Design Improvements in Conventional Drilling Machine to Control Thermal Necrosis during Orthopaedic Surgeries

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Abstract: Bone drilling operation is performed to join fractured bone tissues during physical trauma. Natural bone growth and remodelling of fractured bone fragments is possible by immobilisation of affected bone. Immobilisation is achieved by use of screws and plates with drilling facilities. Similarly internal fixation of screws [1] during intramedullary nailing often involves bone drilling. The heat generation model [2] has proved that, generation and accumulation of heat above temperature level of 47°C for one minute during drilling is the alarming signal for thermal necrosis which causes irreversible bone damage. To study bone drilling in concern with thermal necrosis, threshold temperature has to be the prime concern and accordingly drilling parameters and specifications are to be selected. In this study, drilling process is conducted on a sheep rib bone. Optimization of drilling parameters such as drilling speed, feed rate and drill specification like drill tool diameter is suggested using Taguchi and ANOVA method. Results indicate drill diameter is most influencing factor contributing 90.71% for heat generation, followed by feed rate 5.69% and drill speed 2.22%. Based on discussions and conclusions a drill machine with attachments of infrared thermometer, speed sensor and camera is designed and fabricated. This machine alarms surgeon when temperature level at drill site increases above 47°C, which is a threshold temperature of thermal necrosis.

Keywords: Bone drilling, thermal necrosis, threshold temperature, optimization, infrared thermometer

1. Introduction

The bone is physiologically active and reactive tissue and explained chemically as Ca10(PO4)6(OH)2. The axial and appendicular skeleton structure forms the supporting frame for soft tissues, organs and muscles attachments of an animal body. Bones take the substantial load during body movement, lifting weights and running. Bones are calcified connective tissue, comprising of minerals, collagenous protein, lipids and water.

Drilling in bone tissue is a better option for insertion of fixations. Depending on the severity of accidents and trauma situations the numbers of drills require may be in multiples. The bone drilling is a precision work, from mechanical engineering aspect [3] as it involves handling of drilling machine with controlling of spindle speed, manual feed rate, depth of cut, drill tool geometry, chip flow rate and from therapeutic aspect the bone cell thermal damage (thermal necrosis) [4] and patient early rehabilitation are prime considerations and so this precision task demand knowledge, skill and experience of surgeons. In previous research work it is clear that if the temperature at drilling location reaches more than 470°C and remains the
same for one minute, it could damage the cells permanently and so considered as threshold temperature. During interactive sessions with medicinal experts, currently to control heat generation a number of drilling techniques along with coolant supply, like push hard i.e. more feed rate or push-pull i.e. removing the drilling tool number of times from the drill hole are adopted. The causes of heat accumulation while bone drilling can be explained as; shear deformation across shear region [5], rubbing in between the drill bit [6] rake face, chip, friction among the tool flank face and recently formed work piece wall’s [7] and so to have an accurate information about temperature level there is necessity to make improvements in the existing conventional drilling machine by the fitments like infrared thermometer and camera to alarm the surgeons about thermal necrosis.

2. Materials and Methods

The aim of research is, to make design improvements in conventional drilling machine and thereby avoid thermal insult in the course of orthopaedic drilling. For drilling sheep rib bone is selected because it is a suitable large-animal typical for biomedical research. Other factors are availability, ease of supervision and housing, animal price, and receiving to society as a research animal [8, 9 and 10]. In this study, sheep rib bone acquired from a local butcher. First, all the soft flesh tissues were detached along the specimen surface by a surgical tool after that the bone specimen kept in buffer solution. To achieve a realistic environment of surgery and accuracy, while drilling the bone with conventional drilling machine sample is placed in a special container. The container is filled with saline water, with a provision of heating the normal saline solution and a thermostat to maintain a precise body temperature 37°C. The average dimensions of specimen were thickness 2.5 mm and surface area 10mmX6mm, across which heat distribution is to be studied. The known bone properties [11] were as in table 1.

