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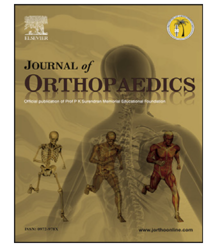

Original Article

Optimization of multiple quality characteristics in bone drilling using grey relational analysis

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ABSTRACT

Purpose: Drilling of bone is common during bone fracture treatment to fix the fractured parts with screws wires or plates. Minimally invasive drilling of the bone has a great demand as it helps in better fixation and quick healing of the broken bones. The purpose of the present investigation is to determine the optimum cutting condition for the minimization of the temperature, force and surface roughness simultaneously during bone drilling.

Method: In this study, drilling experiments have been performed on bovine bone with different conditions of feed rate and drill rotational speed using full factorial design. Optimal level of the drilling parameters is determined by the grey relational grade (GRG) obtained from the GRA as the performance index of multiple quality characteristics. The effect of each drilling parameter on GRG is determined using analysis of variance (ANOVA) and the results obtained are validated by confirmation experiment.

Results: Grey relational analysis showed that the investigation with feed rate of 40 mm/min and spindle speed of 500 rpm has the highest grey relational grade and is recommended setting for minimum temperature, force and surface roughness simultaneously during bone drilling. Feed rate has the highest contribution (59.49%) on the multiple performance characteristics followed by the spindle speed (37.69%) as obtained from ANOVA analysis.

Conclusions: The use of grey relational analysis will simplify the complex process of optimization of the multi response characteristics in bone drilling by converting them into a single grey relational grade. The use of the above suggested methodology can greatly minimize the bone tissue injury during drilling.

1. Introduction

Drilling of bone is common to produce hole for screw insertion to fix the fractured parts in wide range of orthopaedic surgeries. Bone drilling temperature and forces plays a very important role on the outcome of orthopaedic operation because a higher dose of them produces high heat effected zone and micro cracks in the bone resulting in damage or even

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death of the bone cells (osteonecrosis) surrounding the drilled hole. This damage or death of bone cells may delay the process of healing or reduce the stability and strength of the fixation.[1–5] Moreover, the improper surface finish hampers the proper engagement of the screws with the bone surrounding the drill site and can lead to the loosening of fixation.[5] In past, many researchers have studied the process of bone drilling to evaluate the effect of spindle speed and feed rate on temperature force and surface roughness. Thompson[6] reported that the temperature increases at 2.5 mm and 5.0 mm from the drill hole with increasing speed from 125 rpm to 2000 rpm. Vaughan and Peyton[7] suggested that increasing the spindle speed from 1000 rpm to 10000 rpm increases the bone drilling temperature. Matthews and Hirsch[8] investigated the bone drilling process on human femora and observed no significant changes in drilling temperature on increasing the spindle speed from 345 rpm to 2900 rpm. Brisman[9] performed drilling experiments on bovine cortical bone with drilling speeds of 1800 and 2400 and reported that the drilling temperature increases with the increase in the drilling speed. Hillery and Shuaib[10] conducted drilling investigations on human and bovine bone and found that the temperature decreases significantly with increasing drill speed from 400 rpm to 2000 rpm. Nam et al[11] conducted bone drilling experiments on bovine ribs with 600 rpm and 1200 rpm and suggested that the temperature increases with increasing the drilling speed. Sharawy et al[12] drilled pig jaw bones with three spindle speed of 1225 rpm, 1667 rpm, and 2500 rpm and showed that the temperature decreases with increase in spindle speed. Lee et al[3] performed drilling experiments on bovine bone in the ranges of 800 rpm–3800 rpm and concluded that the bone drilling temperature rises with increase in drill speed. The effect of increase in feed rate on temperature is reported by Augustin et al[13] and Lee et al,[3] they found that the temperature decreases with increase in feed rate as the increase in feed rate increases the rate of heat generation rate but causes reduction in drilling time therefore less total heat is generated. The review of the effect of spindle speed on bone drilling temperature suggests no consistent trend. Some suggests low spindle speed as they found that the temperature increases with increase in spindle speed while others suggest a decrease in temperature with increase in spindle speed.

