



Original Article

Effect of Drilling Techniques on Microcracks and Pull-Out Strength of Cortical Screw Fixed in Human Tibia: An In-Vitro Study

RAVINDER PAL SINGH ¹, VISHAL GUPTA,² PULAK MOHAN PANDEY,¹
and ASIT RANJAN MRIDHA³

¹Department of Mechanical Engineering, Indian Institute of Technology, Delhi, New Delhi, India; ²Department of Mechanical Engineering, Thapar Institute of Engineering and Technology, Patiala, India; and ³Department of Pathology, All India Institute of Medical Sciences, New Delhi, India

(Received 17 February 2020; accepted 6 July 2020; published online 13 July 2020)

Associate Editor Kent Leach oversaw the review of this article.

Abstract—The strength between the cortical screw and bone following an orthopaedic implant surgery is an important determinant for the success of osteosynthesis. An excessive axial cutting force during drilling produces microcracks in the bone surface, resulting in reduced strength between the screw and bone, resulting in loosening of implant. The present work, investigates the influence of drilling parameters on microcracks generated in the drilled surface and pull-out strength of screw fixed in cortical bone of human tibia. The holes were drilled by two different techniques: conventional surgical bone drilling (CSBD) and rotary ultrasonic bone drilling (RUBD), by a recently developed operation theatre (OT) compatible machine. Cutting force generated in drilling of human tibia using RUBD was 30–40% lesser than that of CSBD. Scanning electron microscopy (SEM) also revealed that RUBD produced significantly lesser and thinner microcracks than that of CSBD in human bones. Biomechanical pull-out test results showed that, the pull-out strength of screws inserted into drilled holes by RUBD was much higher (100–150%) than that of CSBD. A significant difference in pull-out strength ($p < 0.05$) between RUBD and CSBD was revealed by statistical analysis at 95% confidence interval.

Keywords—Bone drilling, Microcracks, Pull out strength, Rotary ultrasonic bone drilling, Bone.

INTRODUCTION

An osteosynthesis is required for the treatment of the major injuries to bone and includes the insertion of screws, wires, and plates to align and immobilize the fractured bones for proper healing. Besides various

host and environmental factors, the success of such procedures also depends upon several mechanical factors such as axial cutting force, temperature generation during drilling, microcracks that are produced in the bone, which can affect the stabilization of the implant (screw/plate).^{16,20} The strength between screw and cortical bone is one of the important factors for stabilization of fractured bones.²² It has been demonstrated that the design and geometry of the screw influenced the strength between screw and bone.^{16,17} Many authors^{6,17,22} in the past two-three decades have strived to improve the pull-out strength of the screw by conventional drilling. Modification of drill bit design⁶ and the drilling techniques¹¹ could improve the strength between the screw and bone. Conventional drilling to insert screw in the bone generated high axial cutting force and torque. It produced microcracks in the bones,^{5,8} as well as fractures³¹ in the drilled surface of the bone. The minor cracks can disappear following regrowth of the bone tissues,^{18,19} but a larger number of longer and wider microcracks can lead to the weakening of strength between the cortical screw and bone and thus causing loosening of the screws and implant failure.⁷

The regeneration capacity of the bone is also affected by heat generation during drilling. An excessive temperature can cause thermal osteonecrosis^{4,30} and impairs the regrowth of bone. To overcome these problems, ultrasonic-assisted drilling (UAD) technique, which involves drilling of bone with linear ultrasonic vibrations in drilling direction, was introduced. It was found that UAD produced lesser cutting force/torque,^{3,26} lower temperature rise during

Address correspondence to Ravinder Pal Singh, Department of Mechanical Engineering, Indian Institute of Technology, Delhi, New Delhi, India. Electronic mail: ravinderpalsingh89@yahoo.com

drilling,¹ better surface finish² and fewer and shorter number of microcracks^{23,31} as compared to conventional drilling technique. Singh et.al²³ reported that ultrasonic-assisted drilling produced no microcracks but increased the duration of drilling time.

In the recent past, researchers¹² introduced a new drilling technique (rotary ultrasonic bone drilling) for orthopaedic drilling, which consisted of imparting linear ultrasonic vibrations to a rotating hollow cylindrical diamond abrasive coated drilling tool. The experiments were performed on porcine bone by a computer numeric control (CNC) vertical milling machine. RUBD generated lesser cutting force and torque¹⁰ and better biomechanical pull-out strength¹¹ as compared to CSBD.

Majority of previous works^{6,9,17,22,29} to test the pull-out strength have been performed by conventional drilling using the bulky lathe and CNC operated machines,¹¹ which cannot be used in an operation theatre (OT). No research has been reported in which the pull-out strength of cortical screw fixed in human bone have been determined, for holes drilled by recently developed rotary ultrasonic bone drilling process.¹⁰ It has been reported^{13-15,21} that the human bones exhibits different mechanical and biological behaviour than animal bones. Moreover, the effects of the RUBD process on the microcracks generated in the

human bones has also not been reported yet. The present work includes the analysis of the microcracks generation and the pull-out strength of screw inserted in cortical bone for holes drilled by RUBD and CSBD. The drilling experiments were performed on the cadaveric bone (tibia) by a compact OT compatible RUBD machine.

MATERIALS AND METHOD

Machine

Figure 1 displays the RUBD machine prototype which was used for bone drilling in the present study. The detailed specifications and design have been discussed in our previous study.²⁶ The developed prototype consists of an ultrasonic generator which provides the ultrasonic vibration at 20 kHz frequency. Figure 1b presents the drilling setup. The bone specimen held in fixture was placed above the dynamometer (SCHUNK type, Model: delta SI330-30, Fig. 1c), and the rotating tool penetrated into the bone surface to produce a hole. The cutting force produced during drilling was recorded by dynamometer (*ATI/DAQ software*) in both RUBD and CSBD techniques. Table 1 shows the detailed specification of the various component of the developed machine prototype.

