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Abstract: Bone drilling is a well-known process in operative fracture treatment and reconstructive surgery. The cutting ability of the drill is lost when used for multiple times. In this study, the effect of different levels of drill wear on bone temperature, drilling force, torque, delamination around the drilling region and surface roughness of the hole was investigated using a series of experiments. Experimental results demonstrated that the wear of the drill is strongly related to the drilling force, torque, temperature and surface roughness of the drilled hole. Statistical analysis was performed to find the effect of various factors on multiple response variables in the bone drilling process. The favorable conditions for bone drilling are obtained when feed rate, drill speed and the roughness of the cutting edge of the drill were fixed at 30 mm, 2000 rpm and up to 2 mm, respectively. Further, analysis of variance (ANOVA) was performed to determine the factor with a significant impact on the response variables. F-test and p-value indicated that the feed rate had the highest effect on grey relational grade followed by the roughness of the drill. This study suggests that the sharp drill along with controlled drilling speed and feed rate may be used for safe and efficient surgical drilling in bone.

Keywords: ANOVA analysis; bone; delamination; drill roughness; drilling force; drilling temperature; drilling torque; orthopedics.

Introduction

Skeletal fracture of bones requires fixing fragments of the bones by attaching plates for compression and immobilization. This is achieved by intervening the bones with a mechanical drill at required location for preparation of holes followed by fixation of plates with screws. Bone drilling is also an essential operation for attaching prosthetics and other reconstruction surgical procedures. Surgical drills of various sizes and lengths are used for producing holes in bone. Concomitant problems of drilling in the bone are excessive heat generation, large drilling force and torque and skiving of the drill on the surface of bone. Drilling may either raise the temperature exceeding the thermal threshold level or cause unnecessary stress in the bone leading to the cracking of the bone near the drilling site [1, 2]. Adverse drilling conditions may compromise implant stability leading to progressive loosening of the fixation. The consequence is either the delay in the regeneration of bone and healing process or repeating surgical procedures. One of the known sources of overheating and overstressing the bone in the drilling process is the use of a blunt drill [3, 4].

Surgical drills wear out due to repeated use, interaction with chemicals and even during sterilization and storage. The wear of the drill due to repeated use is caused by mechanical and thermal loads during the drilling process. Repeated use of a surgical drill causes wear of the cutting edges which may significantly alter the mechanics of bone cutting. Several research studies have investigated the effect of drill wear on the outcome of the process. Studies have found that a worn drill could induce more heat in the bone [4–10] and large drilling force [11]. A recent study has found a significant difference in plunging depth when sharp and blunt drills were used [12]. Major factors contributing elevated temperature in bone drilling (thermal necrosis) are the axial thrust force, size of the drill, drilling speed, irrigation and roughness of the cutting edge of the drill [13]. In addition to thermal and mechanical damage, the cutting edges of a worn drill may get or may cause complete breakage of the tool during incision [14]. Blunt drill may significantly increase the drilling time and may be detrimental to the soft tissues or blood vessels due to large and uncontrolled drilling forces. The

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issues described may seriously compromise the precision and safety in the drilling process.

Advanced understanding of the mechanics of the drill-bone interaction is vital for the designing and development of automated surgical systems in orthopedics and related fields. However, previous studies were mainly concerned with the measurements of force and temperature in the bone drilling and unable to relate quantitatively the amount of wear of the drill to the level of force, torque and temperature rise in the bone. The only attempt to improve the durability of the drills was the application of coatings to the drills [15]. Successful implementation of drilling in bone was achieved either by controlling the parameters using conventional methods [16] or by surgical systems assisted by sensors [17]. The idea of robot-assisted drilling in bone for monitoring, controlling, accuracy and reliability of the manipulation has already been realized in few research centers with no drill wear monitoring system. This research study provides scientific information on using a sharp and a blunt drill of various levels and discusses the most suitable conditions for safe and efficient drilling in the bone.

