup, a laparoscopic surgical environment was tried to be simulated. The compressed air required for the operation of the test system is provided by a Tornado HM2050F compressor. Air pressure is regulated by Vema brand (0-10 bar) pressure regulating valve. The flow rate was measured with a flow control valve, VA10S-15 with a flow meter of

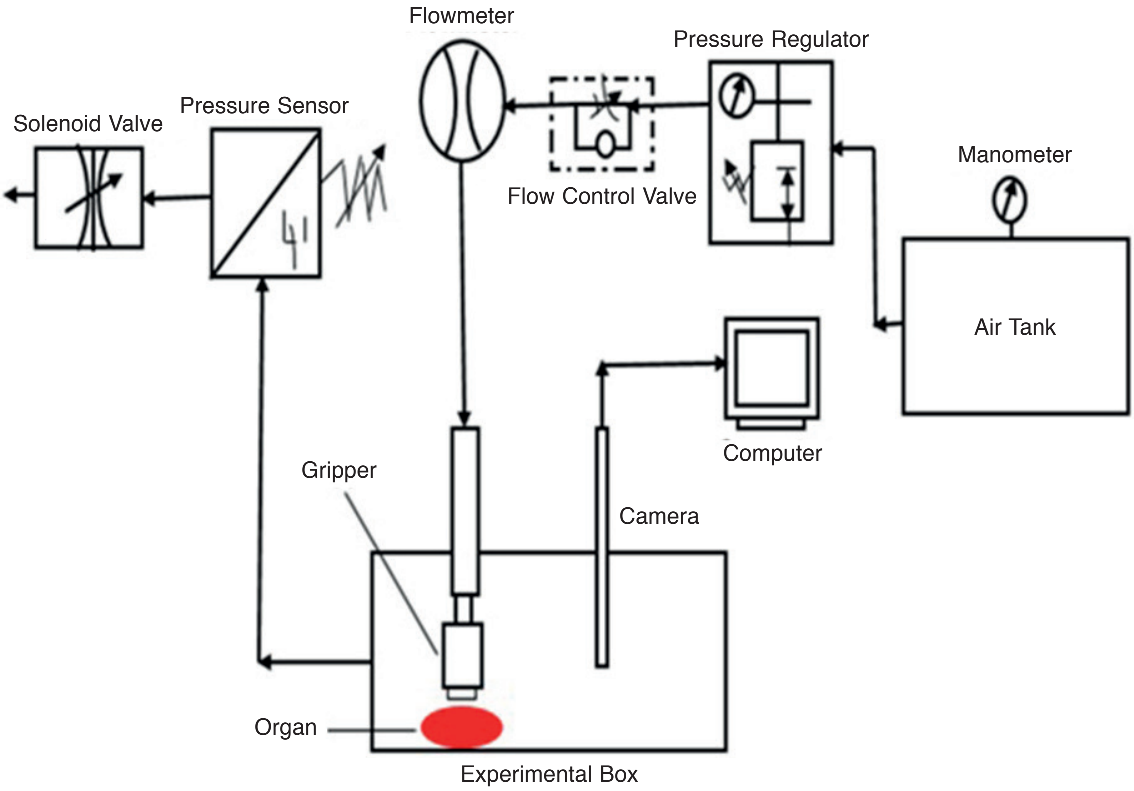

Fig. 3. Experimental setup

1.2-12 m^3/h. The weights of gizzard and skin tissues that can be lifted by four different holders connected to Troy air gun were measured by electronic balance.

3. Experimental design and optimization

3.1. Experimental design and conducting the experiments. In Taguchi method, it is possible to reduce the number of experiments significantly. The Taguchi method uses some functions to determine quality characteristics. These functions convert the obtained data into signal to noise ratio (S/N ratio). For the conversion of S/N ratios, three different equations are used: "nominal is best", "larger is better" and "smaller is better". In this study, the "larger is better" function was used since the maximum value for the measured weights for each experiment was desired (1).

