Medical Engineering and Physics 41 (2017) 1–8

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Rotary ultrasonic bone drilling: Improved pullout strength and reduced damage

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ARTICLE INFO

Article history:
Received 27 June 2016
Revised 29 August 2016
Accepted 14 November 2016

Keywords:
Rotary ultrasonic bone drilling
Conventional surgical bone drilling
SEM
Microcracks
Pullout force

ABSTRACT

Bone drilling is one of the most common operations used to repair fractured parts of bones. During a bone drilling process, microcracks are generated on the inner surface of the drilled holes that can detrimentally affect osteosynthesis and healing. This study focuses on the investigation of microcracks and pullout strength of cortical-bone screws in drilled holes. It compares conventional surgical bone drilling (CSBD) with rotary ultrasonic bone drilling (RUBD), a novel approach employing ultrasonic vibration with a diamond-coated hollow tool. Both techniques were used to drill holes in porcine bones in an in-vitro study. Scanning electron microscopy was used to observe microcracks and surface morphology. The results obtained showed a significant decrease in the number and dimensions of microcracks generated on the inner surface of drilled holes with the RUBD process in comparison to CSBD. It was also observed that a higher rotational speed and a lower feed rate resulted in lower damage, i.e. fewer microcracks. Biomechanical axial pullout strength of a cortical bone screw inserted into a hole drilled with RUBD was found to be much higher (55–385%) than that for CSBD.

1. Introduction

Bone fracture is common and can happen as a result of road accidents, falls, sports injuries, etc. In many cases, bone drilling is necessary to insert screws, wires and fixing plates in a surgical procedure, for immobilization and alignment of parts for proper healing.

A Success rate of these surgeries depends on the recovery time of patients, as well as biomechanical pullout strength of inserted screws. The latter is one of the important parameters for screw stabilization [1], since instability of a screw in the bone tissue can occur after a surgical operation [2,3]. Such failures may be due to diminished mechanical resistance of the bond. It was reported that an implant loosening rate was 2–7% [4–6] or even higher [2]. Apparently, pullout strength of the screw depends upon its design and geometry [2,7]. Thus many studies were conducted [2,7–10] to improve this parameter. Bertollo et al. [11] performed a comparative study of pullout strength of a 4.5 mm-diameter screw, inserted into a predrilled hole made with 2- and 3-fluted drill bits with diameter of 3.2 mm. No significant difference was found between pullout strengths for holes drilled with those methods.

Holes predrilled for screws are made with a conventional drilling process. But this process itself generates compressive forces and a torque that could be a cause of microcrack generation in the drilled bone. Tensile and compression force generate different types of microcracks and damage modes in the bone [12–15]. According to previously reported in-vitro investigations [16,17], microcracks were generated on the inner surface of drilled holes after bone drilling. An increase in the level of these microcracks could be the reason for a decrease in the stiffness and elastic modulus of the bone, which may further cause damage to it [18–21]. Some of these microcracks could disappear thanks to remodeling [21–23], but an increase in the length of these microcracks can lead to fracture [16,24]. If a length of microcracks is increased significantly this may be the cause of implant failure. Since the bone-drilling process generates an excessive amount of heat it can cause thermal necrosis.

To meet this challenges, a new drilling scheme – ultrasonically assisted vibrational bone drilling was introduced with the aim to reduce cutting forces and heat generation. In this scheme ultrasonic vibrational pulses are applied to a drill bit. Alam et al. [25] performed experimental study on bovine bone using ultrasonically assisted drilling and found that force and torque

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http://dx.doi.org/10.1016/j.medengphy.2016.11.004

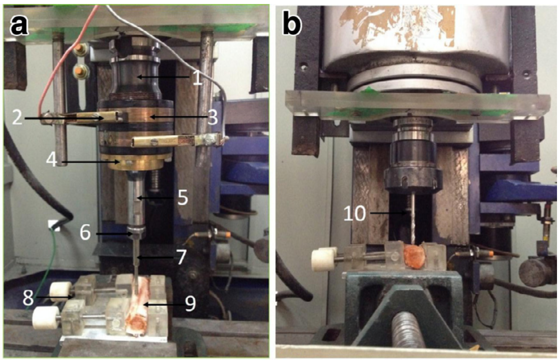

Fig. 1. Experimental setups: (a) RUBD and (b) CSBD 1) CNC collet; 2) carbon brushes; 3) slip rings; 4) collar; 5) horn; 6) nut and collet; 7) hollow tool; 8) holding fixture for bone; 9) bone sample; 10) conventional surgical drill bit.

significantly reduced as compared to the conventional drilling method. They also reported [26,27] that temperature could be reduced with this technique. Wang et al. [28] performed a comparative investigation of temperature changes in bone drilling with vibrational and conventional methods. Their study showed that vibration-assisted drilling generated lower temperature as compared to conventional drilling. In another experimental study, they reported that vibrational bone drilling generated fewer and shorter microcracks [16]. It was also reported that ultrasonically assisted drilling, resulted in a better surface as compared to the normal drilling method [29]. Recently, Singh et al. [17] compared the microcracks generated by ultrasonic bone drilling with abrasive particles and by the conventional method. They reported that the former did not generate any microcracks on the inner surface of the bone. However, using loose abrasive particles in bone drilling may cause infection and the drilling took a long time.

