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Statistical Modeling Optimization and Sensitivity Analysis of Tool's Geometrical Parameters on Process Force in Automatic Cortical Bone Drilling Process

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P A P E R I N F O	*A B S T R A C T*

One of the most prevalent machining processes in medical treatments is bone drilling process. During bone drilling, excessive process force can cause breakage, crack initiation and severe damage to bone tissue. In this paper, a systematic study with simultaneous use of response surface method, sensitivity analysis based on Sobol method and regression analysis is performed for investigation the effect of helix angle and point angle of the tool as the most important geometrical parameters on imposed force to the bone during drilling process. Initially, using design of experiments and response surface method, imposed force to the bone is modeled and the governing second order linear regression equation is derived and verified. Then, using Sobol sensitivity analysis, with ability to quantify the sensitivity, it is attempted to investigate the effect of input parameters on drilling force. Finally, optimization of the process inputs is followed to find the best combination which yields the desired drilling force. The minimum drilling force, within the range of input parameters, coincides with point angle of 90 and helix angle of 18. This minimal force is lower than the force in surgery and standard tools. The results showed that an increasing in point angle leads to an increase in drilling force. Also, it is concluded that there is an optimum value for using the helix angle in bone drilling process with minimum imposed force.

1. INTRODUCTION

Bone is an important limb in different species including humans. The goal of bone surgery is to keep damaged segments of the bone close to each other in the way that self-recovery of the bone is guaranteed. Drilling is quite often a must in order to keep bone segments fixed. As ubiquitously known, when bone tissue undergoes excessive force, the tissue would be severely damaged and can eventuate in crack initiation or breakage. During bone drilling, the axial force is imposed on bone. Many parameters such as process and tool geometry parameters affect the axial force of bone drilling process. In case of tool geometry, the tool diameter, point angle and also helix angles are prominent ones. There are some reports addressing the minimization of the axial force in the literature. Singh et al. [1] compared the effects of rotational speed, feed rate and tool diameter on cutting

force and temperature in conventional and rotary ultrasonic bone drilling. They concluded that the cutting force up to 40% and temperature up to 55% were lesser in rotary ultrasonic technique. Ying et al. [2] compared the conventional cutting (CC) and ultrasonic vibration assisted cutting (UVAC) bone drilling processes. Their results showed that UVAC can decreases the cutting force but increases the temperature. Shu et al. [3] proposed a novel drill bit with the ability of self-centering for drilling of low-trauma bones. They reported that the proposed drill bit could significantly reduce the cutting force. They also developed an experimental setup for comprehensive analysis of bone drilling process. Zhang et al. [4] compared the cutting force between continuous and step-by-step bone drilling process. They concluded that step-by-step drilling technique can reduce the cutting force in drilling process of cortical bones. Gupta et al. [5] studied the effects of various drilling techniques such as conventional surgical drilling, rotary ultrasonic bone

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drilling and rotary bone drilling of cutting force in bone drilling process. Their results showed that rotary ultrasonic technique using hollow tool can significantly reduce the cutting force. Sui and Sugita [6] studied the effects of process parameters and bone material on drilling force. They concluded that increasing the feed rate and drill diameter lead to increasing the drilling force. Also, they proved that drilling force is the highest in bovine cortical bone while it is the lowest for Sawbones 3401. Sarparast et al. [7] investigated the force and temperature in high-speed bone drilling process. Their results showed that the high-speed drilling process leads to decrease in drilling force and temperature. Also, they concluded that rotational speed, feed rate and tool diameter are as the most important affecting parameters in high-speed drilling process. Alam et al. [8] studied the effect of drill wear on bone temperature and cutting force in drillibg process. They concluded that the sharp drill has a significant effect on decreasing the cutting force and temperature. Zolfaghari et al. [9] developed a model based on response surface methodology to investigate the effects of tool rotational speed, feed rate and tool diameter on temperature in bone drilling process. They showed that the process temperature will be increased with increasing the rotational speed and tool diameter. Singh et al. [10] reported that the point angle between 130- 140 can minimized the process force. Augustin et al. [11] reported that with increasing the bore diameter, contact surface of the bone-tool increases leading to higher frictional forces and process force. Considering saw bone they also mentioned that with an increase in bore diameter, bone strength decreases and that lengthen the recovery period. Up to now, there is no standard code to dictate standard geometry for the bone drilling tool. Currently there are some studies working to present the standard tool geometry for bone drilling process. Some find the conventional drilling tool for metals very promising for bone drilling process. Pandey et al. [12] reported that the dimensional accuracy of the bore and drilling force are preferable when standard tool with point angle of 118 and helix angle of 30 are used in bone drilling. Tuijthof et al. [13] considering different tools, including the diameter of 3.5 mm, studied the effect of tool geometry and feed rate on drilling axial force on both cortical and trabecular bones. They found conflicting effects in combination of parameters. However, they reported with a constant tool diameter, the most influential parameters are point angle and helix angle and there should be an optimum combination of them both. Singh et al. [14] considering three different tool geometries with the same diameter of 4 mm studied the dimensional accuracy and bore surface roughness and found the standard geometry the best among all three. Green et al. [15] studied different point and helix angles found that point angle of 118 and helix angle of 28 would eventuate into the lowest drilling force. Höller [16]