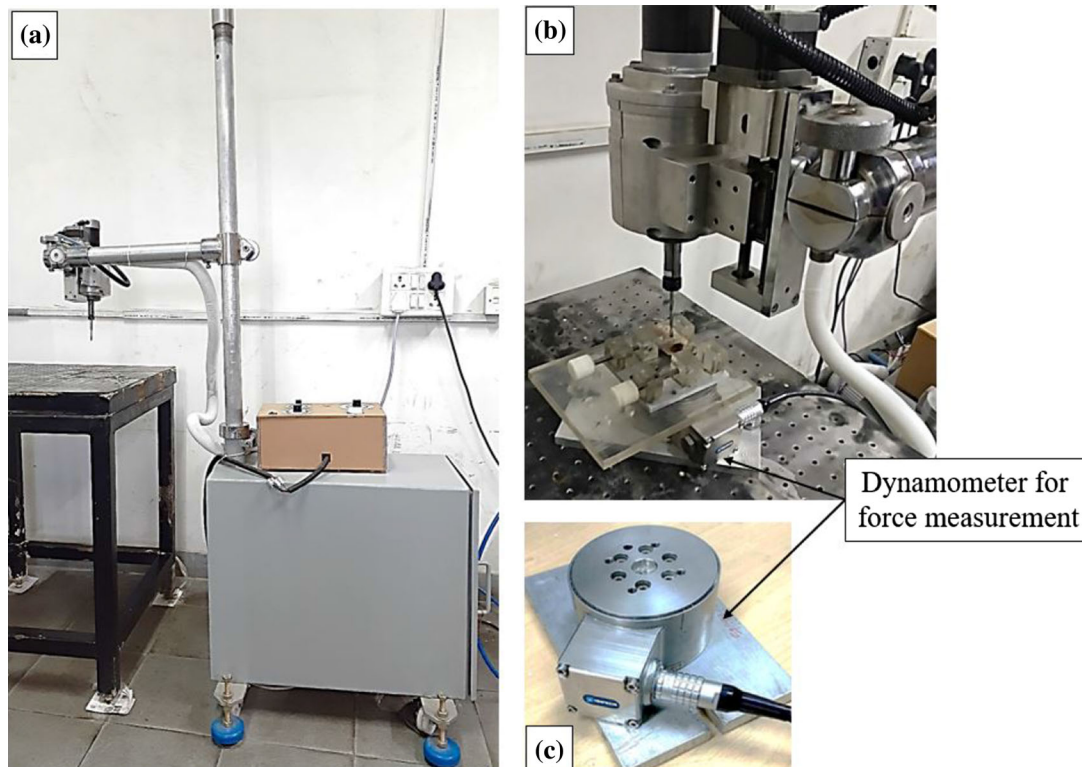


FIGURE 1. (a) Rotary ultrasonic bone drilling machine, (b) drilling setup and (c) dynamometer.

TABLE 1. Components and specification of the developed machine prototype.

S. no.	Component	Specifications	Function
1	Ultrasonic transducer	Power—800 W Type—piezoelectric	Helps in providing initial vibration to the horn/sonotrode
2	Ultrasonic generator (power supply)	20 kHz frequency, 220 V	Supply power to the ultrasonic transducer
3	Direct current motor	Type—brushless direct current motor, 24 V, 70 N-mm 20-40 A	Provides rotational feed to the drilling tool
4	Feed motor	Type—stepper, 3.8 V, 60 N-mm	Provide axial linear feed to the rotating tool
5	Drill bit/tool	Diameter = 3 mm to 5 mm Length = 90 mm	Removes material during drilling and penetrates inside
6	Ultrasonic horn/sonotrode	Material- SS-316, Length= 70 mm	Amplifies the linear vibrations
7	Lead screw	Diameter= 10 mm, Pitch=1 mm	Converts the rotary motion of stepper motor to the linear feed

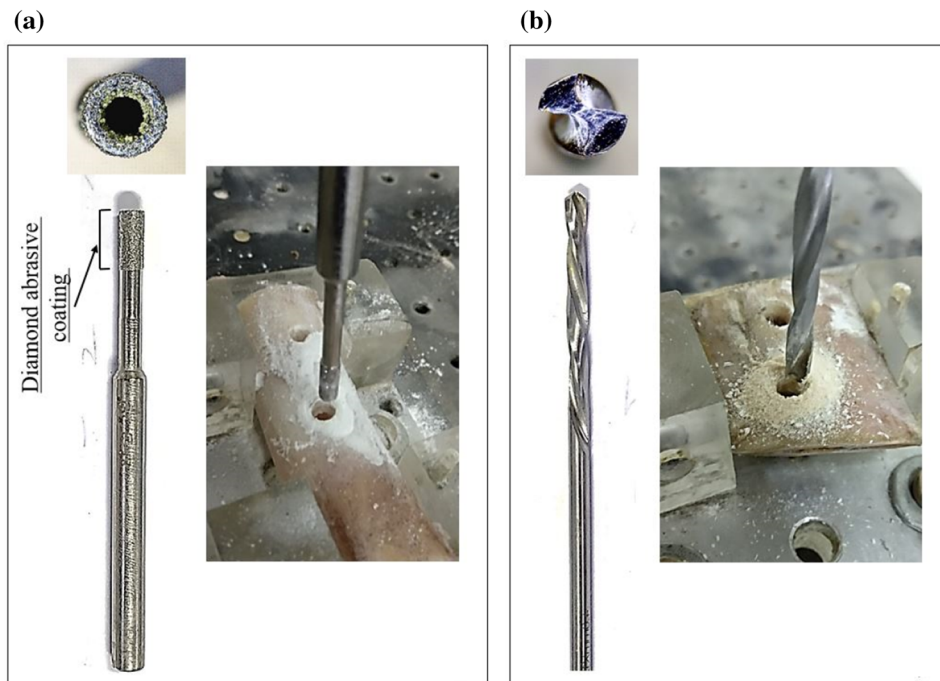
**FIGURE 2. (a) Diamond abrasive coated RUBD tool and (b) CSBD tool for drilling operations.**

Figure 2 displays different tools which were used in different techniques. In RUBD, a hollow cylindrical tool with electroplated abrasive diamond particles at the drilling end (Fig. 2a) was designed to give a linear amplitude of 18–20 μm at the drilling end.²⁶ In CSBD process, a conventional two-flute surgical-grade drill bit (Fig. 2b) were used. The End views are displayed at the top of the respective images and the drill holes in the bone specimens are shown by RUBD and CSBD process, respectively.

Sample Preparation

The experiments were performed on the human tibia, which were obtained at autopsies from All India Institute of Medical Sciences, New Delhi. The specimens were cut immediately after the autopsy and kept in 10 percent buffered formalin solution (formaldehyde- Sigma Aldrich) to preserve and maintain the structural integrity.²⁸ The drilling was performed at room temperature within 30 minutes of sample extracted from the formalin solution. The holes were

