Micromilling surface patterns for enhanced Kirschner wire bone drilling

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Management of heat generation in bone drilling is important, as heat is the primary cause of secondary thermal injury and necrosis. One of the most common drilling tools used in orthopedic surgery – Kirschner wire (K-wire) – can heat tissue due to inefficient debris evacuation. Furthermore, K-wires cannot be replaced by traditional fluted drills as they are used to temporarily fix bones during some operations. To enhance the debris clearing and cutting edge properties of K-wire without compromising the overall surface area and holding force, K-wires with micromilled surface channels (about 100 µm in width) at the tip were created and evaluated. A table-top 3-axis machining center was used to mill three different surface patterns with varying channel spacing and orientation. The K-wires with and without surface channels were drilled into synthetic bone samples and the torques and thrusts of each type were compared. Results showed adding surface channel to the K-wire could reduce the cutting force and lower the heat generation, indicating the benefit of micro-channels on the surface of the K-wires.

1. Introduction

Drilling is one of the most commonly utilized procedures in orthopedic surgery. Of the many types of drilling tools available to surgeons – including twist and cannulated drills – the type most frequently culled into service beyond cutting holes is the Kirschner wire (1-3). Originally introduced early in the twentieth century by the surgeon Martin Kirschner, Kirschner wires (K-wires) are normally slender, smooth stainless steel pins with a sharpened tip and are specifically designed to hold bone fragments together (pin fixation) before, during, and after surgical procedures (4).

Typically, K-wires are used to temporarily fix bones together during some operations, only being removed post-operatively once definitive fixation has been established. They can be used for definitive fixation if the fragments are small such as in hand and wrist injuries. The relative ease of insertion and often minimal resulting trauma to the surrounding tissue have increased their use and made K-wires one of the most popular devices in orthopedic surgery settings (4).

Within most clinical settings there are two main K-wire tip designs used, the diamond and trocar (shown in Fig. 1). Though there is a literature describing the cutting mechanics of the diamond tip – comprised of two angled facets meeting at a point (3) – we have limited the focus of our investigations to the trocar tip – made of three equally angled planes ending in a single point. Currently, the trocar tip K-wire is more commonly used in surgical settings. It is worth noting that a third type of K-wire tip introduced by Medin (Nové Město na Moravě, Czech Republic), deemed the Medin K-wire, has a unique cutting edge that anticipates much of what we have presented here (5).

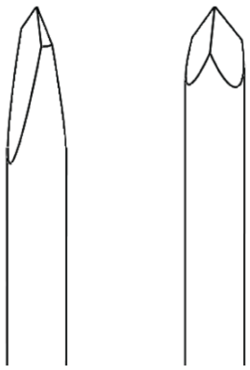

Fig. 1. The diamond and trocar K-wire tips.

Over the course of a century of use, two main challenges remain for the traditional K-wires. The first is the ability to migration while fixed within a patient (3,4,6,7). In order for K-wires to effectively pin bones together and for those bones to remain in place, the surface area of the shank needs to be in contact with as much of the surrounding bone environment as possible. To accomplish this task, the surface area of K-wire needs to be relatively large and continuous. This has meant using a straight, cylindrical shaft that attempts to balance the ease of surgical insertion while mitigating the effects of K-wire migration. While threaded K-wires are available commercially to minimize migration in orthopedic surgical procedures, they have yet to see widespread clinical adoption.

The second great challenge of drilling with K-wires is the accumulation of heat (1,2,8-10). Because the tip of traditional K-wires has no space for clearing debris from the site, the bone debris becomes compacted at the tip, creating more friction, and generating heat. It is this heat accumulation that is one of the more significant problems in bone drilling in general and drilling with K-wires in particular (1,2,8,11,12). Such heat generation affects the surrounding bone and tissue and results in thermal damage manifest primarily in osteonecrosis caused by the temporary or permanent loss of blood supply to the tissue or bone. Not only does this adversely affect health outcomes and prolongs healing, but it makes the K-wire more likely migrate over time (3), resulting in secondary injury and necessitating compensatory surgery.