Materials and methods

Specimen for drilling

Bone excised from the middle diaphysis of bovine femur and tibia was used in drilling experiments. The age of the animal was approximately 3 years. All bone specimens were obtained from young cows of almost the same age and place of breeding. The specimens were visually inspected for any damage or disease before the experiments. Healthy bone specimens among several others obtained from a local slaughterhouse were selected for drilling experiments. Though the structural composition such as the volume fraction of organic and inorganic constituents of the bone, orientation of osteons, volume fraction of lacunae and Haversian canals and number of cells at various layers is slightly different, however, due to the extremely complex nature of the microstructure of bone, it is not possible to look into this issue in the current study. The average thickness of the bone specimen was 8–9 mm. Ethical approval was not required as drilling tests were performed on fresh bone obtained immediately after slaughter.

Drilling force, torque and temperature measurements

A vertical drilling machine (Wadkin Machine Tools, UK) was used in drilling experiments (Figure 1). Drilling thrust force and torque were measured using a calibrated two-component dynamometer (Kistler type 9271A, Winterthur, Switzerland). The bone specimen was fixed on a custom designed fixture clamped to the dynamometer.

Figure 1: Experimental setup for bone drilling.

Figure 2: Temperature measurement in bone drilling.

A calibrated infra-red camera (InSb 320 SM/M, Germany) with a temperature resolution of 20 mK and a spatial resolution of 20 μm per pixel was used for surface temperature measurements in drilling. The surface temperature of the bone was recorded from the time the drill started penetrating into the bone until it passed through the cortex (Figure 2). Force and temperature data were obtained in the presence of irrigating the drilling region with tap water at room temperature. The water was slowly injected between the flutes of the drill bit to avoid interference between the camera and surface of the bone exposed to the camera.

Surface roughness and delamination measurements

Delamination was measured on the top surface of the bone where the drill first touched the bone and started penetration. Delamination around the drilled hole was measured only at the entry of the holes using a digital microscope (KEYENCE VHX-S50, Itasca, IL, USA) with a typical resolution of 1 μm . The microscope can measure the linear and curvilinear features of regular or irregular geometrical shapes. The amount of delamination was calculated in percentage by dividing the diameter of the delaminated area by the diameter of the drilled hole. After delamination measurements, a mechanical hack-saw was used to cut the drilled hole into two halves along the drilling direction to expose the internal curved surface for scanning and

Figure 3: (A) Delamination measurement at the entrance of the hole; (B) roughness measurement of the internal surface of the hole (along the dashed line).

Figure 4: Scans obtained from the Alicona InfiniteFocus system showing sharp and blunt cutting edges (drill Ø4.8 mm).

roughness measurement. Roughness of the internal surface of the drilled holes was measured using the Taylor Hobson CLI 2000 system. A 6 mm distance was scanned in each specimen leaving a small distance from the entrance and exit part of the hole. The scanning was performed by moving the sample over the cross-slide while the object was stationary. The delaminated area around the hole at the top surface of the bone and the internal surface of the hole for roughness measurement is shown in Figure 3.

Drill-wear measurement

The position of the scan area was first determined using the SmartScope Flash 200 Optical Measuring Microscope. The drills were first positioned in a chuck under the measuring microscope and then transferred for roughness measurements. The roughness was measured along the line shown with arrowheads (drill Ø4.8 mm). Surface topography of the cutting lips of the drill was measured using the Alicona InfiniteFocus Microscope. The equipment can measure roughness up to 0.03 μm. An object of X5 with a resolution of 23.48 μm was used for all measurements. A scan distance was established by focusing on the lowest and highest levels on the cutting edges of drills.

The obtained data set was used to construct a three-dimensional (3D) map of the surface of the cutting edges (Figure 4). The acquired data on roughness were processed using Alicona IFM 3.5.01 software. The system allowed magnification of important areas of the drills to precisely determine the size and position of magnified features.

