Lei Chen ORCID iD: 0000-0003-4042-9912

Evaluation of Heat Generation in Unidirectional versus Oscillatory Modes During K-Wire Insertion in Bone

Running Head: Heat Generation During K-Wire Insertion

Yuanqiang Luo BS[1,2], Lei Chen PhD[1,*], Fred T. Finney MD[3], Dae Woo Park PhD[4,†], Paul G. Talusan MD[3], James R. Holmes MD[3], Albert J. Shih PhD[1]

[1] Department of Mechanical Engineering, University of Michigan, Ann Arbor, Michigan, USA

[2] Department of Mechanical and Vehicle Engineering, Hunan University, Changsha, Hunan, China

[3] Department of Orthopaedic Surgery, University of Michigan, Ann Arbor, Michigan, USA

[4] Division of Convergence Technology, National Cancer Center, Goyang, South Korea

***Corresponding author:** Lei Chen, PhD

Address: 1043E H. H. Dow Building, 2300 Hayward Street, Ann Arbor, MI, 48109, USA

Tel: (734) 604-5897; Fax: (734) 647-9379; Email: leichan@umich.edu

This is the author manuscript accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/jor.24345.

[†]**Co-Corresponding author:** Dae Woo Park, PhD

Address: 323 Ilsan-ro, Ilsandong-gu, Goyang-si, Gyeonggi-do, 10408, Republic of Korea

Tel: +82-31-920-2241; Email: bigrain@ncc.re.kr

Author Contribution Statement:

Descriptions of individual author contributions are listed below. All authors have read and approved the final submitted manuscript.

Yuanqiang Luo: experiments, data acquisition and processing, manuscript drafting and editing.

Lei Chen: study design, data processing, statistical analysis, manuscript drafting and editing.

Fred Finney: surgeon recruiting, manuscript editing.

Dae Woo Park: experiments, data processing.

Paul Talusan: surgeon recruiting, manuscript editing, supervision.

James Holmes: surgeon recruiting, manuscript editing, supervision.

Albert Shih: manuscript editing, supervision.

ABSTRACT

Heat generation during insertion of Kirschner wires (K-wires) may lead to thermal osteonecrosis and can affect the construct fixation. Unidirectional and oscillatory drilling modes are options for K-wire insertion, but understanding of the difference in heat generation between the two modes is lacking. The goal of this study was to compare the temperature rise during K-wire insertion under these two modes and provide technical guidelines for K-wire placement to minimize thermal injury. Ten orthopedic surgeons were instructed to drill holes on hydrated ex-vivo bovine bones under two modes. The drilling trials were evaluated in terms of temperature, thrust force, torque, drilling time, and tool wear. The analysis of variance showed that the oscillatory mode generated significantly lowered peak bone temperature rise (13% lower mean value, $p = 0.036$) over significantly longer drilling time (46% higher mean time, $p < 0.001$) than the unidirectional mode. Drilling time had significant effect on peak bone temperature rise under both modes ($p < 0.001$) and impact of peak thrust force was significant under oscillatory mode ($p < 0.001$). These findings suggest that the drilling mode choice is a compromise between peak temperature and bone exposure time. Shortening the drilling time was the key under both modes to minimize temperature rise and thermal necrosis risk. To achieve faster drilling, technique analysis found that “shaky” and intermittent drilling with moderate thrust force are preferred techniques by small vibration of the drill about the K-wire axis and slight lift-up of the K-wire once or twice during drilling.

Keywords: Kirschner wire, bone temperature, unidirectional mode, oscillatory mode, drilling technique.

INTRODUCTION

In orthopaedic surgery, Kirschner wires (K-wires) are commonly drilled into bones for fracture fixation and guided cannulated screw placement[1]. During K-wire insertion, high friction is generated between the rotating wire and the compressed bone debris, causing substantial frictional heat generation and temperature rise[2–5]. Exposure to high temperature for certain time duration may lead to thermal osteonecrosis, resulting in loss of bone fixation, pin site infections and difficulties with healing[2,6]. Understanding the heat generation and bone temperature rise during K-wire insertion is critical for optimal surgical outcome.

Research has been conducted to study major factors associated with heat generation and temperature rise in bone drilling to minimize the risk of thermal osteonecrosis. Brisman[7] correlated higher thrust force and faster spindle speed with greater heat generation. Abouzgia et al.[8] observed that bone temperature increased with thrust force at first and then decreased at even higher thrust force due to decreased drilling time. A study by Augustin et al.[9] showed that increase in drill diameter and drill rotational speed caused significant temperature rise, while the impact of feed rate was smaller and the effect of drill point angle was negligible. Hillery et al.[10] reported that too low or too high spindle speed both caused high temperature rise. Lee et al.[11] found that bone temperature rise increases with higher spindle speed and smaller feed rate. However, the resulting longer exposure time to elevated temperature might cause thermal injury.