reviewing surgery and machining standards and handbooks and reviewing the literature found conflicting reports. He eventually, for the diameter of 3.5 mm for drilling tool, introduces point angle of 105 and helix angle of 27 as the optimized minimum force state. While surgery standards, confirm a tool with point angle of 78 and helix angle of 14. Metal machining standard, also, proves a different combination of point angle of 118 and helix angle of 22-30. Tahmasbi et al. [17] using design of experiment found that lowering tool diameter causes the lower bone drilling force while increasing feed rate raises the force. Having a general look over the reported studies one can notice different inferences and presented data which is attributed to the incorrect and incomplete relation between studied input and output parameters. To address this issue and achieving the optimum tool geometry for bone drilling requires an accurate design of experiment to quantify the effect of point angle, helix angle and rake angle on drilling force and temperature [18]. It should be born in mind that the material and coating of the tool should meet the medical requirement of a surgery. Moreover, up to now, no statistical sensitivity analysis has been applied to quantify the effect of different tool parameters on bone drilling force.

In this paper considering the main tool geometry parameters like point and helix angles, for the first time a linear second order regression equation was derived using response surface method in order to predict bone drilling force. The interactional effects and individual effects were analyzed and optimization was performed. Furthermore, Sobol sensitivity analysis was used to quantitatively obtained the effect of different parameters on bone drilling force.

1. 1. Application of Mathematical and Statistical Methods in Process Analysis

In engineering problems involving experimentation and simulation, where output is complicatedly dependent on many input factors, using experiment designed by statistical methods can markedly assist design, modeling and analysis of the process. One of the greatest methodologies in this field is response surface method [19]. Design of experiments not only helps to save time and effort, but also reveals defects of experimentation along with trouble nshooting [20]. The accuracy of experimentation as well as fitted model, the interactional effect of parameters, optimization of the process is revealed by response surface methodology (RSM) and are considered as advantages of this method [21]. This method is capable to find a relation between input and output parameters in the form of a second order linear regression equation. General form of the equation considering parameters and their interactions can be written in the form of equation (1).

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_i \sum_j \beta_{ij} x_i x_j + \varepsilon \tag{1}$$

1. 2. Sensitivity Analysis Methods Sensitivity analysis is robust for the case of system analysis and it illustrates the effect of input parameters on outputs of a system. Sensitivity analysis studies the uncertainties of the output and relates that to the uncertainties of the input parameters [22]. One of the main methods is Sobol sensitivity analysis. In this method, for the defined model Y=f(X), where Y is the output and $X(x_1 , x_2 , ... , x_n)$ is the vector of input parameters, output variance (V) can be defined as the summation of each separated term as defined in Equation (2):

$$V(Y) = \sum_{i=1}^{n} V_i + \sum_{i \leq j \leq n}^{n} V_{ij} + \cdots + V_{1,...,n} \qquad (2)$$

where V_i is the first order effect for each input factor $x_i (V_i = V[E(Y|x_i)])$ and $V_{ij} = V[E(Y|x_i , x_j)] - V_i - V_j$ to $V_{1 , ... , n}$ shows the interaction among n factors. Sensitivity index can be defined as the ratio of variance of every order to the total variance e.g. $S_i = \frac{V_i}{V}$ is the first order sensitivity index and $S_{ij} = \frac{V_{ij}}{V}$ is the second order sensitivity index and so on. The overall index which defines the effectiveness of each parameter is defined as the summation of its ordered sensitivity indices as presented in Equation (3) [23].