Larger is better:

$$S/N_L = -10\,log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2}\right) \tag{1}$$

where n is the number of observed values, y is the observed data and S/N_L is the signal to noise ratios [24, 25]. Orthogonal array selection in Taguchi method depends on the factors selected, the interactions of these factors, the number of levels for each factor, and the purpose of the experiment. Therefore, for correct orthogonal array selection, firstly, the test parameters and levels are determined. Table 1 shows the selected test parameters and their levels.

Table 1
Test parameters and levels selected as control factors

Parameters	Level 1	Level 2	Level 3	Level 4
Grippers (Nt)	Gripper 1	Gripper 2	Gripper 3	Gripper 4
ir pressure (Ap, bar)	3.5	4.5	5.0	5.5
Flow rate $(\text{Fr}, \text{m}^3/\text{h})$	2.2	2.6	2.8	3.0
Tissue type (t)	Gizzard	Skin	–	–

The first step of the Taguchi method is to select an appropriate orthogonal array based on the selected test parameters as control factors. The most suitable sequence $[L_{16}(4^3{\times}2^1)]$ was selected to determine the optimum weight parameters and to analyze the effects of these specified parameters. Therefore, Taguchi L_{16} orthogonal array was used for experimental design and 16 experiments were performed. As a result of the experiments, the optimization of the measured weight values is achieved with S/N ratios. The weight values measured by the

Table 2
Weight values and S/N ratios obtained from experiments

Test no.	Control factors				Weight (gr)	
	Gripper Type (Nt)	Air pressure (Ap)	Flow rate (Fr)	Tissue type (t)	W (gr)	S/N_W (dB)
1	Gripper 1	3.5	2.2	Gizzard	23.91	27.5716
2	Gripper 1	4.5	2.6	Gizzard	28.61	29.1304
3	Gripper 1	5.0	2.8	Skin	14.85	23.4345
4	Gripper 1	5.5	3.0	Skin	18.85	25.2727
5	Gripper 2	3.5	2.6	Skin	12.38	21.8544
6	Gripper 2	4.5	2.2	Skin	11.12	20.9221
7	Gripper 2	5.0	3.0	Gizzard	22.94	27.2119
8	Gripper 2	5.5	2.8	Gizzard	24.55	27.8010
9	Gripper 3	3.5	2.8	Gizzard	20.61	26.2816
10	Gripper 3	4.5	3.0	Gizzard	26.16	28.3528
11	Gripper 3	5.0	2.2	Skin	12.28	21.7840
12	Gripper 3	5.5	2.6	Skin	22.60	27.0822
13	Gripper 4	3.5	3.0	Skin	20.94	26.4195
14	Gripper 4	4.5	2.8	Skin	19.01	25.5796
15	Gripper 4	5.0	2.6	Gizzard	20.69	26.3152
16	Gripper 4	5.5	2.2	Gizzard	16.80	24.5062

experiments carried out according to the L_{16} Taguchi test design and the S/N ratios calculated using (1) are shown in Table 2.

After 16 experiments, the mean weight value was 19.7375 g and the average S/N ratio was 25.5949 dB.

3.2. Determination of optimum parameters. The experimental parameters, which are expressed as control factors in Table 3, are differentiated according to the selected orthogonal array while the different levels and their possible effects were taken into account. These levels show the average values for each level of the weight values and signal to noise ratios calculated for the analysis of the weight measurements in the experimental study. These values are used to calculate the estimated values for the specified optimum parameters.

Another requirement in the calculation of the optimum value is the determination of the optimum levels. Optimum levels can be determined by evaluating different levels of control factors based on the results of combinations produced by the L16 orthogonal array. These levels are used to plot the main effect graphs (Fig. 4).