Therefore, in this study, efforts were made to reduce microcracks and increase axial biomechanical pullout strength of the cortical bone screw in a bones drilled with RUBD. The findings were compared with results of the CSBD method used with the same process parameters. A diamond-coated hollow tool was used for RUBD while a conventional orthopaedic surgical drill bit was employed in CSBD. An in-vitro study also showed a link between microcracks generated in the drilled-hole surface and axial pullout strength of the cortical bone screw.

2. Materials and method

2.1. Experimental setup and drilling procedure

In-vitro drilling of bone was conducted using a vertical-axis CNC milling machine. To perform RUBD, a separate ultrasonic-vibration tool assembly was designed and fabricated; it was clamped on a chuck of the CNC machine. This device and a generator (acquired from Unitech Allied Automation, India) operated at a frequency of approximately 20 kHz with a power of 800 W. Electric signals were supplied to the ultrasonic device with designed slip rings and carbon brushes Fig. 1(a). The device was coupled with one end on the housing and the CNC collet attached to the other end. Hollow drill tools of constant wall thickness (0.8 mm) with diamond coating were designed in house and manufactured by the Ajex & Turner Wire Dies Company, India. These tools were attached to the ultrasonic device and the complete assembly was mounted on the CNC machine head Fig. 1(a).

To perform CSBD, the assembly was unclamped from the CNC machine, and a surgical drill bit was used Fig. 1(b). New surgical drill bits were taken from the orthopedic operation theater of Government Hospital Sector 32, Chandigarh, India, provided by *Trimed Systems Pvt. Ltd.* Since bones have complex shapes, for ensuring safe drilling, a special bone-holding fixture was designed and fabricated. Experiments were performed in two sets. In the first set of experiments, microcrack analysis was carried out for the RUBD and CSBD processes while mechanical pullout strength was measured in the second set.

Table 1
Process parameters and their values for in-vitro experiment.

Parameters	Units	Microcracks analysis		Pullout analysis	
		RUBD	CSBD	RUBD	CSBD
Rotational speed	rpm	500–1500–2500		500–1500–2500	
Feed rate	mm/min	10–30–50		10–30–50	
Drill diameter	mm	4.5		4.0	
Vibration amplitude	µm	16	NA	16	NA
Vibration frequency	kHz	20	NA	20	NA

NA: Not applicable.

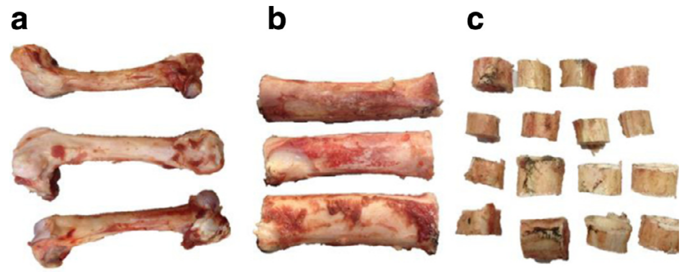

Fig. 2. Porcine bone specimens used for in-vitro study: (a) bones; (b) specimens for pullout strength and (c) specimens for microcrack analysis.

The literature analysis showed that low magnitude of speed and feed rate is preferred in the surgical drilling [30]. The experiments were planned and performed according to the process parameters for both the drilling processes, as listed in Table 1. In this work, no statistical method was used to plan the experiments. Suitable combinations of parameters which show the effect of variable rotational speed with a constant feed rate and variable feed rate with a constant rotational speed were used to study the pullout strength and microcracks. These parameters were chosen on the basis of the literature review conducted [25–27,30,31]. Alam et al. [27] reported that variation in the vibrational amplitude from 4 to 20 µm did not show any significant effect on a process temperature. While in another study [25] it was reported that forces decreased significantly with a change in the amplitude from 5 to 15 µm, and with further increase in the amplitude, no significant change was found in the cutting forces during bone drilling. So the vibrational amplitude of 16 µm and frequency of 20 kHz were chosen for the present study.

2.2. Preparation of bone specimens

In-vitro investigations were performed on fresh middle diaphysis parts of porcine bones taken from a local animal slaughter house Fig. 2(a). The drilling experiments and pullout tests were performed with in two hours. Therefore the effect of dehydration was minimized. No animal was sacrificed or killed for the present in-vitro study; only samples (bone) used in the food industry were taken. Porcine bones were chosen due to their resemblance to human bones [32–35]. Bone samples were prepared separately for analysis of microcracks and assessment of biomechanical pullout strength of cortical bone screws. The latter study was carried out on the middle section of the bone Fig. 2(b), whereas for the microcrack analysis, bone samples were further sliced into small pieces Fig. 2(c).

