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Production of Grippers Working with Bernoulli's Principle for Laparoscopic Surgery and Optimization of Parameters that Affect Air Speed Required for Pulling Force

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Laparoscopic surgeries are conducted using instruments and a camera inserted through tubes into the body, without conventional large incisions. Existing grippers used in laparoscopy are long and have a geared structure. Since tissues should be compressed for adequate gripping, grippers increase the risk of tissue damage. In this study, to prevent tissue damage, non-contact grippers were produced and tested for gripping and lifting performance in terms of air speed. Non-contact gripping was achieved by vacuum by reducing the pressure between the compressed air sent to the gripper operating based on Bernoulli's principle and the object to be lifted by the gripper surface. Each gripper's air velocity required to generate buoyancy was optimized using the Taguchi method to investigate usability. By using the Taguchi L_{16} orthogonal array, 16 experiments were conducted using 4 grippers, 4 air pressure conditions and 4 flow rates designed for air speed tests in increasing buoyancy. The results were analyzed using signal-to-noise ratio, analysis of variance and three-dimensional plots. The optimum combination consisted of 6.5 bar pressure and 3.4 m^3/h air flow. The most effective factor was the gripper type. The results are important in preventing organ injuries when lifting flexible and sensitive tissues in laparoscopic surgery.

Keywords: Laparoscopic gripper, Non-contact gripper, Pulling force, Taguchi method

Introduction

Laparoscopic surgery requires specially designed tools to safely grip and move internal organs.[1,2] In laparoscopic surgery, small incisions are made to place the surgical instruments without making large incisions in the human body. As a result of small incisions, the patient experiences less pain and has smaller scars in comparison to open surgical operations. This characteristic of laparoscopic surgery is advantageous for the patient.[3–7] The existing grippers used in laparoscopic surgery are long and have a geared structure. Tissues must be sufficiently compressed so that they do not slip out of the grippers. This raises the risk of tissue damage. Although various grippers have been developed, geared grippers are used in most laparoscopic surgery procedures.[8] The purpose of the present study is to design and produce a gripper model for preventing tissue damage caused by geared clamps while gripping tissues during laparoscopic surgery and operating using Bernoulli's principle by the use of air flow. This is only possible by keeping the tissue in contact with the gripper with minimal or no contact. Bernoulli's principle explains the relationship between the speed and pressure of fluids. Pursuant thereto, there is an inverse proportion between the speed of the fluid in motion and the pressure exerted by the fluid. According to Bernoulli's principle, as the speed of the fluid increases in the region between the gripper surface and the object being gripped, the pressure in that zone decreases, and meanwhile, a pulling force occurs between the gripper and the object due to the variation in pressure between the top and bottom surfaces of the object that is gripped. There are non-contact grippers that are operated by using Bernoulli's principle and academic studies in the industrial field. Bernoulli's principle has been used to lift various delicate materials, including thin silicone plates,[9] woven fabrics and jelly blocks,[10] vegetables[11] and skin layers.[12] Some studies have shown that the Bernoulli technique may be used as a safe gripping technique during a surgical operation.[13,14] The Taguchi method, which is widely used in the scientific field for reduction of numbers of experiments and optimization in a study, was also used for the same purposes in this study.[15,16] In the literature, it was observed that different types of grippers are used especially in medical robots, and gripper design has an important place especially in

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medical applications.[17,18] Moreover, the Taguchi method is a commonly acknowledged technique in the field of design of experiments (DOE). It has been proven as valuable technique increating high-quality products at a lower cost. This approach is widely used in the industry and many scientific studies, particularly in the automotive, medical equipment, electronics and food processing industries.

In this study, grippers were designed and produced to prevent tissue damage caused by geared grippers while gripping tissues during laparoscopic surgery, and their performances were tested. Sixteen experiments were carried out to obtain the maximum air speed in different parameters from the produced grippers, and the Taguchi technique was utilized in the experimental design and optimization processes. The experimental results were evaluated using analysis of variance (ANOVA) and three-dimensional plots. Moreover, with this study, it was aimed to provide a unique value to the literature in terms of designing and producing new grippers different from grippers used in the literature and testing their performances.