While it has been shown that the heat generated by regular twist drills is significantly below that of K-wires, twist drills with their fluted edges cannot fulfill the adequately fixate bones in the same manner that K-wires. A few solutions to this problem have been suggested, including hammering the K-wire into the region (13) or multi-step procedures wherein an initial hole is drill then filled with a K-wire, but none have replaced the traditional model in orthopedic surgery.

Hence the modification of a K-wire to minimize the detriments of heat generation while maintaining the benefits of a simple smooth shank for fixation has important clinical benefits.

In this paper a micromilling system to mill surface patterns on the tip of trocar K-wires to help remove bone debris from the cutting area is first introduced. A three-axis drilling test stand was developed to drill the K-wires into synthetic bone samples to measure and compare the thrust forces and torques. Results of the reduction of thrust force are presented.

2. Materials and methods

2.1 Micromilling system

The micromilling system (seen in Fig. 2) was designed to mill channels on the trocar plane surface. The K-wire was secured by a 5C collet to a dual-axis manual rotary table that was used to tilt the trocar plane in increments of 1°. Three linear stages (Model 200cri, Siskiyou Instrument, Grants Pass, Oregon) were combined to make a three-axis system to move a vertically mounted high-speed spindle (EM-801, NSK, Tokyo, Japan) along a desired path.

Four three-plane trocar tips with three planes and 30° bevel angle were ground from 2.0 mm stainless steel rods. These three planes were 120° rotation increments about the midline. A vitreous bond cubic Boron Nitride (CBN) grinding wheel in a Chevalier surface grinding machine (Model Smart-B818) was utilized to grind the tip of three-plane K-wire. As shown in Fig. 2, a microscope digital camera (Model MU035, AmScope, Irvine, California) was used during micro-channel milling to monitor when the tip of endmill first made contact with the surface of the K-wire and to track the progression of the mill during machining.

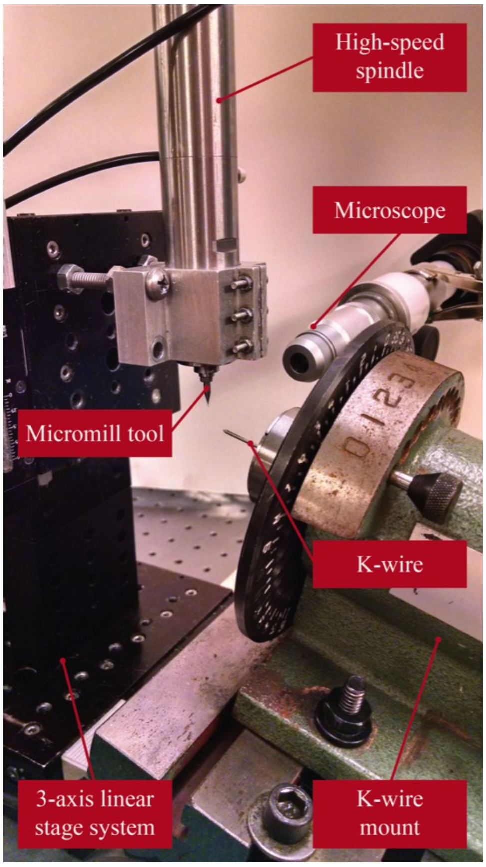

Fig. 2. The micro-milling setup used to create surface patterns on K-wire tips.