Duration of a bone-drilling procedure is a crucial factor; for the chosen range of the feed rates, a hole in a bone with wall thickness of 5 mm can be produced within 6–30 s. Experiments were performed on the same bone and two holes drilled with two studied

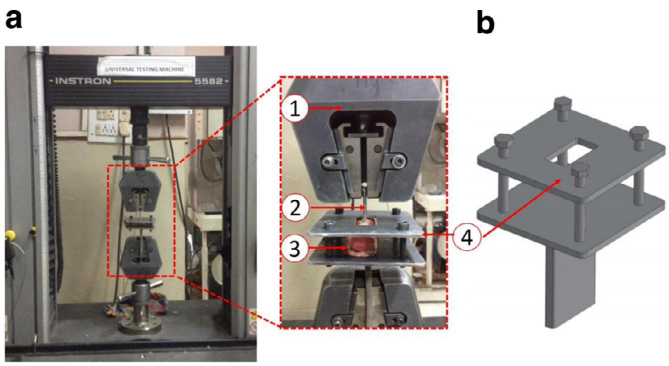

Fig. 3. (a) Testing setup for biomechanical pullout strength and (b) CAD model of bone-holding fixture. 1) grip; 2) cortical bone screw; 3) bone sample; 4) bone holding fixture.

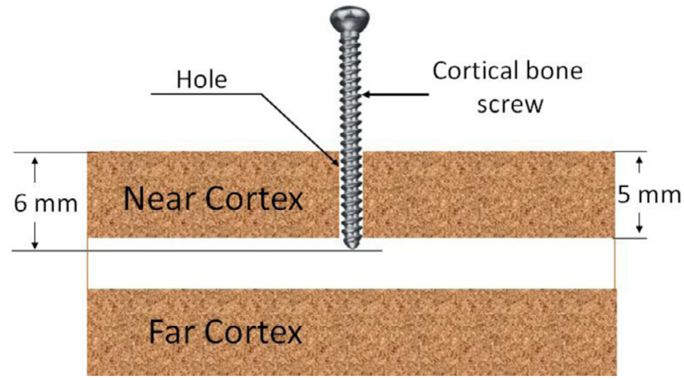

Fig. 4. Schematic diagram of screw inserted into bone.

drilling techniques were approximately 30–40 mm apart in order to, on the one hand, avoid interaction of holes and, on the other hand, to allow maximal comparability of the obtained results.

2.3. Analysis of microcracks and hole quality

Drilled samples were examined for microcracks and surface morphology using a scanning electron microscope (Zeiss EVO 50 & EVO 18 Special) with magnification of 500X. A stereo zoom microscope (Discovery V20) was employed to observe the quality of drilled holes.

2.4. Measurement of biomechanical pullout strength

Axial pullout strength of cortical screws inserted in the bone was determined with INSTRON-5582, a single-action universal testing machine with a modified setup (Fig. 3). Cortical screws were pulled out from the bone sample with a crosshead speed of 0.5 mm/min. To accommodate middle diaphyses of bone samples with different shapes, a special bone-holding fixture was designed and fabricated Fig 3(b).

A series of experiments were executed to assess the biomechanical pullout strength. In total 20 experiments were performed, 10 for holes drilled with each analyzed drilling process (RUBD and CSBD). Drilled holes were made in the bone samples using a drill diameter of 4.0 mm with both processes, and cortical bone stainless steel screws with diameter of 4.5 mm (length 50 mm, head diameter 8 mm and pitch 1.7 mm) were inserted into the drilled holes. New cortical bone screws were used every time to insert in the drilled bone sample for comparability of results. Thickness of bone samples was approx. 5.0 mm in the pullout study; screws were inserted in the drilled hole at a depth of approx. 6 mm (Fig. 4).

3. Results

3.1. Microcrack analysis

In the first set of experiments, effects of rotational speed of the tool and the feed rate on formation of microcracks in the drilled bone were investigated for both processes. The experiments were performed according to a run order listed in Table 2; the drill diameter (4.5 mm) was kept constant. In order to investigate microcracks generated on the inner surface of the bone, specimens drilled with different operations and techniques were observed with SEM. The effects of rotational speed and feed rate on microcrack generation are shown in typical microscopic images for the two drilling methods in Figs. 5 and 6, respectively. Microcracks generated by the two processes are marked with red. No microcracks were found in RUBD for drilling speeds of 500 rpm to 2500 rpm at feed rate of 10 mm/min Fig. 5(a,c,e), while in case of CSBD they were generated in all conditions. An increase in the rotational speed resulted in a decrease in the width and number of microcracks Fig. 5(b,d,f).