Besides aforementioned drilling parameters like thrust force, drill rotational speed, tool diameter, and feed rate studied based on regular fluted drill bits. For bone drilling with K-wires, tip geometry and drilling mode also affect the bone temperature. A K-wire design by Piska et al.[12] with two steep flutes for bone chip removal resulted in significantly lower bone temperature compared to commonly used trocar and diamond tips. Also, they found that trocar tip K-wires generated higher temperature than diamond tip ones. Liu et al.[13] modified trocar tip K-wires with notches for debris evacuation and reported reduced bone temperature rise.

K-wires can be inserted under two different drilling modes: unidirectional and oscillatory modes. Unidirectional drilling mode inserts K-wires into the bone with conventional one-directional rotation, while oscillatory drilling mode advances the K-wire while oscillating about its longitudinal axis. The oscillatory drilling mode, first invented by Nichter et al.[14] in 1992, intended to reduce vascular, nerve and tendon damage around the drilling site. Anderson et al.[15] reported that through tests on pig metacarpals, oscillation of K-wires caused lower temperature rise compared to unidirectional drilling. However, understanding of how the temperature rise reduces and guidelines on how to improve drilling techniques to avoid thermal osteonecrosis under two drilling modes are still lacking.

This study aims to evaluate K-wire insertion under unidirectional and oscillatory drilling modes in terms of temperature rise, thrust force, torque, drilling time, and tool wear to understand the effect of drilling mode on the bone temperature rise and provide guidelines for surgical drilling technique improvements.

METHODS AND MATERIALS

Bone Sample Preparation

Cortical bone samples were prepared using mid-diaphyseal section of one adult bovine femur, which have been commonly used for bone drilling experiments[11,16]. The residual soft tissue on the cortical surface was removed. These bone samples were cut from the same bovine femur to minimize material property variation. Cortical bones were sectioned, milled and ground to bone block samples of 35 x 21 x 5 mm, as shown in Fig. 1(a). Eight drilling tests were conducted on each bone sample with drilling locations evenly distributed on sample surface. Preliminary tests showed that a 7.0 mm distance between adjunct holes and to the bone sample boundaries was adequate to avoid structural influence on bone temperature distribution. To ensure precise K-wire placement positions, eight pilot holes (1.0 mm deep and 0.8 mm in diameter as marked in Figs. 1(b) and (c)) were pre-drilled using a computer-controlled drilling machine. Eight thermocouple holes (2.0 mm deep and 0.8 mm in diameter as marked in Figs. 1(b) and (c)) were pre-drilled with 2.0 mm distance to adjunct pilot hole centers for embedded thermocouple fixation. Prepared bone samples were kept refrigerated at -7 °C. Before drilling tests, bone samples were thawed to room temperature (24 °C) and soaked in saline for one hour to simulate the hydrated bone condition under in-vivo environment.

Experimental Design

The bone drilling experimental setup is shown in Fig. 2. The bone sample was clamped by two aluminum brackets onto a piezoelectric dynamometer (Model 9256C1 by Kistler, Winterthur, Switzerland) for the measurement of thrust force and torque during drilling. A surgical hand drill (Model 4200 Cordless Driver 2 by Stryker, Kalamazoo, MI) was used to conduct each bone drilling test at pilot hole location with a 2.0 mm diameter trocar-tipped K-wire with 15° bevel angle. The spindle speed of the hand drill under two drilling modes were measured by a tachometer and results are shown in Fig. 3. The drill had 1400 rpm maximum spindle speed under unidirectional mode and 1300 rpm maximum spindle speed with 4.4 Hz oscillation frequency under oscillatory mode. A K-type thermocouple wire (Model 5TC-TT-K-36-36 by Omega Engineering, Norwalk, CT) was fixed inside the adjunct thermocouple hole with high conductivity thermal paste (Model OT-201 by Omega Engineering, Norwalk, CT) at the tip to ensure its proper contact with the bottom of thermocouple hole, as illustrated in Fig. 1(c).