2.2 Tool path along the K-wire surface

As shown in Fig. 3, four surface micro-channel patterns were generated in this investigation. The regular surface that was unmodified beyond the initial tip grinding is shown in Fig. 3(a). Fig. 3(b) to 3(d) show a paired parallel channel pattern, a single knurling pattern composed of a single intersecting cross-sectional pair of channels, and a double knurling pattern composed of two intersecting cross-sectional pairs, respectively. For the two patterns with only two channels milled along the surface, the starting point of the material removed was midway along the unmodified cutting edge. The starting points for the double knurling pattern were one-third and two-thirds along the length of the unmodified cutting edge. In all cases, the endmill was a solid carbide two-flute square end micro mill with 100 µm in diameter from Kyocera (Costa Mesa, California). The speed of the end-mill during milling was 60,000 rpm. The channel was started at the surface of the top left side of the tip at a depth of 50 µm and advanced at a speed along the channel of 10 mm/min. The tool path was repeated in the second path to further increase the channel depth to 100 µm with another 50 µm depth of cut along the same tool path. Fig. 4 shows photos of the machined K-wire surfaces.

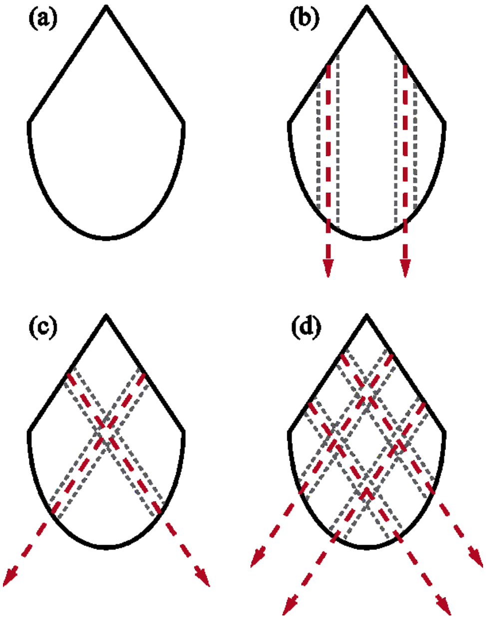

Fig. 3. Schematic representation of the micro-milling paths along a single face of the k-wire: (a) an unmodified surface, (b) two parallel channels, (c) single knurling pattern, and (d) double knurling pattern. Here the solid black line represents the edge of K-wire face, the dashed red line represents the micro-milling path and direction.

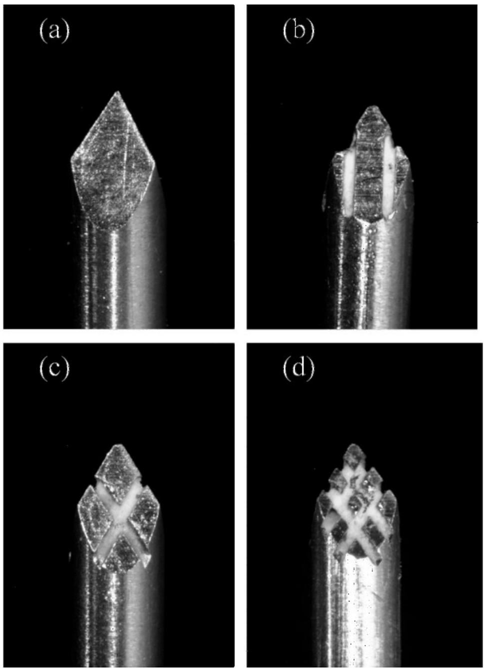

Fig. 4. Photographs of K-wires with (a) an unmodified surface, (b) two parallel channels, (c) single knurling pattern, and (d) double knurling pattern.

2.3 Drilling experiment

The experimental setup for the drilling was designed to capture the differences in the thrust force and torque produced of the K-wires as a function of their different surface patterns.

To ascertain the most clinically translatable results, a Stryker hand drill was used to drive a K-wire during the drilling experiment. Drilling was done at the full speed of the drill (1,000 rpm) with the batteries that powered the drill charged and replaced between trials to ensure a consistent power output. The drill was securely fastened to the vertical axis of a servo-controlled, 3-axis linear actuator system (Fig. 5) and advanced at a constant feed rate (1 mm/s) for 5 mm. This feed rate was chosen based on previous experiments tracking the motion of surgeons during drilling procedures and is in line with those observations made by (11,14).