Materials and Methods

Production and Working Principle of Grippers

In this study, 4 grippers operating with Bernoulli's principle were designed and produced using a three-dimensional (3D) printer to prevent tissue damage caused by grippers while gripping tissues during laparoscopic surgery. The full sections of the grippers produced for the experiments showing the air flow are shown in Fig. 1, and the solid models are shown in Fig. 2. The grippers were made of 32-micron sensitive bio-compatible liquid resin in the 3D printer produced by 3D Systems, with the model name Projet 3510 HD Plus. In the gripper designs, a deflector was placed in the center of the gripper surface so that the compressed air coming from the center of the gripper would change direction without directly hitting the object that is held, so that flexible and sensitive materials could be held without being damaged by the strong air jet. While the compressed air flows down the central channel, after it hits the deflector without touching the object, it is deflected laterally from the narrow space between the gripper surface and the object and flows out over the shape of the gripper surface (Fig. 1). According to Bernoulli's principle, when the speed of the fluid increases in the region between the gripper surface and the object, the pressure in that zone decreases, and as a result, a pulling force is formed on the object towards the gripper surface due to the pressure difference.

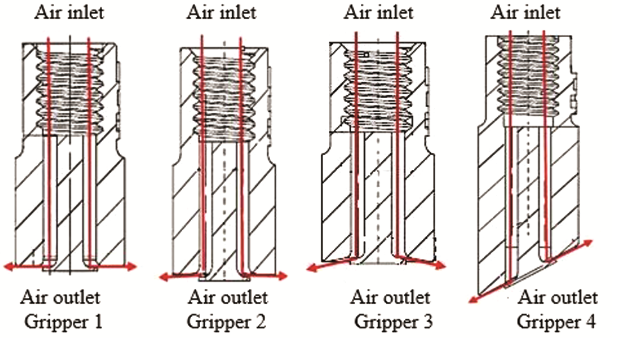

Fig. 1 — Gripper airflow models

Gripper 1, Gripper 2 and Gripper 3 had a gripper surface diameter of 10 mm, length of 20 mm, hole diameter of 4.8 mm and deflector diameter of 5 mm. Gripper 4 had a diameter of 10 mm, a length of 30 mm and a deflector diameter of 5.8 mm. The gripper surface and the deflector of Gripper 4 were made at an angle of 30° for situations that require angled gripping. All grippers were designed to pass through trocars with a standard hole diameter of 5–15 mm used in laparoscopic surgery. In order to contribute to the buoyant force, 12 venturi channels were opened on the surface of Gripper 2 to increase the air speed on the gripper surface. In doing so, it was aimed to make an additional contribution to the lifting action applied by the gripper by using the vacuum created in the middle part of the venturi channels.

Experimental Setup

An experimental setup was created to perform air speed tests with the four grippers that were produced and test their applicability in laparoscopic surgery and their gripping capacity (Fig. 3). In the experiments, an air tank with 50 liters of capacity, a maximum pressure of 8 bars and an air compressor with a 200 L/min flow rate capacity were used. The pressure of the air entering the system was measured with a

Fig. 2 — Laparoscopic gripper models used in experiments

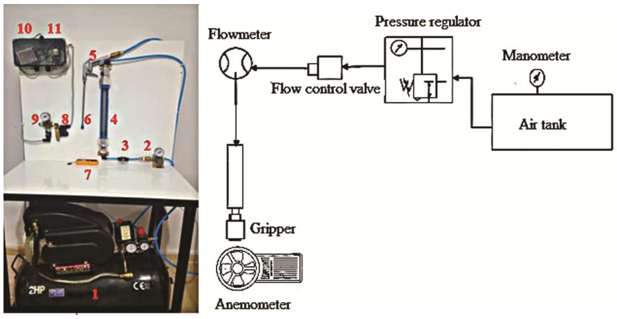

Fig. 3 — Experimental setup and air flow chart

pressure regulator. The speed of the air was adjusted with a one-way flow control valve, and the flow rate was adjusted with a flowmeter. The maximum air speed measurement tests of the four different grippers that were produced were carried out with a Benetech GM816 model anemometer.

As seen in Fig. 3 (a), 1 is the compressor and air tank, 2 is the pressure regulator, 3 is the one-way flow control valve, 4 is the flowmeter, 5 is the air gun, 6 is the gripper, 7 is the anemometer, 8 is the solenoid valve, 9 is the pressure sensor, 10 is the adapter, and 11 is the relay.