Ten orthopedic surgeons, including eight residents in training ranging from first through fifth year of residency along with two faculty, were recruited to perform bone drilling tests. Each surgeon was instructed to drill 10 times at pilot hole locations on the same bone sample, five holes under the unidirectional (clockwise) mode along one pilot hole array and five holes under the oscillatory mode along another row, yielding 100 drilling tests in total. To counterbalance the learning effect, randomly selected half of the surgeons did unidirectional mode first and the other half started with oscillatory mode. A new and sharp K-wire and a fully charged battery were used to drill five holes under each drilling mode. When a K-wire insertion test failed to penetrate through the bone due to improper techniques or excessive tool wear was observed (twisted and burnt tip), the surgeon would start the next hole with new K-wire and battery. For each drilling test, the surgeon was instructed to touch the pilot hole on bone surface with a stationary K-wire, push the trigger(s) all the way down for consistency in spindle speed, and start to drill immediately. The bone sample was cooled for three minutes after each hole drilled to avoid the heat accumulation.

During each drilling test, thrust force, torque, and temperature data were recorded simultaneously by a multi-channel digital oscilloscope (Model DL750 by Yokogawa, Tokyo, Japan) with 2000 Hz sampling rate. To quantify the hand drill feed motion, a digital camera (Model ILCE-5100 by Sony, Tokyo, Japan) with 1920 x1080 pixels was used to record the K-wire insertion at 23 Hz sampling rate for each drilling test.

Data Analysis

To synchronize the recorded drill motion with force, torque and temperature data, the video frame on which the surgeon pushed the trigger(s) and started drilling was aligned with the time when torque measurement showed obvious increase and defined as 0 s of drilling time. Image processing was conducted using the Kanade-Lucas-Tomasi (KLT) feature tracking algorithm[17]. Figure 4(a) shows the starting frame of a surgeon drilling under oscillatory mode (drilling time = 0 s). In a close-up view of the drill, a pixel, represented by the red square, was selected as the tracking pixel with a size of 0.2 × 0.2 mm, which was calculated using the known K-wire diameter (2.0 mm). Fig. 4(b) illustrates the hand drill axial displacement images captured at 0, 4, 8 and 12 seconds of drilling time. The axial displacement of the drill along with drilling time was quantified by the change of tracking pixel position. Total drilling time was identified based on the time frame when the hand drill axial displacement reached the bone thickness (5 mm).

Peak thrust force, torque, and temperature were also identified for each set of recordings from individual drilling tests. The number of holes drilled by the K-wire (qualitative indicator for tool wear), surgeon and drilling mode used were also used as data analysis variance. During the tests, three surgeons did not penetrate through the bone sample under the unidirectional mode at the fifth hole. Two other surgeons failed at their first unidirectional drilling and thus finished the remaining four holes with a new K-wire. These five drilling trials were regarded as unfinished tests and the corresponding data were eliminated as outliers. Thus, 45 sets of unidirectional drilling data and 50 sets of oscillatory drilling data were analyzed. In this study, a p value < 0.05 was considered statistically significant.

To compare the heat generation and drilling time of the unidirectional and oscillatory modes, analysis of variance (ANOVA) was conducted to compare effects of the drilling mode, number of holes drilled, and surgeon on peak bone temperature (the dependent variable). The ANOVA was also conducted with drilling time as the dependent variable, the drilling mode and number of holes drilled as fixed factors, and the surgeon as a random factor. Drilling mode included two levels (unidirectional and oscillatory); number of holes drilled had five levels (hole #1 to #5); and surgeon had ten levels (surgeon #1 to #10). Post hoc Tukey tests were conducted on the number of holes drilled.

To study the drilling techniques under a specific drilling mode, the ANOVA was conducted on unidirectional and oscillatory data sets with the peak bone temperature as dependent variable, the number of holes drilled as the fixed factor and the surgeon as random factor. Peak force and torque and drilling time were covariates. The ANOVA evaluated main effects of all these factors on peak bone temperature under unidirectional or oscillatory drilling mode. Post hoc Tukey tests were also conducted for number of holes drilled.

RESULTS

For the influence of three independent variables (drilling mode, number of holes drilled, and surgeon) on the peak bone temperature, as summarized in Table 1, main effects of drilling mode and surgeon were statistically significant with $p < 0.05$, while the number of holes drilled was insignificant. The post hoc test of number of holes drilled showed insignificant difference ($p > 0.05$) between holes. As shown in Fig. 5(a), a significantly higher peak bone temperature was generated under the unidirectional mode (130.7 ± 4.7 °C) than the oscillatory drilling mode (117.0 ± 4.4 °C).

