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RECIPROCATING BONE SAW: EFFECT OF BLADE SPEED ON CUTTING RATE

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ABSTRACT

Power reciprocating saws are used in surgical procedures to cut bone. Improved cutting rates are desirable in order to reduce operative time and improve patient outcome. A fixture was developed to test the effect of blade speed on cutting rate of bovine cortical bone. It was hypothesized that the volumetric cutting rate would increase in a linear manner for a fixed stroke length and a constant thrust force. A 7.0 N thrust force was applied. The reciprocating stroke length was held constant at 3.0 mm. Using an 18 TPI blade, cutting rate was determined to increase in a slightly non-linear manner, with disproportionately higher cutting rate at higher blade speeds. The data implies that a higher reciprocating frequency may invoke more efficient cutting.

Keywords: Bone Sawing, Reciprocating

INTRODUCTION

Powered reciprocating saws are used to shape and transect bone. While hand saws perform well, powered saws are desirable due to their higher cutting rates and compact size. Higher cutting rates reduce the time required for surgical procedures. This is especially important in cases where a patient extremity is under tourniquet. In addition, frictional heating between the blade and the bony bed can occur, resulting in elevated temperature at the bone surface. High temperatures are known to cause thermal necrosis of bone cells [1]. The death of bone cells due to high temperature can prolong patient healing time and decrease the efficacy of implant fit.

In bone sawing processes, higher cutting rates can be achieved by increasing blade speed [2]. For reciprocating saws, blade speed is dependent on two parameters: stroke length and reciprocating rate. It is preferable to increase blade speed through an increase in reciprocating rate, rather than by changing stroke length. In confined areas, a reciprocating saw with a longer stroke length increases the likelihood of damaging adjacent tissue.

Outside of orthopedic medicine, reciprocating saws for construction and demolition employ orbital action, which is an alteration to the straight-line reciprocating path of conventional saws. For orbital action, the path of the blade is an ellipse in which the major axis coincides with primary stroke direction and the minor axis is normal to the surface of the workpiece. The small amplitude chopping of orbital action is present in construction/demolition reciprocating saws to improve cutting rates in wood and metal. As of this writing, no data has been published on the effectiveness of orbital action in sawing bone.

A novel bone saw with orbital action has been developed for this study. The aim of this research was to investigate the effect of blade speed on cutting rate of a reciprocating saw with constant orbital action and constant stroke length.

BACKGROUND

Reciprocating saws are used to cut bone in a variety of surgical procedures. The saws generally come in two sizes and related configurations. For oral and maxillofacial surgery, reciprocating saws and related blades are quite small, often referred to by surgeons as micro reciprocating saws or simply as “small bone” saws. These saws are being used, for example, by oral surgeons for alveolar ridge reduction and removal of mandibular tori, rather than the more time-consuming approach of using burs [3,4]. In orthognathic surgery, reciprocating saws are commonly used to perform maxillary osteotomies. Micro reciprocating saws are also used in the retrieval of bone grafts, such as in calvarial and iliac crest bone harvests [5]. The configuration of a micro reciprocating saw is cylindrical as shown in Figure 1.

Figure 1 TYPICAL CONFIGURATION OF A MICRO RECIPROCATING SAW.

The second type of reciprocating saw is commonly referred to as a “large bone” saw. This configuration resembles the pistol grip configuration of a sagittal saw. Large bone reciprocating saws and a representative blade are shown in Figure 2. A typical application of this saw is in unicompartmental knee arthroplasty or in a median sternotomy [6]. The sternal version of the saw has an attachment to guard the tip of the reciprocating blade, so as to avoid piercing tissue and organs.

(A)

(B)

Figure 2 (A) LARGE BONE RECIPROCATING SAWS AND (B) REPRESENTATIVE BLADE AS USED IN EXPERIMENT.

