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A STUDY ON THE CUTTING RATE PERFORMANCE OF A NOVEL SAGITTAL BONE SAW

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ABSTRACT

Conventional sagittal saws have been shown to generate significant heat at the cutting interface due to high friction and slow cutting rates. To investigate means of reducing sawing temperatures, a new sagittal sawing mechanism was developed to experiment with cutting parameters such as blade speed, stroke length, and thrust force. A unique aspect of the new mechanism is the ability to create blade movement in a direction normal to the oscillating motion. This enables the user to generate a thrust force by mechanical means, rather than through the application of a thrust force by hand. For this initial study, the new mechanism was characterized as a conventional sagittal saw, with cutting rates measured as a function of blade speed for a constant externally applied thrust force. The relationship between cutting rate and oscillatory blade speed was not linear in the region tested. At lower blade speeds, the cutting rate leveled off. As blade speed increased beyond an apparent threshold, cutting rates increased significantly for a relatively small change in blade speed.

Keywords: Bone Sawing, Sagittal

INTRODUCTION

The aim of this research was to introduce a new sagittal bone sawing mechanism, capable of blade motion perpendicular to the cutting direction, and to create a baseline study for the effect of blade speed on the cutting rate of bovine cortical bone. Conventional sagittal saws used in bone sawing have some areas where design improvements could increase cutting efficiency and thereby have a positive impact on patient outcomes. First, the continual application of a downward force by a surgeon on a sagittal saw causes significant friction as the saw blade teeth slide across the bone. This friction creates heat in the surrounding bone tissue. High temperatures are known to cause necrosis of bone cells, increasing the time necessary for healing and decreasing the quality of fit for replacement joints [1]. Second, the application of the downward thrust force can create an unsafe condition when the saw blade suddenly breaks through the bone at the end of the cut, potentially causing the surgeon to unintentionally thrust the saw blade into surrounding tissue. Finally, inefficient bone sawing affects the time required for surgical procedures, which is particularly important if the patient is under tourniquet, such as in total knee arthroplasty.

The authors have developed a new sagittal sawing mechanism that is conducive to research investigations of sawing parameters that may have an effect on cutting efficiency. The first of these parameters to be investigated was oscillating speed. It has been shown that the speed at which the blade passes over the bone affects the friction of cutting [2], so blade speed may affect heat generation and cutting performance.

BACKGROUND

Previous studies have been done on the orthogonal machining of bone, that is, the process of a rigidly-held, single-tooth cutter making a single pass across a rigidly held specimen at a prescribed depth of cut. Jacobs et al. investigated chip formation during orthogonal machining of bone and paid particular attention to the orientation of the osteons with respect to the cutter [3]. Jacobs noted that cutting depth and rake angle both had a significant effect on the forces during cutting, and that various combinations produced dramatically different chip structures. Wiggins and Malkin extended upon Jacobs' work by considering much larger depths of cut and evaluating parameters based on specific energy instead of force. They found that increasing the depth of cut and increasing the rake angle (having a sharper-angled tooth wedge) resulted in more efficient cutting [4]. Itoh, et al. [5], Yeager et al. [6], and Sugita and Mitsuishi [7] conducted similar studies. Krause studied the effect of imposing ultrasonic vibrations to reduce the friction at the bone-tool interface and found that it did decrease the energy expenditure of cutting [2].

Orthogonal machining studies, however, may not completely represent the cutting conditions of multi-tooth bone sawing blades, in which a relatively constant force is applied, and the cutting rate is allowed to vary. This reversal of the independent and dependant variables may affect the overall performance of the device. Furthermore, chip buildup and clogging on a blade with multiple teeth affect real devices, but are neglected in single tooth orthogonal machining studies. Finally, the interactions of multiple teeth may affect performance. For these reasons, a research device more similar to a conventional surgical sagittal saw than an orthogonal machining tool was developed.