For the impact of three independent variables (drilling mode, number of holes drilled, and surgeon) on drilling time, main effects of both drilling mode and surgeon were statistically significant. The number of holes drilled had no significant influence on drilling time. No significant difference was observed between holes in post hoc test ($p > 0.05$). As shown in Figure 5(b), the unidirectional drilling mode yielded significantly shorter drilling time (M = 11.2 s, SD = 0.9 s) than the oscillatory drilling mode (M = 16.4 s, SD = 0.8 s).

Under the unidirectional drilling mode, the main effects of surgeon and drilling time on peak bone temperature were statistically significant while the influences of number of holes drilled, peak thrust force and peak torque were insignificant.

Under the oscillatory drilling mode, the main effects of surgeon, drilling time, and peak thrust force on peak bone temperature were all statistically significant, while the main effects of number of holes drilled and peak torque were insignificant.

DISCUSSION

Comparison of Two Drilling Modes

The ANOVA results show that the oscillatory drilling mode generated 13% lower mean peak bone temperature rise and 46% longer drilling time than the unidirectional mode. The power in bone drilling has two components: translational power (thrust force × axial feed rate) and rotational power (torque × angular speed). The rotational power is typically over 30 times higher than translational power in the bone drilling set up in this study. Power multiplied by the drilling time is energy, which is equal to the multiplication of torque, angular speed, and drilling time. Most of the energy (over 99%) is converted into heat, causing the bone temperature rise[18].

A similar level of torque was measured under two drilling modes. Since the oscillatory drilling mode had lower average angular speed due to the periodical oscillations of drill, the rotational power and heat generation rate were lower. However, for oscillatory drilling, the bone material removal rate is lower, (i.e., the energy needed to remove a specific volume of bone material was distributed among longer drilling time period) leading to lower peak temperature but longer exposure to temperature rise. While lower bone temperature rise decreased the risk of bone osteonecrosis, longer exposure time could increase the accumulative thermal dose[19,20] and chance of thermal injury. The choice of drilling mode is a compromise between peak temperature and bone exposure time based on the surgical case.

Drilling Technique

The ANOVA results showed that drilling time had statistically significant impact on peak bone temperature under both the unidirectional and oscillatory drilling modes. Figure 6 shows the peak bone temperature versus drilling time of all 95 successful tests under two drilling modes. A shorter drilling time generally lead to lower bone temperature rise. Under a specific drilling mode, similar spindle speed and torque were provided by the hand drill motor, resulting in similar thermal power. Thus, a shorter drilling time led to smaller amount of total thermal energy generated. A shorter drilling time also reduced the bone exposure time to heat, which further lowered the thermal injury risk.

To achieve shorter drilling time, thrust force was the major haptic feedback that surgeons could control. Intuitively, faster drilling needed larger thrust force. However, under the unidirectional drilling mode, the surgeon with the highest averaged peak thrust force used the longest average drilling time and generated the highest averaged peak bone temperature. Excessive thrust force applied by this surgeon under the unidirectional mode led to severe twisting and deformation of the K-wire compared to regularly experienced wear, failed penetration of the fifth hole (U5), and burned the bone sample after exposure to temperatures over 300 °C at U5, as in Fig. 7. Under both drilling modes, excessive thrust force caused higher risk of fracturing bones and bending the K-wire. High thrust force could also result in plunging the K-wire into surrounding soft tissue after penetrating the bone, which leads to collateral tissue injury[21]. Thus, moderate thrust force should be applied under both drilling modes.

To investigate the drilling techniques for shortening the drilling time with moderate thrust force, measured bone temperature, thrust force, and axial displacement versus time of all 95 successful drilling trials were studied. It was found that every surgeon tended to use a specific technique to apply thrust force and control drill feed rate under both drilling modes. As shown by the ANOVA results in Table 1, such choices of techniques by different surgeons had statistically significant impact on drilling outcomes including peak bone temperature and drilling time. Drilling techniques used by surgeons are summarized into four categories:

(1) Continuous drilling: Under the unidirectional drilling mode, the surgeons pushed the K-wire against the bone constantly with an increasing thrust force until it penetrated through, as the red thrust force curve in Fig. 8(a). Such technique resulted in the highest temperature rise and even failed penetration as hole U5 in Fig. 7. It could be explained by the compressed debris. During drilling, the heat generation was partitioned among the bone, K-wire, and debris. If the thrust force was continuously applied along the axial direction, bone debris was compressed tighter and tighter, generating higher frictional force and excessive tool wear which further increased heat generation.