$$S_{Ti} = S_i + \sum_{i \neq j} S_{ij} + \cdots \qquad (3)$$

2. MATERIALS AND METHODS

As previously mentioned, in this paper, a systematic study with simultaneous use of response surface method, sensitivity analysis based on Sobol method and regression analysis is performed for investigation the effect of helix angle and point angle of the tool as the most important geometrical parameters on imposed force to the bone during drilling process. For this purpose, point angle and helix angle are considered as input variables and maximum drilling force during the process was considered as the output of the process. Fresh bovine bone (cow having age of 3 to 4 years) was used for making experimental samples (Figure 1) [24]. To ease experimentation both ends of bovine ankle bone was cut with a saw. The depth of the drilling was limited to 4 mm. As bone properties changes dramatically with time, it was attempted to be sure that the carcass which was to give the bone, is fresh [25]. Figure 2 depicts geometry of a standard tool with different specifications. Tools are HSS standard steels with diameter of 3.5 mm and in order to guarantee sharp edges they were un-used (Figure 3). The reason behind tool selection is the general inclination of the researchers and surgeons and also marketing availability. These tools possess three different helix angle of 14, 20.5 and 27 and point angle was formed with a too sharpener tool with angles of 90, 112.5 and 135 and angles were checked with angular gauges (Table 1).

Tabriz automatic drilling machine was used to perform experimentation. To measure drilling force a laboratory load cell was used (Figure 4). Snapshot of an experimentation is depicted in (Figure 5). Rotational speed and feed rate were tuned to 2000 rpm and 30 mm/min, respectively.
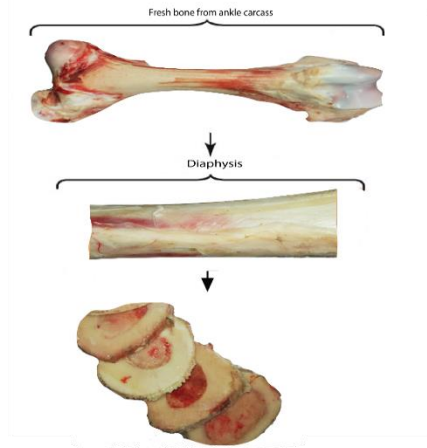
Figure 1. Fresh bovine bone from fresh ankle carcass
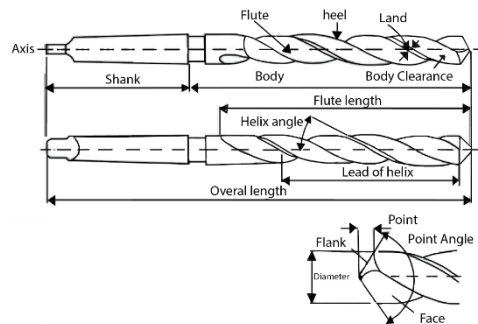
Figure 2. Standard drilling tool with geometrical specifications

Figure 3. Standard drilling tool (Diameter: 3.5 mm) with different point and helix angles
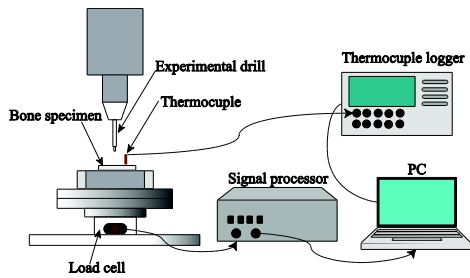
Figure 4. CNC automatic drilling machine

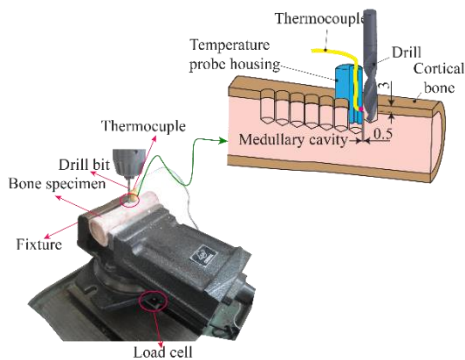**Figure 5.** Experimentation in bone drilling process

TABLE 1. Machining input parameters in three different stages

	Minimum	Mean	Maximum
Helix angle	14	20.5	27
Point angle	90	112.5	135

According to design matrix (Table 1), 11 sets were examined. Table 2 shows the results. Using response surface method and data analysis a governing second order linear regression equation was derived considering the best fit to the data points and analysis of the output data was performed.