Experimental Design and Optimization

In the experimental design and optimization processes, the Taguchi technique was utilized. The Taguchi technique is used to optimize process parameters. It is a design of experiments method that is extremely valuable in the industry. Researchers can substantially decrease the number of experiments with analyses carried out with the Taguchi method. The purpose of optimization is to determine which variable contributes significantly to the quality of the product in the experiment by taking the mean values of different processing parameters determined by the Taguchi technique. The technique is used to determine which variable contributes significantly to the quality of the product in the experiment.[19,20] The most important one among these factors affecting quality is the loss function that occurs based on customer expectations. The values of the loss function are transformed into a signal noise (S/N) ratio.[21,22] Generally, three different quality features are used in signal to noise (S/N) ratio analysis — smaller is better, larger is better and nominal is better. Since the highest value for the maximum air speed measured for each experiment was desired, the "larger is better" function was used in this study (Eq. (1)).

Larger the better: $\eta = S/N_L = -10\,log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2}\right)$ …(1)

Table 1 — Parameters and their levels selected for the experiments

Parameters	Level 1	Level 2	Level 3	Level 4
Grippers (G)	1	2	3	4
Air pressure(Ap, bar)	4.5	5.5	6.5	7.0
Flow rate (Fr, m³/h)	2.2	2.6	3.0	3.4

Here, n is the number of observed values and y is the observed data.

Determination of Control Factors and Orthogonal Array

Orthogonal array selection for the Taguchi technique depends on the chosen factors, their interactions, the quantity of levels for each factor and the purpose of the experiment. Therefore, the experiment levels and variables are determined first for the correct orthogonal array selection. The selected experimental parameters and their levels are presented in Table 1.

The most suitable array [L16 (4^3)] was chosen to decide on the optimal experiment parameters and investigate the influences of these parameters that were determined. Therefore, the Taguchi L16 orthogonal array was made use of for the experimental design, and 16 experiments took place.

Conducting Experiments and S/N Ratios

Sixteen experiments were performed in accordance with the Taguchi L16 (4^3) array that was selected to establish the optimal experiment parameters and investigate the influence of these parameters. The gripping strength values measured as in the experiments conducted were optimized based on their S/N ratios. The air speed values measured by the experiments carried out according to the L_{16} Taguchi experimental design and the S/N ratios determined using Eq. (1) are shown in Table 2.

After 16 experiments were carried out, the mean air speed value was found to be 8.15625 m/s, whereas the mean S/N ratio was 18.11176 dB.

Determination of Optimum Parameters

The experimental parameters, expressed as the control factors, are distinguished in Table 3 by taking into account different levels and their possible influence according to the chosen orthogonal array. The levels here show the signal to noise ratio values calculated for the analysis of the air speed measurements in the experimental study and the mean values determined in relation to each level of the air speed values. The imputed values for the optimum parameters that were found were calculated using these values.

Another requirement for optimum value calculation is to determine the levels that are optimal. These

Table 2 — Experimental design, experimental results and S/N ratios

Test No.	Experimental Parameters			Experimental Results	
	Grippers (G)	Air Pressure (Ap, bar)	Flow Rate (Fr, m^3/h)	Air Speed (As, m/s)	S/N
1	Gripper 1	4.5	2.2	8.1	18.1697
2	Gripper 1	5.5	2.6	9.6	19.6454
3	Gripper 1	6.5	3.0	10.2	20.1720
4	Gripper 1	7.0	3.4	10.4	20.3407
5	Gripper 2	4.5	2.6	9.1	19.1808
6	Gripper 2	5.5	2.2	6.5	16.2583
7	Gripper 2	6.5	3.4	10.2	20.1720
8	Gripper 2	7.0	3.0	7.5	17.5012
9	Gripper 3	4.5	3.0	8.1	18.1697
10	Gripper 3	5.5	3.4	8.5	18.5884
11	Gripper 3	6.5	2.2	6.7	16.5215
12	Gripper 3	7.0	2.6	7.8	17.8419
13	Gripper 4	4.5	3.4	8.0	18.0618
14	Gripper 4	5.5	3.0	6.8	16.6502
15	Gripper 4	6.5	2.6	6.4	16.1236
16	Gripper 4	7.0	2.2	6.6	16.3909