Experimental procedure for statistical analysis

Drilling tests were performed using orthopedic surgical drills with known surface roughness of the cutting lips. A total of 12 sterilized drills of Ø4.8 mm used for roughness measurements and drilling experiments were donated by a local hospital. The drills were divided into four categories according to the number of holes drilled. Each set of drills containing three drills were sharp (new), used for 100 holes, 200 holes and 300 holes, respectively. The surface roughness along the cutting lips of each drill was measured and divided into four categories. The average roughness of the cutting edges in each set of drills was in the range 0–2 μm (sharp), 2–3 μm (100 holes), 3–4 μm (200 holes) and 4–5 μm (300 holes). Each set of drills with the prescribed average roughness in combination with drilling parameters was used in drilling experiments for obtaining data for statistical analysis. The force, torque and temperature were measured simultaneously during the drilling process, whereas hole surface roughness and delamination around the hole were measured after drilling.

Results

Figures 5–7 are representative results of the data used in statistical analysis. The drilling force, torque, bone temperature, hole roughness and delamination were measured using different values of drill speeds and feed rates (Table 1). A rougher profile of the used drill was measured compared to the sharp drill. The drilling force was observed to rise when the drill with a more rough profile of cutting was used (Figure 5). Conversely, the torque was observed to drop when the drill with a more rough profile was used. This may be due to the slip of the blunt edges of

Figure 5: Effect of drill roughness on drilling force and torque. Drill speed – 3000 rpm; feed rate – 50 mm/min.

Figure 6: Variation of bone temperature with drill roughness. Drill speed – 3000 rpm; feed rate – 50 mm/min.

between the drill and the bone. The effect of drill roughness on bone temperature is shown in Figure 6.

After acquiring force, torque and temperature data during drilling tests, bone specimens were transferred for checking the surface quality of the drilled holes and delamination around them. Variation of hole roughness and delamination with drill roughness is shown in Figure 7. The internal surface area of the drilled hole was scanned along the depth of the hole. A slight increase in delamination was measured when a drill with rougher cutting edges was used compared to the sharp drill.

Statistical analysis

Experimental design

the drill on the bone material in the tangential direction. Such conditions did not generate enough tangential force (which is responsible for generating torque about the middle of the drill) compared with that produced using a sharp drill. Lower bone temperature was also measured when a sharp drill was used. Lower temperature rise in the bone using a sharp drill was due to the reduced friction

In this study, response variables were analyzed under the effect of three different factors namely the feed rate (mm/min), drill speed (rpm) and drill roughness (μm). Various levels of these factors are considered in the experiments (Table 1). Effect of these factors was analyzed in terms of responses such as force, torque,

Figure 7: Variation of hole roughness and delamination with drill roughness. Drill speed – 3000 rpm; feed rate – 50 mm/min.

Table 1: Experimental parameter and their levels used in drilling experiments.

Factors (units)	Level 1	Level 2	Level 3	Level 4	Level 5
Feed rate (mm/min)	30	40	50	60	70
Drill speed (rpm)	1000	1500	2000	2500	3000
Drill roughness (μm)	0–2	2–3	3–4	4–5	–

temperature, delamination and hole roughness. Out of these responses, a higher value of hole roughness is desirable as it may play a vital role in the bond between the hole and the fixative devices. However, for other responses, a lower value is better. Therefore, in our experiment, some responses need to be minimized while others need to be maximized.

Taguchi method is an important tool for generating design for the experiment with multiple factors with each factor having multiple levels. Taguchi method helps to identify a small number of experimental setups to study the effect of entire factors with various levels using a special design of orthogonal arrays. For these experiments, a full factorial design involves 100 different experimental setups or drilling tests. Therefore, a minitab is used to generate the experimental setup based on the Taguchi orthogonal array. With the factors and levels mentioned earlier and based on the Taguchi orthogonal array, 25 different sets of experimental designs were generated. The experiments were then carried out by fixing the value of factors according to the experimental design.

Data analysis

With the setup based on the Taguchi orthogonal array, experiments were conducted and data collected on the response variables. Our experimental design involved the effect of three different factors on five responses. The effect of the unified response was analyzed rather than analyzing the effect of factors on each individual response. Grey relational analysis (GRA), which is a common tool for converting multiple performance indicators into a single grey relational grade [18], was used to obtain a unified value from five different responses. The following steps are implemented to obtain a grey relational grade.