Table 3
S/N ratios (dB) and average weight values

Control factors	Weight (W)			
	Nt	Ap	Fr	t
S/N ratios (dB)				
Level 1	26.35	25.53	23.70	27.15
Level 2	24.45	26.00	26.10	24.04
Level 3	25.88	24.69	25.77	–
Level 4	25.71	26.17	26.81	–
Delta	1.90	1.48	3.12	3.10
Means (gr)				
Level 1	21.43	19.46	16.03	23.03
Level 2	17.75	21.23	21.07	16.44
Level 3	20.41	17.69	19.75	–
Level 4	19.36	20.57	22.10	–
Delta	3.68	3.54	6.07	6.59

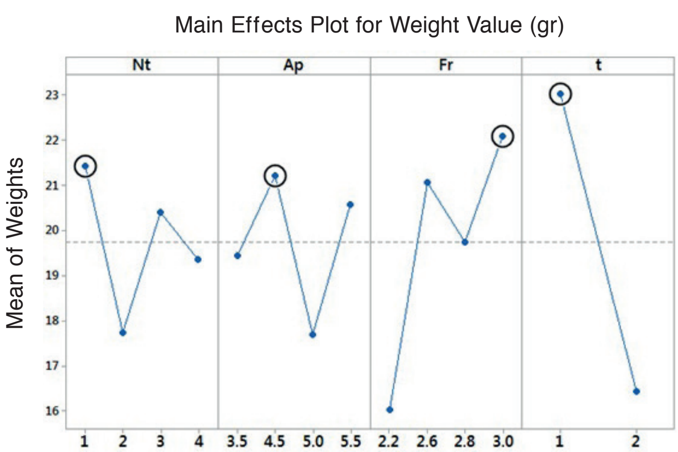

Fig. 4. Effect graphs of experimental parameters for weight

Average weight distributions calculated according to control factors and levels are indicated in Fig. 3. Since the "Larger is better" model was selected in the study, the maximum mean values for all levels were evaluated to determine the optimal combination of control factors. Accordingly, the optimum combination of test parameters for the weight values was determined as $A_1B_2C_4D_1$ (A_1 = Gripper 1, B_2 = 4.5 bar, C_4 = 3 m^3/h flow rate, and D_1 = Gizzard tissue).

4. Evaluation of experimental results

4.1. Effect of test parameters on weight. Figure 5a indicates the effect of grippers and air pressure on weight. Here, it is observed that the gripper type 1 and 4.5 bar pressure can increase the amount of weight that can be lifted. This is similar to the optimized parameters obtained by the Taguchi method. On the other hand, at the lowest value of the air pressure in the same graph, Gripper 2 and Gripper 3 shows that the weight values decrease. Gripper 2 has 12 venturi channels and Gripper 3 has a 10-degree angle surface.

Therefore, this implies that these characteristics affect the performance of the holders negatively at low air pressure and positively at high air pressure. In addition, when Gripper 4 is examined, this gripper performs better than Gripper 2 and Gripper 3 at low air pressure. This is associated with 12 venturi channels on the lifting surface.

Figure 5b shows the effects of the grippers and flow rate on weight. Here, Gripper 1 showed the best performance again. When the graph is examined, it is observed that the performance of Gripper 1 is lower at the lowest flow rate and that of Gripper 2 and Gripper 3 at the highest flow rate. Therefore, according to this graph, Gripper 1 is recommended for low flow rate, Gripper 2 and Gripper 3 are recommended for high flow