Table 3 — Mean air speed and S/N ratios (dB)

	Means				
Parameters	Level 1	Level 2	Level 3	Level 4	*Delta*
		S/N ratios (dB)			
Gripper type (G)	19.58	18.28	17.78	16.81	2.78
Air pressure (P, bar)	18.40	17.79	18.25	18.02	0.61
Flow rate (Fr, m^3/h)	16.84	18.20	18.12	19.29	2.46
		Air speed (m/s)			
Gripper type (G)	9.575	8.325	7.775	6.950	2.625
Air pressure (P, bar)	8.325	7.850	8.375	8.075	0.525
Flow rate (Fr, m^3/h)	6.975	8.225	8.150	9.275	2.300

levels can be identified by evaluating different levels of the control factors depending on the outcomes of combinations produced by the L_{16} orthogonal array. These levels are employed to producethe main impact plots (Fig. 4).

The mean air speed distributions calculated according to the control factors and the levels are shown in Fig. 4. Since the "larger is better" feature was chosen in this study, the highest mean values for all levels were evaluated to determine the optimal control factor combination. Accordingly, the optimum combination of experiment parameters for the air speed values was determined as $A_1B_3C_4$ (A_1 = Gripper 1, B_3 = 6.5 bar pressure and C_4 = 3.4 m^3/h flow rate).

Analyses of Experimental Results

Analysis of Variance

Analysis of Variance (ANOVA) is a statistical analysis technique that is employed to identify and analyze the individual relationships of all experimental parameters in the Taguchi technique. In this study, the effects of gripper type, air pressure and fluid flow rate parameters on the air speed were investigated by using the ANOVA method. In the analysis process, the distributions of the percentages of all control factorswere utilizedto calculate their effects on the observed quality characteristics. The experiment results were analyzed in a 95% confidence interval.[23,24] The ANOVA table on the experimental results is demonstrated in Table 4.

According to the results of the ANOVA depicted in Table 4, the most effective factor affecting the air speed values was the gripper type with a contribution of 49.75%. This factor was followed by the flow rate with a contribution of 36.23%. The air pressure effect was 2.41%, and the error was obtained to be 11.61%. These results had similarity to those reported in a similar study in the literature.[25]

Mathematical Model for Experimental Results

Regression analysis is a common method used to model and analyze different variables that have a relationship among those including a dependent variable and one or more independent variables.

Considering the accuracy rate, in a high-accuracy equation, the result can be reached in a short time by using the experiment parameters without experimenting. In this study, the 3rd-order polynomial regression (cubic regression) model for the gripping strength and the mathematical model for the gripping strength were obtained, and the R^2 value of this model was found to be 88.39. The mathematical model that was obtained is shown in Eq. (2).

$$As = -37 - 4.09Gn - 50.3Ap + 155Fr + 1.33Gn^2 + 8.75Ap^2 - 55.4Fr^2 - 0.163Gn^3 - 0.5Ap^3 + 6.58Fr^3 \quad \ldots (2)$$

The results obtained from each of the 16 experiments and the mathematical model results obtained by the 3rd-order polynomial regression (cubic regression) model are compared in Fig. 5. As seen in the figure, the experimental results and the mathematical model (Eq. (2)) results almost overlapped. Only in the ninth experiment, a noticeable difference occurred. This situation originated from the fact that the accuracy rate of the mathematical model was 88.39%.