Jacob et al[14] investigated the drilling of bovine tibia with several drill bits under different conditions of feed rate and rotational speed to study the behaviour of thrust force. They found that the thrust force increases on increasing the feed rate and decreases with the increase in spindle speed. Wiggins and Malkin[15] used common surgical twist bit, general purpose twist bits and specially constructed spade bit to study the variation of the thrust force with feed rate. They reported that with all types of drill bits the increase in feed rate causes increase in thrust force. Udiljak et al[16] performed bone drilling investigations with various cutting speed and feed rate and observed the similar phenomenon as reported by Jacob et al Ueda et al[17] used Taguchi method to optimize the drill bit specifications for minimum force generation during drilling of porcine femur without optimizing the drilling parameters. Similar results were observed by Lee et al[18] using their theoretically developed mechanistic model and experimental investigation on bovine bone for predicting thrust force in

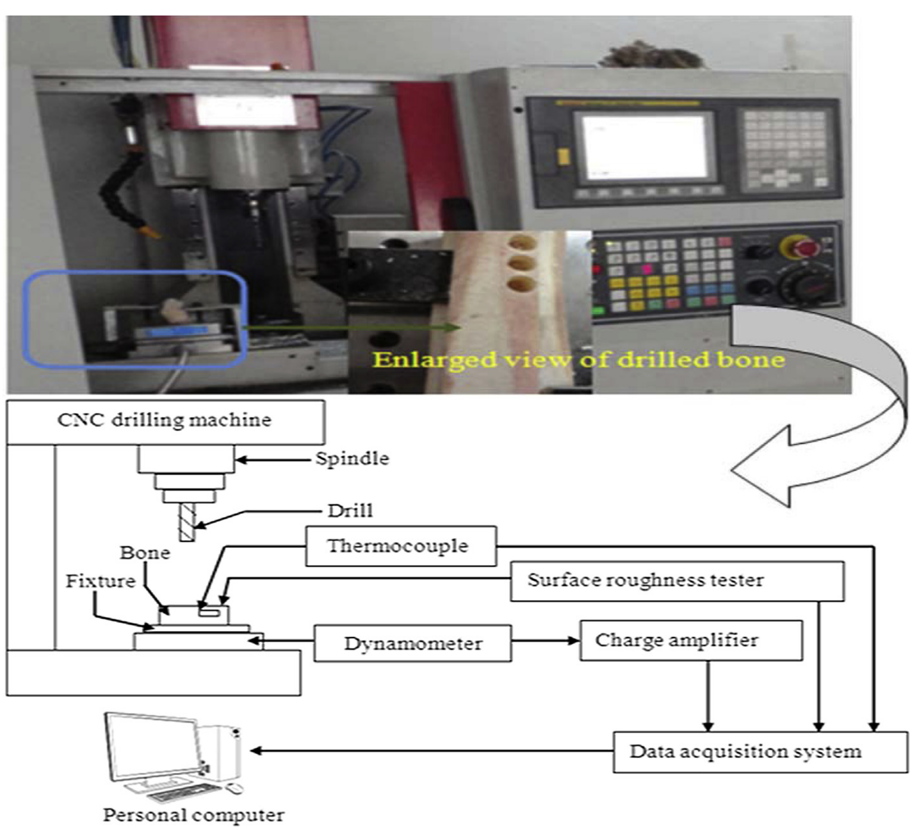

Fig. 1 – Experimental set up.

Table 1 – Factors and level considered for drilling.

	Control factor	Level 1	Level 2	Level 3
A	Feed rate (mm/min)	40	50	60
B	Spindle speed (rpm)	500	1500	2500

bone drilling. Wang et al[19] studied the effect of spindle speed and feed rate on the forces produced during drilling of bovine bone and reported similar trend as observed by Jacob, Udiljak and Lee. Alam et al[5] drilled bovine femur and observed the influence of spindle speed and feed rate on surface roughness of the drilled hole.