Reciprocating frequencies of large bone saws are approximately 13,000 cycles per minute (217 Hz) and stroke lengths are generally around 3.0 mm. When comparing micro reciprocating saws to large bone saws, the reciprocating frequency of the micro saws tends to be greater, but the stroke length is less. Average blade speed is proportional to both the reciprocating frequency and stroke length, so by this measure both types of saws have comparable blade speeds.

Building on the knowledge base from metal machining theory, bone sawing has been studied extensively as an orthogonal cutting process [7, 8]. During orthogonal cutting, a single cutting edge, which is wider than the workpiece, is positioned so that the cutting edge is perpendicular to the direction of cutting. For orthogonal studies, however, blade speed has been limited by the speed at which the bed of a mill or a shaper can traverse, which is an order of magnitude less than blade speeds of a typical surgical reciprocating saw. In order to study the effect of higher blade speeds on cutting rate, a new reciprocating sawing fixture was developed.

EXPERIMENTAL FIXTURE

Reciprocating blade motion is created with a modified slider-crank mechanism. However, instead of converting the rotation of the crank into pure linear reciprocation, this mechanism creates a blade path that resembles an ellipse. The horizontal component (major axis of the ellipse) provides the primary stroke action, and the vertical component (minor axis of the ellipse) provides the orbital action. The magnitude of orbit is controlled by adjusting the distance between the crank center and the pivot point.

Referring to Figure 3, point A on the crank travels in a circle of radius R around the origin, O. Link AB, of length L, translates and rotates about point C. By moving the location of the pivot point C (i.e. changing the offset distance W), the degree of orbital path at point B is affected. The saw blade is attached near point B and therefore reciprocates and plunges into the bone on the return stroke of the saw.

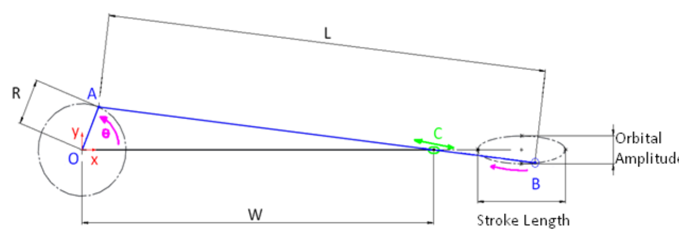

Figure 3 SCHEMATIC REPRESENTATION OF MODIFIED SLIDER-CRANK MOTION RESULTING IN ORBITAL CUTTING ACTION.

The blade path is not exactly an ellipse, but for brevity, the derivation of its exact path in terms of the variables in Figure 3 will be omitted. The magnitudes of the stoke length and orbit are given by the following equations:

$$Magnitude\ of\ stroke\ length = 2R \tag{1}$$

$$Magnitude\ of\ orbit\ \approx 2R\,|1 - \frac{L}{W}| \tag{2}$$

The physical implication of Eq. (1) and (2) is that by adjusting the distance to the pivot point, W, and the magnitude of the crank offset, R, the aspect ratio and scale of the elliptical saw blade path are determined. For this experiment, an orbital amplitude (magnitude of minor axis of ellipse) of 0.04 mm was used.

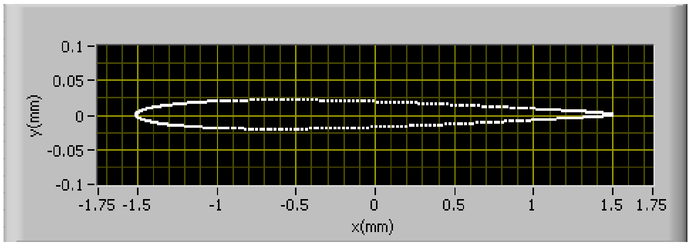

Figure 4 DIAGRAM OF BLADE PATH FOR A SINGLE TOOTH. (W=202.47 mm, L=200 mm, R=1.5 mm - Note that Y is scaled at approximately 5x for visibility of the orbital blade path).