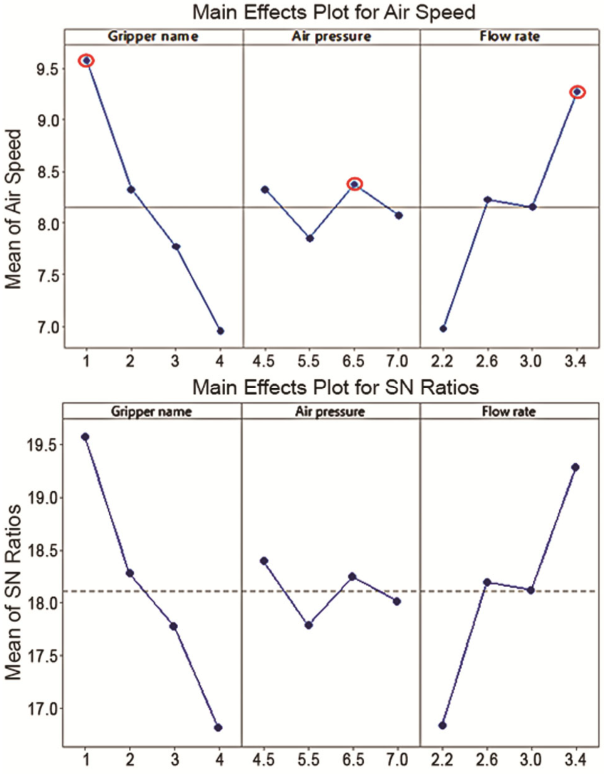

Fig. 4 — Main impact plots of gripper type, air pressure and flow rate for air speed and SN ratios

Comparison of Validation Experiments and Imputed Values

The objective of validation experiments that constitute the final step of the Taguchi method is to evaluate quality features. In addition to this, validation experiments are employed for testing the accuracy of the process of optimization. Validation experiments are carried out to test the determined optimum combination of the experiment parameters and levels. Based on the optimum combination found regarding the air speed by considering the individual impact of the experiment parameters, $A_1B_3C_4$ (A_1=Gripper 1, B_3 = 6.5 bar, C_4 = 3.4 m^3/h flow rate) estimated speed value (A_s) was calculated according to the equation given below.

$$\eta_g = A_1 + B_3 + C_4 - 2\eta_{\frac{S}{N}} \quad \ldots (3)$$

$$A_s = 10^{\eta g/20} \quad \ldots (4)$$

In the equations, $A_1B_3C_4$ are the signal to noise ratios of the optimum factor levels, η_g is the S/N ratio found for the optimum levels, and $\eta_{S/N}$ are the mean S/N ratios determined for the speed values. A_s is the imputed value calculated for the speedvalues. The imputed value was calculated for the air speed by

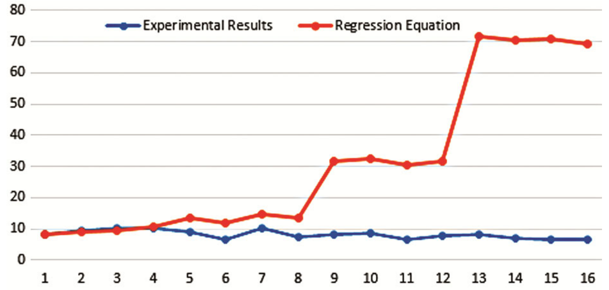

Fig. 5 — Comparison of experimental results and regression equation results on air speed based on experiment numbers

Table 4 — ANOVA results for maximum air speed

Variance Source	Degrees of Freedom (df)	Sum of Squares (SS)	Mean Squares (MS)	F-Value	P-Value	Contribution Rate (%)
Gripper type (G)	3	14.5669	4.8556	8.57	0.014	49.75
Air pressure (Ap)	3	0.7069	0.2356	0.42	0.748	2.41
Flow rate (Fr, m^3/h)	3	10.6069	3.5356	6.24	0.028	36.23
Residual Error *(e)*	6	3.3987	0.5665	—	—	11.61
Total	15	29.2794	—	—	—	100.00

Table 5 — Comparison of experimental and imputed values

	For Taguchi method			For 3rd order polynomial equation		
Levels	Exp.	Pred.	Error (%)	Exp.	Pred.	Error (%)
			Air speed (m/s)			
$A_1B_3C_4$ (Optimum)	10.06	11.080	10.130	10.06	10.660	5.620
$A_2B_1C_2$ (Random)	9.10	8.570	5.820	7.50	8.210	8.640
$A_3B_1C_3$ (Random)	8.10	8.016	1.029	7.80	7.620	2.300

using Eqs (3) and (4), and it was obtained as 1.5201. Researchers utilize the confidence interval (CI) for comparing the outcomes of the validation experiments tothe imputed value and validate the quality feature. Moreover, the mean value of the three validation experiments conducted with the optimum parameters should be between the lower and upper limit totals of this calculated confidence interval. The following equation is used to calculate the CI value.