During drilling, a piezoelectric dynamometer (Model Type 9273, Kistler, Winterthur, Switzerland) was mounted to the bottom of the setup to measure the thrust force and the torque, which were the metrics used to signify the mechanical energy produced among the different surface patterns.

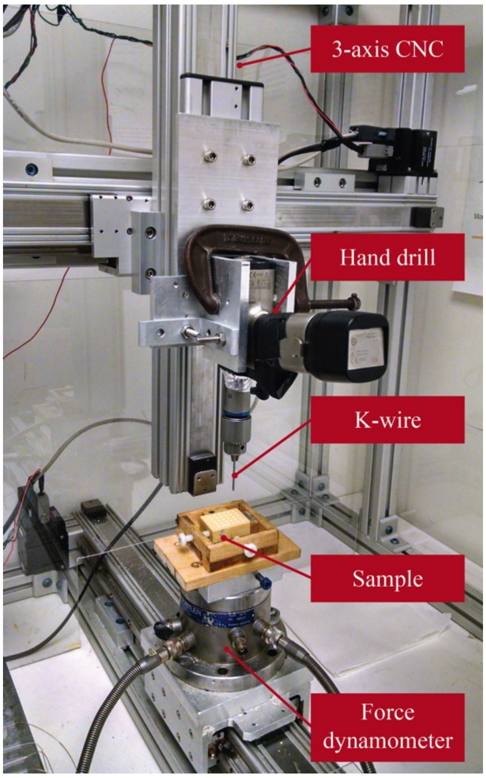

Fig. 4. The drilling testbed comprised of a three-axis servo-linear actuating system, a Stryker surgical hand drill, K-wire, a fixture to hold the sample, and a force dynamometer to measure the thrust force and torque.

For consistent results, the use of real bones was forgone in these experiments as the heterogeneity of organic samples would be large enough to significantly affect the outcomes of these experiments. In this study, we used a synthetic biomechanical testing materials developed by Sawbones$^{\text{TM}}$ (Sawbones, Vashon, WA) to mimic bone. Specifically, the hardest available polyurethane foam blocks with 50 pounds per cubic foot density from Sawbones^{TM} was selected. The consistency of the material was deemed a priority over the shortcomings in physiological realism. In this way the results from hole drilled from each of the tests could be compared directly using a work-material with consistent properties.

For each type of K-wire, two drilling trials were conducted. The first trial run consisted of drilling 20 holes in a 4 x 5 grid with 5 mm edge-to-edge spacing. The second trial consisted of drilling 35 holes in a 7 x 5 grid with 5 mm edge-to-edge spacing. These two trials were chosen to identify trends due to the prolonged drilling as would be common in surgical procedures that require sequential drilling. The grid spacing was chosen so that the material integrity of the hole to be drilled would not be compromised.

To analyze the effectiveness of the surface pattern on force reduction, the peak thrust force for each drilled hole was identified and pooled for each K-wire type. These peak thrust forces were then normalized and compared against the unmodified K-wire to compare performance.

3. Results

Fig. 6 shows an example of a sample thrust force measurement during a single hole with each of the four types of K-wire. The force profiles for each hole for K-wire surface pattern appeared to be generally consistent and equivalent, with a noticeable difference seen at their amplitude (as seen in Fig. 6).

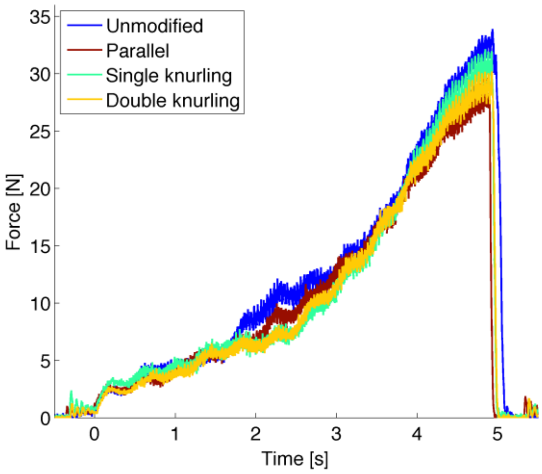

Fig. 6. Comparison of the force profile in drilling for four types of K-wire surface pattern.

