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Temperature Prediction in High Speed Bone Grinding using Motor PWM Signal

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Abstract

This research explores the feasibility of using motor electrical feedback to estimate temperature rise during a surgical bone grinding procedure. High-speed bone grinding is often used during skull base neurosurgery to remove cranial bone and approach skull base tumors through the nasal corridor. Grinding-induced heat could propagate and potentially injure surrounding nerves and arteries, and therefore, predicting the temperature in the grinding region would benefit neurosurgeons during the operation. High-speed electric motors are controlled by pulse-width-modulation (PWM) to alter the current input and thus maintain the rotational speed. Assuming full mechanical to thermal power conversion in the grinding process, PWM can be used as feedback for heat generation and temperature prediction. In this study, the conversion model was established from experiments under a variety of grinding conditions and an inverse heat transfer method to determine heat flux. Given a constant rotational speed, the heat conversion was represented by a linear function, and could predict temperature from the experimental data with less than 20% errors. Such results support the advance of this technology for practical application.

Keywords

Bone grinding; Thermal Effects; Pulse-width modulation (PWM)

1. Introduction

Grinding using a miniature diamond bur (as known as diamond drill) is a common procedure in the expanded endonasal approach to the skull base for brain cancer treatments. This endoscopic approach uses the nose as a natural corridor to operate on the base of the skull, craniocervical junction, and the brain to both approach and resect tumors with

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minimal disturbance to surrounding tissues. High-speed (60,000 rpm) diamond burs are able to grind and remove the bone surrounding the optic nerve, cavernous sinus, carotid artery, or branches of the trigeminal nerve to expose tumors and other pathological areas. Surgeons can feel the resistance and manually control the grinding tool carefully to avoid mechanically damaging critical neural tissues, while, the thermal damage around the grinding region is left entirely uncertain. In particular, grinding often creates a large amount of heat at tool-material interface, which can potentially propagate and injure the surrounding neural tissues, possibly resulting in blindness, loss of facial muscle control, or stroke as a result of blood coagulation in the carotid artery during surgery. Despite limited research, such concern has been raised recently in the medical community [1].

Thermal issues in bone machining have been studied extensively as reviewed in [2–3]. Although the temperature rise highly depends on tool types (e.g., drill, bur, K-wire), operating parameters (e.g., speed, force), and irrigation, suppressing the heat is always challenging due to the small range of temperature tolerance prior to the tissue damage, which occurs at 43°C [4]. For example, the temperature during drilling of bone could reach 90°C with high-speed twist drill [5], and over 50°C with milling tools [6–7]. Hosono et al. [8] have even reported temperatures as high as 174°C in high-speed bone grinding using 5 mm diamond bur. Instead of seeking optimal machining parameters, this paper aims to explore a method to monitor the temperature change without direct measurement, thus creating real-time feedback during operation.

Monitoring spindle power is often used in machining processes to assess machine performance, tool condition, and process stability [9–10]. A similar concept is applied in this study, with the aim of gathering thermal energy feedback information. The high-speed electric motor used (Stryker Corp., Kalamazoo, MI) is controlled via pulse-width-modulation (PWM), which alters the current input and provides adequate torque to overcome the motor loading. Therefore, the change of the PWM signal reflects the mechanical resistance on the grinding tool, which is positively correlated to heat generation. To demonstrate this idea, a series of experiments under a wide range of grinding conditions were conducted in this study to measure and draw the correlation between the PWM signal and heat generation, deemed the heat conversion function. The capability of this conversion function to predict bone temperature is also analyzed.

2. CONCEPT

Heat generated on the grinding interface is conducted to the tool, bone, and bone debris, and is also dissipated by convection via irrigated saline. Assuming a full mechanical to thermal power conversion [11], the total heat (P_M) partitioned to the bone (P_H) can be described by

$$P_H = \varepsilon P_M = \varepsilon (T\omega) \quad (1)$$

where T and ω are the motor torque and angular velocity (rotational speed), respectively, and ε is the partition ratio. Although the rotational speed is adjustable, surgeons typically use the full speed (60,000 rpm) to operate as higher speeds proffer better stability during bone removal. Therefore, it is reasonable to assume a constant ratio under such a fixed grinding condition (i.e., the same tool, speed, and work-material), and that P_H and T are linearly correlated.