$$CI = \sqrt{F_{\alpha:1,Ve} x V_{ep} x \left(\frac{1}{n_{eff}} + \frac{1}{r}\right)} \quad \dots(5)$$

Here, in Eq. (5), $F_{\alpha:1Ve}$($F_{1,6}$= 5.9874 from F table)is the F ratio of the level of significance α, α is the level of significance (95%), V_e denotes the degrees of freedom of the error (V_e = 6), V_{ep} is the error variance (V_{ep} = 0.5665), r indicates the number of validation experiments, and n_{eff} shows the number of results that are measured effectively.

$$n_{eff} = \frac{N}{1+V_t} \quad \dots(6)$$

Here, in Eq. (6), N denotes the total number of experiments (16), V_t indicates the total degrees of freedom (9) of the experiment parameters for which the average was found by taking into account Table 4. In the present study, 3 validation experiments were conducted by taking the optimum combination determined for the maximum air speed values measured into account. Considering these values, the number of effectively measured results was calculated as n_{eff}=1.6 for the measured speed. When the experimental results were evaluated within the 95% confidence interval and when Eq. (5) and Eq.(6) were considered, the confidence interval for the measured speed values was found as (CI) = 1.8025. The mean value of the 3 validation experiments carried out for the accuracy of the optimization and confidence interval calculation was 10.0666 m/s. In this case, the $(11.087-3.2505) < 10.0666 < (11.087 + 3.2505) = 7.8365 < 10.0666 < 14.3375$ interval was obtained, and the validation experiments resided inside the confidence interval. Therefore, the optimization process was successful.

The comparison of the predicted values determined with the Taguchi method to the experimental results is presented in Table 5. The imputed results and experimental values were found to be highly similar to each other. In reliable statistical analyses, the values of the errors must be smaller than 20%.

The experimental results were compared to the Taguchi method results and the imputed values obtained from the 3rd-order polynomial equation, and the results of the comparison are displayed in Table 5. The variation between the validation test result values and the values obtained using the Taguchi method was found to be very small. Accordingly, the results found with the validation experiments showed that the optimization process was successful.

Effects of Experiment Parameters on Air Speed

Three-dimensional plots were used for the effects of the experimental parameters on the air speed (Fig. 6).

The effects of the gripper type and pressure on the air speed are shown in Fig. 6a. Here, the results on Gripper 1 showed that as the pressure increased, the air speed increased. The effects of the gripper type and flow rate on the air speed are presented in Fig. 6b. Here, Gripper 1 showed the best performance as in Fig. 6a. According to this result, as the flow rate increased in Gripper 2, the air speed also increased. The lowest air speed demonstrated in Fig. 6b as 2.2 m^3/h was in Grippers 2 and 3. The effects of the flow rate and air pressure on the air speed are presented in Fig. 6c. In the figure, it is seen that the air speed increased as the flow rate and air pressure increased. Since high air speed was desired in this study, as seen in the plots, Gripper 1, with a high flow rate and a high air pressure value, provided the best result. Moreover, the effects of the flow rate and air pressure on the air speed are presented in Fig. 6b. Accordingly, the highest air speed was seen at a 7-bar pressure and a 3.4 m^3/h flow rate. This finding was similar to those on the parameters optimized with the Taguchi method.