SAGITTAL SAWING MECHANISM DESIGN

The design of this new sagittal sawing fixture is primarily centered on the dynamics of the blade path and less so on the tool-chip interface. The goal of the fixture design was to provide a platform for research into sawing parameters that may have an effect on cutting efficiency. A novel approach has been taken to decouple the cutting and thrust movement of the blade. One hypothesis driving this design decision was that a high thrust force during a portion of the cutting path may create a significant depth of cut per saw blade tooth, thereby increasing cutting rates and sawing efficiency. In present sawing devices, the thrust force is applied as a constant throughout the cutting path. A constant thrust force creates a constant frictional force. An interrupted thrust force results in a jackhammer-like motion, analogous to percussive drilling of rock [8]. This jackhammer motion of the saw blade may increase cutting efficiency.

In this new sawing mechanism, the frequency of oscillation in the cutting direction is mechanically coupled to the frequency of oscillation in the thrust direction. It was determined that the thrusting frequency should be an even multiple of the cutting frequency. This creates cutting paths that resemble a figure-eight as shown in fig. 1. Uneven multiples of thrust and cutting frequency produce a blade path that is asymmetric. An asymmetric blade path creates a bias in the cutting direction of the sagittal saw, causing the blade to pull to one side which reduces control and makes cutting difficult. This condition was verified with an initial prototype.

With this new sawing mechanism, both the amplitude and length of the figure-eight can be varied independently. As the amplitude of the figure-eight approaches zero, the mechanism creates the blade path of a traditional sagittal saw, which is pure oscillatory motion.

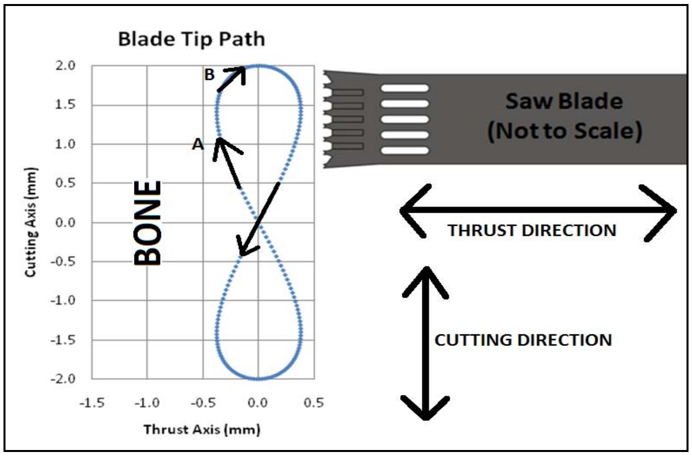

Fig 1 VARIOUS BLADE THRUST AND CUTTING MOTIONS USED TO CREATE FIGURE-EIGHT SAWING PATTERNS. THE PLANE OF THE BONE SURFACE IS NORMAL TO THE THRUST AND CUTTING DIRECTIONS.

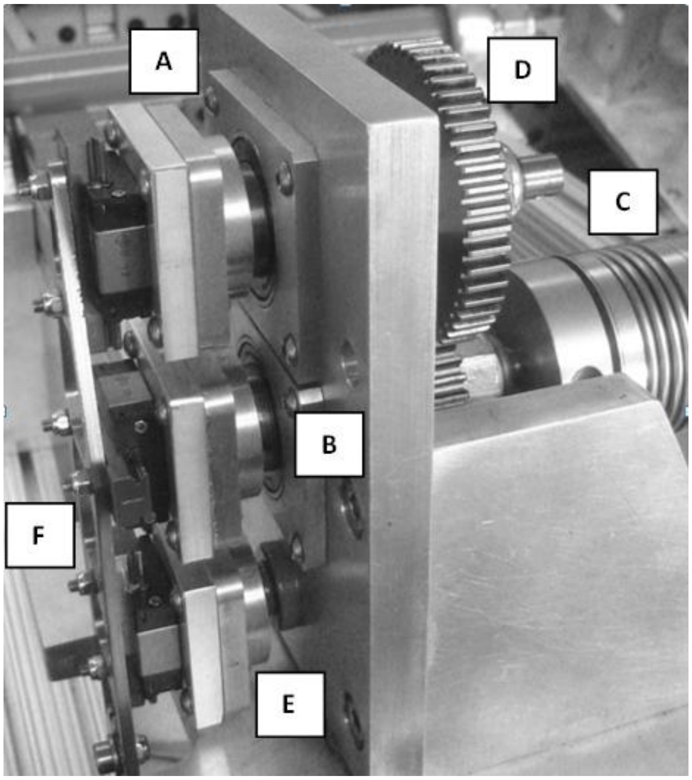

Fig 2 MECHANISM FOR INDEPENDENTLY CONTROLLING THRUST AND CUTTING MOTION IN SAGITTAL SAWING.