In order to maintain a certain rotational speed, motor torque was created by an input current via PWM from the console. PWM is a common technology used in motor control which converts the DC input into a square wave with a variable on-to-off ratio, so the average on-time varies from 0 to 100 percent to control the input power [12]. Theoretically, the duty

cycle (between 0 and 100%) is linearly proportional to the motor torque, and thus also to the heat generation based on Eq. (1). Figure 2 shows an example of PWM signal when the spindle motor (used for the following experiments) rotates with and without grinding the bone. A clear duty cycle change could be observed in the PWM signal, indicating good sensitivity of the PWM signal.

3. EXPERIMENTS

The experimental study was designed to establish the correlation between PWM duty cycle and heat generation, and then to verify whether this correlation model can be used to predict bone temperature during any given grinding condition. The experimental procedures and data analysis are presented in this section.

3.1 Experimental Setup

Figure 3 shows the experimental setup, including three linear stages (Siskiyou Model 200cri) to control 3-axes movement of the grinding tool, a Stryker motor console, and a surgical tool spindle. The grinding-bit was a 4 mm diameter ball-shape diamond bur (Stryker 4.0 mm Diamond Round Bur #5820-12-40). The rotational speed was fixed at 60,000 rpm, the standard operation speed. A contact angle (α = 30°) was created to represent the hand-held grinding procedure, suggested by neurosurgeons.

The bone sample was cut from a bovine femur bone due to both its homogenous thermal properties and for the fact the cranial bone in the anterior skull base near sphenoid sinus is mostly cortical bone. The bone sample was carefully tailored into a square shape (about 24 mm × 20 mm × 6 mm) and the surface was ground using a CNC surface grinder (Chevalier Smart-818). Ground bone samples were sealed and preserved in the freezer under −20°C. In the experiment, the bone sample was attached on a fixture as shown Fig. 2, and leveled using a dial indicator traveled across the surface by the linear stage. Determination of the datum surface was done by moving the grinding bit slowly (with 10 μm step) toward the bone surface until the resistance created by wheel-bone contact was sensed. Four type K thermocouples (Omega Engineering Inc. Model 5TC-TT-K-36-72) with 0.13 mm diameter were placed close to the grinding path, roughly 2 mm from the edge of ground region and 4 mm apart from each other. The temperature data sampled at 2 Hz rate and were used to quantify the heat generation (to be introduced in the next section).

To monitor the PWM of the 3-phase brushless DC motor within the Stryker device, the voltage signal between one phase and the ground was wired to an oscilloscope (Agilent Infiniium 54833A DSO) for signal capturing. Since the sampling rate must be high enough to precisely define the duty cycle change (in μs), continuous sampling and writing to the computer required a large amount of memory and data buffer. Instead, an alternative approach was used by taking several instant signal shots (scanned at 50 MHz by the oscilloscope) at the beginning, middle, and the end of the grinding path since the depth of cut is constant; the spindle loading over the process should be the same.

3.2 Test Matrix

The testing conditions are listed in Table 1. These conditions were aimed at creating different torque levels, covering a wide range of grinding depths, and evaluating multiple feed rates. To avoid mechanical damage in a surgical operation, surgeons usually move the grinding tool gently and slowly since the cranial bone is thin (1 to 3mm) around the operating region. Thus, the maximum depth was no larger than 0.5 mm and the feed rate was kept at between 20 to 60 mm/min by observation.

In addition to motor loading, Tests 7 and 8 were designed to quantify the effects of motions on the partition ratio (ε). The primary motion is in Z-direction (a paint-brush motion); however due to a hand-held control, grinding in X-direction could occur, though less frequently. Note that only two thermocouples were used for tests in the X-direction motion since the tool shank moved transversely.

3.3 Data Analysis

An inverse heat transfer method (IHTM) for spherical grinding wheels, developed in our previous studies [13–14], was adopted to determine the heat generation for each test. The inverse method searches for a proper heat source that creates the temperature data in FEA to best fit the experimental measurements. Figure 3(a) shows the bone model for the grinding tests in X-direction, with TC1 and TC2 corresponding to the thermocouple positions. Similar to the model for the primary motion (Z-direction) in [14], the spherical grinding tool is decomposed into elemental grinding wheels (EGWs), with each EGW individually grinding to generate heat, as illustrated schematically in Fig. 3(b). The heat flux (q_i) under each EGW is proportional to its depth of cut (a_i), contact area ($b_E \times l_b$), and tangential speed, which can be converted to the EGW radius (r_i) with a constant rotational speed, such that

$$q_i = Q \frac{a_i r_i}{b_E l_b} \quad (2)$$

where Q is a proportional constant, the unknown to be determined by the IHTM. By integrating the obtained heat flux over the heat applied area (the highlighted region in Fig. 3(a)), the total heat generation (in watts) can be calculated.