2. ANALYSIS AND MODELING OVER DATA

Considering the results from force analysis using analysis of variance (ANOVA) listed in Table 3. ANOVA shows the effect of different parameters mentioned in regression equation and therefore, it is crucial in analysis and modeling of data. ANOVA table in design of experiments reveals the input factors and their interactional effects over the response of the system [20].

Considering a preferable reliability of experimentation equal to 95% in this study, the p-value of 0.05 was considered to obtain the effect of different parameters [20]. PRESS of the fitted model to data point can show the accuracy of the governing equation which

TABLE 2. Layout of experiments based of RSM

	Helix angle (Degree)	Point angle (Degree)	Force (N)
1	14	90	25.6
2	14	135	102.4
3	27	90	65.2
4	27	135	153.4
5	20.5	90	37.4
6	20.5	135	59.3
7	14	112.5	54.4
8	27	112.5	103.7
9	20.5	112.5	52.17
10	20.5	112.5	55.5
11	20.5	112.5	58.9

TABLE 3. Analysis of variance for cortical bone drilling force

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
Model	4	11784.6	11784.6	2946.15	12.43	0.005
Linear	2	9083.9	9083.9	4541.97	19.16	0.002
helix angle	1	3262	3262	3262	13.76	0.01
point angle	1	5821.9	5821.9	5821.93	24.56	0.003
Square	2	2700.6	2700.6	1350.32	5.7	0.041
(H.A)*(H.A)	1	2699.7	2482.2	2482.22	10.47	0.018
(P.A)*(P.A)	1	0.9	0.9	0.92	0	0.952
Error	6	1422.4	1422.4	237.07		
Total	10	13207				

is critical in the field of design of experiments. Lower value of this factor means the more accuracy of the prediction. In this paper the minimum value was achieved for second order full quadratic regression model [20]. Considering the values R-sq= 89.23 %, R-sq (pred)= 53.94% and R-sq (adj)= 82.23% as well as favorable distribution of the analysis of residuals, according to Figure 5, it can be implied that the presented model possesses a great precision. In case of RSM, a great factor showing the accuracy of the fitted model is R-sq which can be computed using Equation (2). As R-sq approaches 1 (100%) the correlation of the fitted model increases and therefore more precise prediction of the model is expected. Another prominent parameter is the analysis of the distribution of the residuals based on

Equation (4). A fitted model should pass close to the data points and the difference between the model and data points should be random in nature. The distance between model and data points can be discovered by R-sq and its random distribution can be seen in figure 6. Both proves that fit was perfect and random in terms of distribution of residuals.

$$FORCE = 150 - 26.79(HA) + 1.12(PA) + 0.741(HA)^2 + 0.0012(PA)^2 \qquad (4)$$

Figure 7 shows a 3D surface plot that describes the variations of drilling force with point and helix angles as input variables.

3. 1. Effect of Input Variables on Bone Drilling Force
In this section, considering the established model and effective parameters, it is attempted to clarify the effect of point angle and helix angle on drilling axial force. Diagrams in Figures 7 to 10 show the force evolution based on variation in input parameters using developed model by RSM [23].
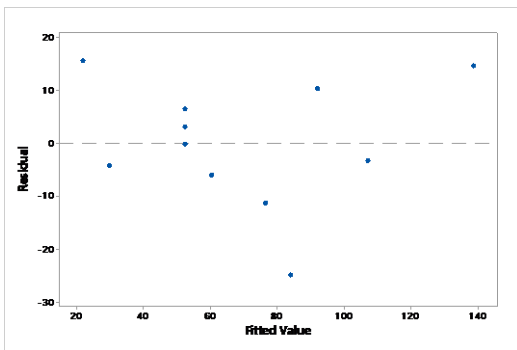

