Inspiration from Victorian times in Ultrasonic Surgical Tool Design

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Abstract. This work is devoted to the investigation of performance of surgical tools used in orthopaedics in terms of the occurrence of signs of necrosis, the accuracy of the cut and cutting tool design. For the comparison of the surgical tool performance different types of cutting devices were studied in a series of experiments. A Victorian surgical saw, its copy, a contemporary surgical saw, a surgical scalpel and an ultrasonic blade designed for a surgical application were chosen for the performance assessment. Such geometrical parameters as cutting edge shape, angle of teeth inclination, and sharpness of the cutting tools were analysed in terms of the quality of the cut and signs of necrosis. As a result of the analysis of experimental data obtained and theoretical insight the authors have come up with a creative solution for a novel design for a surgical ultrasonic blade which benefits from the design advantages of each of the analysed surgical tools and eliminates their drawbacks.

1. Introduction

The first report of the use of ultrasound in dentistry was published in 1952 when an industrial ultrasonic grinder was used to prepare cavities in extracted human teeth [1], and further applications in medical practice started to emerge rapidly. In 1970, Balamuth patented use of ultrasonic frequency vibratory forces for removal of layers of highly compliant biological tissue [2] and in 1967, Kelman reported the use of a combination of low frequency ultrasound and aspiration for removal of human tissue [3]. In 1955, another high-frequency longitudinal vibrating surgical cutting instrument for bone surgery was introduced and in 1974, Volkov reported on the simplification of orthopaedic procedures using an ultrasonic cutting device [4]. His device used a 25–30 kHz mechanical longitudinal vibration to drive an end-effector (scalpel or saw), which was modified depending on the task performed. It was emphasized that simple orthopaedic operations could be performed through a smaller incision than before. Further success and development took place in the area of ultrasonic bone scalpsels for precise bone osteotomy [5] and for sawing and uniting bony fractures. Advantages of ultrasonic devices applications were also claimed in the removal of callus without damage from titanium osteosynthetic material, in particular callus from the slots of screws allowing fixation plate removal, [6]. The success of an ultrasonic device application can be traced to the ability of ultrasound to cut bone under finer control and with less pressure than for rotary or hand chisels. Nevertheless any development of an ultrasonic cutting instrument must account for associated vibrational energy, and the use of such a device may be very different from the cutting process associated with rotary burrs. An ultrasonic surgical hand piece usually consists of four basic elements: a generator or power supply, an ultrasonic motor (transducer), a mechanical wave amplifier (referred to as an acoustic horn) and a sonotrode (or probe) [1]. The generator converts electrical signals at low-frequency into high-frequency current to drive the transducer for conversion into longitudinal or transverse low amplitude mechanical vibrations, at 20–60 kHz for the applications reviewed [1]. The vibration amplitude is usually of the order of a few microns and so this is transmitted to a horn which is used to increase or decrease the amplitude. These vibrations are finally transmitted longitudinally along the length of the probe/tip. The horn and tip are normally profiled to achieve a specified mechanical gain [1]. An ultrasonic chisel, as developed for surgically cutting bone in contrast to a curved insert, has a straight ultrasonic tip and is used and shaped as a chisel that oscillates in longitudinally. The ultrasonic chisel differs in its ability...
to remove bone compared to a conventional rotary drill. Further development and miniaturisation of the ultrasonic hand piece has evolved novel tip or blade designs for the facilitation of certain medical and surgical procedures. Although the success of ultrasound in orthopaedics was first noted in 1974, surgical devices still have not been routinely replaced by ultrasonic hand pieces. Therefore this research represents the continuation of years of research in the area of ultrasonic blades at the University of Glasgow and is concentrating on the investigation and experimental testing of an Victorian surgical saw, a copy, a contemporary surgical saw, a surgical scalpel, and an ultrasonic blade designed for a surgical application (Fig. 1) in terms of performance assessment, i.e. cutting edge shape, angle of tooth inclination, sharpness of the cutting, the quality of the cut, and signs of necrosis.

Figure 1. Surgical tools tested for the performance analyses

2. Analysis of the Victorian saw shape
In the search for some inspiration for a novel and more efficient ultrasonic blade design for orthopaedic surgery, an antique Victorian saw used for an orthopaedics in the XIX century (Figure 2) was borrowed from the Museum of the Royal College of Surgeons of Edinburgh for a thorough scientific investigation and performance assessment.