Referring to the sawing mechanism shown in fig. 2, the cutting and thrust path of the saw blade is controlled independently by two off-center crankshafts, **A** and **B**. The overall aspect ratio and size of the figure-eight blade path is dependant on the displacement of each crank from the shaft center axis. Linear guides are used to isolate the desired linear component from the circular motion produced by the crankshaft. Off-center crankshaft and linear guide **A** controls the cutting path of the blade, while off-center crankshaft and linear guide **B** controls the thrust path of the blade. The shape of the figure-eight is modified by changing the phase offset of the gears. A 90° offset produces a nearly symetric figure-eight, while other offsets tend to bend the shape towards an arc. Spur gears **D,** in a 2:1 ratio, were used to couple the crankshafts and to provide the necessary phase offset. Crankshaft **A** rotates at ω, while crankshaft **B** rotates at 2ω.

Referring again to fig. 2, a 2¼ horsepower router (Porter Cable, Model 892, Jackson, TN) was used to power the sawing mechanism. The router was attached to the mechanism drive shaft through a high speed aluminum coupling **C**. A stationary shaft and bearing assembly **E** act as a pivot point about which the blade holder **F** oscillates.

EXPERIMENTAL PROCEDURE

After designing and constructing the sagittal sawing mechanism, a design of experiments (DOE) was developed to determine which independent factors and interactions of factors could have the greatest effect on cutting rates in bovine cortical bone. Prior to conducting extensive research on the cutting rate effectiveness of various figure-eight amplitudes and stroke lengths, it was determined that baseline data for the new sawing mechanism should be established by conducting tests in the configuration of a traditional sagittal saw. Therefore, the amplitude of the off-center cam for thrust force motion was set to zero so that pure oscillatory cutting motion was generated.

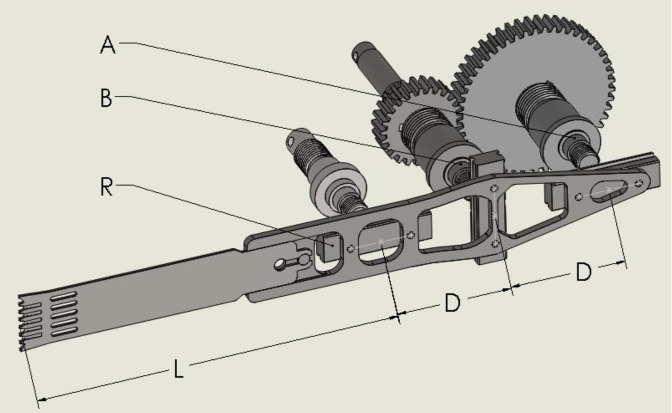

Fig 3 CRANKSHAFT ARRANGEMENT USED TO ACHIEVE TRADITIONAL SAGITTAL SAWING MOTION – PURE OSCILLATION IN THE CUTTING DIRECTION.

Figure 3 shows a schematic of the sawing mechanism. For this experiment, the offset of crankshaft **B** was set to zero, producing pure oscillatory motion. The distance from the tip of the saw blade tooth to the center of the pivot axis, shown by dimension **L**, was determined to be 150.1mm. The distance from the pivot axis to crankshaft **A** was equal to twice the dimension **D**, or 95.2mm. The off-set for crankshaft **B** was zero, while the offset for crankshaft **A** was 1.16mm. This arrangement resulted in traditional sagittal motion with a blade oscillation angle of 1.40 degrees in the cutting direction. Using a small angle approximation, the total distance traveled by one cutting tooth was 3.66mm during 1.40 degrees of blade oscillation.

From a survey of the literature and from practical experience, oscillating speed in the cutting direction was determined to be an important experimental factor for initial investigation. A screening test was devised to determine the effect of cutting speed on cutting rate. The purpose of the test was to determine if cutting speed should be represented as a two or three level factor in future full factorial DOE studies.