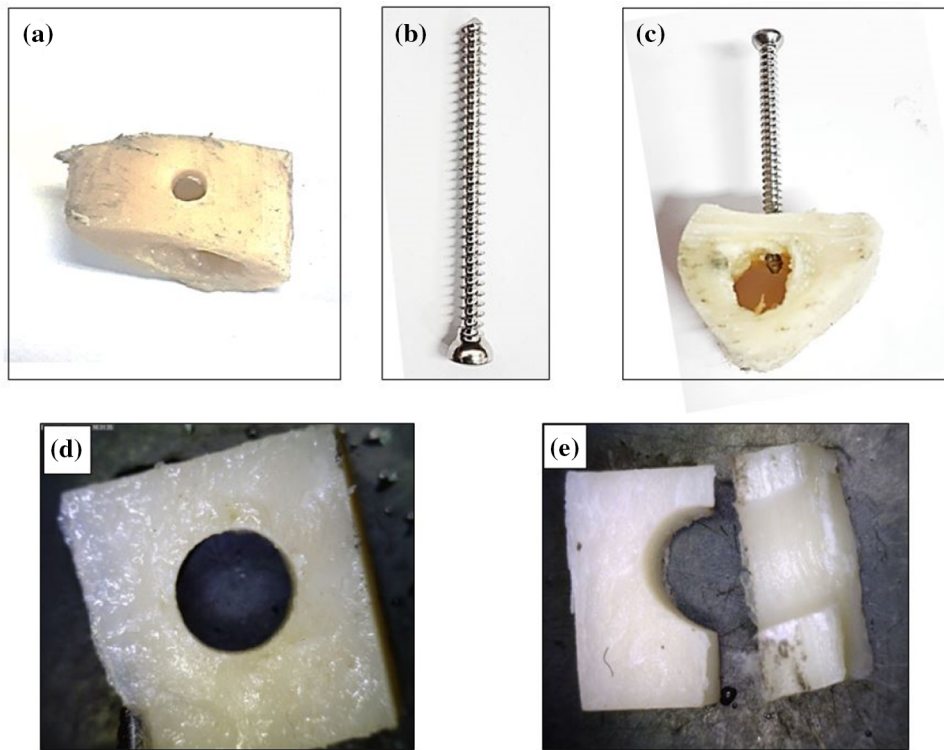


FIGURE 3. (a) Bone specimen after drilling process, (b) cortical screw, (c) bone specimen for pull-out test, (d) rectangular cross-section cut from the bone specimen after drilling and (e) bone specimen for microcracks analysis.

drilled by the two technique (RUBD and CSBD) at same parameters on the samples cut from the same bone. The samples were again preserved in the formalin solution after the experiments.

Figure 3a shows the drilled bone sample, Fig. 3b represents the cortical screw of pitch 1 mm, diameter 3.5 mm and thread length 40 mm. The screw was inserted into the drilled hole with 3 rev/min (ASTM F 543-02). Figure 3c displays the bone specimen with an inserted screw into the entire thickness of bone cortex to study the pull-out strength. Figure 3d represents a rectangular cross-section of bone with a central drill hole. The bone specimen was sectioned along the center of the hole to get two semi-circular cross-section (Fig. 3e). This semi-circular cross-section of drill hole was examined under scanning electron microscopy (SEM) for microcracks analysis.

Pull-Out Strength Measurement

The bone specimen with inserted screw into the cortical part as shown in Fig. 3c was held in a specially designed fixture (Fig. 4), which could hold bone samples of different sizes and shapes firmly during the test procedure. The pull-out test was carried out by single action universal testing machine (INSTRON-5582) as

shown in Fig. 4. The head of the cortical screw was held in the upper cross head and fixture was held in the lower cross head of the testing machine (refer Fig. 4). In order to eliminate the effect of transverse load during test, the bone specimen with cortical screw fixed in drilled hole was carefully placed inside the fixture so that only axial tensile load can be applied on the cortical screw. The screw was held coaxially with the direction of applied load during the pull-out experiment. Total 20 experiments were performed for the comparative study, and the crosshead rate (pull-out speed) for all the experiment was set to 0.5 mm/min.

Microcracks Analysis

Scanning electron microscope (SEM) images of the bone specimens were taken by Zeiss EVO 50 with the magnification of $\times 500$ to analyse the microcracks in the drilled surface.

Selection Parameter

Previous studies^{2,3,10,11,32} showed that rotational speed and feed rate have the most significant effect on the cutting force as compared to other parameters. High axial cutting force during drilling produces

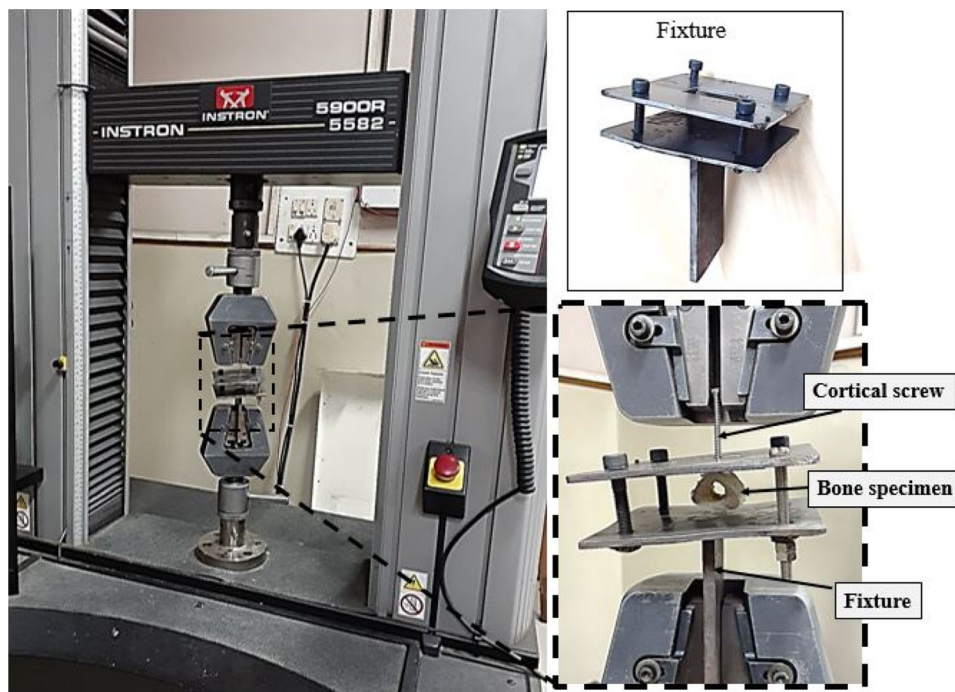


FIGURE 4. Universal testing machine for the pull-out test and fixture for holding bone specimen.

microcracks in the drilled surface of bone and weakens the strength between bone and screw thus reduces the pull-out strength of the screw.¹¹ Therefore in the present work, the effect of rotational speed and feed rate on microcracks and pull-out strength was studied. Whereas, other drilling parameter like drill diameter, diamond abrasive particle size (for RUBD), were kept constant. Our previous study showed that rotational speed below 1000 rpm produced high cutting force²⁶ and the speed above 3000 rpm generated high temperature²⁵ which resulted in problems like necrosis. Thus in the present work, the rotational speed was varied from 1000 rpm and 3000 rpm. The feed rate was maintained between 10 mm/min and 50 mm/min, since in the preliminary experiments²⁶ it was found that the feed rate below 10 mm/min was associated with prolonged drilling time and thus, increasing the temperature at drilling site. The feed rate above 50 mm/min resulted in high cutting force. Previous studies^{3,10} showed that an increase in ultrasonic amplitude from 5 to 15 μm was associated with the decrease in cutting force and temperature, but further increase of amplitude above 15 μm had no significant additional beneficial effect on cutting force and temperature. Therefore, in this study the RUBD tool was designed to provide a linear amplitude of 18–20 μm at 20 kHz ultrasonic frequency.