(2) Shaky drilling: With this drilling technique, surgeon vibrated the hand drill about the K-wire axis by a small amount, as shown by the shaky green axial displacement curves in Fig. 8. The orbital motion of the rotating K-wire helped evacuation of bone debris, which carried away portion of heat from the cutting area. Heat reduction

mechanism of this drilling technique was similar to the modified K-wires with notched or fluted cutting tips[13,22]. Due to the oscillation and vibration nature of the oscillatory mode, shaky drilling was spontaneous even if the surgeon tried to apply constant thrust force on the hand drill. This was the reason why continuous drilling technique was not found under the oscillatory drilling mode.

(3) Intermittent drilling: Surgeons slightly lifted up the hand drill once or twice during the drilling, generating one or two notches on the thrust force profile as the blue curves in Fig. 8. By lifting up the drill, bone debris evacuation was more efficient with larger gaps than shaky drilling. When the K-wire tip and bone were shortly separated, heat convention happened between the cutting area and the surrounding air, cooling down both the rotating K-wire and the bone sample. With such technique, surgeons achieved the fastest drilling time and the lowest bone temperature rise.

(4) Pecking drilling: Lifting up the drill slightly during penetration helped heat dissipation. However, lifting up too many times, as shown by the multiple notches in thrust force and axial displacement of the black curves in Fig. 8, was not effective because it slowed down the material removal process. The K-wire would scratch bone tissue little by little without efficient drilling process, leading to heat accumulation and temperature rise at the cutting area over a long time period.

In summary, shaky and intermittent drilling techniques are preferred while continuous or pecking drilling should be avoided to achieve shorter drilling time and lower bone temperature rise to minimize thermal injury during K-wire insertion under both unidirectional or oscillatory modes.

CONCLUSIONS

In conclusion, this study investigated the heat generation during K-wire insertion under the unidirectional and oscillatory drilling modes. Our findings demonstrated that the oscillatory mode generates lower bone temperature rise but needs longer drilling time than the unidirectional mode, suggesting that the choice of drilling mode should be a compromise between peak temperature and bone exposure time based on the surgical case. Shortening the drilling time is the key under both modes to control temperature rise and reduce the risk of thermal necrosis. To achieve faster drilling, shaky and intermittent drilling techniques with moderate thrust force applied are preferred techniques by small vibration of the drill about the K-wire axis and slight lift-up of the K-wire once or twice during drilling.

ACKNOWLEDGEMENTS

This work is supported by Department of Orthopaedic Surgery Research Advisory Committee at University of Michigan. The authors would like to thank Jaron Scott from University of Michigan Orthopaedic Research Lab for his assistance on bone sample preparation. All authors declare that there is no conflict of interest related to this study.

REFERENCES

1. Franssen BBGM, Schuurman AH, Van der Molen AM, Kon M. 2010. One century of Kirschner wires and Kirschner wire insertion techniques: a historical review. Acta Orthop Belg 76:1–6.

2. Khanna a, Plessas SJ, Barrett P, Bainbridge LC. 1999. The thermal effects of Kirschner wire fixation on small bones. J Hand Surg Br 24:355–7.

3. Pandey RK, Panda SS. 2013. Drilling of bone: A comprehensive review. J Clin Orthop Trauma 4:15–30.
4. Namba RS, Kabo JM, Meals RA. 1985. Biomechanical effect of point configuration in Kirschner wire fixation. Clin Orthop Relat Res 214:19–22.
5. Graebe A, Tsenter M, Kabo M, Meales RA. 1992. Biomechanical effects of a new point configuration and a modified cross-sectional configuration in Kirschner-wire fixation. Clin Orthop Relat Res 283:292–296.
6. Bachus KN, Rondina MT, Hutchinson DT. 2000. The effects of drilling force on cortical temperatures and their duration: An in vitro study. Med Eng Phys 22:685–691.
7. Brisman DL. 1997. The effect of speed, pressure, and time on bone temperature during the drilling of implant sites. Int J Oral Maxillofac Implants 11:35–7.
8. Abouzgia MB, James DF. 1995. Measurements of shaft speed while drilling through bone. J Oral Maxillofac Surg 53:1308–1315.
9. Augustin G, Davila S, Mihoci K, et al. 2008. Thermal osteonecrosis and bone drilling parameters revisited. Arch Orthop Trauma Surg 128:71–77.
10. Hillery MT, Shuaib I. 1999. Temperature effects in the drilling of human and bovine bone. J Mater Process Tech 93:302–308.
11. Lee JE, Ozdoganlar OB, Rabin Y. 2012. An experimental investigation on thermal exposure during bone drilling. Med Eng Phys 34:1510–1520.

12. Piska M, Yang L, Reed M, Saleh M. 2002. Drilling efficiency and temperature elevation of three types of Kirschner-wire point. J Bone Jt Surg Br 84:137–140.