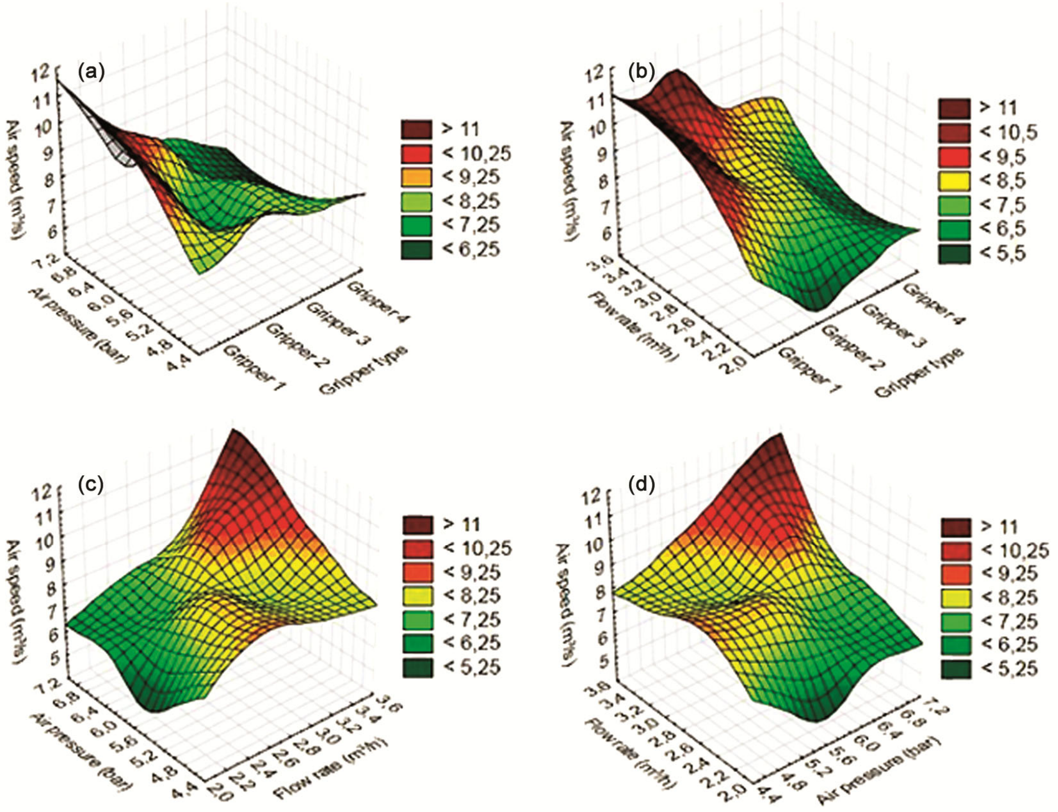

Fig. 6 — Effects of air pressure, flow rate and gripper type on air speed

Conclusions

Four grippers with different structures were designed for air speed experiments and produced in a three-dimensional (3D) printer. For the experiments, a special experimental setup was formed, and air speed was measured with a digital anemometer.

It is possible to list the results obtained in this study as follows:

- According to the results of the 16 experiments that were conducted, the mean air speed value was found to be 8.15625 m/s, and the mean S/N ratio was found to be 18.11176 dB.
- The S/N ratios calculated according to the experiment parameters and levels, and the optimum value calculated according to the plot of the mean air speed distributions was determined as $A_1B_3C_4$(A_1= Gripper 1, B_3 = 6.5 bar pressure, C_4 = 3.4 m^3/h air flow rate) for 16 experiments and their (4^3) possible combinations.
- The most effective factor in the analysis of variance (ANOVA) performed using the maximum air speed experimental results was the gripper type with a contribution rate of 49.75%. The gripper type was followed by the air flow rate with a contribution rate of 36.23%.
- As seen in the three-dimensional plots, Gripper 1 gave the desired high air speed results. In addition to this, in the same plots, it may be seen that as the flow rate and air pressure increased, the air speed, and thus, the gripping strength increased.
- The calculated Taguchi imputed value was found to be 11.08 Newton. In the validation experiments carried out by considering the optimal levels ($A_1B_3C_4$), the mean holding strength value was calculated as 10.06 Newton.
- The calculated Taguchi imputed value and the mean value of the validation experiments were compared, and the error rate was found to be 10.13%. For a reliable analysis, the error values in this comparison should be lower than 20%.
- In the three-dimensional plots, it may be observed that Gripper 1 gave the desired air speed results that affected the high pulling force. In addition to this, in the same plots, it may be seen that as the flow rate and air pressure increased, the gripping strength increased.

In laparoscopic surgery, grippers with a geared profile structure that are operated by using a clamping force are used to prevent organs and tissues from slipping out of the grippers. Since tactile feedback cannot be received during gripping, there is a risk of damage to organs due to the use of a clamping force. Thus, this study has a unique value in that it includes an experimental study that will benefit gripper types designed for the field of laparoscopic surgery.

References

1 Rosen J, Hannaford B, MacFarlane M P & Sinanan M N, Force controlled and teleoperated endoscopic grasper for minimally invasive surgery-experimental performance evaluation, *IEEE Trans Biomed Eng*, **46(10)** (1999) 1212–1221, doi:10.1109/10.790498.