The time required to drill a hole is dependent (inversely related) on the feed rate during the drilling. In our previous study²⁴ it was found, that the cortical

thickness of human tibia varies from 4 to 5 mm, therefore the time required to drill a hole for feed rate of 10 mm/min is approximately 25–30 s and for 50 mm/min is 6–7 s, for both the techniques. Therefore, at constant feed rate the drilling time for both the techniques (RUBD and CSBD) is same. All the drilling experiments in the present study were completed between 6 to 30 s. Table 2 represents the different drilling parameters taken for microcracks and pull-out test in the present study.

Statistical Analysis

In order to establish that there is significance difference between the pull-out strength of cortical screw in RUBD and CSBD technique, paired sample t-test was carried out at unique test condition by repeating the experiments five times for RUBD and five times for CSBD. The t-test was carried out using a statistical software (MINITAB 17) at a confidence interval of 95%.

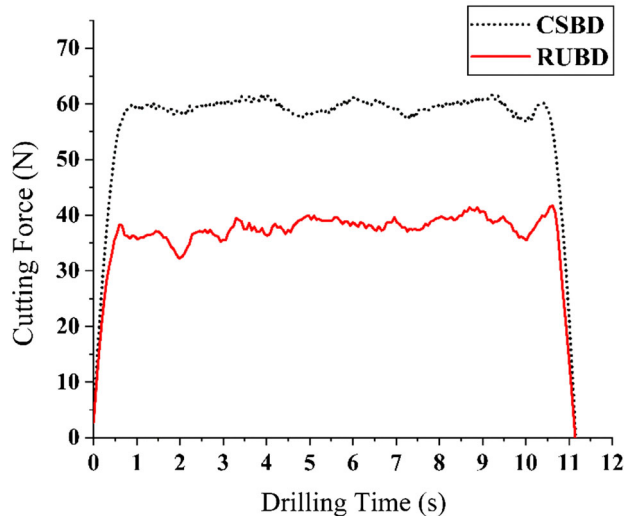
RESULTS

Axial Cutting Force

Axial cutting force is an important factor which effects the microcracks generated in the drilled surface of the hole. Therefore, in order to understand the microcracks generated in the drilled surface by the two

TABLE 2. Different drilling parameters for microcracks analysis and pull-out test.

S. no.	Parameters	Abbreviation	Drilling techniques	
			RUBD	CSBD
1	Rotational speed (rpm)	N	1000–2000–3000	1000–2000–3000
2	Feed rate (mm/min)	F_r	10–30–50	10–30–50
3	Drill diameter (mm)	D_d	3.5	3.5
4	Diamond abrasives (grit size)	D_a	120	NA
5	Ultrasonic amplitude (μm)	A_p	18–20	NA

**FIGURE 5. Cutting force generated during drilling in RUBD and CSBD process at $N = 2000$ rpm, $F_r = 30$ mm/min, and $D_d = 3.5$ mm.²⁴**

drilling techniques i.e. RUBD and CSBD. It becomes necessary to understand the evolution of axial cutting force produced during the drilling experiments. It was found in our previous studies^{24,25} that the axial cutting force generated by RUBD during drilling is considerably lesser than the CSBD process. Figure 5 represents the axial cutting force, which was recorded by a SCHUNK dynamometer (*Model: delta SI330-30*) during drilling on tibia by RUBD and CSBD. The force produced during drilling was captured by ATI-DAQ F/T software. It could be seen that RUBD process produced significantly lower cutting force (30–40%) than that of CSBD (Fig. 5). Our previous studies^{24,25} provides the detailed experimental investigation on cutting force produced during drilling by RUBD and CSBD on human cadaver bones.

Effect on Microcracks

Figure 6 shows the microcracks (marked with yellow lines) developed in the drilled surface of the bone

at different rotational speed and drilling techniques. From the figures, it is clearly seen that at a lower rotational speed of 1000 rpm, CSBD produced longer, wider and larger number of cracks (Fig. 6a); whereas, at higher speed of 3000 rpm, there were smaller, thinner and lesser number of cracks (Fig. 6b). This was due to the rise in cutting force on the bone surface with the increase in the rotational speed as reported in the previous studies.^{3,10,21,26,32} In RUBD, even with lower speed (rpm 1000), the cracks were few, much thinner and shorter (Fig. 6c) as compared with CSBD, and at high speed (rpm 3000) no cracks were visible (Fig. 6d). Similarly, Fig. 7 shows the effect of feed rate on the microcracks development. It was observed that the length and width of cracks increased as the feed rate increased from 10 mm/min to 50 mm/min in CSBD. However, no crack was found at the feed rate of 10 mm/min in RUBD, and significantly lesser and minor cracks were visible at feed rate of 50 mm/min. This was due to the axial cutting force, which was produced during the two drilling techniques. Figure 5 demonstrates the evolution of the cutting force during drilling it could be clearly seen that RUBD produces significantly lesser cutting force than CSBD thus resulting in smaller or no microcracks on the drilled surface.

Effect on Pull-Out Strength

Table 3 displays the drilling experiments which were performed to measure the pull-out force in RUBD and CSBD technique. In first three experiments (i.e. s. no. 1–3) the rotational speed was varied from 1000 rpm to 3000 rpm keeping feed rate and drill diameter constant to 30 mm/min and 3.5 mm, respectively. Whereas, in last two experiments (4 and 5) feed rate was varied from 10 to 50 mm/min keeping rotational speed and drill diameter constant to 2000 rpm and 3.5 mm, respectively. A total of 5 experiments were repeated two times for both RUBD and CSBD technique. The average pull-out force and standard deviation for each drilling experiment for both the techniques are shown in Table 3. Hence, a total of 20 experiments (10 each