13. Liu Y, Belmont B, Wang Y, et al. 2017. Notched K-wire for low thermal damage bone drilling. Med Eng Phys 45:25–33.

14. Nichter LS, Richlin S, Navarrette PM, Kosari K. 1992. The biomechanical efficacy of an oscillating K-wire driver. Ann Plast Surg 29:289–292.

15. Anderson SR, Inceoglu S, Wongworawat MD. 2018. Temperature rise in Kirschner wires inserted using two drilling methods: forward and oscillation. Hand 13:423–427.

16. Karaca F, Aksakal B. 2013. Effects of various drilling parameters on bone during implantology: An in vitro experimental study. Acta Bioeng Biomech 15:25–32.

17. Tomasi C, Kanade T. 1993. Shape and motion from image streams: a factorization method. Proc Natl Acad Sci 90:9795–9802.

18. Lee JE, Rabin Y, Ozdoganlar OB. 2011. A new thermal model for bone drilling with applications to orthopaedic surgery. Med Eng Phys 33:1234–1244.

19. Sapareto SA, Dewey WC. 1984. Thermal dose determination in cancer therapy. Int J Radiat Oncol Biol Phys 10:787–800.

20. Tai BL, Palmisano AC, Belmont B, et al. 2015. Numerical evaluation of sequential bone drilling strategies based on thermal damage. Med Eng Phys 37:855–861.

21. Gao Y, Wang Q, Zhu H, Xu Z. 2017. Timing for surgical stabilization with K-wires after open fractures of proximal and middle phalangeal shaft. Sci Rep 7:31–34.

22. Oh HJ, Kim BI, Kim HY, et al. 2017. Implant drill characteristics: thermal and mechanical effects of two-, three-, and four-fluted drills. Int J Oral Maxillofac Implants 32:483–488.

Figures

Fig. 1. Bone sample preparation: (a) photo of the prepared bone sample and (b) locations and (c) cross sectional view of pilot and thermocouple holes.

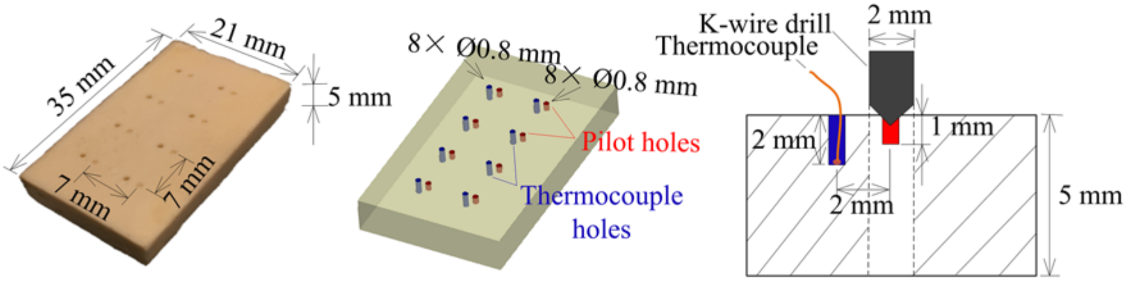


Fig. 2. Experimental setup for bone drilling tests.

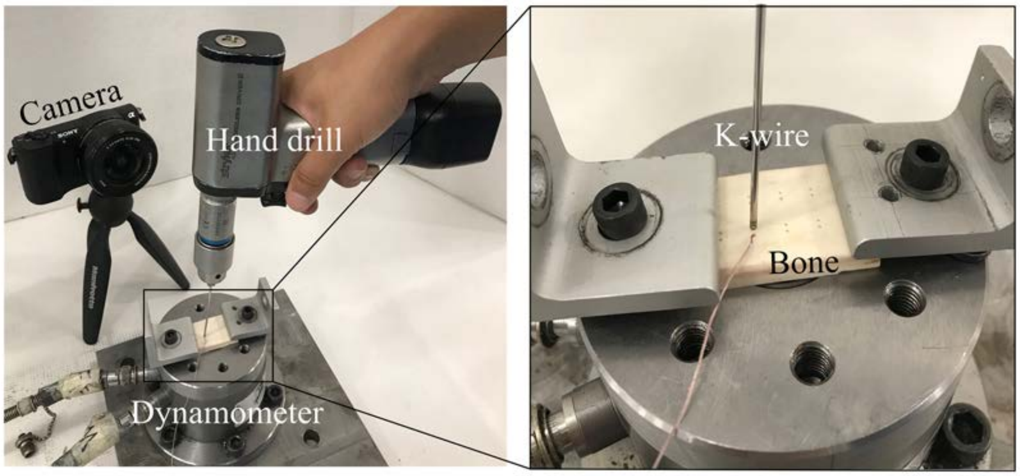


Fig. 3. Spindle rotational speed of the surgical hand drill used under the unidirectional and oscillatory drilling modes.

