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Editor's comment: This paper addresses an important issue faced by orthopedic surgeons when sawing through bone: how to minimize thermal damage to adjacent healthy tissue? The authors have conducted a systematic investigation into the effects of sawing parameters on the depth of osteonecrosis at the cut surface – a factor implicated in the aseptic loosening of orthopedic implants. These findings will be of interest to surgeons who use such tools in their clinical practice.

Richard Black, Editor in Chief

Effect of applied force and blade speed on histopathology of bone during resection by sagittal saw

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ABSTRACT

A sagittal saw is commonly used for resection of bone during joint replacement surgery. During sawing, heat is generated that can lead to an increase in temperature at the resected surface. The aim of this study was to determine the effect of applied thrust force and blade speed on generating heat. The effect of these factors and their interactions on cutting temperature and bone health were investigated with a full factorial Design of Experiments approach for two levels of thrust force, 15 N and 30 N, and for two levels of blade oscillation rate, 12,000 and 18,000 cycles per minute (cpm). In addition, a preliminary study was conducted to eliminate blade wear as a confounding factor. A custom sawing fixture was used to crosscut samples of fresh bovine cortical bone while temperature in the bone was measured by thermocouple ($n = 40$), followed by measurements of the depth of thermal necrosis by histopathological analysis ($n = 200$). An analysis of variance was used to determine the significance of the factor effects on necrotic depth as evidenced by empty lacunae. Both thrust force and blade speed demonstrated a statistically significant effect on the depth of osteonecrosis ($p < 0.05$), while the interaction of thrust force with blade speed was not significant ($p = 0.22$). The minimum necrotic depth observed was 0.50 mm, corresponding to a higher level of force and blade speed (30 N, 18,000 cpm). Under these conditions, a maximum temperature of 93 °C was measured at 0.3 mm from the kerf. With a decrease in both thrust force and blade speed (15 N, 12,000 cpm), the temperature in the bone increased to 109 °C, corresponding to a nearly 50% increase in depth of the necrotic zone to 0.74 mm. A predictive equation for necrotic depth in terms of thrust force and blade speed was determined through regression analysis and validated by experiment. The histology results imply that an increase in applied thrust force is more effective in reducing the depth of thermal damage to surrounding bone than an increase in blade speed.

1. Introduction

The use of power saws in orthopedics has existed since at least 1890 as evident from US Patent 436,804 awarded to M.J. Roberts for an "Electro Ostetome" that relied upon a unique reciprocating mechanism to rapidly translate the blade with an electric motor. In contemporary joint replacement surgery, reciprocating saws have largely been replaced by battery powered tools that oscillate the blade at high frequency, 10,000–20,000 oscillations per minute (cpm), through a relatively small angle, typically 4–5°. Oscillating (sagittal) saws are used, for example, in total knee arthroplasty to prepare flat surfaces on the condylar ends of the femur and tibia in order to facilitate attachment of an artificial knee implant. Unfortunately, heat is generated during the bone sawing process, which can lead to higher temperatures that over time can cause cellular damage at the resected surface [1]. During sawing, a surgeon has control over applied thrust force and blade speed, which are two parameters that can affect temperature. Blade speed is

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proportional to the product of blade length and oscillation rate of the saw.

The primary motivation behind the implementation of temperature abatement strategies during bone resection and preparation by sagittal saw has been the identification of a link between osteonecrosis and aseptic implant loosening. During bone cutting, heat energy derived from shear deformation of bone and friction between the blade and the bone can cause osteonecrosis at or near the resection plane [1,2]. The local effect of heat on bone is further enhanced by cortical bone's relatively poor thermal conductivity at 0.58 ± 0.018 W/mK in the longitudinal direction [3] and low temperature threshold for irreversible osteocyte cell death at 47–50 °C [4,5]. Eriksson and Albrektsson found that heating rabbit cortical bone to 50 °C for 1 min led to implant loosening and significantly reduced osteointegration when compared to a control [6]. In addition, mechanical deformation from sawing can cause micro-cracks that can lead to osteocyte apoptosis [7]. As a result, the absence of osteocytes triggers targeted osteoclastic bone resorption of the damaged area [8].

Sawing experiments have been conducted to determine the effect of saw blade design and kerf (saw cut) irrigation on cutting temperature. Toksvig-Larsen et al. found that different sagittal saw blade designs did not significantly reduce temperatures below the critical limit for heat induced bone necrosis [9]. The effect of irrigation on the necrotic threshold temperature is less clear, with Toksvig-Larsen and Ryd [10] reporting no difference in temperature due to irrigation of the kerf, while Wächter and Stoll [11] demonstrated that intermittent sawing combined with irrigation was able to adequately reduce bone temperatures. However, it appears that in practice surgeons are reluctant to forcefully irrigate the saw blade as it is difficult to inject fluids into the kerf. In addition, the kerf in total knee arthroplasty is typically obstructed by the cutting guide.