Figure 6. Distribution of residuals when fitted model is compared with data point (point graph produced by Minitab software package)
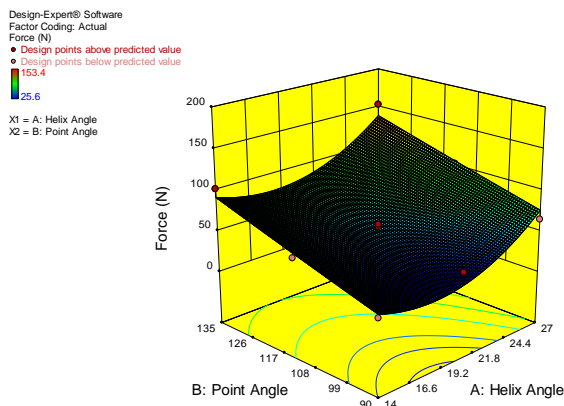

Figure 6. Distribution of residuals when fitted model is compared with data point (point graph produced by Minitab software package)

3. 1. 1. Effect of Helix Angle on Drilling Force
Considerong Figures 8, 10 and 11, it can be inferred that with increase in helix angle, firstly axial force experiences a reduction and then it increases. Increasing the helix angle up to 18° eases the chip removal and causes lower frictional and preventive forces between chips and bore wall and therefore causes a reduction in axial force. However, increasing helix angle more than 18°, due to the boosting surface, normal force and frictional forces causes the accumulation of chips in tools slot and therefore, an increase in axial force. In the former part of the diagram, the effect of chip's weight overweighs that of friction but in the latter part the frictional forces are dominant. It can be implied therefore, that for keeping the drilling force minimized, the helix angle should be opted around 18°.

3. 1. 2. Effect of Point Angle on Drilling Force
As depicted in Figures 9, 10 and 12, the lower point angle leads to decreasing the axial force. As point angle reduces, the surface of the tool in contact with the bone decreases and therefore penetrating force reduces and material removal is facilitated with lower required force. On the contrary, if the point angle increases, the required force for penetrating in the bone will be increased [26, 27]. When process force is higher, there is higher possibility for bone damage or breakage. Contour of Figure 10 reveals that in order to have the minimized force, helix angle and point angle should be selected as 18 and 90, respectively.

3. 1. 3. Sobol Sensitivity Analysis of Point and Helix Angles on Axial Drilling Force
As Before considering the Sobol sensitivity analysis, some points should be presented based of managerial insight. In using the Sobol method, the regression equation must be sufficiently accurate. Changes should be made between test intervals and the experimental data should be accurate enough.

Also, as the dimension of input parameters has no effect on the accuracy of the analysis, there is no sensitivity on the units of input parameters. Considering
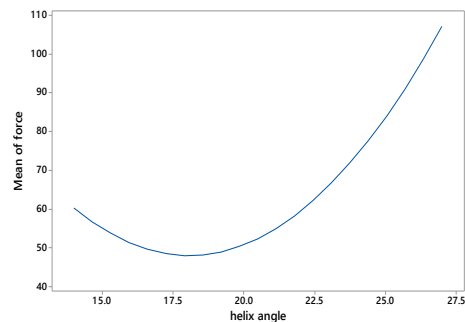

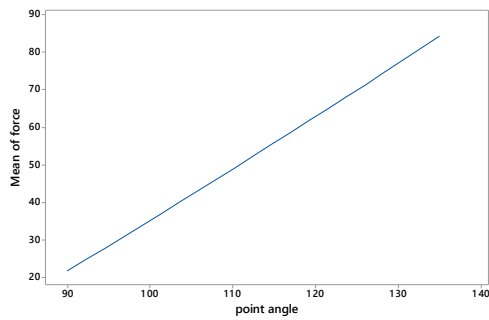**Figure 8.** Effect of helix angle on drilling force