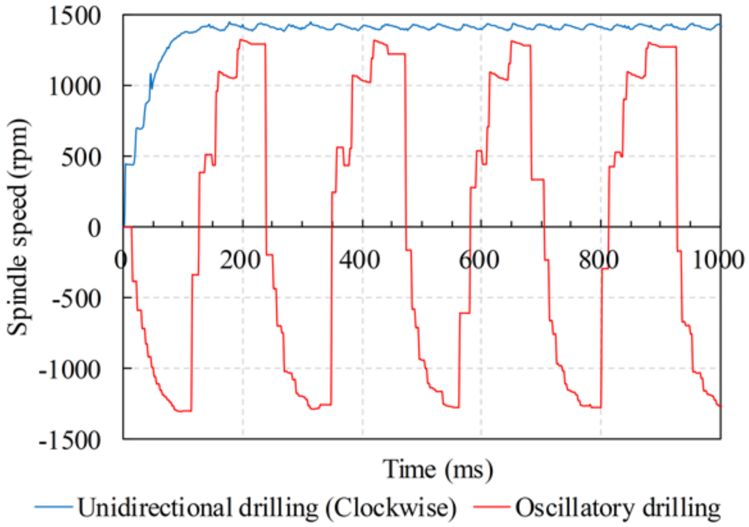


Fig. 4. Image processing of recorded drilling video: (a) starting frame and tracking pixel and (b) axial displacement change along with drilling time.

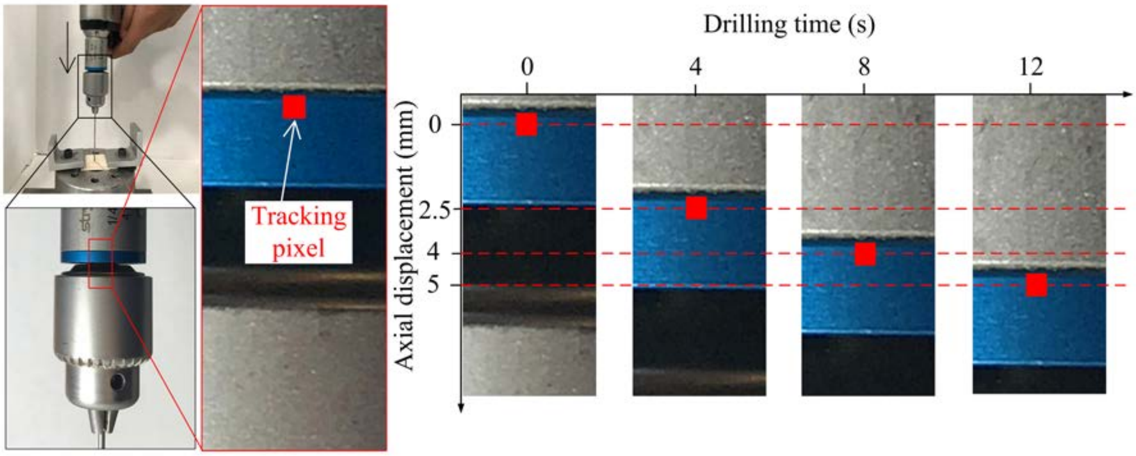


Fig. 5. Impact of drilling mode on: (a) peak bone temperature and (b) drilling time (error bar represents standard deviation).