For duty cycle extraction, as shown in Fig. 1, the on-voltage is 40 V and the PWM frequency is 32 kHz, which corresponds to a cycle time of 31.2 μs. Defining t_{on} as the duration of on-voltage, the duty cycle (p) is the ratio of t_{on} to 31.2. For a non-grinding condition at 60,000 rpm, t_{on} is 4.3 μs and p is equal to 13.8%. Because the oscilloscope at a 50 MHz scanning rate can capture 0.02 μs resolution, it is possible to differentiate small changes in the duty cycle. One instant shot of the signal from the oscilloscope contains 50 data points (pulses). Five shots were taken for the cases of 20 mm/min feed rate, and three shots for those under 40 mm/min. The number of shots was constrained by the time required to save the data to the computer. For analysis, an averaged p of the entire data set was used to represent the duty cycle for a specific case.

4. RESULTS

Using the analysis methods in Sec. 3, the experimental results for the eight testing conditions were calculated and plotted in Fig. 4, where p_{ave} stands for the averaged duty cycle. The first data point (marked as Test 0) is the reference when the spindle rotates at 60,000 rpm without extra loading. As shown, Tests 1 to 6 (±Z motions) formed a strong linear relationship, indicating a constant heat partition ratio under the primary motion (Z-direction). However, Tests 7 and 8 displayed another line with a slightly lower slope. Though still linear, this phenomenon implies that the partition ratio might be a function of grinding direction. Thus, if the grinding motion is undefined, the heat conversion could exist within a certain range as highlighted in Fig. 4. For approximation, an averaged linear function can be drawn between the two boundaries, and used as a heat conversion from PWM duty cycle to heat flux on the bone surface. This conversion function was tested via another set of experiments for validation.

In validation, three tests (denoted as Tests I, II, and III) were conducted with randomly defined depths and feed rates. Tests I and II were in +Z and −X feed motions, respectively. Test III was applied with +Z motion and with the tilt angle (α) equal to zero. Tests I and II were intended to quantify the prediction error caused by using an averaged heat conversion function for two different motions. Test III was used to justify the effect of tilt angle, since α = 30° was simply an estimation of the most common case during operation. One thermocouple was placed at about 2 mm from the grinding path on the bone surface, and the data were extracted and compared to FEA calculation using the heat conversion function in Fig. 4.

Measured duty cycles for Tests I, II, and III were 17.2%, 18.4%, and 19.8 %, which corresponded to 0.53, 0.73, and 0.96 W of heat generation, respectively. Predicted temperature results at the thermocouple position are presented in Fig. 5. As shown, the averaged heat conversion gives a reasonable estimation of temperature profile, despite motion effects existing during heat conversion (i.e., Tests I and II). The tilt angle (Test III) was also found to have very limited effect on the temperature prediction. Overall, the discrepancy at the peak temperature is around 2 to 3°C. Since the temperature response is proportional to the heat generation in a linear system, it can be seen as an error of less than 20% in heat generation prediction. If the grinding motion could be specified in the model, more accurate prediction could be achieved.

5. CONCLUSION

A temperature prediction method using motor PWM signal in the neurosurgical device was presented in this paper. Experimental data under a variety of grinding conditions were analyzed to establish a PWM to heat generation conversion function. The heat and temperature, predicted based on this conversion function, displayed reasonable consistency with empirical measurements under a dry condition, demonstrating the feasibility of the proposed method. Practically, real-time temperature computation is desired since numerical methods, such as FEA, take a long time to derive the temperature. As the temperature response problem is a linear time-invariant system, it is possible to program a regional temperature response to the heat input via a transform function. This has been identified as a continuation of this work.