The study of the effect of feed rate on the generation of microcracks by the two bone drilling process demonstrated that for both processes the length and number of microcracks increased with the feed rate increasing from 10 mm/min to 50 mm/min. Fewer and shorter microcracks were observed for RUBD as compared to holes drilled with CSBD.

3.2. Pullout strength

In the second set of experiments, effects of tool rotational speed and feed rate on the axial pullout strength were studied for cortical bone screws. The experiments were performed by varying the rotational speed and the feed rate while other process parameters were kept constant (Table 3). For each process, two experiments were performed for each rotational speed, and feed rate and the maximum pullout force was measured. For the final results, the average of the two trials was taken into account.

Typical force – displacement diagrams obtained in these tests are given in Fig. 7; they show a change in bone resistance to pullout with respect to time. The data demonstrates that axial pullout strength of cortical bone drilled with RUBD is higher than that of CSBD. Comparison of the two drilling techniques demonstrates that the axial pullout strength of a cortical bone screw grew with the increased rotational speed Fig. 8(a) and decreased with the increased feed rate Fig. 8(b) for both methods. Moreover, pullout strengths of cortical bone screws inserted in the RUBD drilled holes are consistently higher – from 55% to 385% – than for CSBD.

It was observed that the axial pullout of the cortical bone screw from the drilled hole caused delamination near the hole in the RUBD method Fig. 9(a); however, no such delamination was observed for the CSBD method Fig. 9(b). This also confirms that significantly higher forces were required to pullout the screw from the hole drilled with RUBD.

4. Discussion

In this work, two drilling methods - an existing (CSBD) method used in the orthopaedic operation theaters and a newly proposed (RUBD) were compared in terms of microcracks generated on the inner surface of drilled holes and a biomechanical pullout force for the cortical bone screw. According to the best knowledge of the authors, no study has been reported on analysis of the effects of rotational speed and feed rate on these two features. Measurement of the axial biomechanical pullout strength is an adequate way to evaluate the stability of screws inserted in the bone [1,7,36].

Table 2
Run order and process parameters in experiments for microcracks analysis.

Drilling method	Run order	Rotational speed (rpm)	Feed rate (mm/min)	Drill diameter (mm)	Vibration amplitude (μm)	Vibration frequency (kHz)
	1	500	10	4.5		
	2	1500	10	4.5		
RUBD	3	2500	10	4.5	16	20
	4	500	30	4.5		
	5	500	50	4.5		
	6	500	10	4.5		
	7	1500	10	4.5		
CSBD	8	2500	10	4.5	NA	NA
	9	500	30	4.5		
	10	500	50	4.5		