Each tooth on the saw blade, however, is a different distance from the crank, so L varies across the width of the bone sample. The variation of L results in variation in orbital amplitude for each saw blade tooth engaging the bone sample. For example, for a bone sample width of 11 mm, the cutting configuration in this study resulted in orbital amplitudes of 0.12 mm, 0.04 mm, and 0.05 mm at the base end, middle, and tip end of the saw blade respectively.

A 2 ¼ horsepower router motor (Porter Cable, Model 892, Jackson, TN) was used to drive the crankshaft. The speed control circuit was removed from the router so that a variable transformer (Staco, Model SPN1510B, Staco Energy Products Co., Dayton, OH) could be used to manually control motor speed from 0-20,000 rpm. The motor was oversized so that reciprocating frequency could be held constant while under load. The reciprocating saw mechanism is shown in Figure 5.

The reciprocating saw mechanism was fixed to one side of a rigid rotating frame, as shown in Figure 6. A counterweight was used to apply a fixed downward thrust force during sawing. The variation in applied thrust force due to the angle of rotation of the frame can be shown to be on the order of 0.1 N for the angles of rotation used in this experiment. This variation is smaller than the accuracy of the force gauge used, thus the applied force was considered to be constant.

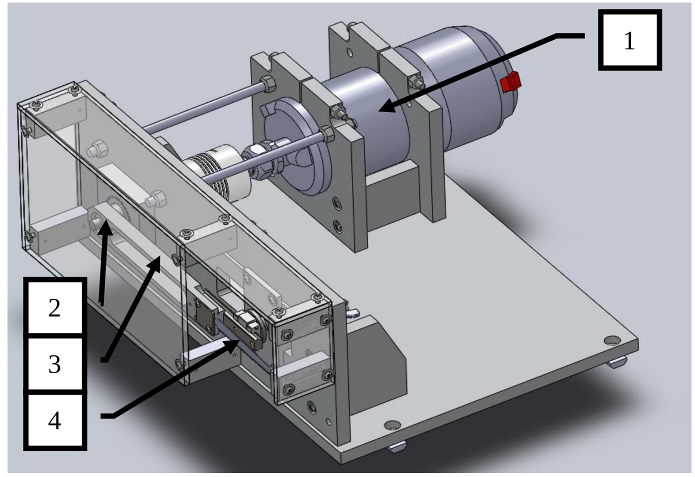

Figure 5 IMPORTANT FEATURES OF THE RECIPROCATING SAWING MECHANISM. (1) DRIVE MOTOR, (2) CRANKSHAFT, (3) CONNECTING ROD, (4) BLADE

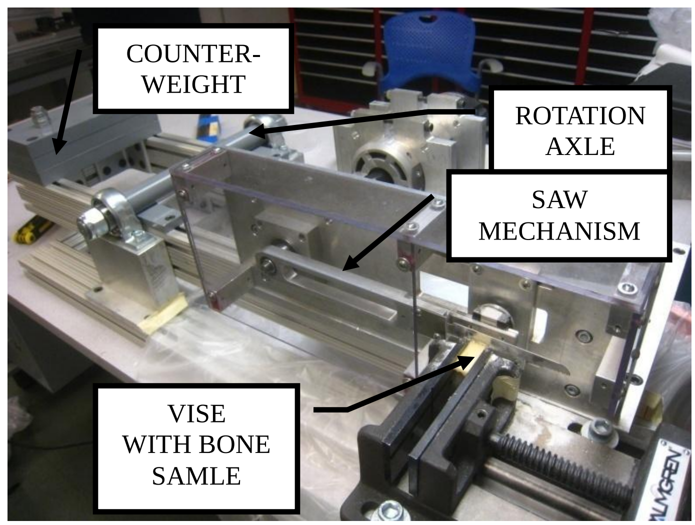

Figure 6 CUTTING FIXTURE USED TO HOLD THE BONE SAMPLE AND RECIPROCATING SAW.