Regarding the robustness of this method, the conversion function is critical and needs to be carefully defined. The heat partition is well known to depend on tool type, size, and rotational speed; however, these are usually controlled factors (i.e., constants) in the high-speed surgical bone grinding. The only variability, though limited, comes from the grinding motion, as indicated in this study. In real practice, irrigation could be another uncertainty. Similar to wet machining processes, it creates forced-convection on the bone surface to suppress the temperature rise. The conversion function would display a smaller slope, but would still remain linear since the convection coefficient is also often seen as a constant.

In summary, this technical paper demonstrated the linear relationship between electrical and thermal power, which could be used in temperature prediction during surgical bone grinding. Further applications could include dental implantology, spine surgery, and general orthopaedic surgery to prevent nerve injury or bone necrosis.

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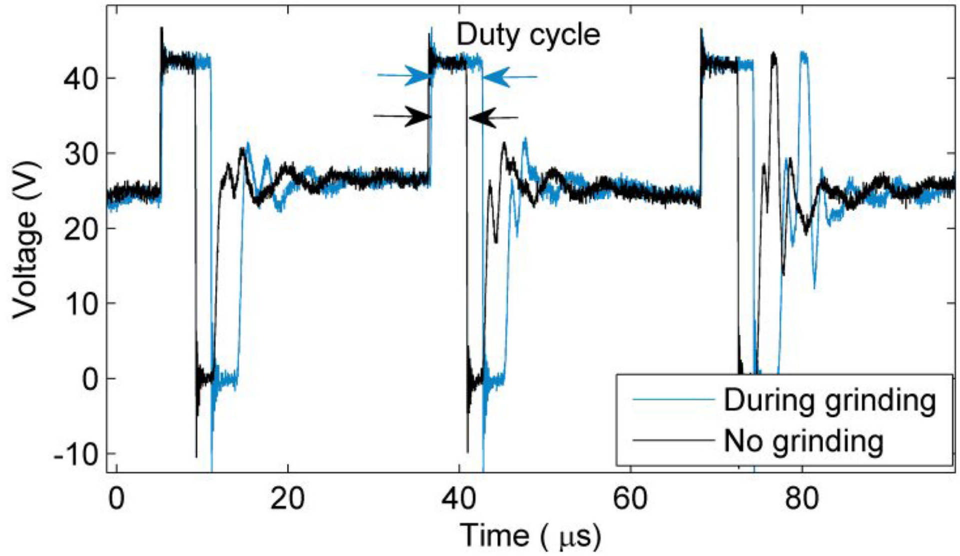

Fig. 1.
PWM duty cycle

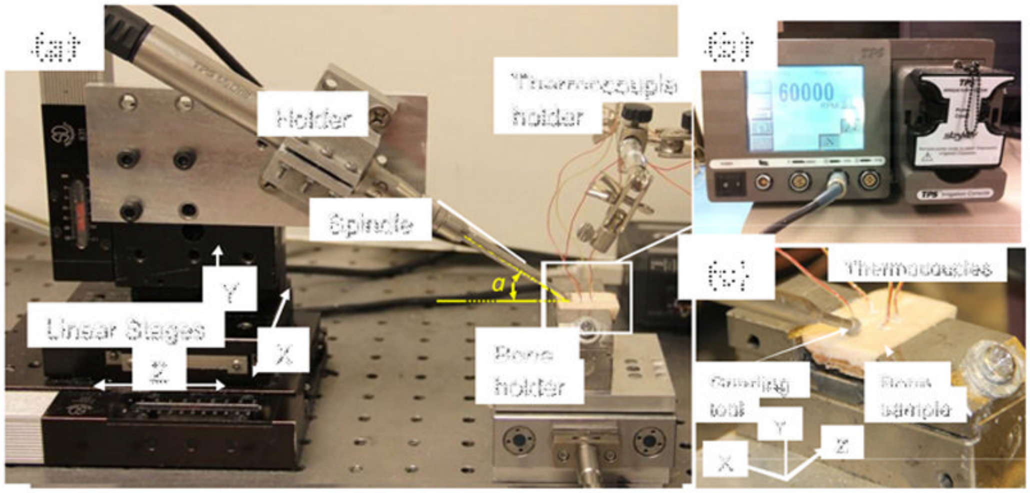

Fig. 2.
Experimental setup: (a) overall apparatus, (b) drill console, and (c) thermocouple setup