Figure 2 XIX century orthopaedic surgical saw
As a result of a series of tests conducted at the Royal Infirmary of Edinburgh to compare the performance of the orthopaedic Victorian and contemporary surgical saws, in terms of signs of necrosis, and by using a thermo-imaging camera, it was observed that the Victorian saw, in contrast with the contemporary surgical saw which reached the level of 90°C and higher, did not cause any dangerous temperature accumulation due to friction the level of temperature at the cutting site was well below 36°C. Therefore the shape of the antique saw rake and teeth was analysed in order to project the shape into an ultrasonic blade design. Photographs of the saw were taken with a macro-camera at a scale of 4.5 microns per pixel and processed using GIMP software (Figure 3).

Figure 3. Saw Shape Approximation
The coordinates of the saw tooth were found (Figure 4) and the average angle of the tooth inclination was obtained (Figure 5).
It should be pointed out that the cutting edge is normally considered to have a finite sharpness and to be constructed of two intersecting flat planes formed by the grinding process, with typical wedge angles in the region of 20º [7]. Herbert’s experiments [8] showed that the main factor influencing durability and work output is the clearance angle or slope of the back of the tooth. This controls the space for debris, but too great a clearance results in the tip of the cutting edge breaking off. A clearance of about 25° on a file with zero rake (a vertical front face) gave best results. Figure 7 shows that the saw teeth are bent sideways alternately, and therefore the saw is expected to cut a path slightly wider than the thickness of the blade. This reduces the contact between the blade and work piece, and as consequence reduces friction, heat generation, possible overheating and damage of the blade. It prevents the saw being pinched and possibly jamming in the slot; it also allows for debris clearance. However, the sideways splay of the teeth (the kerf) also determines the width of the slot and volume of material lost. Therefore it is desirable to have the smallest kerf possible in order to increase the volume recovery of the bone.

Some research is discussed next on saw design in order to highlight the advantages of the Victorian design.

3. An insight into the performance of saws

Generally in ultrasonic procedures an indentation cut with a single pointed cutting instrument takes place. The cutting instrument cuts by perpendicular penetration into the work piece, so that the wedge angle of the cutting instrument is positioned symmetrically about the line of cutting action. Based on the research presented in [7] it was stated that the factors affecting the cutting process are: tool geometry, tool material, work material and cutting conditions and that the magnitude of the interaction is greatest between the first three factors while cutting conditions only marginally affect the instrument geometry [9]. According to [8] the factors affecting the cutting efficiency (i.e. the material removal per stroke) of files are: sharpness of tooth slope of the front face of the teeth (the rake); slope of the back face of the teeth (the clearance); the angles at which the two cuts lie relative to the axis of the file; the different pitches of the two sets of teeth; and the ratio between the two pitches. The cutting edge can be defined as a Fine edge; Burr edge and Blunt edge. The saw under consideration (Fig. 4) was characterised as a Fine edge, a cutting edge optimised for cutting as a result of the sharpening process and exhibiting no characteristics associated with bluntness such as cutting edge deformation, cutting edge dulling, and cutting edge cratering [10].

Some studies developed so far may be considered as macro level work concerned principally with the effect of the wedge-cutting angle and other cutting approach angles. However they do not account for the effect of the cutting edge radius on the cutting forces encountered in orthogonal cutting, and so neglect the effect of edge sharpness on cutting performance. In a study on ultra precision machining [11], the effect of the tool edge on the cutting process is considered and it was confirmed that there is a
significant size effect in the measurement of cutting forces, which can be directly related to the
variation in size of the cutting edge radius. Furthermore, the research indicated that this size effect is
also linked to the localised stresses at the tool tip and the temperature gradient along the tool.
Molecular dynamics studies on the effect of the tool radius on the nanometric cutting process carried
out in [12] confirms that the size ratio of the depth of cut to the radius of the cutting edge is an
important factor in the cutting process. They established that this relationship is linear. These studies
confirm the importance of the cutting angles and the cutting edge radius on the performance of the
cutting instrument, and emphasise the factors affected by these parameters as part of the cutting
process. It has been shown that the shape of the tip profile is important in determining the puncture or
penetration force and the load/displacement profile of the penetration force [7]. Although quite a few
models do not account for variations in the cutting edge radius on the tool, and its effect on the cutting
process, there have been attempts to refine the model for cutting with respect to the limitations due to
the chip produced during the cutting process. The model described in [13] allows the advance
detection of chip breakage. It was also demonstrated that the tool coating is an important factor in the
chip breaking problem. In the study [14], devoted to experimental work on cutting edges of different
radii, 10, 50 and 60 µm, an advantage of the honing process in the form of having homogeneous and
reliable cutting edges was demonstrated in contrast to ground inserts, the cutting edges of which failed
rapidly. It was also emphasised that the lack of coating in the tool-chip contact area leads to a high
wear rate.