Step 1: Normalizing the value of response variables between (0, 1)

For all the response variables, except “hole roughness”, a lower value is preferred. A normalized value for these

response variables is calculated using the following equation.

$$X_{ij} = \frac{\{\max(Y_{ij}) - Y_{ij}\}}{\max(Y_{ij}) - \min(Y_{ij})} \quad (1)$$

where

i = Experiment (1, 2, ..., m)

j = Response variable (1, 2, ..., n)

Y_{ij} = Observed data for response i and experiment j

X_{ij} = Normalized value of Y_{ij} .

For the “hole roughness”, the following equation is used to obtain a normalized value.

$$X_{ij} = \frac{\{Y_{ij} - \min(Y_{ij})\}}{\max(Y_{ij}) - \min(Y_{ij})} \quad (2)$$

Step 2: Calculate grey relational coefficient

Grey relational coefficient helps to express the relationship between normalized experimental results and the ideal result. It can be calculated using the following formula.

$$G_{ij} = \frac{\min_{i,j} \min |X_i^o - X_{ij}| + \alpha \max_{i,j} \max |X_i^o - X_{ij}|}{\max_{i,j} \max |X_i^o - X_{ij}| + \alpha \min_{i,j} \min |X_i^o - X_{ij}|} \quad (3)$$

where X_i^o is the ideal normalized value for the i th response variable and α is a distinguishing coefficient, the value which varies between the range of (0, 1). For our analysis, α is assumed to be 0.5 as some responses need to be minimized and others need to be maximized. It gives equal preference to maximum as well as minimum absolute deviation.

Step 3: Calculate grey relational grade

Grey relational grade is simply a weighted average value of grey relational coefficient of entire response variables for the given experimental setup where equal weight is given to all the response variables.

$$G_i = \frac{1}{n} \sum_{j=1}^n G_{ij} \quad (4)$$

where G_i represents the grey relational grade for the i th experiment.

Out of 25 different experimental setups, the result of five different setups was taken at random. Normalized value, grey relational coefficient and grey relational grade obtained from these setups are shown in Table 2. A higher

Table 2: Result of grey relational analysis for five experimental setups (drill diameter – Ø4.8 mm).

Exp no.	Normalized values of response variables					Grey relational coefficient					Grey grade
	Force	Torque	Temp	Delam	Hole roughness	Force	Torque	Temp	Delam	Hole roughness	
1	0.676	0.526	0.935	0.833	0.250	0.607	0.514	0.915	0.750	0.400	0.637
6	0.757	0.474	0.698	0.667	0.000	0.673	0.487	0.623	0.600	0.333	0.543
11	0.784	0.579	0.721	1.000	0.250	0.698	0.543	0.642	1.000	0.400	0.657
19	0.216	0.789	0.186	0.083	0.833	0.389	0.704	0.381	0.353	0.750	0.515
25	0.270	0.211	0.209	0.250	0.000	0.407	0.388	0.387	0.400	0.333	0.383

The best and worst results are highlighted with bold letters.

value of grey relational grade designates a better result for multi-response variable [19] as it indicates that the experimental result is closer to the ideal normalized value. From the table, it is evident that the highest grey relational grade is 0.657 which is related to the experimental setup when the feed rate, drill speed and drill roughness are fixed at 30 mm, 2000 rpm and 0–2 mm, respectively. The worst result is obtained when the feed rate, drill speed and drill roughness are fixed at 70 mm, 2500 rpm and 0–2 mm, respectively. The best and worst results are highlighted with bold letters (Table 2).

ANOVA

Analysis of variance (ANOVA) is performed using Mini-tab software to determine which parameter has a significant impact on the response variables in terms of grey relational grade. The result of ANOVA is presented in Table 3. The analysis was performed at 95% confidence interval. Results based on F-test and p-value indicated that the feed rate has the highest effect on grey relational grade followed by the drill roughness on the multi-response variables. However, the effect of drill speed was almost

negligible. Further, the table also shows the interaction effect of multiple factors on grey relational grade. The effect of drill speed and drill roughness on grey relational grade was negligible. The interaction effect of feed rate and drill roughness was the most significant. On the other hand, the interaction effect of feed rate and drill speed was minimal. The R^2 value for the model was 94.13% (with an adjusted R^2 value of 87.9%) indicating that the linear model fits well with the data.