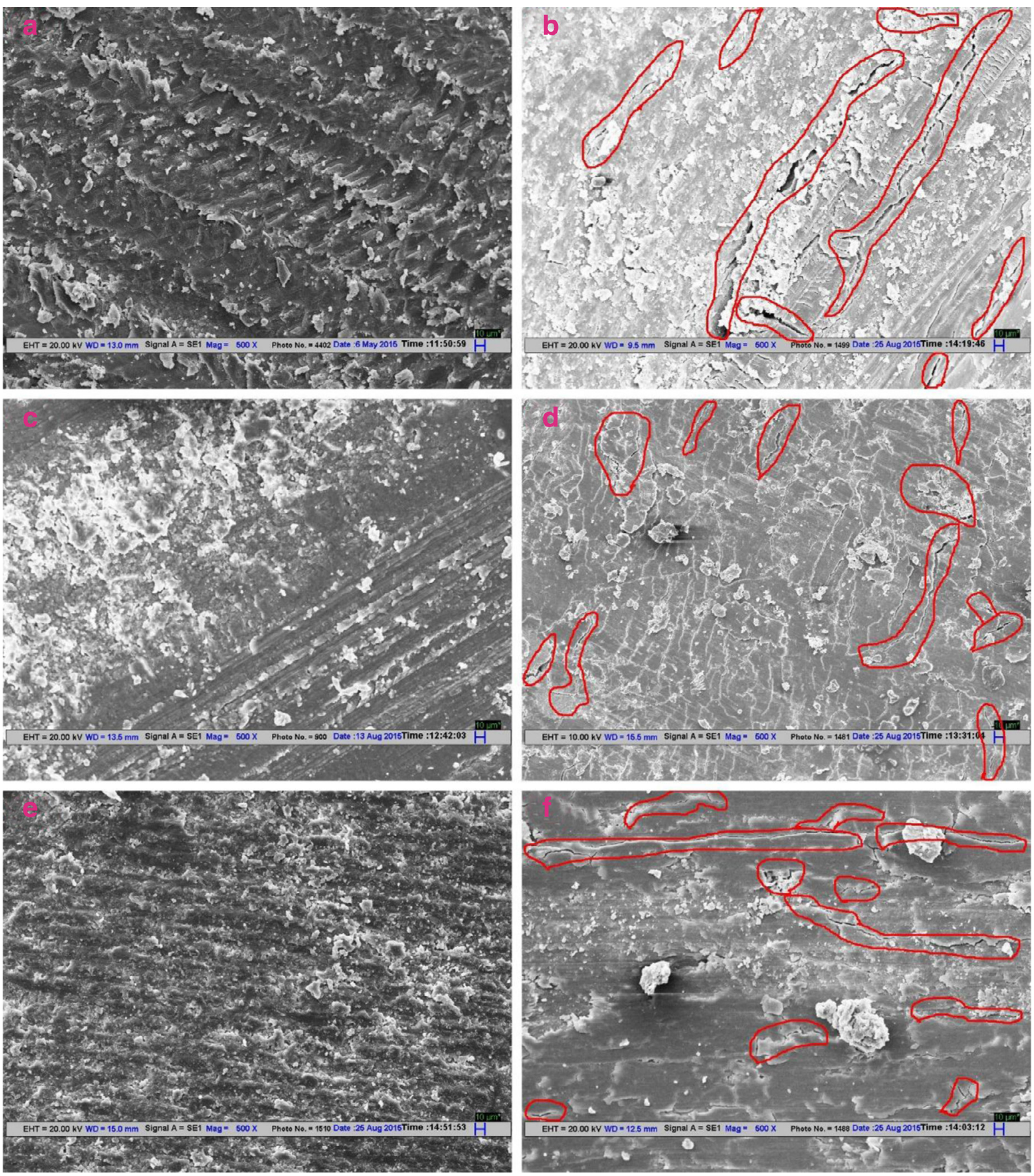

Fig. 5. Effect of rotational speed on microcracks generation: (a), (c), (e) RUBD; (b), (d), (f) CSBD group. (a), (b) 500 rpm; (c), (d) 1500 rpm; (e), (f) 2500 rpm (feed rate 10 mm/min; drill diameter 4.5 mm; for RUBD: vibration amplitude 16 μm; frequency 20 kHz).