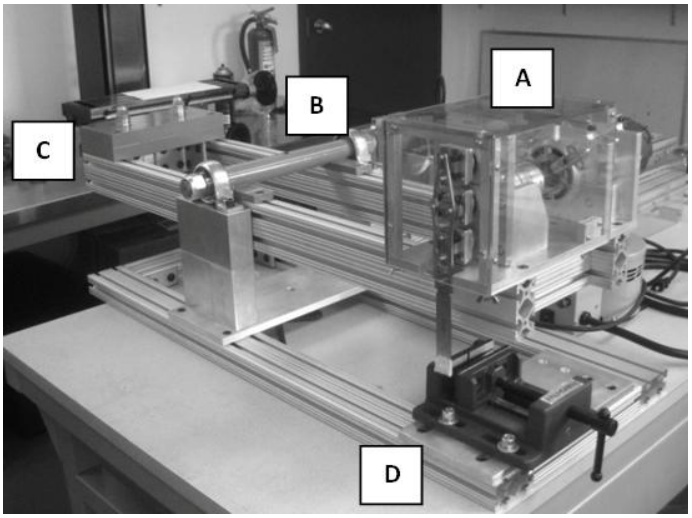

Fig 4 SAGITTAL SAWING FIXTURE USED TO DETERMINE CUTTING RATES OF BONE.

Referring to fig. 4, a test fixture was designed to guide the sawing mechanism through each cut at a prescribed thrust force. The sawing mechanism **A** was bolted to a rigid frame that rotated about a main axle **B**. A counter-mass **C** was used to compensate for the weight of the sawing mechanism. With this fixture, placement of the axel or amount of counterweight could be adjusted to provide a constant thrust force for cutting.

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 fig. 5. The periosteum was removed from the exterior surface of the bone and the medullary cavity was scraped clean by hand to the boney surface. Each sample was approximately 75mm in length, with a rectangular cross sectional area of approximately 8mm x 11mm. The length of the sample corresponded with the primary osteon direction of the long bone, shown by an arrow in fig. 5.

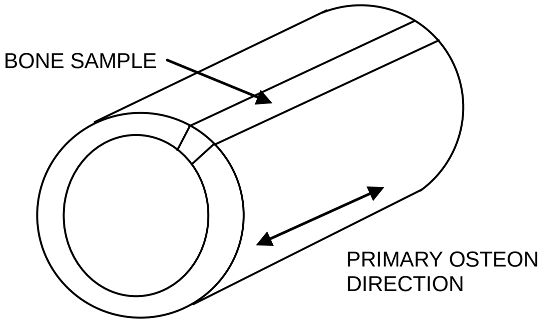

Fig 5 CORTICAL BONE SAMPLES TAKEN FROM THE MID-DIAPHYSIS REGION OF ADULT BOVINE TIBIA.

After processing bone with the bandsaw, samples were placed in a tray of cold water and refrigerated for approximately two hours while thawing occurred. Immediately thereafter, sawing experiments were performed. For each test, the bone samples were removed from the refrigerated tray and secured in a vise **D** that was attached to the sawing fixture as shown in fig 4. The vise was positioned so that the centerline of the bone corresponded to the centerline of the saw blade while in the neutral sawing position.

The pivot axel position of the sawing fixture was adjusted to provide a constant force of 7.6N throughout the cutting range. The thrust force was measured at the tip of the saw tooth, in the middle of the saw blade, using a portable force gage (MG20, Mark 10 Co., Copiague, NY) with an accuracy of ±0.4N.

Four cutting speeds were used, corresponding to oscillating frequencies of 96Hz, 113Hz, 129Hz, and 146Hz. To accurately control blade cutting speed, the stock speed control module was removed from the router. A 120V, 15Amp variable transformer (Staco, Model SPN1510B, Staco Energy Products Co., Dayton, OH) was used to precisely control router speed between 0-180 Hz. The speed of the sawing mechanism was measured using a handheld tachometer (Checkline A2108, Electromatic Equipment Co., Cedarhurst, NY) with a precision of ±1 Hz during sawing.

One sagittal saw blade (Stryker Dual Cut, Model 4125-135-090, Stryker Orthopaedics, Mahwah, NJ) was used for all cutting trials. The saw blade was inspected periodically for wear, but it did not appear to dull during the experiments. Three cuts were made for each blade speed, for a total of 12 cuts. Two bone segments, taken from the same section of bovine bone, were used for the experiments. A standard stopwatch was used to record the cutting time.