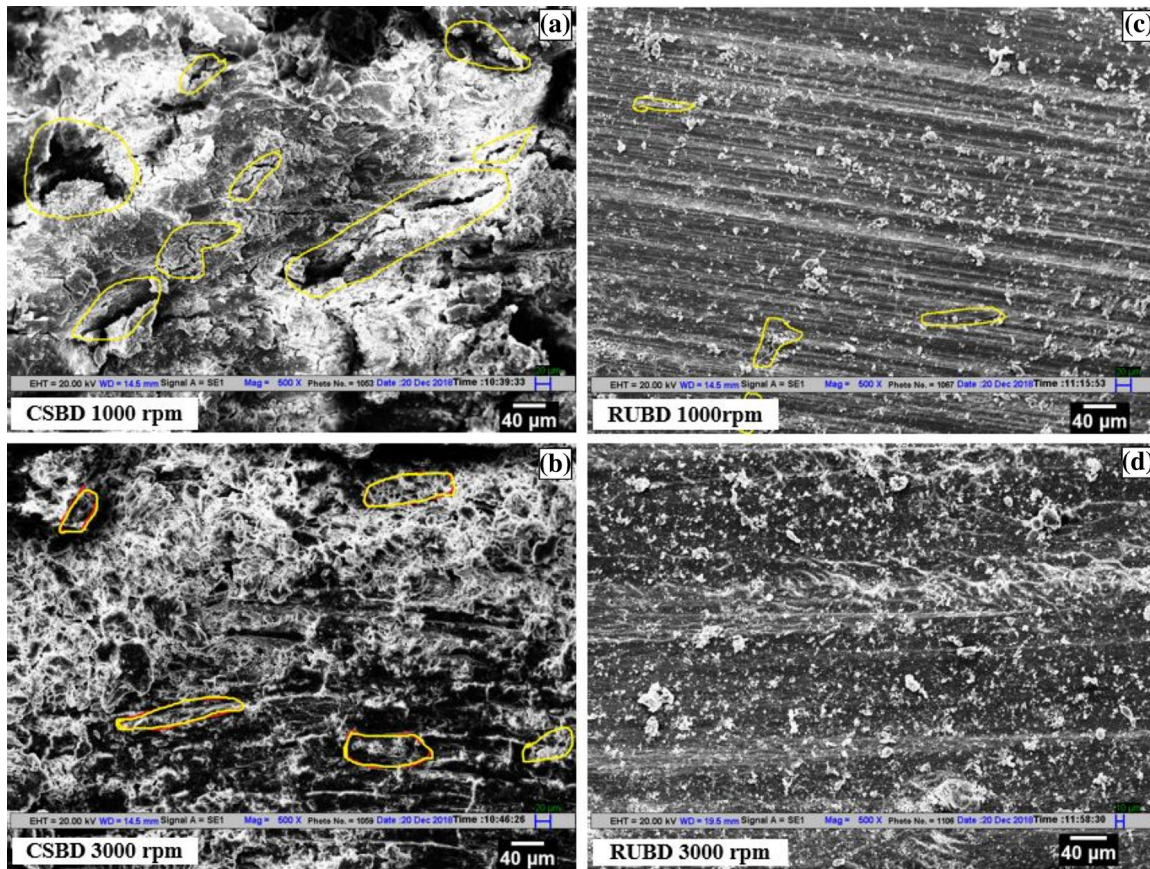


FIGURE 6. Figure: SEM images of microcracks at the inner surface of drilled hole for $N = 1000$ rpm (a, b) and $N = 3000$ rpm (c, d) at a magnification of $\times 500$ for CSBD and RUBD process.

for RUBD and CSBD) were performed in the present study for pull-out test.

Figures 8a and 8b represents the effects of rotational speed and feed rate on pull-out strength in RUBD and CSBD process. Figures 8c through 8g represents the evolution of pull-out force recorded in the two drilling techniques at constant drilling parameters for all the drilling experiments. It was clearly evident that in RUBD process, more force was required to pull out the inserted screw from the drilled hole.

It was observed (refer Fig. 8a) that at a constant feed rate of 30 mm/min, as the rotational speed increased from 1000 rpm to 3000 rpm, the pull-out strength increased from 0.98 kN to 1.41 kN (by 43.8%) in RUBD, and 0.40 kN to 0.93 kN (by 123%) in CSBD. Similarly, at a constant rotational speed of 2000 rpm as the feed rate increased from 10 mm/min to 50 mm/min. The pull-out force decreased from 1.59 kN to 1.15 kN (by 27.7%) for RUBD and, decreased from 0.88 to 0.41 kN (by 53%) in CSBD (refer Fig. 8b). This is because as the rotational speed increases from 1000 rpm to 3000 rpm and feed rate decreases from 50 mm/min to 10 mm/min, the cutting force and torque

decreased^{3,10,21} which leads to the decrease in extent of microcracks (Figs. 6 and 7). Thus increasing the strength between the screw and the bone, and requiring more pull-out force to remove the cortical screw. It was also observed that for any combination of parameters, the pull-out force in RUBD was 100–150% higher than that of CSBD process.

Significant Difference in Pull-Out Strength of RUBD and CSBD

In order to find out the significance difference between the pull-out strength of cortical screw in RUBD and CSBD, a paired sample t-test was carried out using commercially available statistical software (MINITAB 17). Table 4 represents the drilling parameters which were chosen on the basis of our previous studies.^{24–26} 5 experiments on RUBD and CSBD each (i.e. a total of 10) were performed as per the process parameters given in Table 4. Table 5 denotes the pull-out strength recorded for the screw inserted in the drilled hole by the two techniques (CSBD and RUBD). The average pull-out strength for CSBD was 0.59 ± 0.07 kN, and that for RUBD was $1.25 \pm$

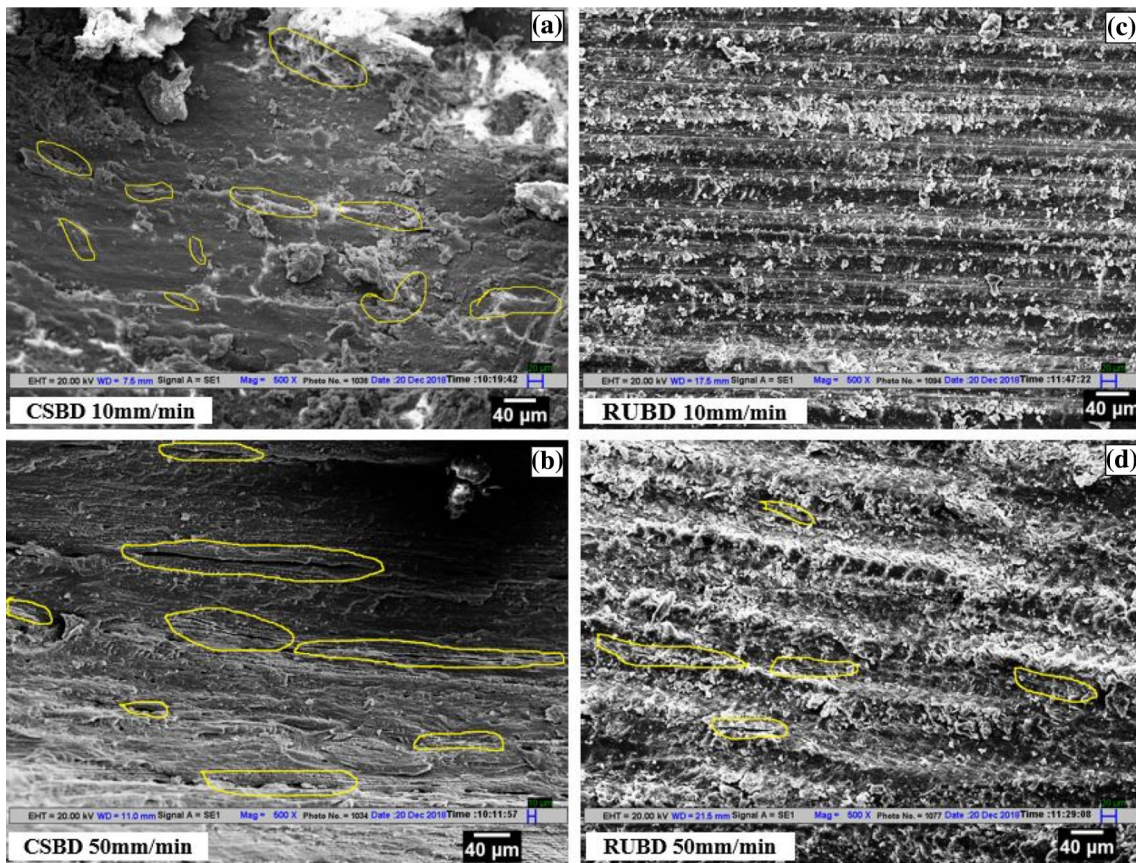


FIGURE 7. SEM images of microcracks at the inner surface of drilled hole for $F_r = 10$ mm/min (a, b) and 50 mm/min (c, d) at a magnification of $\times 500$ for CSBD and RUBD process.