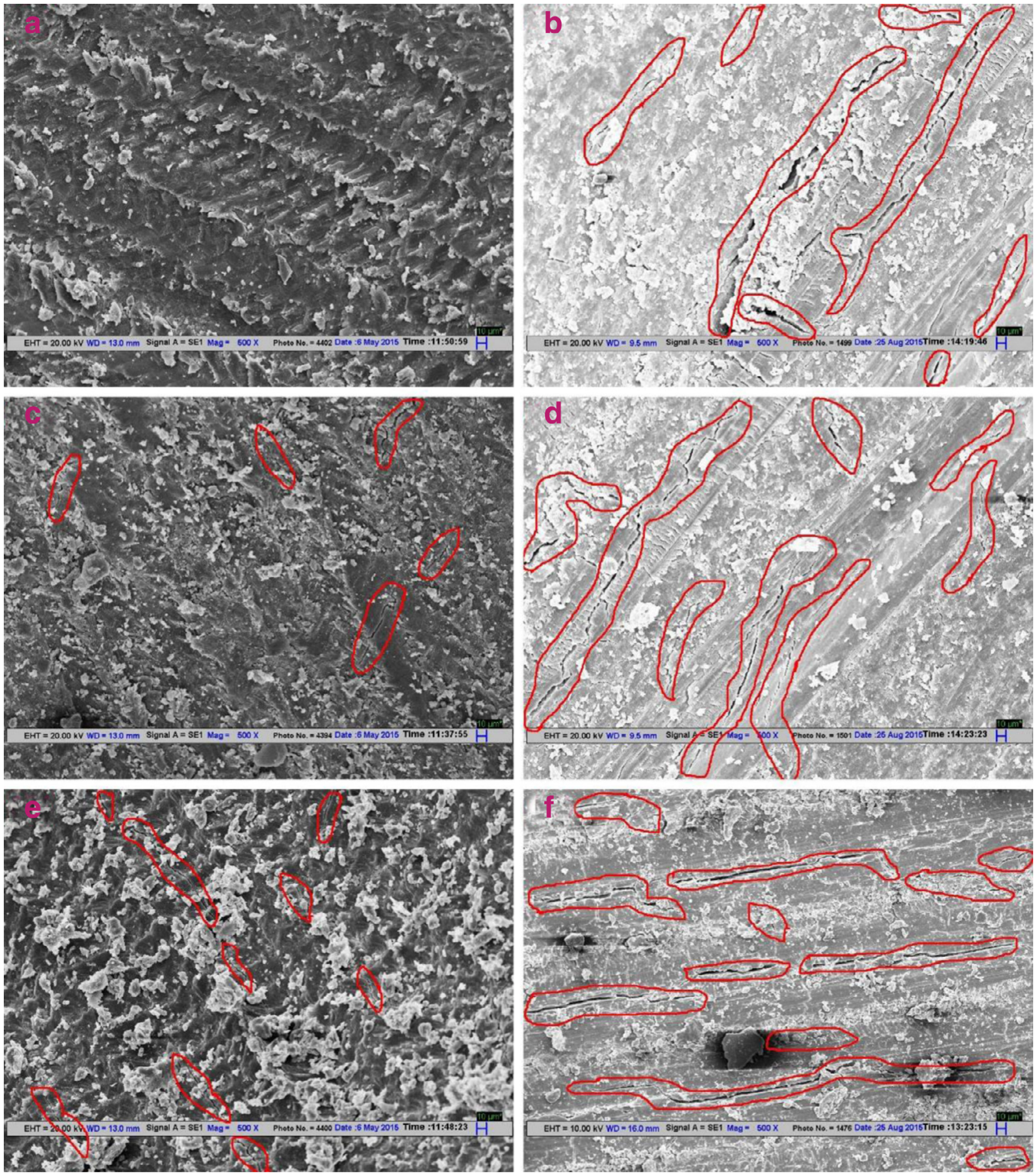

Fig. 6. Effect of feed rate on microcracks generation. (a), (c), (e) RUBD; (b), (d), (f) CSBD. (a), (b) 10 mm/min; (c), (d) 30 mm/min; (e), (f) 10 mm/min. (rotational speed 500 rpm; drill diameter 4.5 mm; for RUBD: vibration amplitude 16 µm; frequency 20 kHz).

Most of the pullout-strength studies for the bone screws were performed with the perpendicular pullout method [2,7–10,37–42], which was also used in this study.

The obtained experimental in-vitro results showed that the length and width of the generated microcracks decreased with the increase in the rotational speed (Fig. 5) and feed rate (Fig. 6). Previously reported investigations of the conventional bone-drilling technique demonstrated that the magnitude of cutting force and torque dropped significantly with an increase in the rotational speed [25,31,43,44] and increased with an increase in the feed rate [25,31,44]. The ultrasonically assisted bone drilling also showed similar trends [25,45]. The hypothesis was that with the increase in the cutting force and torque, more microcracks were caused. O'Brien et al. [18] investigated the effect of microcracks generated on the compact bone of bovine tibiae. They reported that microcracks with length up to 100 µm could be repaired and controlled by using a cement line, while cracks with the lengths between 100 and 150 µm continued to grow even with a cement line close to an osteons. Furthermore, it was concluded that if the length of the microcracks was equal to, or greater than, 300 µm, they could cause bone failure.

The maximum length of microcracks generated by the two drilling processes with respect to each rotational speed [Fig. 5] and feed rate [Fig. 6] was measured with the medical image analysis software Digimizer. Table 4 shows that the maximum length of microcracks generated by CSBD process exceeded 300 µm (except in one case shown in Fig. 5(d)), whereas no microcracks were observed in the bone drilled with RUBD refer Fig. 5(a), (c) and (e). Only Fig. 6(c) and (e) show some microcracks with lengths of 87.6 and 122.2 µm, which were present at higher feed rates of 30 and 50 mm/min, respectively.

For the biomechanical pullout test, two trials were performed for the same combination of processing conditions. Since the drilling experiments were conducted on the CNC machine and the

Table 3
Run order and process parameters in experiments for biomechanical pullout.

Drilling method	Run order	Rotational speed (rpm)	Feed rate (mm/min)	Drill diameter (mm)	Vibration amplitude (μm)	Vibration frequency (kHz)
RUBD	1,2	500	10	4.0	16	20
	3,4	1500	10			
	5,6	2500	10			
	7,8	500	30			
	9,10	500	50			
CSBD	11,12	500	10	4.0	NA	NA
	13,14	1500	10			
	15,16	2500	10			
	17,18	500	30			
	19,20	500	50			

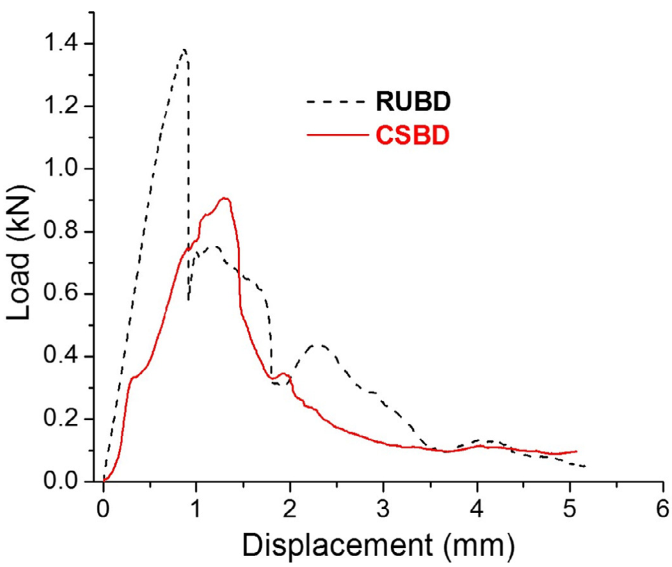

Fig. 7. Force–displacement diagram for axial pullout of cortical bone screw (rotational speed 1500 rpm; feed rate 10 mm/min, drill diameter = 4.0 mm, for RUBD: vibration amplitude 16 μm; frequency 20 kHz).