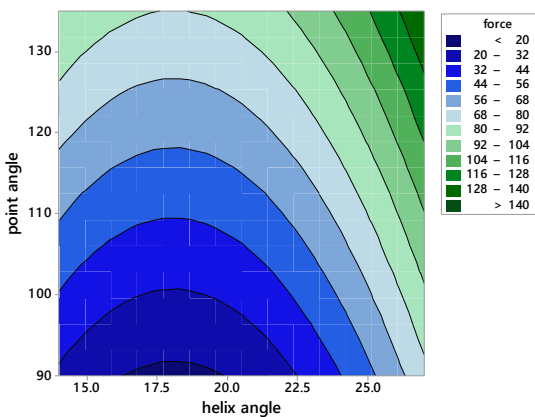**Figure 9.** Effect of point angle on drilling force

Figure 10. 2D contour plot of drilling force with point and helix angles as input variables
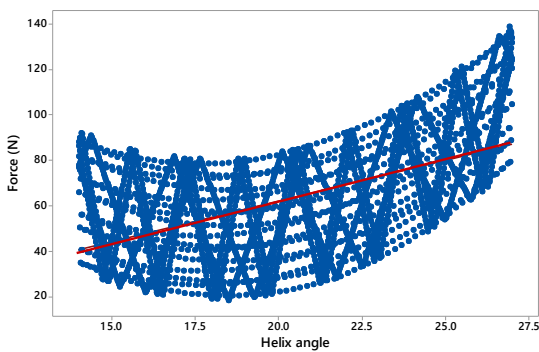

Figure 11. Sensitivity analysis of drilling force with variation in helix angle

Figures 11 and 12, along with ANOVA in RSM, it is inferred that within defined ranges of the point and helix angles, and considering the variation of all parameters at the same time, point and helix angle are similarly effective on drilling force, since, the slope of the diagrams which defines the influence of each parameter is similar for both parameters. Figure 13 shows the results of sensitivity analysis using Sobol method which

confirms the produced results. Figure 13 illustrates the effectiveness of input parameters using Sobol method in which all input parameters can vary at the same time, by using SIMLAB software [23].

3. 1. 4. Optimization of Axial Force in Bone Drilling Process and Comparison with Surgery Tool and Standard Tools
Considering the analysis over the drilling force, optimization of input variables to achieve the minimum drilling force was followed. Computing the minimum drilling force from the model and taking into account the desirability limit, the optimization result is shown in Figure 14. Optimum results and validation
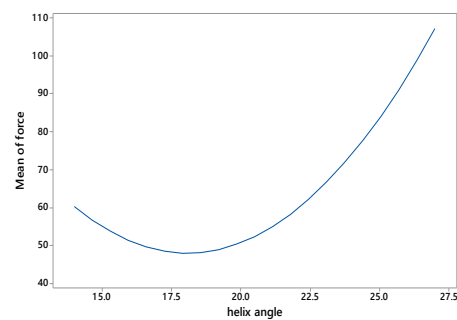

Figure 12. Sensitivity analysis of drilling force with variation in point angle
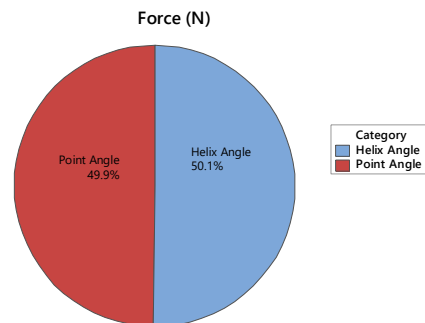

Figure 13. Effect of helix and point angles of drilling force obtained by Sobol sensitivity analysis
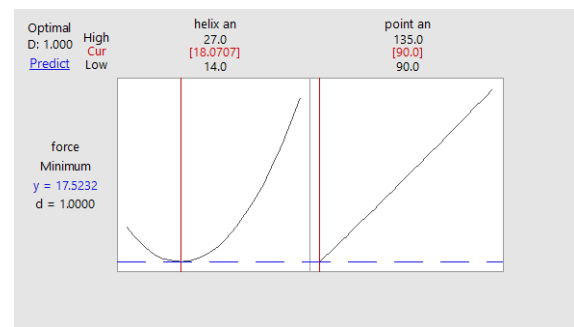

Figure 14. Parameter optimization to achieve minimum drilling force (produced by Minitab software package)

results are listed in Table 4. Moreover, optimum drilling force reported by Farnworth [14], Fuchsberger [12], Green [15] and Natali [13] is presented in Table 5 with the results of current study. Table 5 shows that considering point angle of 90 and helix angle of 18 the minimum force happened.