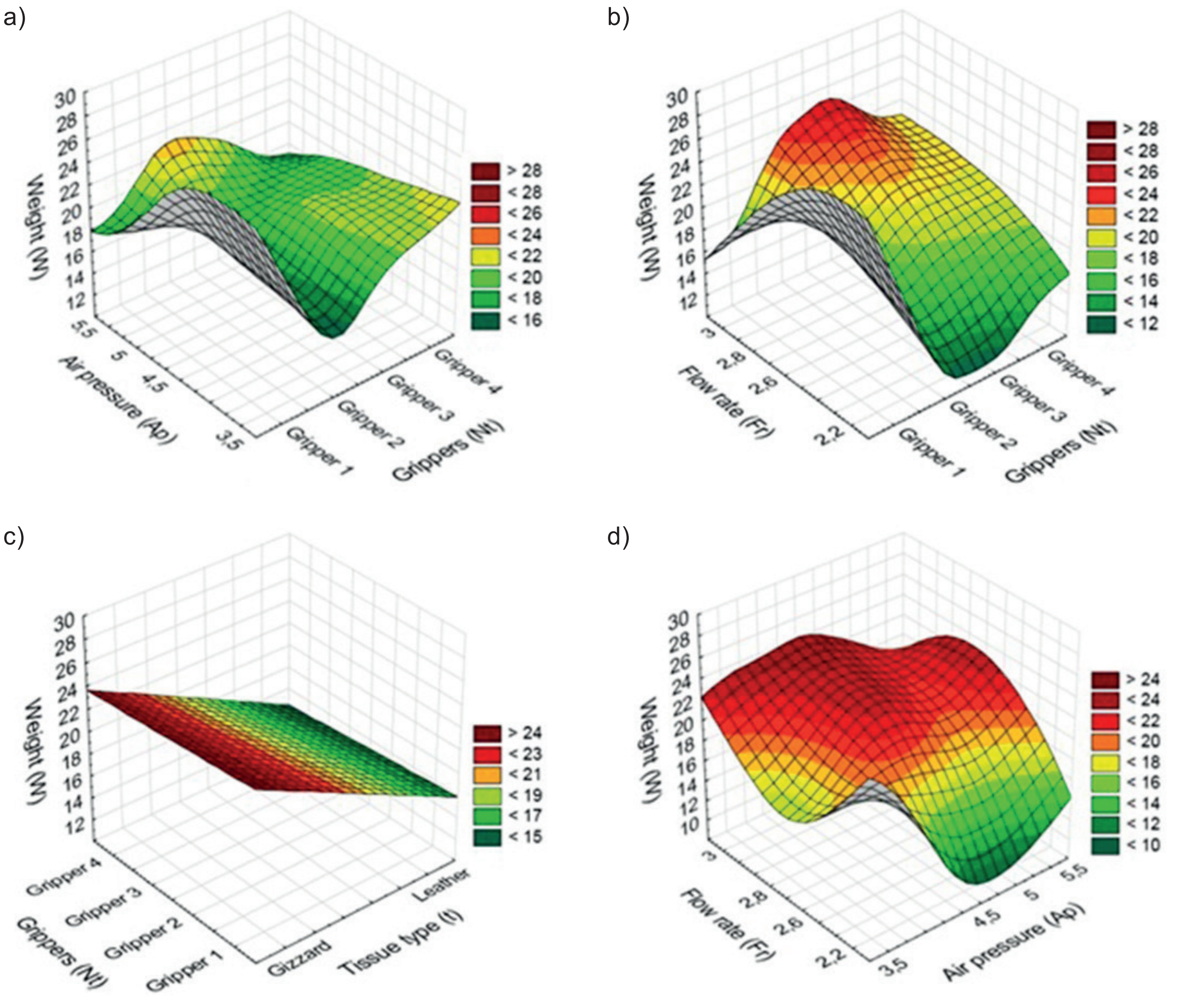

Fig. 5. Effect of test parameters on weight

rate. Fig. 5c demonstrates the effects of tissue type and holders on weight. In this graph it is evident that all the holders performed best in Gizzard tissue. This is thought to be due to the fact that the skin has a thin layer that closes the deflector channel during gripping, which is due to the fact that the grippers do not perform a good vacuuming. The effects of air pressure and flow rate on weight are shown in Fig. 5d. The best lifting performance here is at 4.5 bar pressure and 3 m^3/h flow rate. This is similar to the parameters optimized with Taguchi. In addition, it can be observed that the weight value that can be lifted increases as the flow rate increases. It is detected that high flow rate and 4.5 bar pressure are sufficient for good holding capacity and maximum amount of weight.