Despite of all the above relevant experimental investigations on bone drilling, the problem of high heat affected zone, micro cracks resulting due to the thrust force and the surface finish of the drilled hole still remains the challenging issues. The review of the literature suggests that most of the previous researches were aimed to investigate the effect of drilling parameters on the individual responses such as bone drilling temperature, force and surface roughness. Therefore, present work is focused on finding the optimal level of cutting parameters for simultaneous minimization of temperature (T), force (F) and surface roughness (SR) that can contribute significantly to minimize the bone tissue injury and will produce holes with superior quality.

2. Materials and methods

2.1. *Material*

The work material used is bovine femur as human bones are not easily available, and it is the closest animal bone to replicate the characteristics of human bone.[3–5] The bovine femora were obtained from a local slaughter house immediately after the slaughter and experiments were performed within few hours to retain the mechanical and thermo-physical properties of the bone.[2,3,5] No animals were sacrificed specifically for the purpose of this study. The bone specimens were healthy and visually free from any musculoskeletal disease or damage.

2.2. *Experimental set up*

MTAB 3 axis Flex mill was used for conducting the experiments. An Extech K-type thermocouple with data acquisition software was used for the acquisition of temperature data. The thrust force was measured with Kistler 9257 B piezo-electric dynamometer. The thrust force signal was transmitted to Kistler 5070 multichannel charge amplifier, and stored in Pentium IV computer using Dynoware software for further analysis. The average surface roughness (R_a) of was measured using Mitutoyo surface roughness tester SJ-400. The experimental set up is shown in Fig. 1.

2.3. *Experimental design*

The bone drilling parameters considered are feed rate (mm/min) and spindle speed (rpm) each at three levels. A 3^2 full factorial design with a total of 9 experimental runs were carried out to take in account of the interaction effect on the response. Experiments have been performed by high-speed steel (HSS) drill bit of diameter 6 mm without any coolant. The selection of bone drilling parameters and their levels is based on the wide range of experiments reported in the literature.[1–5] The parameters used and their levels is shown in Table 1.

The responses considered are temperature (°C), thrust force (N) and average surface roughness (μm). The drilling depth is 8 mm, thermocouple is located at a depth of 3 mm from the top of the bone and is 0.5 mm from the edge of the test drill hole.[3] For each experimental run, the surface roughness is calculated at three different positions of the drilled hole and their average is taken as the final value. During bone drilling the value of each response not their mean values must be as low as possible for minimum bone tissue injury.[13] Each combination of experiment is repeated three times and the average of the highest value of each response is considered for analysis.

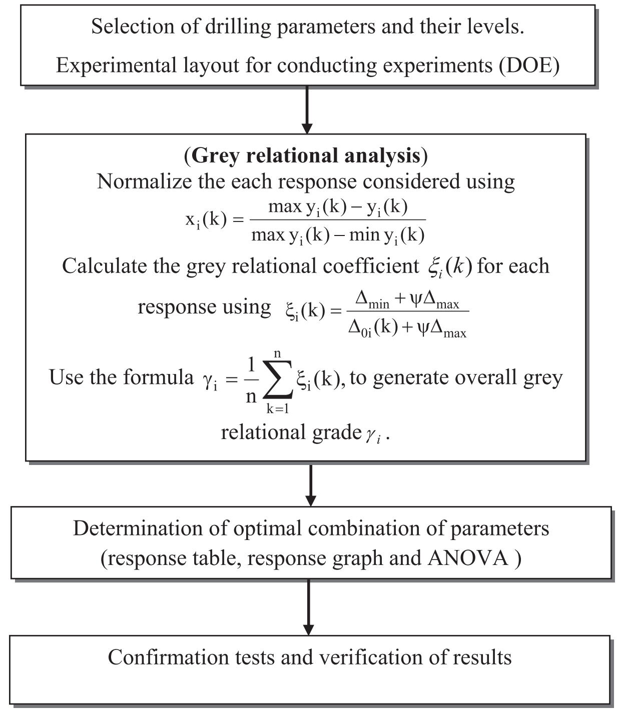

Fig. 2 – Procedure of grey relational analysis.