TABLE 4. Comparison of the optimum combination between experimental and established model

Force (N)	P.A	H.A	Optimization
17.52	90	18	Regression equation
18.40	90	18	Experiment
4.7%	-	-	Error %

TABLE 5. Comparison of optimum states in bone drilling process among different studies

	H.A	P.A	FORCE
Natali et al. [28]	24.0	118.0	82.7
Farnworth et al. [29]	27.0	130.0	132.7
Green et al. [15]	28.0	118.0	129.7
Pandey et al. [12]	30	118	162.4
Standard Surgery drill bit [16]	14	90	30.7
Standard drill bit [16]	26	118	103.2
Holler [16]	27	105	97.5
This research	18.0	90.0	18.4

4. CONCLUSION

In this study using RSM, modeling and optimization of the bone drilling process was followed. Point and helix angles are considered as input parameters and maximum drilling force during the process was taken as the output. The governing second order regression equation was derived and its accuracy was examined. Considering analysis performed, following findings can be highlighted:
1. Regression model can accurately predict drilling tool within the range of input parameters.
2. The results showed that with an increase in the point angle, the contact surface between tool and bore wall expands which boosts frictional forces leading to increase in axial force in bone drilling process.
3. In case of the effect of helix angle on axial force in bone drilling, there is an optimum value. Increasing helix angle up to 18 facilitates chip removal and decreases friction and consequently causes a lower drilling force. However, more raise (upper than 18) in helix angle, leads to a higher drilling force due to higher surface normal and frictional force.

4. Sobol sensitivity analysis quantitatively revealed the effect of each input parameters on drilling force. Accordingly, helix angle has the effectiveness of 50.1% and point angle has the effectiveness of 49.9%.
5. Considering the optimization performed, point angle of 90 and helix angle of 18 results in the lowest axial drilling force in cortical bone drilling process.
6. Drilling force by presented optimum combination (point angle of 90, helix angle of 18 and tool diameter of 3.5 mm) is lower than that by either standard metal drilling tool or surgery tool. This finding can assist tool design at its initial stages.

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Persian Abstract

چکیده

یکی از رایج ترین فرآیندهای ماشینکاری در درمان های پزشکی، فرآیند سوراخکاری استخوان است. طی سوراخکاری استخوان، نیروی فرآیند بیش از حد می تواند سبب شکستگی، شروع ترک و آسیب شدید به بافت استخوانی شود. در این مقاله، یک مطالعه سیستماتیک با استفاده همزمان از روش پاسخ سطح، آنالیز حساسیت بر مبنای روش سوبل و آنالیز رگرسیون به منظور بررسی اثر زوایای مارپیچ و رأس مته به عنوان مهمترین پارامترهای هندسی بر نیروی وارد شده بر استخوان حین فرآیند سوراخکاری انجام می شود. ابتدا، با استفاده از طراحی آزمایش ها و روش پاسخ سطح، نیروی وارد شده بر استخوان مدلسازی شده و معادله رگرسیون خطی مرتبه دوم حاکم بر آن استخراج و تایید می گردد. سپس با استفاده از آنالیز حساسیت سوبل، با توانایی تعیین مقدار حساسیت، تلاش می شود که اثر پارامترهای ورودی بر نیروی سوراخکاری بررسی شود. نهایتاً، بهینه سازی پارامترهای ورودی فرآیند به منظور یافتن بهترین ترکیب که منجر به دستیابی به نیروی سوراخکاری مورد نظر شده دنبال می گردد. حداقل نیروی سوراخکاری، در محدوده پارامترهای ورودی، با زاویه رأس ۹۰ درجه و زاویه مارپیچ ۱۸ درجه به طور همزمان اتفاق می افتد. حداقل نیرو کمتر از نیرو در جراحی و ابزارهای استاندارد می باشد. نتایج نشان می دهند که افزایش در زاویه رأس منجر به افزایش نیروی سوراخکاری می شود. همچنین، نتیجه گرفته می شود که یک مقدار بهینه برای استفاده از زاویه مارپیچ در فرآیند سوراخکاری استخوان با حداقل نیروی وارد شده وجود دارد.