For each trial, the saw was allowed to warm up and reach a steady-state speed. Once the desired speed was reached, the saw was slowly lowered to approximately 0.5mm 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

Volume of bone removed was determined by multiplying the blade width, 1.35mm, by the cross sectional area of the bone sample cut-off. The cross sectional area of bone was measured by taking a digital image of the bone slice using a 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 a 50mm scale marker. A threshold was then applied to the image to isolate the darkened area of the cut bone. The number of pixels in the darkened area was calculated, and the length scale of the image was used to convert this pixel area to a real area. Volumetric cutting rates were calculated by dividing bone volume removed by cutting time. The resultant cutting rates are shown in fig. 6.

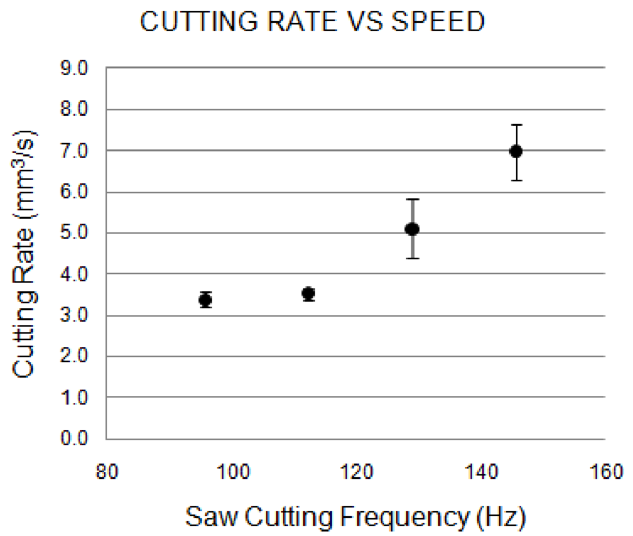

Fig 6 CUTTING RATES IN BOVINE CORTICAL BONE AS A FUNCTION OF SAGITTAL BLADE SPEED.

DISCUSSION

At lower cutting speeds, such as between 80Hz and 110Hz, cutting rates are quite slow and tend to level out at approximately 3.4mm^3/s. There appears to be a knee in the curve around 120Hz, where cutting rates begin to increase steadily. Extrapolating from the experimental data, cutting rates nearly doubled from approximately 3.5mm^3 per second to 6.9mm^3 per second for an increase in blade speed from 112Hz to 145Hz. From this data, there appears to be a threshold speed required to initiate sawing. Once this speed is reached, cutting rates increase steadily with blade speed.

For this screening experiment of cutting rate as a function of cutting speed, thrust force was held constant. It is well known that an increase in thrust force would further increase cutting rates. Also, blade length and oscillating angle were held constant for this experiment. Another means of increasing cutting speed at the tip of a tooth is to hold oscillating speed constant while increasing both oscillating angle and length of the saw blade.

From the point of view of the surgeon, where sawing parameters such as oscillating speed and oscillating angle may be fixed for the sagittal saw available in the operating room, the data here suggests that a longer saw blade should be used to generate greater cutting rates. For a fixed tool oscillating speed, ω, a longer effective radius of oscillation, r, will provide a greater effective cutting speed, v, at the tips of the saw blade teeth, where $v = r\omega$. However, higher tip speed may also result in higher temperatures between the cutting tooth and boney bed on the cut surface. Additional studies must be conducted to determine the interaction of cutting speed, cutting rate, thrust force, and temperature.

CONCLUSION

Bovine cortical bone was cut with a sagittal sawing fixture. The purpose of the experiment was to determine the relationship between oscillating blade speed and volumetric cutting rate. Applied thrust force was held constant at 7.6N. Oscillating angle was held constant at 1.4 degrees. An increase of 52% in blade oscillating speed, from 95Hz to 145Hz, resulted in a cutting rate increase of 106% from 3.4mm^3/s to 7.0mm^3/s. The increase in cutting rate with blade speed was not linear. At lower oscillating speeds, in the region of 90Hz to 120Hz, the cutting rate leveled off at 3.4mm^3/s.

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