2.4. *Grey relational analysis*

Grey relational analysis initiated by Deng[20] is a powerful tool for solving problems with complex interrelationship between the multi objectives in various field of manufacturing.[21–27] GRA uses grey relational generation for calculating the grey relational coefficient to take in account of the complex system problem with uncertain and partial known information.[21–27] A grey relational grade (GRG) is obtained by averaging the grey relational coefficient of the individual responses to convert the optimization of the complex multiple performance characteristics into optimization of a single GRG.[21–27] The level of parameters with the highest grey relational

Table 2 – Experimental conditions and results.

Experiment no.	Actual setting value		Temperature (°C)	Force (N)	Average surface roughness (R_a) (μm)
	A	B			
1	40	500	45.7	12.28	1.04
2	40	1500	49.1	9.53	1.35
3	40	2500	50.7	8.01	1.48
4	50	500	44.5	19.74	1.21
5	50	1500	48.4	13.36	1.46
6	50	2500	50.1	10.14	1.70
7	60	500	46.5	30.85	1.31
8	60	1500	51.2	20.22	1.51
9	60	2500	52.6	16.30	1.78

grade is the optimal level for multi objective optimization.[21–27]

The step by step procedure followed to determine the optimal combination of bone drilling parameters for minimum temperature, force and surface roughness simultaneously during bone drilling is shown in Fig. 2. The detailed discussion on the calculation of the grey relational grade (GRG) using grey relational analysis is mentioned under the subsections below:

2.4.1. *Grey relational generation*

The first step in grey relational analysis is to normalize the data known as grey relational generation (Data pre-processing). Each response measured from the experiment is normalized in the range of 0–1 to get a comparable sequence because of different scope and dimension of the responses.[20–27] In Grey relational generation, normalized data for temperature, force and surface roughness corresponding to lower-the-better (LB) criterion can be expressed as (1):

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (1)$$

where $x_i(k)$ is the value after Grey relational generation, min $y_i(k)$ is the smallest value of $y_i(k)$ for the kth response, and max $y_i(k)$ is the largest value of $y_i(k)$ for the kth response.

2.4.2. *Grey relational coefficient*

After normalizing the original sequence, the next step is the calculation of the grey relational coefficient. The Grey relational coefficient $\xi_i(k)$ can be calculated as (2):

$$\xi_i(k) = \frac{\Delta_{min} + \psi\Delta_{max}}{\Delta_{0i}(k) + \psi\Delta_{max}} \quad (2)$$

where $\Delta_{0i} = \|x_0(k) - x_i(k)\|$ = difference of absolute value $x_0(k)$ and $x_i(k)$; ψ is the distinguishing coefficient. Here the value of ψ is set to be 0.5, the quantity used in most situations[20–26];

$\Delta_{min} = \forall j^{min} \in i \forall k^{min} \|x_0(k) - x_j(k)\|$ = the smallest value of Δ_{0i};

$\Delta_{max} = \forall j^{max} \in i \forall k^{max} \|x_0(k) - x_j(k)\|$ = the largest value of Δ_{0i}.

2.4.3. *Grey relational grade*

Grey relational grade for each experimental run is the average of the grey relational coefficients of each response. Grey relational grade γ_i can be computed as (3):

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \quad (3)$$

where n is the number of process response.

2.5. *Analysis of mean and variance*

Analysis of the means is done for the obtained grey relational grade and depending upon the Δ (Delta) statistics which is the difference between the highest and the lowest average of Grey relational grade for each factor, the rank of the parameters affecting the multiple performance response is listed.[20,22–24]

The contribution of each factor on the multiple performance characteristics in drilling of bone is determined using

Table 3 – Pre-processed data of the experimental results.

Experiment no.	Data pre-processing of the experimental results		
	T	F	SR
1	0.8519	0.8130	1
2	0.4321	0.9335	0.5811
3	0.2346	1	0.4054
4	1	0.4864	0.7703
5	0.5185	0.7658	0.4324
6	0.3086	0.9067	0.1081
7	0.7531	0	0.6351
8	0.1728	0.4654	0.3649
9	0	0.6370	0

Table 4 – Grey relational coefficient of the experimental results.