4.2. Evaluation of test parameters by analysis of variance (ANOVA). ANOVA is used to determine how all the control factors used in the experimental design affect each other, how this affects the performance characteristics, and what changes in the performance characteristics are at different levels [24]. The effects of gripper type, air pressure, flow rate, and tissue type on weight values were evaluated by analysis of variance (ANOVA) and the experimental results were examined at 95% confidence level. The results of variance analysis are shown in Table 4.

When ANOVA results were examined in Table 4, the most effective factor on the weight values was tissue type with 43.34%. This was followed by flow rate with 21.05%. Retention type and air pressure effects were 7.40% and 7.16%, respectively.

4.3. Regression analysis and mathematical model. Regression analyses are used in the modeling and analysis of various variables in which there is a relationship between one dependent variable and one or more independent variables [27]. In this study, weight equation was obtained with 3rd order polynomial regression (cubic regression) model for weight results and R-sq value of this model was 0.981. The obtained mathematical model is shown in (2). This equation is given for the grippers used in this study.

$$W = -32.5Nt + 4.1Ap + 30Fr - \\ - 6.61t + 13.6Nt^2 - 1.2Ap^2 - \\ - 4.5Fr^2 - 1.73Nt^3 + 0.11Ap^3 \tag{2}$$

4.4. Verification tests. The final step of the Taguchi method is to analyze the quality characteristics of the validation experiments. Verification experiments are also used to test the accuracy of the optimization process. In other words, verification tests are performed to test the determined optimum combination of test parameters and levels. The estimated weight value according to the optimum combination (Wp) of $A_1B_2C_4D_1$ (A_1=Gripper 1, B_2=4.5 bar, C_4=3 m^3/h flow rate, and D_1=Gizzard tissue) obtained for the weight considering the individual effects of the test parameters is calculated according to (3) and then (4) [26].

$$\eta_g = \eta_{S/N} + \left(A_1 - \eta_{\frac{S}{N}}\right) + \left(B_2 - \eta_{\frac{S}{N}}\right) + \\ + \left(C_4 - \eta_{\frac{S}{N}}\right) + \left(D_1 - \eta_{\frac{S}{N}}\right) \tag{3}$$

$$W_p = 10^{\eta_g/20} \tag{4}$$

In the equations, A_1, B_2, C_4 and D_1 was the signal to noise ratio of the optimum levels of the factors ($A_1 = 26.35$ dB, $B_2 = 26$ dB, $C_4 = 26.81$ dB and $D_1 = 27.15$ dB from Table 3). $\eta_{S/N}$ is the average of the S/N ratios of all variables ($\eta_{S/N} = 25.5949$ dB). W_p is the estimated value for the weight. The estimated value for the weight calculated using (3) and (4) was 29.99. Confidence interval (CI) was used to compare the result of the validation tests with the predicted value and to verify the quality property. The confidence interval is maximum and minimum and the accuracy of the verification tests is confirmed by comparing the calculated value with the predicted weight value. CI was calculated using (5) [24, 25].

$$\mathrm{CI} = \sqrt{\mathrm{F}_{\alpha:1,\mathrm{Ve}} \times \mathrm{V_{ep}} \times \frac{1}{\mathrm{n_{eff}}} + \frac{1}{\mathrm{r}}} \tag{5}$$

In (4), $F_{\alpha:1}$, v_e ($F_{1,5} = 6.6079$ from F table) denotes the F ratio significance level α, α is significance level (95%), V_e is the degree of freedom of error ($V_e = 5$), V_{ep} is the variance of the error ($V_{ep} = 16.875$), r is the number of confirmation experiments and n_{eff} is the number of effective measured results [24, 25].