EXPERIMENTAL PROCEDURE

Fresh adult bovine tibia were obtained from a local abattoir and placed in a medical freezer at -20 degrees Celsius until time of use. While still frozen, a meat cutting bandsaw (Grizzly, Model G0560, Grizzly Industrial Inc., Muncy, PA) was used to cut cortical bone samples from the mid-diaphysis region of the bovine tibia as shown in Figure 7. The periosteum was removed from the exterior surface of the bone and the medullary cavity was scraped clean by hand to the bony surface. Each sample was approximately 75 mm in length, with a rectangular cross sectional area of approximately 8 mm by 11 mm. The length of the sample corresponded with the primary osteon direction of the long bone, shown by an arrow in Figure 7.

The counter weight was adjusted to provide a constant force of 7.0 N throughout the cutting range. The thrust force was measured at the tip of a saw tooth, in the middle of the sawing portion of the blade. Force was measured with a portable gauge (MG20, Mark 10 Co., Copiague, NY) to an accuracy of ±0.4 N.

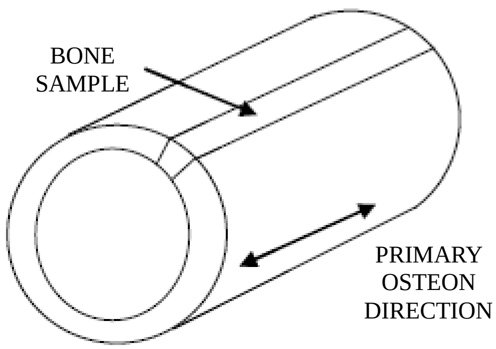

Figure 7 CORTICAL BONE SAMPLES TAKEN FROM THE MID-DIAPHYSIS REGION OF AN ADULT BOVINE TIBIA.

Four blade speeds were used, 90.3 mm/s, 345 mm/s, 558 mm/s, and 760 mm/s, corresponding to reciprocating frequencies of 14 Hz, 52 Hz, 84 Hz, and 114 Hz. Blade speeds were calculated as a function of cutting frequency and reported as root mean square values (RMS). Equation 3 was used to calculate the RMS blade speed, where R (mm) is the crankshaft offset, and f is the cutting frequency (Hz).

$$V_{RMS} = \frac{2\pi f R}{\sqrt{2}} \tag{3}$$

The cutting frequency of the sawing mechanism was measured using reflective tape on the motor drive shaft and a handheld tachometer (Checkline A2108, Electromatic Equipment Co., Cedarhurst, NY) with a precision of ±1 Hz during sawing.

One 18 TPI (teeth per inch) reciprocating saw blade (Brasseler USA, Model# KM-458, Savannah, GA) was used for all cutting trials. The saw blade was inspected under a microscope for wear, but it did not appear to have dulled during the experiments. Four cuts were made for each reciprocating frequency for a total of 16 cuts.

For each trial, the saw motor was allowed to warm up and reach a steady-state speed. Once the desired speed was reached, the saw was slowly lowered to approximately 0.5 mm above the bone sample. The saw was then released and the timer started. As the saw completed the cut, the total time was recorded and the bone sample was collected. Bone sample cut-offs were placed in sealed bags and returned to the refrigerator for further analysis.

RESULTS

The volume of bone cut was determined from the cross sectional area of the newly cut surface, multiplied by saw blade kerf thickness, 1.0 mm. Given the irregular shape of the cut cross sectional area, it was measured by taking a digital image of the bone slice using an image processing technique with ImageJ software (open source Java code from the US National Institute of Health website http://rsbweb@nih.gov/ij/).

The cut surface of the bone slice was dyed black and imaged against a white background with an 18.84 mm scale marker. The blue plane of the image was extracted for the best contrast, and the image was thresholded to highlight only the dyed area. The software determined the real area of the bone by scaling the number of pixels in the highlighted area by the scale marker. The average volumetric cutting rate was determined by dividing this volume by the time measured to cut through the bone sample. Average results from the sawing experiments are shown in Figure 8. The error bars represent one standard deviation in the experimental data.