Experiment no.	Grey relational coefficient		
	T	F	SR
1	0.7714	0.7279	1
2	0.4682	0.8825	0.5441
3	0.3951	1	0.4568
4	1	0.4933	0.6852
5	0.5094	0.6809	0.4684
6	0.4197	0.8428	0.3592
7	0.6694	0.3333	0.5781
8	0.3767	0.4833	0.4405
9	0.3333	0.5794	0.3333

Table 5 – Grey relational grade for each experimental run.

Experiment no.	Grey relational grade	Rank
1	0.8331	1
2	0.6316	3
3	0.6173	4
4	0.7262	2
5	0.5529	5
6	0.5406	6
7	0.5269	7
8	0.4335	8
9	0.4154	9

analysis of variance (ANOVA).[21–27] The analysis is done at a significance level of $\alpha = 0.05$ (confidence level of 95%). Fisher's F-test is used is to determine the change in which bone drilling parameter significantly influences the multiple response output.

2.6. *Confirmation test*

Confirmation test is carried out to verify the results obtained .The predicted grey relational grade for the optimal combination of the parameters is calculated from the equation (4).

$$\widehat{Y}_0 = Y_{0m} + \sum_{i=1}^{k} (\overline{Y}_{0i} - Y_{0m}) \tag{4}$$

where $\widehat{Y}_0$ is the estimated grey relational grade, Y_{0m} is the total mean grey relational grade, $\overline{Y}_{0i}$ is the mean value of the grey relational grade at the optimal level and k is the number of parameters affecting the multiple response.[22,23]

3. Results

The results obtained by using the methodology mentioned in the previous section are given under this section. The experimental conditions used to conduct the bone drilling experiments and the results obtained for each experimental trial are shown in Table 2.

The response data for temperature, force and surface roughness obtained from the experimental investigations (shown in Table 2) are normalized (pre-processed) using (1) and are listed in Table 3.

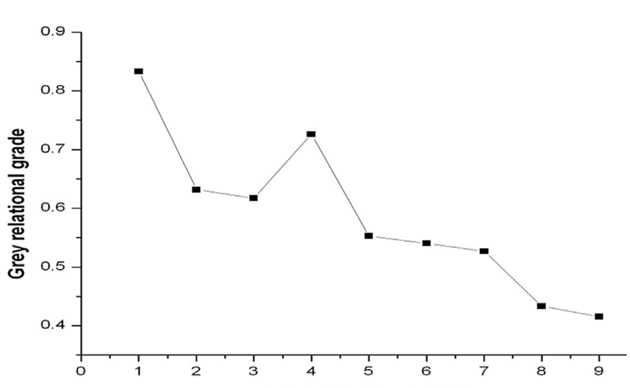

Fig. 3 – Grey relational grade verses experiment number.

Table 6 – Response table for Grey relational grade.

Process parameters	Level 1	Level 2	Level 3	Δ (Max–Min)	Rank
A	0.6940	0.6066	0.4586	0.2354	1
B	0.6954	0.5393	0.5244	0.1710	2
Total mean value of the grey relational grade is = 0.5864.					

The grey relational coefficient obtained for the each experimental run by using (2) is shown in Table 4.

Table 5 shows Grey relational grade for each experimental run (computed using (3)) along with their rank and the relationship between them is shown in Fig. 3.

Table 6 shows the results obtained from the analysis of the mean. The value of the means is plotted as the response graph and is shown in Fig. 4.

The results obtained from the analysis of variance (ANOVA) and F-test is mentioned in Table 7.

The result of the confirmation test performed for the validation of the optimal setting (A1B1) of drilling parameters obtained from GRA is shown in Table 8.

4. Discussions

There has been an increasing demand for minimally invasive drilling of bone during orthopaedic surgery for better fixation and quick healing of the broken bones. The review of the past work in this area clearly depicts that most of the authors mainly focused on the determination of the effect drilling parameters on the damage induced. There is a lack of studies aimed on the determination of the optimal level of the drilling parameters for minimizing the drilling damage caused to the bone. In this work, an attempt has been made to find out the best setting of spindle speed and feed rate for minimizing the thermal and the mechanical damage induced to the bone simultaneously during drilling by applying GRA. Bone drilling is a process involving complex relationship between the responses which can be handled very well by GRA. Therefore the authors have applied GRA as novel approach for multi objective optimization of bone drilling.