Table 4
Analysis of variance (ANOVA) for experimental results

Variance source						
Weight (W, gr)	Degree of freedom (DF)	Sum of squares (SS)	Mean squares (MS)	F-Value	P-Value	Contribution rate (%)
Nt	3	29.69	9.897	0.59	0.650	7.40
Ap	3	28.73	9.578	0.57	0.660	7.16
Fr	3	84.44	28.146	1.67	0.288	21.05
t	1	173.84	173.844	10.30	0.024	43.34
Error (*e*)	5	84.38	16.875	–	–	21.05
Total	15	401.08	–	–	–	100.00

Table 5
Comparison of experimental combinations with estimated values

Levels	For Taguchi method			For 3rd order polynomial equation		
W (gr)	Exp.	Pred.	Error (%)	Exp.	Pred.	Error (%)
$A_1B_2C_4D_1$ (Optimum)	32.02	29.99	6.33	32.02	25.65	19.89
$A_2B_4C_3D_1$ (Random)	24.55	21.76	11.36	24.55	22.22	9.49

$$n_{eff} = \frac{N}{1 + V_t} \tag{6}$$

In (6), N denotes the total number of experiments (16), and V_t is the total degree of freedom (= 10) of the test parameters for which the average is calculated by considering Table 4. In this study, three validation experiments were performed considering the optimum combination determined for the measured weights. When these values were taken into account, the calculated weight was $n_{eff} = 1.45$. When the test results were evaluated in 95% confidence interval and when (5) and (6) were taken into consideration, the confidence interval was found as (CI) = 10.68 for the measured weight values. The average of the three validation experiments carried out for the accuracy and confidence interval calculation of the optimizations was 32.02 gr. In this case, $(29.99 - 10.68) < 32.02 < < (29.99 + 10.68) = 19.31 < 32.02 < 40.67$ was obtained and verification tests were performed within the confidence interval. Therefore, the optimization was carried out successfully. Table 5 shows the comparison of the predicted values obtained with the Taguchi method and the experimental results. Estimated and experimental values were very close. Error values for reliable statistical analysis should be less than 20% [26].

In Table 5, the experimental results are compared with the estimated values obtained from the Taguchi method and the 3rd order polynomial equation. The difference between the validation test results and the results obtained by the Taguchi method was very small. In this case, the results obtained by the verification experiments show that the optimization was carried out successfully.

5. Conclusions

In laparoscopic surgery, grippers with a tooted structure that works with clamping force are used to prevent the organs slipping from the grippers. There is a risk of damaging the organs as a result of the clamping force due to the lack of tactile feedback during retention. In this study, four different grippers are designed and manufactured to solve this problem. The maximum weights that can be lifted by the grippers with different parameters were examined after production. The Taguchi method was used to reduce both time and experimental costs. For experimental design, Taguchi L_{16} orthogonal array was selected and 16 experiments were conducted. In the experiments, two different structures such as gizzard and skin were chosen. The experimental results were evaluated with three-dimensional graphs and analysis of variance and the mathematical model with 98.10% R-sq value was obtained by regression method. It is possible to list the results obtained from the study as follows:

- After 16 experiments, the effects of experimental parameters were evaluated with three-dimensional graphs. As a result of this evaluation, Gripper 2 and 3 were found to be useful for high air pressure and Gripper1 and 4 were found to be useful for low air pressure.
- Gripper 1 was recommended for low flow rate and Gripper 2 and Gripper 3 were recommended for high flow rate.
- According to the experimental results, Gripper 1 showed the best performance and the optimization result confirmed this.
- The highest liftable weight data were obtained in gizzard tissue.
- The optimum parameters obtained after optimization were similar to the ones shown in the three-dimensional graphs. This indicates that the optimization was successfully implemented.
- Three validation tests were performed for the accuracy of the optimization, and these results were within the calculated confidence interval.
- According to the ANOVA, the most effective factor was tissue type with 43.34%.
- When the average of estimated value and validation experiments calculated by Taguchi method is compared, the error rate was 6.33%.