Discussion

Major concerns for practitioner performing bone drilling are force and torque as they can feel it during the process. Temperature rise, delamination around the hole and surface quality of the drilled hole are of secondary importance to them as they cannot measure or feel them during the process. These variables are affected by factors such as drill speed, feed rate and quality of the drill bit. The stability of fixation strongly depends on the frictional condition between the screw and the bone [20]. The roughness of the screws may contribute to stabilization

Table 3: ANOVA analysis for feed rate, drill speed and drill roughness.

General linear model: grey relational grade versus feed rate, drill speed, drill roughness					
Source	DF	Adj SS	Adj MS	F-value	p-Value
Analysis of variance					
Feed rate	4	0.307328	0.076832	138.29	0.000
Drill speed	4	0.009946	0.002486	4.48	0.004
Drill roughness	3	0.036886	0.012295	22.13	0.000
Feed rate*drill speed	16	0.025824	0.001614	2.90	0.002
Feed rate*drill roughness	12	0.039942	0.003328	5.99	0.000
Drill speed*drill roughness	12	0.007803	0.000650	1.17	0.331
Error	48	0.026669	0.000556		
Total	99	0.454398			
Model summary					
S	R-sq	R-sq(adj)			
0.0235712	94.13%	87.90%			

and restriction of the motion between the plate and the bone. The surface roughness of the hole will play a similar role in the stabilization of fixation as well as faster bone regeneration around the screws or other implants anchoring the bone.

A sharper drill advances in the bone with more freedom and thus causing less pressure on the drill. The cutting ability of the drill is lost when the cutting lips become blunt. Blunt cutting lips instead of shearing the bone material gash and fragment the particles from the bone which are trapped in the drilling track causing increased friction in the cutting region. Accumulation of bone debris in the channels of the drill hinders heat transfer from the drilling region. Besides using saline for cooling the drilling region, surgeons used to push and pull the drill at small intervals to avoid unnecessary stress on the bone. A sharp drill accompanied by pressure applied in the drilling direction can facilitate faster penetration. This condition allows less contact time between the drill and the bone and minimizes friction and surgical time. Novel drilling methods such as those with vibrations imposed on the drill bit (vibrational drilling) are to be studied to enhance the cutting mechanics with the objective of improving safety and efficacy [21, 22]. Intermittent contact of the drill and bone in vibrational drilling could significantly increase the drill life due to intermittent contact over the time of penetration.

Drilling systems and process conditions used in bone surgical procedures are different from those used in manufacturing industries. Surgeons and technicians use hand power drills for producing holes in the bones using drilling parameters not known to them. The core skills required for drilling the bone using a hand-held surgical drill are the use of appropriate pressure on the drill, sensing the required depth of the hole and penetration with controlled rate. Bone drilling systems for drill wear identification are not yet realized in real orthopedic surgical procedures. Limited data available in this area and the use of conventional drilling systems in clinical settings have made the decision of replacing the drill bit a difficult task. In addition, the unavailability of real-time monitoring systems for drill condition in surgical clinics has made the available systems risky for surgical incisions.

Conclusion

The study has found the surface roughness of the cutting lips of the drill to be an important index for bone drilling. A drill with rough cutting edges produces large drilling force, elevated temperature, increased delamination

around the drill hole, lower torque and rough hole surface. The aim of the study was to find optimum drilling conditions where minimum force, torque, temperature, delamination and maximum hole roughness are achieved. The surface quality of the cutting edges of the drill and feed rate were found to be important factors affecting the outcome of the process. The speed of penetration of the drill must be kept at minimum as it may cause traumatic incision. A drill after multiple uses may be closely monitored as it may induce high temperature and large drilling force compared to a sharp drill. The analysis in this study could be a possible input to the intelligent drilling systems for bone and other soft tissue surgical procedures involving drilling operation.

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Ethical approval: The conducted research is not related to either human or animal use.

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