TABLE 3. Experiments for the pull-out test.

S. no.	Parameters			Drilling technique					
				CSBD			RUBD		
				Experiment no.		Avg. \pm SD (kN)	Experiment no.		Avg. \pm SD (kN)
1	1000	30	3.5	1st	2nd		0.40 \pm 0.03	1st	
2	2000	30		0.42	0.38	0.61 \pm 0.07	0.9	1.05	1.26 \pm 0.05
3	3000	30		0.56	0.66	0.93 \pm 0.11	1.22	1.29	1.41 \pm 0.23
4	2000	10		0.85	1.0	0.88 \pm 0.04	1.25	1.57	1.59 \pm 0.23
5	2000	50		0.85	0.9	0.41 \pm 0.05	1.75	1.42	1.15 \pm 0.08
				0.37	0.44		1.2	1.09	

For RUBD: $D_a = 120$ grit size, and $A_p = 18\text{--}20$ μm .

0.13 kN. It can also be seen in Table 5 that the pull-out strength for all the drilling experiments comes with the range of upper control limit ($UCL = +3\sigma$) and lower control limit ($LCL = -3\sigma$), thus the process is under statistical control. Table 6 clearly indicates that the difference between the mean of pull-out strength is within the range of confidence interval at 95%, also the p -value is 0.000 which is less than 0.05. Thus, there is a significant difference between the mean of pull-out

strength of cortical screw inserted in the hole drilled by RUBD and CSBD techniques.

DISCUSSION

The present work includes the experimental investigation on a recently developed OT compatible RUBD machine to study the cutting force, micro-

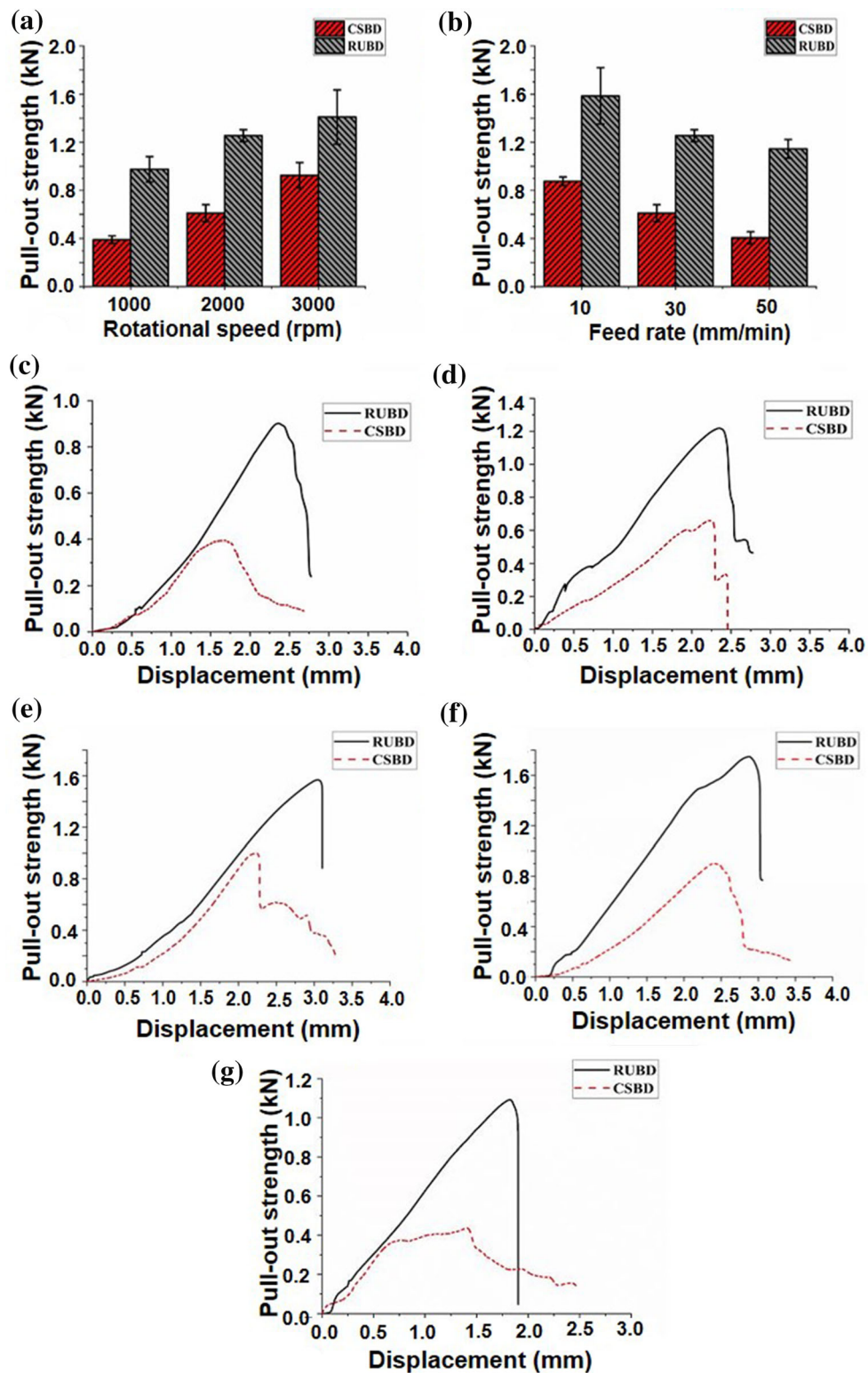


FIGURE 8. Effect of (a) rotational speed and (b) feed rate on pull-out strength for RUBD and CSBD process and evolution of pull-out strength during testing for (c) $N = 1000$ rpm, $F_r = 30$ mm/min and $D_d = 3.5$ mm, (d) $N = 2000$ rpm, $F_r = 30$ mm/min and $D_d = 3.5$ mm, (e) $N = 3000$ rpm, $F_r = 30$ mm/min and $D_d = 3.5$ mm, (f) $N = 2000$ rpm, $F_r = 10$ mm/min and $D_d = 3.5$ mm, (g) $N = 2000$ rpm, $F_r = 50$ mm/min and $D_d = 3.5$ mm, RUBD and CSBD process.

TABLE 4. Drilling parameters for t-test.

Drilling technique	N (rpm)	F_r (mm/min)	D_d (mm)	D_a (grit size)	A_p (μm)
RUBD	2000	30	3.5	120	18–20
CSBD	2000	30	3.5	NA	NA

TABLE 5. Experiment details.