Table 1: Thermal properties of bone

| property                  | Value |
|---------------------------|-------|
| Thermal conductivity      | 0.54  |
| Specific heat (J/(kgK))   | 1260  |
| Density(kg/m³)            | 1800  |

To measure the temperature of bone at heat affected drilling site, infrared thermometer (specifications in Table No. 6) is used. Thermocouple’s distant location from drilling site, thermal conductivity of bone material is the limitations that can be avoided by infrared thermometer. At every experiment cycle, drilling was performed and at the same time temperature was measured. To know the effect of three known variables drill tool diameter, drilling speed [12] and drilling feed rate on bone temperature, which is an unknown variable or response, experimentation is conducted. For experimentation purpose, three different drill tools [13] of diameter 2.5, 3.2 and 4.5 mm are used. Drill tool diameters are selected considering the standard drill diameters frequently used by surgeons. Tool geometry features helix angle 300, point angle 1180 and web thickness 0.9 mm. Three feed rate values 50.60 and 70 mm/min. and three drill speed ranges 1000, 1500 and 2000 rpm were selected. In this way, combination of three control factors [14] viz, spindle speed, feed rate and drill diameter, with three levels form 27 combinations [15]. 27 sheep rib bone samples were drilled.

Table 2: Drilling control factors and levels

| Levels | Drill Diameter (mm) | Feed Rate (mm/min) | Spindle Speed (rpm) |
|--------|---------------------|--------------------|---------------------|
| Level 1| 2.5                 | 50                 | 1000                |
To confirm the effect of temperature [16] on bone cells, drilled samples were checked by histopathology. For histopathology [17], paraffin method is preferred [18]. Only the drilled bone samples affected by thermal necrosis [19] i.e. samples with sufficient empty vacuoles were considered. In case of histopathological failure, the particular experiment was repeated with the same three drilling parameters assigned to that experiment number.

| Experiment Number | Drill diameter (mm) | Feed rate (mm/min) | Drill speed (rpm) | Temperature (°C) | S/N ratio (dB) |
|-------------------|---------------------|--------------------|-------------------|------------------|----------------|
| 1                 | 2.5                 | 50                 | 1000              | 41.32            | -32.322        |
| 2                 | 2.5                 | 50                 | 1500              | 41.01            | -32.2578       |
| 3                 | 2.5                 | 50                 | 2000              | 39.72            | -31.9802       |
| 4                 | 2.5                 | 60                 | 1000              | 40.91            | -32.2366       |
| 5                 | 2.5                 | 60                 | 1500              | 40.21            | -32.0867       |
| 6                 | 2.5                 | 60                 | 2000              | 38.9             | -31.799        |
| 7                 | 2.5                 | 70                 | 1000              | 40.1             | -32.0629       |
| 8                 | 2.5                 | 70                 | 1500              | 39.12            | -31.848        |
| 9                 | 2.5                 | 70                 | 2000              | 37.51            | -31.4829       |
| 10                | 3.2                 | 50                 | 1000              | 45.93            | -33.2419       |
| 11                | 3.2                 | 50                 | 1500              | 45.21            | -33.1047       |
| 12                | 3.2                 | 60                 | 2000              | 44.56            | -32.9789       |
| 13                | 3.2                 | 60                 | 1000              | 43.73            | -32.8156       |
| 14                | 3.2                 | 60                 | 1500              | 43.29            | -32.7278       |
| 15                | 3.2                 | 60                 | 2000              | 42.19            | -32.5042       |
| 16                | 3.2                 | 70                 | 1000              | 43.21            | -32.7117       |
| 17                | 3.2                 | 70                 | 1500              | 43.19            | -32.7077       |
| 18                | 3.2                 | 70                 | 2000              | 42.61            | -32.5902       |
| 19                | 4.5                 | 50                 | 1000              | 49.12            | -33.8252       |
| 20                | 4.5                 | 50                 | 1500              | 49.31            | -33.8587       |
| 21                | 4.5                 | 50                 | 2000              | 48.62            | -33.7363       |
| 22                | 4.5                 | 60                 | 1000              | 48.19            | -33.6591       |
| 23                | 4.5                 | 60                 | 1500              | 47.92            | -33.6103       |
| 24                | 4.5                 | 60                 | 2000              | 47.69            | -33.5685       |
| 25                | 4.5                 | 70                 | 1000              | 47.12            | -33.4641       |
| 26                | 4.5                 | 70                 | 1500              | 47.19            | -33.477        |
| 27                | 4.5                 | 70                 | 2000              | 46.72            | -33.3901       |

Table 3: Temperature of bone sample at drilling site and Completed orthogonal array L_{27}
Using Minitab software Taguchi Analysis [20] is performed. As during drilling process the minimum temperature is preferred, to achieve optimum grouping of control factors, smaller the best (SB) quality characteristics is selected. The equation for Signal to noise ratio is, 
\[ S/N = -10 \log \frac{1}{n} \sum Y_i \] 
Where, \( Y_i \) is temperature response in that particular run and \( n \) is sample size.