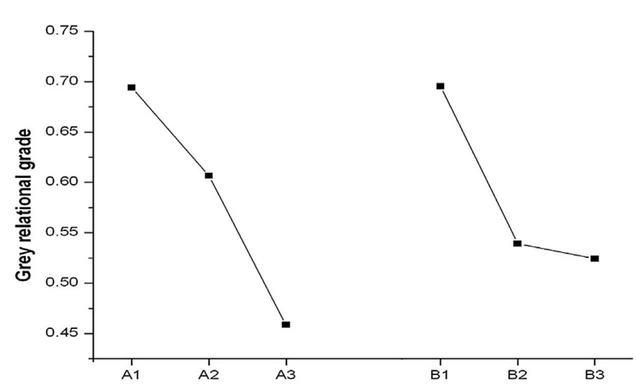

Fig. 4 – Response graph for each level of drilling parameters.

Table 7 – ANOVA results for grey relational grade.

Parameter	DOF	SS	V	F ratio	P (%)
A	2	0.0849	0.0424	42.24	59.49
B	2	0.0538	0.0269	26.76	37.69
Error	4	0.0040	0.0010		2.82
Total	8	0.1427			100

Where, DOF = Degree of freedom.
SS = Sum of squares.
V = Variance.
P = Percent contribution.

Table 4 gives the GRC for each response for every experimental run. From Table 4 the optimal level of bone drilling parameters for the minimization of the individual response can be determined. The experimental run corresponding to the highest GRC is the optimal level for the individual response.[20–27] Table 5 shows the GRG computed as the multi objective performance index. From the study of Table 5, it is clear that the experiment number 1 exhibits the best multiple performance characteristics with the highest grey relational grade for bone drilling. The response table (Table 6) and response graph (Fig. 4) shows the effect of the parameters on the on the multiple response characteristics. Higher the slope of the graph shows that the corresponding parameter has more influence on the multiple performance response.[21] The feed rate has the highest influence on grey relational grade followed by the spindle speed. The optimal combination of parameter level for bone drilling is identified as: level 1 of drill diameter (A1) and level 1 of feed rate (B1). The percentage contribution of feed rate and spindle speed to the multi performance grey relational grade is 59.49 and 37.69 respectively as obtained from analysis of variance (Table 7). The significance of both the parameters is also confirmed by the *F*-test. Larger the *F* value indicates that the change in process parameter have more strong affect on the multiple performance index.[21] The value of the predicted grey relational grade for the confirmation test carried out at the optimal level of the parameter i.e. A1B1 is 0.8030 and that obtained from the experiment is 0.8331. Thus, a gain in the grey relational grade is obtained which implies that the grey relational analysis can be effectively used for multiple response optimization of the bone drilling process.

5. Conclusions

The present paper uses grey relational analysis for multi objective optimization of bone drilling process. The results obtained from the above investigations are summarized as follows:

Table 8 – Confirmation experiment result.

	Optimal process parameters	
	Predicted	Experimented
Level	A1B1	A1B1
GRG	0.8030	0.8331

1) Grey relational analysis shows that the investigation with feed rate of 40 mm/min and spindle speed of 500 rpm has the highest grey relational grade and is recommended setting for minimum temperature, force and surface roughness simultaneously during bone drilling.
2) Feed rate has the highest contribution (59.49%) on the multiple performance characteristics followed by the spindle speed (37.69%) as obtained from ANOVA analysis.
3) The results of the confirmation test suggests that the grey relational analysis is suitable for optimizing the multiple response simultaneously in drilling of bone within the range of the parameters studied.
4) The use of above suggested methodology will simplify the complex process of optimization of the multi response characteristics in bone drilling and will assist the surgeon to perform bone drilling with minimum bone tissue damage.

Conflicts of interest

All authors have none to declare.

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