Drilling techniques	Pull-out force (kN)					Average \pm standard deviation
	Experiment no.					
	1st	2nd	3rd	4th	5th	
CSBD	0.52	0.61	0.55	0.7	0.58	0.59 ± 0.07
RUBD	1.15	1.08	1.26	1.35	1.4	1.25 ± 0.13

TABLE 6. t-Test paired sample for mean (using MINITAB).

Test statistics	Drilling technique	
	RUBD	CSBD
Mean	1.24	0.59
Variance	0.0179	0.0047
Difference between mean's	0.656	
Confidence interval	(0.4976, 0.8144)	
Observations	5	
Pearson's correlation	0.344	
df	4	
p-Value	0.000	
t-Value	11.5	

racks produced in the drilled surface and the pull out strength for cortical screw. The drilling experiments were performed on hard human bones (tibia) by two different drilling technique: RUBD, using diamond abrasive coated tool and CSBD using conventional twist drill bit. According to best knowledge of author's no prior comparative study of RUBD and CSBD has been reported on human bones.

The in-vitro experimental investigation (refer Fig. 5) revealed that the cutting force produced in RUBD was 30 to 40% lesser as compared to CSBD process. Lower force generation in RUBD in contrast to CSBD was due to an intermittent contact by ultrasonic vibration between the tool and the bone, and the point contacts of diamond abrasive particles with the bone. In CSBD, the tool remains in continuous contact with the bone surface. Since an area of contact between the tool and workpiece influenced the cutting force, the smaller contact area in RUBD (due to presence of point contact) as compared to CSBD contributed to the lesser

amount force generation. Alam *et al.*³ reported in their drilling investigations on bovine cortical that, incorporating ultrasonic vibrations to the conventional tool reduced the cutting force due to decrease in the contact time. Singh *et al.*²⁶ and Gupta and Pandey¹⁰ reported that the size of chips may also be associated with the higher cutting force in CSBD, for same parameters CSBD produced larger size chips as compared to RUBD. The results corroborated with the RUBD study of Gupta and Pandey¹⁰ on porcine bone using CNC machine.

O'Brien *et al.*⁷ performed experimental investigations on bovine cortical to study the effect of microcracks on bone failure. The study revealed that shorted and thinner cracks could be repaired by bone itself, but microcracks greater than $300\mu\text{m}$ resulted in bone failure. It was found in our prior study²⁶ that among different drilling parameters rotational speed and feedrate were the most significant parameters that effect the cutting force produced during orthopaedic drilling. The study of microcracks produced in the drilled surface was performed using an initial hypothesis that cutting force is directly related to the microcracks generated in the drilled surface. Figures 6 and 7 shows the microcracks results obtained in the present study. It was observed that the number and intensity of microcracks generated increased with the decrease in rotational speed for both RUBD and CSBD techniques. This was due to reason that cutting force and torque decreases with the increase in rotational speed.^{3,10,26,27} The mean frictional coefficient between the rotating tool and workpiece (bone) decreases with the increase in rotational speed which results in lower cutting forces at higher rotational speed. Our prior study²⁶ also reported that the increase in rotational speed resulted in lower cutting force for both CSBD

and RUBD. Figure 7 shows that increase in feedrate resulted in larger microcracks. This was due to the higher cutting force generated at higher feed rate due to the increase in the depth of cut and material removal rate.^{12,26,27} The microcracks produced in RUBD were lesser as compared to CSBD due to the cutting force generated by the two drilling technique. Wang *et al.*³¹ reported that vibration assisted drilling resulted in lesser microcracks as compared to the conventional drilling. Gupta *et al.*¹¹ also reported that the high cutting force in conventional drilling leads to wider and larger number of microcracks in conventional drilling as compared to rotary ultrasonic drilling of porcine bone.

Biomechanical pull-out strength is an important factor to determine the stability of the screw fixed in the osteosynthesis process.^{16,17,20} Most of the prior studies^{11,16,17,20,22} for pull-out strength uses perpendicular pull-out method similar methodology was used in the present work also. For pull-out strength test each experiment shown in Table 3 was repeated twice. The pull-out results obtained in Figs. 8a and 8b clearly indicates that, increase in rotational speed and decrease in feedrate resulted in the increase in the pull-out strength. This was due to the intensity of the microcracks generated, Fig. 6 indicates that lesser number of microcracks were generated at higher rotational speed. Whereas, Fig. 7 shows that higher feedrate resulted in larger number of microcracks. The error bar in the Figs. 8a and 8b indicates the maximum and minimum pull-out force recorded during the two trials. Figure 8 also revealed that for any combination of parameters the maximum pull-out strength of RUBD was 100 to 150% higher than CSBD. This was due to the cutting mechanism of the two drilling techniques and the axial force produced during the drilling. Figure 5 shows that RUBD generated lesser cutting force thus resulted in lesser microcracks as compared to CSBD. The increase in the intensity and width of microcracks in the drilled surface of bone reduced the stability between the inserted screw and the bone surface. Thus it requires lesser force to pull-out the screw from the bone surface.

CONCLUSION

The present study revealed that RUBD process generated much shorter, thinner and lesser number of microcracks as compared to the CSBD process, thus providing minimal damage to the cutting surface of the human tibia bone. The extent of microcracks inversely correlated with pull-out strength and a larger number of microcracks were associated with decreased pull-out strength, thus the pull-out strength of the screw in-

serted in hole drilled by RUBD was greater than that of CSBD.

FUNDING

This work was supported by the Society for Research and Initiatives for Sustainable Technologies—SRISTI (Sanction No.: MOU BET. IITD AND SRISTI), Ahmedabad, Gujarat.

CONFLICT OF INTEREST

None.

ETHICAL APPROVAL

Ethical approval was received from both Institute ethics committee (IEC) AIIMS Ref No: IEC-273/01.06.2018, RP-32/2018 and from IEC IITD Ref No: Ethics Application P-024.