3. Results

| Levels  | Drill Diameter (mm) | Feed Rate (mm/min) | Spindle Speed (rpm) |
|---------|----------------------|--------------------|---------------------|
| Level 1 | -32.01               | -33.04             | -32.82              |
| Level 2 | -32.82               | -32.78             | -32.87              |
| Level 3 | -33.62               | -32.64             | -32.77              |
| Delta   | 1.61                 | 0.40               | 0.10                |

Signal to noise is a quality indicator for the scattering around target values. High S/N ratio is indication of high signal value than random noise value. Average value for each control factor is calculated by using Minitab. Average value for level 1, drill diameter i.e. 2.5mm is calculated by taking the average of signal to noise ratio value related to 2.5mm i.e. experimentation number 1 to 9 from table 2. 
\[ (-32.3232) + (-32.2578) + (-31.9802) + (-32.2366) + (-32.0867) + (-31.799) + (-32.0629) + (-31.848) + (-31.4829) / 9 = -32.0086 \text{ dB} \]  
Similarly average values of other control factors are calculated. Delta is calculated by subtracting the maximum and minimum values of average responses, for example Delta value for drill diameter is equals to \((-32.01) - (-33.62) = 1.61\). The Rank indicates the ranking of every delta value among the other ones, for example the delta value for drill diameter is 1.61, for feed rate [21] is 0.40, spindle speed is 0.10 and so rank of drill diameter is 1. Rank also indicates the influencing capacity of that factor.

| Source          | DF | Seq SS | Contribution (%) | Adj SS | Adj MS | F-Value | P-Value |
|-----------------|----|--------|------------------|--------|--------|----------|---------|
Drill Diameter & 2 & 296.85 & 90.71 & 296.85 & 148.42 & 659.93 & 0.00 \\
Feed Rate & 2 & 18.62 & 5.69 & 18.622 & 9.31 & 41.40 & 0.00 \\
Spindle Speed & 2 & 7.275 & 2.22 & 7.275 & 3.63 & 16.17 & 0.00 \\
Error & 20 & 4.498 & 1.37% & 4.498 & 0.22 & & \\
Total & 26 & 327.25 & 100% & & & & \\

Increased samples quantity gives better observation base and so 27 response values are recorded. Total number of observations (n) are 27 and DF= (n-1), hence total of degree of freedom (DF) is 26. Error indicates the observations with each predictor having same value and as in the observation three control factors contributing to 27 readings, the error comes to 20. Sequential sums of squares (Seq SS) depend on the order the terms are entered into the model and are measures of variation for different components of the model, drill diameter data is entered in most sequentially and so drill diameter Seq SS is 296.85 whereas spindle speed values are most disturbed and so its value is 7.275. The adjusted sum of squares (Adj SS) quantifies the amount of variation in the response data that is explained by each term in the model. A sufficiently large F-value indicates that the term or model is significant, drill diameter most significant with F-value of 659.93 and spindle speed the least with F-value 16.17.

![Main effects plot for mean of means](image.jpg)

**Figure 2**: Main effects plot for mean of means
Response curve indicates graphical representation of change of performance characteristics with the change in drilling parameter level. Figure 2 shows the response graph for drill diameter, feed rate and spindle speed.

4. **Improved Orthopaedic Drilling Machine**

It is observed that if an orthopaedic drilling machine is equipped with some basic electronic devices like thermal sensors, that can keep inform the surgeon about temperature level at drilling site, in this way, thermal necrosis can be controlled. For this the temperature at drilling site should be monitored continuously and a signal should be sent to indicate if temperature is above 47°C. To realize this, a non-contact, distantly temperature measuring Infrared thermometer is mounted on drilling machine.
4.1 Drill specifications