The method used in this study, which is important for laparoscopic surgery, is considered to be a reference for similar studies. The original aspect of this study is the comprehensive testing of the performance of different types of grippers designed for laparoscopic surgery. In subsequent studies, the performance of each of the gripper in individual animal tissues can be tested. By altering the gripper designs, newer grippers can be designed and their performance can be evaluated.

References

[1] J. Dankelman, C.A. Grimbergen, and H.G. Stassen, *Engineering for patient safety: Issues in minimally invasive procedures*, Lawrence Erlbaum Associates, New Jersey, London, 2005.

[2] M. Trommelen, "Development of a medical bernoulli gripper," M.S. thesis, Department of Biomedical Engineering, Delft Univ. of Technol., Delft, Netherlands, 2010.

[3] B.T. Bethea, A.M. Okamura, M. Kitagawa, T.P. Fitton, S.M. Cattaneo, V.L. Gott, W.A. Baumgartner, and D.D. Yuh, "Application of haptic feedback to robotic surgery", *J. Laparoendosc. Adv. Surg. Tech.* 14(3), 191–195 (2004), DOI: 10.1089/1092642041255441.

[4] M.G. Munro, "Laparoscopic access: Complications, technologies, and techniques", *Curr. Opin. Obstet. Gynecol.* 14(4), 365–374 (2002).

[5] G. Tholey, J.P. Desai, and A.E. Castellanos, "Force feedback plays a significant role in minimally invasive surgery: Results and analysis", *Ann. Surg.* 241(1), 102 (2005), DOI: 10.1097/01.sla.0000149301.60553.1e.

[6] F. Erzincanli, J.M. Sharp, and A.M. Dore, "Grippers for handling of non-rigid food products", in *Proceedings of Euriscon'94*, Malaga, Spain, 1994, pp. 798–806.

[7] B. Ozcelik and F. Erzincanli, "A non-contact end-effector for the handling of garments", *Robotica* 20(4), 447–450 (2002), DOI: 10.1017/S0263574702004125.

[8] B. Ozcelik and F. Erzincanli, "Examination of the movement of a woven fabric in the horizontal direction using a non-contact end-effector", *Int. J. Adv. Manuf. Technol.* 25(5–6), 527–532 (2005), DOI: 10.1007/s00170–004–2075–x.

[9] S. Davis, J.O. Gray, and D.G. Caldwell, "An end effector based on the Bernoulli principle for handling sliced fruit and vegetables", *Robot. Comput. Integr. Manuf.* 24(2), 249–257 (2008), DOI: 10.1016/j.rcim.2006.11.002.

[10] R. Sam and N. Buniyamin, "A bernoulli principle based flexible handling device for automation of food manufacturing processes", in *Proceedings of ICCAIS*, Saigon, Vietnam, 2012, pp. 214–219: IEEE, DOI: 10.1109/ICCAIS.2012.6466590.

[11] G. Dini, G. Fantoni, and F. Failli, "Grasping leather plies by Bernoulli grippers", *CIRP Ann.* 58(1), 21–24 (2009), DOI: 10.1016/j.cirp.2009.03.076.

[12] Y. Liu, C. Liu, W. Liu, Y. Ma, S. Tang, C. Liang, Q. Cai, and C. Zhang, "Optimization of parameters in laser powder deposition AlSi10Mg alloy using Taguchi method", *Opt. Laser Technol.* 111, 470–480 (2019), DOI: 10.1016/j.optlastec.2018.10.030.

[13] P.M. Nia, H.S. Jenatabadi, P.M. Woi, E. Abouzari-Lotf, and Y. Alias, "The optimization of effective parameters for electrodeposition of reduced graphene oxide through Taguchi method to evaluate the charge transfer", *Measurement* 137, 683–690 (2019), DOI: 10.1016/j.measurement.2019.02.015.