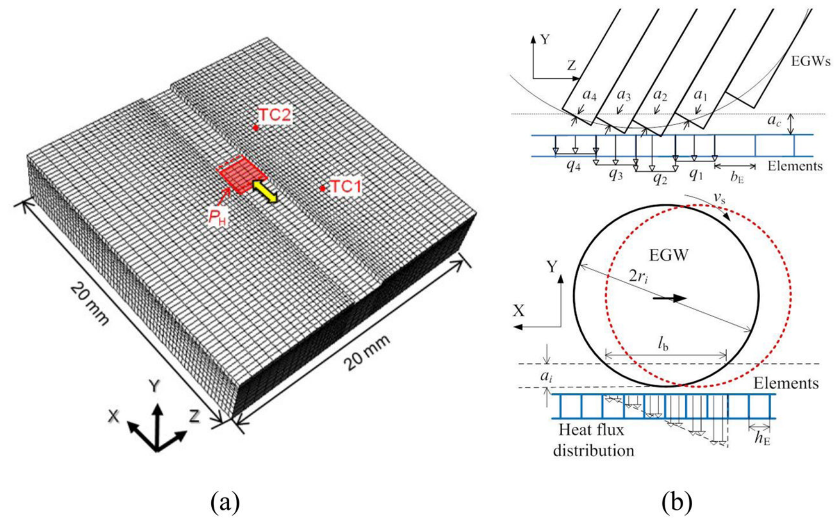

Fig. 3.

Finite element bone thermal model for X-direction motion: (a) FEA mesh and (b) heat flux distribution

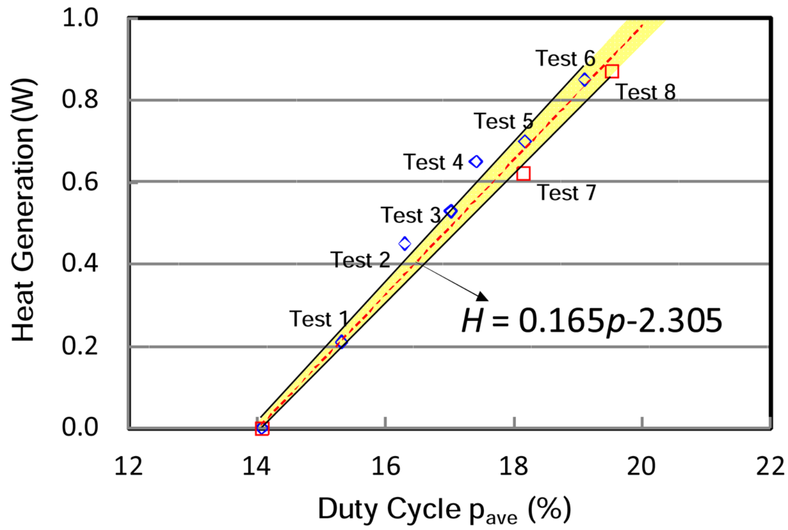

Fig. 4.
Results of averaged duty cycle (p_{ave}) vs. heat generation

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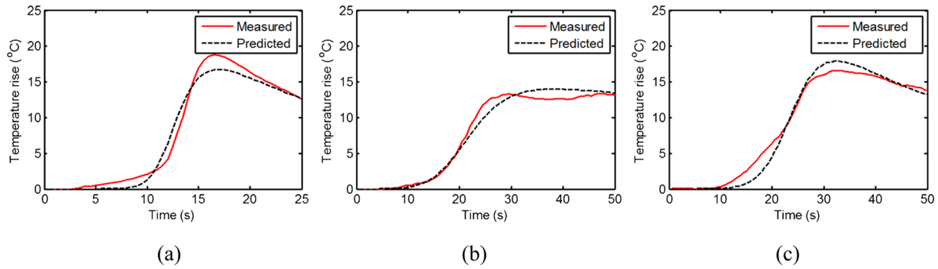

Fig. 5.
Results of predicted and measured temperatures at TC1 for (a) Test I, (b) Test II, and (c) Test III

Table 1

Test Matrix

Test #	Depth of cut (mm)	Feed rate (mm/min)	Motion
1	0.1	20	+Z
2	0.25	20	+Z
3	0.25	40	+Z
4	0.4	20	+Z
5	0.4	20	−Z
6	0.4	40	−Z
7	0.4	20	+X
8	0.4	20	−X