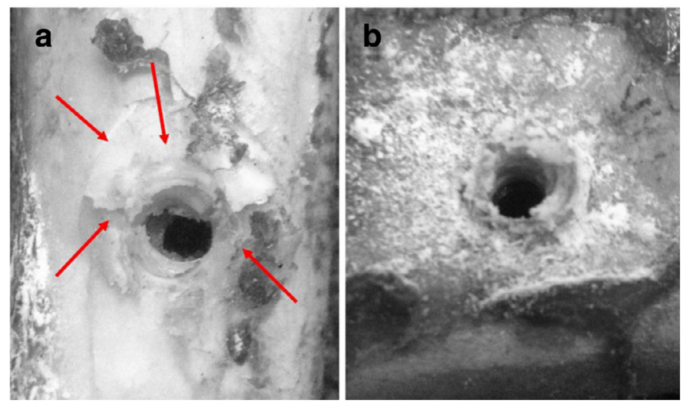

Fig. 9. Specimen after axial pullout: (a) RUBD hole (arrows shows delamination area); (b) CSBD hole (rotational speed 1500 rpm; feed rate 10 mm/min; drill diameter 4.0 mm; for RUBD: vibration amplitude 16 μm; frequency 20 kHz).

designed RUBD tool could drill without cracks providing high surface quality with very good circular profile, the measured force data demonstrate low variability. The axial biomechanical pullout strength for the cortical-bone screw increased with an increase in the rotational speed and decreased with an increase in the feed rate (Fig. 8). The error bars in Fig. 8 represent the maximum and minimum values of the measured pullout force. This shows that the grip of the inserted cortical bone screw is higher when there are fewer microcracks on the inner surface of drilled holes. As discussed, the proposed RUBD process demonstrated fewer and shorter microcracks on the inner surface of the drilled holes. As a result, the axial pullout strength in this case is much higher as compared to that of the existing bone-drilling method (CSBD). The reason for this is a lower cutting force and torque generated in RUBD similar to the previous studies reporting lower cutting forces and torques generated by ultrasonically assisted bone drilling [25]. In RUBD, the cutting mechanism is different, resulting in a cylindrical machined rod and powdered chips obtained in the drilling due to the hollow profile of the tool Fig. 10(a), whereas fragmented chips were formed in CSBD Fig. 10(b).

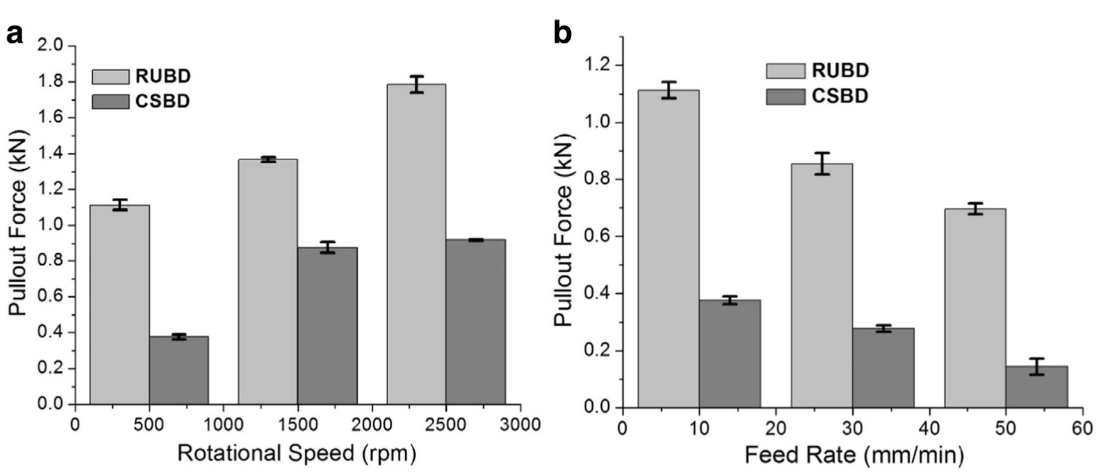

Fig. 8. Effects of rotational speed (a) and feed rate (b) on axial pullout force for two bone-drilling methods.

Table 4
Maximum length of microcracks (in µm) from SEM images corresponding to two drilling processes.