[14] Y. Li and L. Zhu, "Optimization of user experience in mobile application design by using a fuzzy analytic-network-process-based Taguchi method", *Appl. Soft Comput.* 79, 268–282 (2019), DOI: 10.1016/j.asoc.2019.03.048.

[15] S. Akyalcin, L. Akyalcin, and M. Bjørgen, "Optimization of desilication parameters of low-silica ZSM-12 by Taguchi method", *Microporous Mesoporous Mater.* 273 256–264 (2019), DOI: 10.1016/j.micromeso.2018.07.014.

[16] R. Zhang and X. Wang, "Parameter study and optimization of a half-vehicle suspension system model integrated with an arm-teeth regenerative shock absorber using Taguchi method", *Mech. Syst. Signal Process.* 126 65–81 (2019), DOI: 10.1016/j.ymssp.2019.02.020.

[17] N.P. Kim, D. Cho, and M. Zielewski, "Optimization of 3D printing parameters of Screw Type Extrusion (STE) for ceramics using the Taguchi method", *Ceram. Int.* 45(2), 2351–2360 (2019), DOI: 10.1016/j.ceramint.2018.10.152.

[18] J. Baby and K. Shunmugesh, "Optimization of Glass Fiber Reinforced Polymer (GFRP) using Multi Objective Taguchi function and TOPSIS", *Mater. Today Proc.* 11, 952–960 (2019), DOI: 10.1016/j.matpr.2018.12.024.

[19] A.B. Naik and A.C. Reddy, "Optimization of tensile strength in TIG welding using the Taguchi method and analysis of variance (ANOVA)", *Therm. Sci. Eng. Prog.* 8, 327–339 (2018), DOI: 10.1016/j.tsep.2018.08.005.

[20] S.K. Khare, S. Agarwal, and S. Srivastava, "Analysis of surface roughness during turning operation by Taguchi Method", *Mater. Today Proc.* 5 (14), 28089–28097 (2018), DOI: 10.1016/j.matpr.2018.10.050.

[21] L. Ai, G. Zhang, W. Li, G. Liu, and Q. Liu, "Optimization of radial-type superconducting magnetic bearing using the Taguchi method", *Physica C Supercond. Appl.* 550, 57–64 (2018), DOI: 10.1016/j.physc.2018.03.013.

[22] Z. Nawrat, "Robin heart progress-advances material and technology in surgical robots", *Bull. Pol. Ac.: Tech.* 58(2), 323–327 (2010), DOI: 10.2478/v10175–010–0030–6

[23] C. Zielinski and T. Winiarski, "General specification of multi-robot control system structures", *Bull. Pol. Ac.: Tech.*, 58(1), 15–28 (2010), DOI: 10.2478/v10175–010–0002-x

[24] G. Samtaş and S. Korucu, "The optimization of cutting parameters using Taguchi Method in milling of tempered aluminum 5754 alloy", *Düzce Üniversitesi Bilim ve Teknoloji Dergisi* 7(1), 45–60 (2019), [in Turkish], DOI: 10.29130/dubited.423795.

[25] G. Samtaş and S. Korucu, "Optimization of cutting parameters for surface roughness in milling of cryogenic treated EN AW 5754 ($AlMg_3$) aluminum alloy", *Politeknik Dergisi* 22(3), 665–673 (2019), [in Turkish], DOI: 10.2339/politeknik.457957.

[26] F. Kara, "Optimization of surface roughness in finish milling of AISI P20+S plastic-mold steel", *Mater. Technol.* 52(2), 195–200 (2018), DOI: 10.17222/mit.2017.088.

[27] M.H. Cetin, B. Ozcelik, E. Kuram, and E. Demirbas, "Evaluation of vegetable based cutting fluids with extreme pressure and cutting parameters in turning of AISI 304L by Taguchi method", *Journal of Cleaner Production* 19(17–18), 2049–2056 (2011), DOI: 10.1016/j.jclepro.2011.07.013.