REFERENCES

- ¹Alam, K., E. Hassan, and I. Bahadur. Experimental measurements of temperatures in ultrasonically assisted drilling of cortical bone. *Biotechnol. Biotechnol. Equip.* 29:753–757, 2015.
- ²Alam, K., A. V. Mitrofanov, and V. V. Silberschmidt. Measurements of surface roughness in conventional and ultrasonically assisted bone drilling. *Am. J. Biomed. Sci.* 2009. <https://doi.org/10.5099/aj090400312>.
- ³Alam, K., A. V. Mitrofanov, and V. V. Silberschmidt. Experimental investigations of forces and torque in conventional and ultrasonically-assisted drilling of cortical bone. *Med. Eng. Phys.* 33:234–239, 2011.
- ⁴Augustin, G., S. Davila, K. Mihoci, T. Udiljak, D. S. Vedin, and A. Antabak. Thermal osteonecrosis and bone drilling parameters revisited. *Arch. Orthop. Trauma Surg.* 128:71–77, 2008.
- ⁵Behiri, J. C., and W. Bonfield. Crack growth resistance in cortical bone: concept of microcrack toughening. *J. Biomech.* 30:763–769, 1995.
- ⁶Bertollo, N., H. R. M. Milne, L. P. Ellis, P. C. Stephens, R. M. Gillies, and W. R. Walsh. A comparison of the thermal properties of 2- and 3-fluted drills and the effects on bone cell viability and screw pull-out strength in an ovine model. *Clin. Biomech.* 25:613–617, 2010.
- ⁷Brien, F. J. O., D. Taylor, and T. C. Lee. The effect of bone microstructure on the initiation and growth of microcracks. *J. Orthop. Res.* 23:475–480, 2005.
- ⁸Burr, D. B., C. H. Turner, P. Naick, M. R. Forwood, W. Ambrosius, M. S. Hasan, and R. Pidaparti. Does micro-damage accumulation affect the mechanical properties of bone? *J. Biomech.* 31:337–345, 1998.
- ⁹Chen, L., C. Tai, P. Lai, D. Lee, T. Tsai, T. Fu, C. Niu, and W. Chen. Pullout strength for cannulated pedicle screws with bone cement augmentation in severely osteo-

- porotic bone : influences of radial hole and pilot hole tapping. *Clin. Biomech.* 24:613–618, 2009.
- ¹⁰Gupta, V., and P. M. Pandey. An in-vitro study of cutting force and torque during rotary ultrasonic bone drilling. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* 232:1549–1560, 2018.
- ¹¹Gupta, V., P. M. Pandey, and V. V. Silberschmidt. Rotary ultrasonic bone drilling : improved pullout strength and reduced damage. *Med. Eng. Phys.* 41:1–8, 2017.
- ¹²Gupta, V., R. P. Singh, P. M. Pandey, and R. Gupta. In vitro comparison of conventional surgical and rotary ultrasonic bone drilling techniques. *Proc. Inst. Mech. Eng. Part H J. Eng. Med.* 234:398–411, 2020.
- ¹³Hillery, M. T., and I. Shuaib. Temperature effects in the drilling of human and bovine bone. *J. Mater. Process. Technol.* 92–93:302–308, 1999.
- ¹⁴Hillier, M. L., and L. S. Bell. Differentiating human bone from animal bone: a review of histological methods. *J. Forensic Sci.* 52:249–263, 2007.
- ¹⁵Hou, Y., C. Li, H. Ma, Y. Zhang, M. Yang, and X. Zhang. An experimental research on bone drilling temperature in orthopaedic surgery. *Open Mater. Sci. J.* 9:178–188, 2015.
- ¹⁶Hsu, C., C. Chao, J. Wang, S. Hou, Y. Tsai, and J. Lin. Increase of pullout strength of spinal pedicle screws with conical core: biomechanical tests and finite element analyses. *J. Orthop. Res.* 23:788–794, 2005.
- ¹⁷Kim, Y., W. Choi, and K. Rhyu. Assessment of pedicle screw pullout strength based on various screw designs and bone densities—an ex vivo biomechanical study. *Spine J.* 12:164–168, 2012.
- ¹⁸Li, X., Y. Huang, L. Zheng, H. Liu, X. Niu, J. Huang, F. Zhao, and Y. Fan. Effect of substrate stiffness on the functions of rat bone marrow and adipose tissue derived mesenchymal stem cells in vitro. *J. Biomed. Mater. Res. A* 102A:1092–1101, 2013.
- ¹⁹Li, X., Y. Yang, Y. Fan, Q. Feng, F. Z. Cui, and F. Watari. Biocomposites reinforced by fibers or tubes as scaffolds for tissue engineering or regenerative medicine. *J. Biomed. Mater. Res. Part A* 102:1580–1594, 2014.
- ²⁰Lill, C. A., E. Schneider, J. Goldhahn, A. Haslemann, and F. Zeifang. Mechanical performance of cylindrical and dual core pedicle screws in calf and human vertebrae. *Arch. Orthop. Trauma Surg.* 126:686–694, 2006.
- ²¹MacAvelia, T., M. Salahi, M. Olsen, M. Crookshank, E. H. Schemitsch, A. Ghasempoor, F. Janabi-Sharifi, and R. Zdero. Biomechanical measurements of surgical drilling force and torque in human versus artificial femurs. *J. Biomech. Eng.* 134:124503, 2012.
- ²²Ono, A., M. D. Brown, L. L. Latta, E. L. Milne, and D. C. Holmes. Triangulated pedicle screw construct technique and pull-out strength of conical and cylindrical screws. *J. Spinal Disord.* 14:323–329, 2001.
- ²³Singh, G., V. Jain, and D. Gupta. Comparative study for surface topography of bone drilling using conventional drilling and loose abrasive machining. *Proc. IMechE Part H J. Eng. Med.* 229:225–231, 2015.
- ²⁴Singh, R. P., P. M. Pandey, C. Behera, and A. R. Mridha. Effects of rotary ultrasonic bone drilling on cutting force and temperature in the human bones. *Proc. Inst. Mech. Eng. Part H J. Eng. Med.*, 2020. <https://doi.org/10.1177/0954411919889913>.
- ²⁵Singh, R. P., P. M. Pandey, and A. R. Mridha. An in-vitro study of temperature rise during rotary ultrasonic bone drilling of human bone. *Med. Eng. Phys.* 79:33–43, 2020.
- ²⁶Singh, R. P., P. M. Pandey, A. R. Mridha, and T. Joshi. Experimental investigations and statistical modeling of cutting force and torque in rotary ultrasonic bone drilling of human cadaver bone. *Proc. IMechE Part H J. Eng. Med.* 234:148–162, 2020.
- ²⁷Soriano, J., A. Garay, P. Aristimuño, L. M. Iriarte, J. A. Eguren, and P. J. Arrazola. Effects of rotational speed, feed rate and tool type on temperatures and cutting forces when drilling bovine cortical bone. *Mach. Sci. Technol.* 17:611–636, 2013.
- ²⁸Stefan, U., B. Michael, and S. Werner. Effects of three different preservation methods on the mechanical properties of human and bovine cortical bone. *Bone* 47:1048–1053, 2010.
- ²⁹Tsai, W., P. Chen, T. Lu, S. Wu, S. Shih, and S. Lin. Comparison and prediction of pullout strength of conical and cylindrical pedicle screws within synthetic bone. *BMC Musculoskelet. Disord.* 9:1–9, 2009.
- ³⁰Udiljak, T., D. Ciglar, and S. Skoric. Investigation into bone drilling and thermal bone necrosis. *J. Med. Biomed. Res.* 2:103–112, 2007.
- ³¹Wang, Y., M. Cao, Y. Zhao, G. Zhou, W. Liu, and D. Li. Experimental investigations on microcracks in vibrational and conventional drilling of cortical bone. *J. Nanomater.* 1–5:2013, 2013.
- ³²Yuan, A., W. Wang, Y. Shi, N. Yang, and X. Yuan. Experimental analysis of drilling process in cortical bone. *Med. Eng. Phys.* 36:261–266, 2016.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.