The role of tool material properties on chip control has neither been fully understood nor
considered as significant in the past. Nevertheless, the study presented in [13] presents a formula
which describes the energy transformed into heat within the temperature field in the contact area, i.e.
between the cutting tool chip and the work piece. This amount of thermal energy generated in the
machining process that is transferred into the chip depends on the thermal conductivity of the cutting
tool. When the thermal conductivity of the cutting tool is very low, the temperature in the chip area,
and especially in the lower side of the chip, will be very high. However, cutting tool materials with
low thermal conductivity show short contact lengths and produce chips with small radii. For this
reason, the chips immediately leave the cutting tool and the crater wear on the tools is very close to the
cutting edge.

It should be pointed out that thermal conductivity of most cutting tool materials, coated as well as
uncoated, increases with increasing temperature. Only a few materials, such as aluminium oxide or
silicon nitride, behave in the opposite way, i.e., as temperatures increase, their thermal conductivity
decreases.

Therefore it can not be expected that a purely mechanical model would be valid since we know the
thermal properties have a significant influence on the chip formation process. Several attempts have
been made in the past for making analytical predictions of chip breakability and chip forms/shapes. It
was not possible to do so owing to the complexity of the interactions among the work material, cutting
tool material and geometry, and the cutting conditions. In view of the difficulty involved in developing
purely analytical predictive models for chip breaking, as a practical approach, the feasibility of
predicting the approximate levels of chip breakability through relevant experimental databases and
knowledge-based systems has been demonstrated [13]. This method is an effective compromise
between the time-consuming extensive experimental work and the totally non-scientific operator-
based or handbook-dependent methodologies for selecting conditions that would warrant an effective
chip breaking. Generally there are many different varieties of saw tooth profile for cutting different
materials but all aim to give a blade along which the teeth do not break while cutting, that does not
wear too quickly and remains sharp, that permits dust to escape, which does not jam by friction during
cutting the slot, and where cutting can be performed with least effort [8]. Clearance or relief angles on
saw teeth are different for different materials: very dense material require bigger reliefs than dry soft
material. Serrated cutting edges changed force direction along the cutting edge, improving stiffness
and resistance to vibration, and increasing tool-life [13]. It the teeth are spaced closely the rate of
material removal is reduced. The quality of the sawn surface (roughness, etc.) is, however, improved
with finer teeth [8]. With regard to the conditions of cutting it should be emphasised that dry machining leads to higher mechanical and thermal loading on cutting edges.

4. Experimental set up and results discussion

In [15] a study of in vitro the direction and force of applied loads applied by clinicians when using both a conventional slow surgical hand piece (CH) and an ultrasonic chisel (USC) for cutting bone was presented. Five clinicians took part in the cutting of a bovine bone using either an USC or a CH and the rate of cut was calculated over a fixed time-period and the depth of cut measured using a penetratometer. The magnitude of the longitudinal forces generated was demonstrated as a variable between 1.48 and 3.22 N (USC) and 0.04 and 4.56 N (CH). The CH had a pulling force directed towards the operator ranges from 20.11 to 20.72 N. Both instruments produced a similar range of downward forces, although there was intra- and inter-operator variability. The rate of cut varied in a similar manner, however, the CH produced a significantly greater depth of cut. The forces measured for the ultrasonic chisel varied between each cut made by the clinician and between each individual. The depth of cut ranges from 0.12 to 0.36 mm and 0.21 to 0.71 mm for the ultrasonic chisel and the conventional burr, respectively.

Following this study an experimental test of a copy of the Victorian surgical saw, a contemporary surgical saw, and an ultrasonic blade designed for a surgical application was performed with a clinician handling the blade. For this a copy of the Victorian saw was manufactured based on the average geometrical properties identified in the Section 2. To test all the blades under the same conditions the blade of the contemporary surgical saw (Stryker) was equipped with a handle for testing under ‘hand sawing’ conditions. The ultrasonic blade, operating in the longitudinal mode of vibration at 35 kHz, was designed and tested using ABAQUS software. The view of the cut site and the temperature effect of the ultrasonic tool and the copy of Victorian saw application can be observed in Figure 8.