Table 6: Drill machine and infrared thermometer specifications

|   | Drill machine specifications          | Infrared thermometer specifications                  |
|---|----------------------------------------|------------------------------------------------------|
|   | A) Drill machine specifications        | B) Infrared thermometer specifications               |
| 1 | No load speed                          | Model                                                 |
| 2 | Torque                                | GY-906MLX90614                                        |
| 3 | Chuck capacity                         | Temperature Range                                      |
| 4 | Tool holder type                       | -20°C to 320°C                                        |
| 5 | Number of torque settings              | Temperature Accuracy                                   |
| 6 | Battery type                           | ±2°C                                                  |
|   |                                        | Repeatability                                          |
|   |                                        | 2%rdg                                                 |
|   |                                        | Emissivity                                             |
|   |                                        | 0.95                                                   |
|   |                                        | Spectral Response                                      |
|   |                                        | 0.7-18μ                                               |
|   |                                        | Response Time                                          |
|   |                                        | 500 msec                                               |
|   |                                        | Minimum Spot Size versus Distance ratio               |
|   |                                        | 6:1                                                   |
Laser diode (aiming of infrared thermometer)  
Temperature display  
NPN 7 channel transistor with light emitting diode

Three electronic circuits are fabricated: i] Main Controller Circuit: Orthopaedic drill machine and infrared thermometer, ii] Receiver Circuit: To receive the outputs about drilling site temperature, process the inputs and signal surgeons in terms of digital signal and alarming buzzer, that temperature is above threshold levels and the rectified measures like withdrawal of drilling tool, lowering of drilling speed or feed rate, increasing coolant supply can be adopted. iii] Charging circuit: For continuous and uninterrupted power supply Lithium-ion batteries with is used. The suggested drilling machine with continuous temperature monitoring [22] offers not only accurate control of heat but also time factor, otherwise temperature raise above $47^\circ C$ have to wait for 11 seconds. In this way before attaining temperature up to $47^\circ C$, the corresponding signal received by infrared thermometer and buzzer alarms surgeon. The suggested drilling machine 1) avoids thermal necrosis by controlling the drilling speed, as from the two drilling parameters; speed and feed rate, only speed can be monitored and governed and feed rate is provided manually. Similarly with respect to bone dimensions drill diameter has to be selected without an alternative but here also speed variation can avoid necrosis2) reduce surgery time duration, as above attainment of $47^\circ C$, cooling waiting period is required, 3) offers hassle free surgery, 4) surgeons have not to rely on burning smell or colour change i.e. temperature related activities will be monitored by system 5) patient early rehabilitation.

5. Discussion

The experimentation performed and optimization indicates drill diameter (rank 1, contribution 90.71%) affects temperature rise most followed by feed rate (rank 2, contribution 5.69%) and spindle speed (rank 3, contribution 2.22). Anova analysis conducted with confidence level for 95% and significance level ($\alpha$) =0.05. $P$ value $< \alpha$, specifies the rejection of null hypothesis and acceptance of alternative hypothesis. The $F$-values for respective control factors represents the significance of that term.

Bone drilling is combination of drilling parameters [23] and specifications interaction in biological sphere. For successful conduction, this machining operation has to be conducted within a small temperature range. Though use of coolant and chips removal is recommended for temperature control, the reach of coolant at interface of tool and bone wall is not assured as the factors like stickiness of accumulated debris in drill bit helical grooves and its layered thickness over tool surface, the length of debris (similar to chips), rate of debris breakage are affected by bone mineral density (BMD), age and gender of patient and drill speed.at the same time a special attention has to be provided for micro cracks, which may cause fatigue damages and stress fractures.

6. Conclusion

Primarily drill diameter affects the heat accumulation whereas feed rate is the secondary factor and drill spindle speed is the last one. For all combinations of factors, with drill diameter of 2.5 and 3.2 mm temperature is found below $43^\circ C$ whereas for every combination with drill diameter 4.5 mm temperature is above $47^\circ C$. Variation of drill speed as compared to drill diameter and feed rate is an effective way to control temperature. Another aspect is that apart from manual feed rate and drill tool diameter, drilling speed can be monitored and controlled with modifications in drilling machine. The proposed drilling machine with
speed regulation will be helpful to orthopaedic surgeons by reducing dependency on conventional methods and also to patients by early healing and rehabilitation.

**Ethical Approval:** The sheep rib bone sample is collected from a local butcher after slaughtered during and for their routine trade practice and the sheep is not slaughtered intentionally for this research work. The authors are not related directly with any live animal hence ethical approval is not required.

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