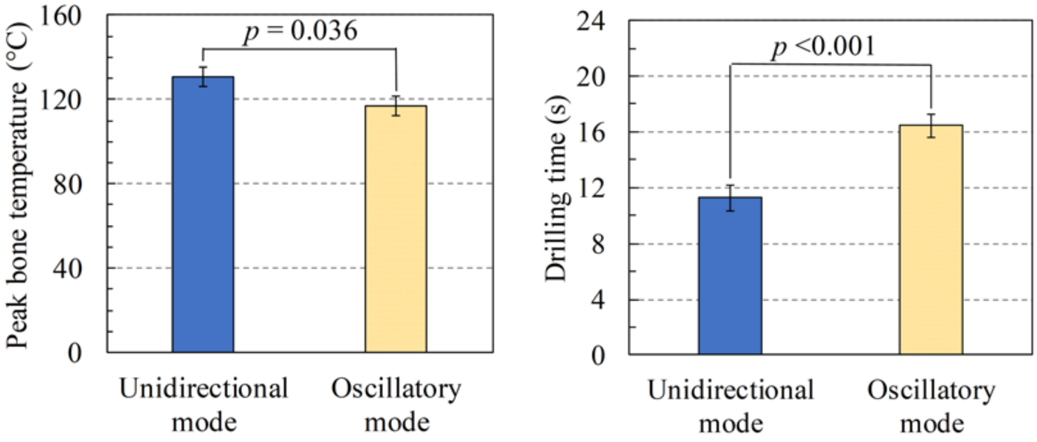


Fig. 6. Correlation between drilling time and peak bone temperature under the unidirectional and oscillatory drilling modes.

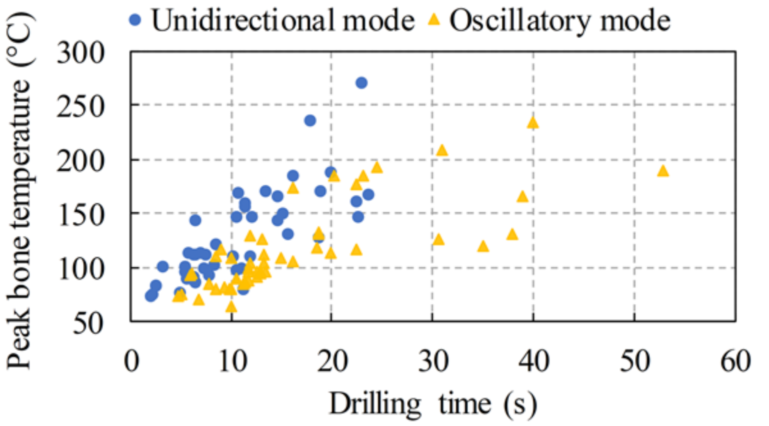


Fig. 7. Tool wear of the K-wire.

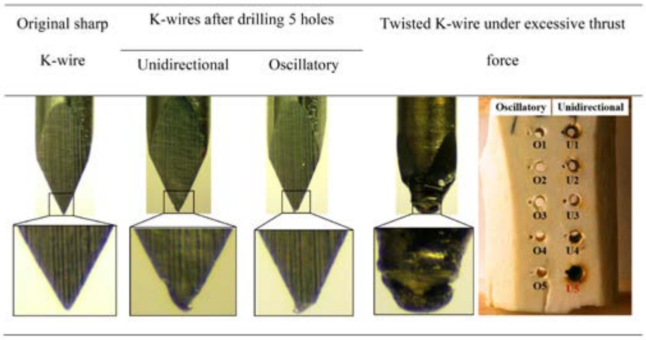
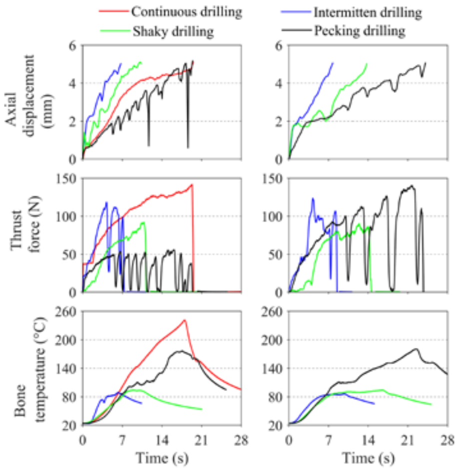


Fig. 8. Four types of drilling techniques utilized by different surgeons under (a) unidirectional and (b) oscillatory drilling modes.



Tables

Table 1. Summary of main effect results from the ANOVA

Dependent variable	Independent variable	*F*	*p*
Peak bone temperature	Drilling mode	4.535	**0.036**
	Number of holes drilled	0.981	0.423
	Surgeon	8.454	**<0.001**
Drilling time	Drilling mode	17.809	**<0.001**
	Number of holes drilled	1.285	**0.283**
	Surgeon	12.002	**<0.001**
Peak bone temperature under the unidirectional mode	Number of holes drilled	1.474	0.237
	Surgeon	4.850	**0.001**

	Drilling time	15.675	<**0.001**
	Peak thrust force	3.379	0.077
	Peak torque	0.061	0.807
Peak bone temperature under the oscillatory mode	Number of holes drilled	1.014	0.414
	Surgeon	7.007	<**0.001**
	Drilling time	40.676	<**0.001**
	Peak thrust force	30.709	<**0.001**
	Peak torque	0.848	0.364

All *p* values in bold are lower than the 0.05 significance level.