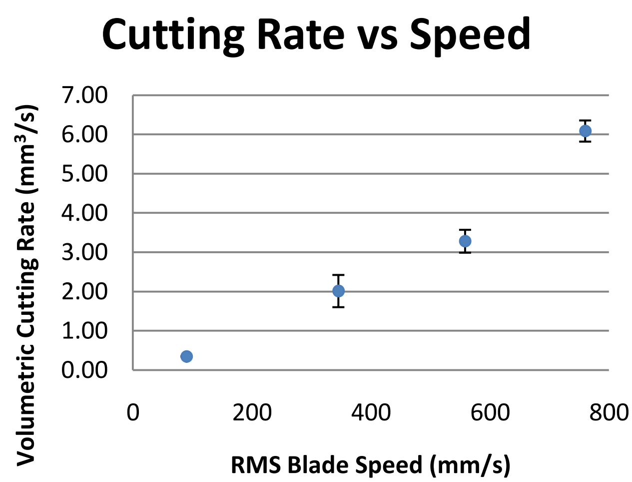

Figure 8 CUTTING RATES IN BOVINE CORTICAL BONE AS A FUNCTION OF ROOT MEAN SQUARE BLADE SPEED.

DISCUSSION

For the lower three blade speeds (90.3 mm/s, 345 mm/s, and 558 mm/s), the volumetric sawing rate increased in a linear manner with blade speed. This is apparent from the data in Figure 8. However, the cutting rate increased beyond a linear extrapolation of the lower speeds when the saw was run at the highest blade speed, 760 mm/s. This unexpectedly high cutting rate could be an indication of a change in cutting mechanics at higher blade speeds, which could have resulted from the viscoelasticity of bone material. Alternatively, the higher cutting rate could be related to an enhancement of the effectiveness of orbital action at higher blade speeds. The orbital amplitude is quite small when compared to the cutting stroke length, so its effect is analogous to vibratory cutting.

Krause [2] investigated the effect of imposing lateral vibrations on a cutter during orthogonal machining of bone. Forced vibrations improved cutting efficiency as apparent from a reduction in cutting forces. Krause suggested that blade vibrations reduced cutting forces by decreasing friction at the interface between the bone and the cutter. He also postulated that blade lateral vibrations could have improved cutting rate by adding energy to aid in crack initiation.

In the experiments conducted here with an orbital action reciprocating saw, the statically applied thrust force is complimented by the dynamic thrust force due to orbital action. On each return stroke of the saw, the mechanism is thrust upward by the orbital amplitude. The mass of the saw resists this upward motion, thereby creating a dynamic thrust force. The dynamic thrust force increases with an increase in reciprocating speed. It is possible that a combination of high blade speed with orbital blade action could act to trigger a more efficient cutting regime.

CONCLUSION

A novel mechanism was developed to create a dynamic thrust force during the return stroke of a reciprocating bone saw. The new mechanism caused the saw blade to follow an elliptical blade path, commonly referred to as orbital action. While holding the orbital amplitude constant at 0.04 mm, experiments were conducted to test the effect of reciprocating blade speed on volumetric cutting rate of bovine bone. It was hypothesized that volumetric cutting rate would increase in a linear manner with an increase in reciprocating frequency. However, cutting rate increased in a non-linear manner at higher blade speed. Volumetric cutting rate increased from 0.35 mm^3/sec at a blade speed of 90 mm/s, to 6.1 mm^3/sec at a blade speed of 760 mm/s. Cutting rates corresponding to blade speeds between 90 mm/s and 560 mm/s appeared linear, but diverged from linearity to higher than expected cutting rates at blade speeds of 760 mm/s. The data implies that a combination of orbital blade action and higher reciprocating speed may invoke more efficient chip formation.

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