Obtaining the peak thrust force for each hole and pooling it for the four types of K-wire surface pattern yields the histograms seen in Figs. 7(a) to 7(d). From this figure the effect on the average thrust force and the overall distribution of the forces as a function surface patterning can be observed.

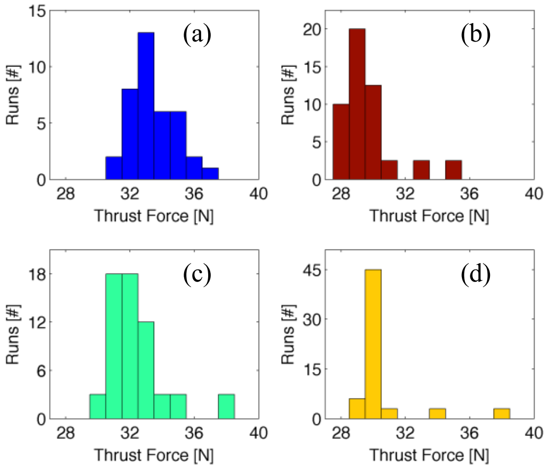

Fig. 7. Histograms of all holes drilled for the surface with (a) an unmodified tip, (b) two parallel channels, (c) a single knurling pattern, and (d) a double knurling pattern.

Figure 8 shows the results of normalizing the peak thrust force to the unmodified K-wire tip pattern can give a measure of the effectiveness of force reduction for each surface pattern. Excluding their outliers, the parallel and double knurling surface patterns show a quantifiably statistical difference ($p < 0.05$) in thrust force from the unmodified surface baseline. Qualitatively, the single knurling pattern also appears to reduce the thrust force.

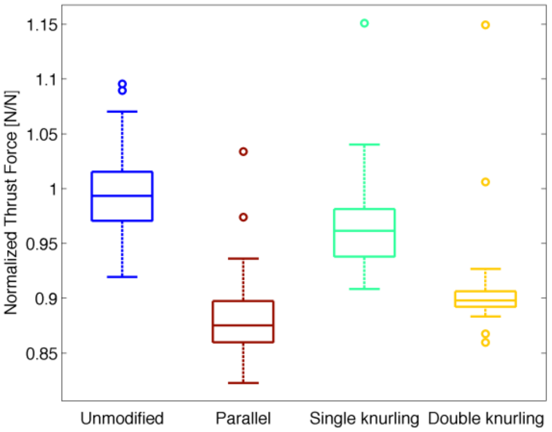

Fig. 7. Boxplot of the normalized thrust force for each surface pattern type, showing the overall trends in thrust force reduction.

4. Conclusions

Our results indicate that adding micro-channels to the three planar surfaces of a trocar K-wire could reduce the drilling thrust force. From this initial investigation, a K-wire with a surface pattern of pair of parallel channels and double knurling pattern composed of two intersecting cross-sectional pairs significantly reduced the thrust force when compared against an unmodified K-wire by 13% and 10%, respectively. The single knurling pattern composed of a single intersecting cross-sectional pair of channels appeared to reduce the thrust force by about 4%. These findings agree with our initial hypothesis that small channels at along the surface of the tip could help evacuate debris and reduce the force necessary to drill a hole.

This small modification to the surface of a K-wire has the larger implication of enhancing bone drilling procedures in clinical settings. By reducing the force necessary to drill the heat generated at the site should be lessened, helping prevent thermal injury to the surrounding tissue. By limiting the thermal damage at and near the drilling site, there is an expectation of beneficial surgical outcomes including a greater ability for stable K-wire placement, decreased recovery time, and reduced side effects.

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