Considering limited success in controlling temperature with saw blade design and practical difficulties with kerf irrigation, parameters affecting operation of the sagittal saw deserve further scrutiny. Unfortunately, there is a paucity of data on the relationship between sawing parameters and the resultant bone temperature. There is, however, significant literature on operational parameters affecting temperature during bone drilling. Acknowledging that sawing and drilling of bone may differ in the mechanics of chip creation and removal, the literature on bone drilling provides important insight and guidance into the methodologies used to investigate the problem of heat generation during bone removal. A comprehensive review of the literature on the relationship between drilling parameters and thermal osteonecrosis was recently provided by Augustin et al. [12]. From the parameters identified, the most relevant to sawing are feed rate and drill speed, which are analogous to thrust force and blade speed, respectively. The investigative method traditionally used in research on bone drilling is to measure the maximum temperature rise with a thermocouple placed in the bone. A multifactorial study on drilling parameters revealed that an increase in drill speed was associated with a higher temperature rise in the bone as measured by thermocouple, whereas an increase in feed force generally resulted in a lower temperature rise [13].

In addition to temperature measurement by thermocouple, the effect of higher temperatures on health of the boney bed can be deduced by histopathological analysis. Although this method has not been applied to bone sawing research, a recent histology study on process parameters related to bone drilling revealed that high temperatures resulted in osteocyte death as evident from an increased depth of empty lacunae from the surface of the drilled hole [14].

The objective of the current study is to determine the effect of applied thrust force and blade speed on health of the boney bed by using thermocouples to measure temperature in the bone near the resected surface and by studying the histopathology of the bone to determine a necrotic depth. Drawing upon the research on bone drilling, it was hypothesized that an increase in thrust force and blade speed would correspond to a decrease in the necrotic depth. To test the hypothesis, a custom bone sawing fixture was developed and a full factorial Design of Experiments (DOE) approach was employed. Prior to conducting the DOE, initial studies were pursued to determine proper sample size for statistical significance and to determine if wear was a confounding factor.

2. Materials and methods

2.1. Oscillating saw and fixture

A custom apparatus was designed for sagittal sawing experiments (Fig. 1). The fixture was fitted with an AC electric oscillating tool (Fein Multimaster, Fein Power Tool, Inc., Pittsburgh, PA, USA). This tool is primarily used in wood and metal working applications, but has the same 4–5° sweep angle and rate of oscillation as contemporary sagittal saws. However, unlike cordless surgical saws, where blade speed can fluctuate as a condition of the battery's state of charge, the corded oscillating saw maintains a constant blade speed while under load as confirmed in screening studies by stroboscope (Nova Strobe, Monarch Instrument, Amherst, NH, USA). This is more suitable for cutting experiments where the effect of blade speed is a parameter being investigated.

The oscillating saw was attached to vertical guide rails with low friction linear bearings to facilitate orthogonal cross-cutting of the bone workpiece, Fig. 1. Applied thrust force, normal to the workpiece surface, was generated by the weight of the tool and adjusted with a counterweight pulley system. A force gage (MG20, Mark 10 Company, Copiague, NY) with an accuracy of ±0.4 N was placed beneath the center of the saw blade to confirm the range of thrust forces being investigated. Oscillation rate was controlled by the tool's variable speed dial and prior to each cut was confirmed by stroboscope.

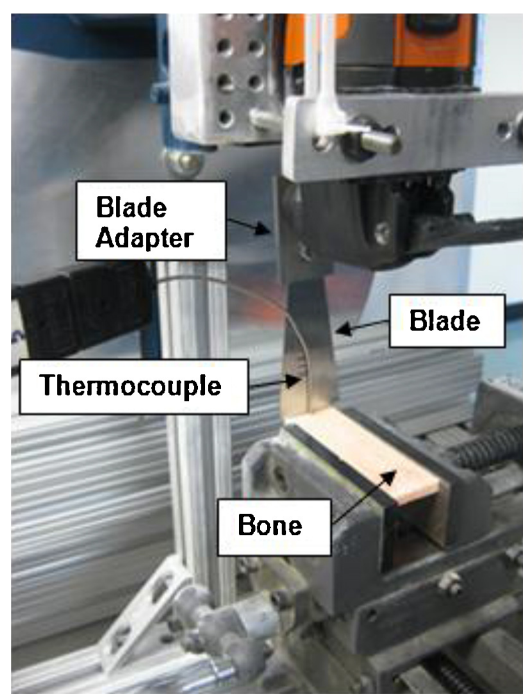

Fig. 1. Sawing apparatus used to cross cut bone under various conditions of blade speed and thrust force.