Figure 8. Cutting area after the test with an ultrasonic blade and a copy of the Victorian saw

The temperature accumulated during the test with an ultrasonic blade was measured using a thermal imaging camera FLIR and reached 115°C for the blade 1(a) (Figure 9). Investigation of the blade condition revealed the existence of a manufacturing defect which contributed substantially into the excessive temperature accumulation by increasing the amount of friction between the blade and the bone (Blade 1 in Figure 9). Therefore, one of the reasons for such a rapid temperature accumulation during the test with an ultrasonic blade could be the excess of material at the tip of the blade (manufacturing defect) or simply the large contact area of the blade with the bone at the cut sight. The manufacturing defect was eliminated by modifying the technique of blade fabrication (Figure 9, Blade 2) which allowed a reduction in temperature at the cut site down to 55 °C (Blade 2 in Figure 9). Nevertheless, the contact area reduction requires significant design or cutting technique modification. The technique which introduces short delays and applies only the tip of the blade to bone cutting, reduces in this way the contact surface and a reduces the temperature accumulated down to 54 °C (Figure 9, Blade 1(b)). Nevertheless to avoid any sign of necrosis some further minimisation of the contact area is required. This effect was also confirmed in [16] for the saw tooth radius, the maximum temperature increases with increase in the tool edge radius, which occurs as a heat transfer along the tool edge due to the increased size of the contact region.
Results of the experiments with a copy of Victorian saw and Stryker blade saw confirmation that the temperature at the cut site never exceeded 36°C. However it should be pointed out that normally Stryker blade is used as a contemporary orthopaedic surgical tool operating at very high speed causing very high rate of temperature accumulation (well above 90°C). For the saw based on the Stryker blade, the clinician confirmed that operating it by hand, at low speed similar to that for an ultrasonic blade and the copy of the Victorian saw, the clinician confirmed that a much higher load should be applied as well as a higher pulling force.

Nevertheless, if now we investigate the shape of a surgical scalpel, as studied at the Royal Infirmary of Edinburgh in terms of performance in bone cutting during orthopaedic surgery (Figure 10), it is possible to notice that the cross-section of the scalpel reduces towards the top of the blade.

Therefore inspired by the Victorian saw performance in terms of saw tooth shape and the possibility for reduction of the contact area through the reduction of the thickness of the blade alone the cross-section, adopting the scalpel design, it has been possible to come up with novel blade design presented in Figure 11.

In contrast to the scalpel shape the blade was reinforced at the top to reduce any significant influence of the coupled modes of vibration. This was achieved by adopting a ‘bowl’ type of cross-section (or combination of two scalpels) with the minimal thickness of the blade along the middle longitudinal line.

5. Conclusions
The work presented is concentrating on the investigation of the performance of surgical tools used, or can be used potentially in orthopaedics in terms of the occurrence of signs of necrosis, the accuracy of the cut and cutting tool design. For the comparison of the surgical tool performance different types of cutting devices were studied in a series of experiments. A copy of the Victorian surgical saw, a contemporary surgical saw blade (Stryker), a surgical scalpel, and a 35 kHz ultrasonic blade designed for a surgical application were chosen for the performance assessment. Such geometrical parameters as cutting edge shape, angle of tooth inclination, and sharpness of the cutting tools were discussed in
terms of the quality of the cut and signs of necrosis. As a result of the analysis of the experimental data obtained it was concluded that minimisation of the contact area due to the optimal design and surgical tool handling technique affects the friction at the cut site in the most pronounced way, reducing the temperature accumulated from 115°C down to 54°C. This is an improvement comparing to the results obtained at the Royal Infirmary of Edinburgh (90°C) for a different design of ultrasonic blade tested at 20 and 35 kHz. Manufacturing problems resulting in the excess of material or roughness of the blade surface contribute to the parasitic temperature increase. The maximum temperature also increases with increase in the tool tooth radius due to the increased size of the contact region [16].

Therefore to avoid any sign of necrosis some further minimisation of the contact is required. That is why the authors have suggested a creative solution for a novel design for a surgical ultrasonic blade which benefits from the design advantages of each of the analysed surgical tools, and eliminates their drawbacks (Fig.11). According to the finite element analyses the performance of the blade presented should reduce the contact area at the cut site and therefore the temperature accumulated. Additionally a reinforced symmetrical design will help to reduce undesirable effect of the coupled modes of vibration. Results of the experiments with a copy of the Victorian saw and the Stryker blade saw confirmed the temperature at the cut site never exceeded 36°C. Future work will be devoted to the test of a novel ultrasonic blade in comparison with the performance of the surgical scalpel and Victorian saw in terms of the cut accuracy, and signs of necrosis. The test will be performed under the same conditions, blade sharpness, under the same unified perpendicular loading, and on the same bone sample. The saws will be tested following [14] with a cutting speed of 50 m/min and a feed rate \( f = 0.1 \) mm/rev. Further work will also involve the consideration of the result obtained in [17] stating that a spherical pit proves to be superior to a groove in meeting the various directions of chip flow and can provide a positive rake angle to the main part of the cutting edge, regardless of the chip flow direction.

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