2 van Vaelen M A, *Human-Product Interaction in Minimally Invasive Surgery*, PhD Dissertation, Delft University, 2003.

3 Cuschieri A, Whither minimal access surgery: Tribulations and expectations, *Am J Surg*, **169(1)** (1995) 9–19.

4 Moreno-Egea A, Torralba J A, Morales G, Fernández T, Guzmán P, Hita G, Girela E, Corral M, Campillo A & Aguayo J L, Laparoscopic repair of secondary lumbar hernias: Open vs. laparoscopic surgery, A prospective, nonrandomized study, *Cir Esp*, **77(3)** (2005) 159–162, doi:10.1016/s0009-739x(05)70828-9.

5 Dedemadi G, Sgourakis G, Karaliotas C, Christofides T & Kouraklis G, Comparison of laparoscopic and open tension-free repair of recurrent inguinal hernias: A prospective randomized study, *Surg Endosc Other Intervent Tech*, **20(7)** (2006) 1099–1104, doi:10.1007/s00464-005-0621-8.

6 Roumm A R, Pizzi L, Goldfarb N I & Cohn H, Minimally invasive: Minimally reimbursed? An examination of six laparoscopic surgical procedures, *Surg Innov*, **12(3)** (2005) 261–287, doi:10.1177/155335060501200313.

7 Stefanoni M, Casciola L, Ceccarelli G, Spaziani A, Conti D, Bartoli A, Di L Z, Bellocchi R & Valeri R, The biliopancreatic diversion, A comparison of laparoscopic and laparotomic techniques, *Minerva Chir*, **61(3)** (2006) 205–213.

8 Trommelen M, *Development of a medical Bernoulli gripper*, Master's Thesis, Delft University of Technology, 2010.

9 Brun X F & Melkote S N, Analysis of stresses and breakage of crystalline silicon wafers during handling and transport, *Sol Energy Mater Sol Cells*, **93(8)** (2009) 1238–1247, doi:10.1016/j.solmat.2009.01.016.

10 Erzincanli F & Sharp J M, Meeting the need for robotic handling of food products, *Food Control*, **8(4)** (1997) 185–190, doi:10.1016/S0956-7135(97)00047-9.

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

12 Dini G, Fantoni G & Failli F, Grasping leather plies by Bernoulli grippers, *CIRP Ann*, **58(1)** (2009) 21–24, doi:10.1016/j.cirp.2009.03.076.

13 Sun S, Li J-Y, Hu P-Y& Wu S-J, Starfis™-assisted off-pump obliteration of massive coronary arteriovenous fistulae, *Tex Heart Inst J*, **32(4)** (2005) 595–597.

14 Gentilli S, Ferrero A, Velardocchia M & Garavoglia M, Laparoscopic adrenalectomy: Advantages of an atraumatic suction grasper, *Surg LaparoscEndosc*, **8(5)** (1998) 335–337.

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

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

17 Nawrat Z, Robin heart progress-advances material and technology in surgical robots, *Bull Pol Acad Sci Tech Sci*, **58(2)** (2010) 323–327, doi:10.2478/v10175-010-0030-6.

18 Zieliński C & Winiarski T, General specification of multi-robot control system structures, *Bull Pol Acad Sci Tech Sci*, **58(1)** (2010) 15–28, doi:10.2478/v10175-010-0002-x.

19 Roy R K, *A primer on the Taguchi Method*, (Van Nostrand Reinhold, New York) 1990.

20 Ross P J, *Taguchi Techniques for Quality Engineering*, **2nd edn**, (McGraw-Hill Prof., New York) 1996.

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

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

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

24 Kıvak T, Optimization of surface roughness and flank wear using the Taguchi method in milling of Hadfield steel with PVD and CVD coated inserts, *Meas*, **50** (2014) 19–28, doi:10.1016/j.measurement.2013.12.017.

25 Ertürk Ş & Samtaş G, Design of grippers for laparoscopic surgery and optimization of experimental parameters for maximum tissue weight holding capacity, *Bull Pol Acad Sci Tech Sci*, **67(6)** (2019) 1125–1132, doi:10.24425/bpasts.2019.130894.