Rotational speed (rpm)	Feed rate (mm/min)	RUBD	CSBD
500	10	No cracks Fig. 5(a)	350.0 µm Fig. 5(b)
1500	10	No cracks Fig. 5(c)	241.9 µm Fig. 5(d)
2500	10	No cracks Fig. 5(e)	328.6 µm Fig. 5(f)
500	30	87.6 µm Fig. 6(c)	375.8 µm Fig. 6(d)
500	50	122.2 µm Fig. 6(e)	422.3 µm Fig. 6(f)

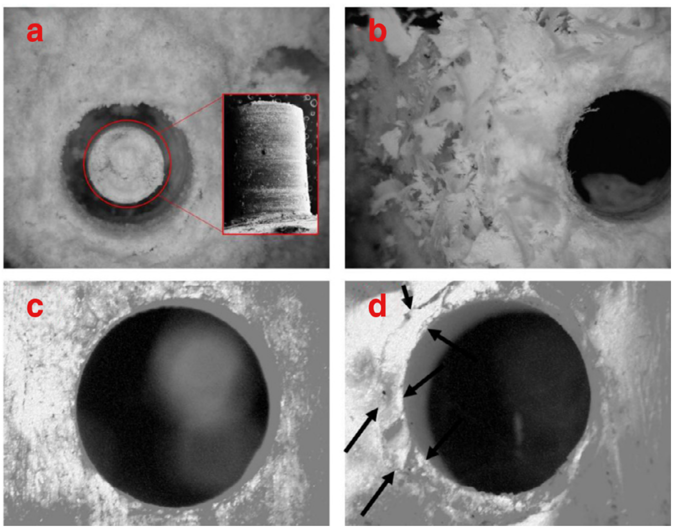

Fig. 10. (a) Drilling of bone with RUBD produced powdered chips and cylindrical machined rod. (b) CSBD produced fragmented chips. Edge quality of holes drilled with RUBD (c) and CSBD (d) (black arrows show delamination near drilled hole edge) (rotational speed 500 rpm; feed rate 10 mm/min; drill diameter 4.5 mm; for RUBD: vibration amplitude 16 µm; frequency 20 kHz).

The hollow tool in the RUBD process generates lower cutting forces and torque ensuring better edge quality produced as compared to that in CSBD. As a result no delamination was observed in the area surrounding the holes drilled with RUBD Fig. 10(c). However, the use of the CSBD method led to poor hole-edge quality resulting in visible signs of delamination around it Fig. 10(d).

5. Conclusion

The findings obtained in the in-vitro test confirmed that RUBD could be a better alternative to conventional bone-drilling techniques. RUBD generated less damage, i.e. fewer and shorter microcracks and, as a result, significantly higher forces are needed to pull the screw out from the drilled hole, providing higher stability for implants and screws inserted in the bone. The obtained results also showed that the increase in the length of microcracks led to decrease in the strength of the bone screw bond; hence, there is a strong correlation between the microcracks and the pullout strength of the bone screw.

Conflicts of interest

None.

Funding

This study is financially funded and supported by the EPSRC-DST project "Modelling of Advanced Materials for Simulation of Transformative Manufacturing Process (MAST)".

Ethical approval

Not required.

Acknowledgments

Authors are thankful to Professor Ravi K. Gupta, Department of Orthopaedics, Government Medical College Hospital Chandigarh Sec. 32B, India, for his valuable suggestions.

References

[1] Ono A, Brown MD, Latta LL, Milne EL, Holmes DC. Triangulated pedicle screw construct technique and pull-out strength of conical and cylindrical screws. J Spinal Disord Tech 2001;14:323–9.
[2] Hsu CC, Chao CK, Wang JL, Hou SM, Tsai YT, Lin J. Increase of pullout strength of spinal pedicle screws with conical core: biomechanical tests and finite element analyses. J Orthop Res 2005;23:788–94. doi:10.1016/j.orthres.2004.11.002.
[3] Lill CA, Schneider E, Goldhahn J, Haslemann A, Zeifang F. Mechanical performance of cylindrical and dual core pedicle screws in calf and human vertebrae. Arch Orthop Trauma Surg 2006;126:686–94. doi:10.1007/s00402-006-0186-6.
[4] K L, Ceder L, Thorngren K-G, Skytting B, Tidermark J, Berntson P-O, et al. Extramedullary fixation of 569 unstable intertrochanteric fractures: a randomized multicenter trial of the Medoff sliding plate versus three other screw-plate systems. Acta Orthop 2001;72:133–40. doi:10.1080/000164701317323372.
[5] Wachtl SW, Gautier E, Jakob RP. Low reoperation rate with the Medoff sliding plate: 1 technical failure in 63 trochanteric hip fractures. Acta Orthop 2001;72:141–5. doi:10.1080/000164701317323381.
[6] Ogbemudia AO, Umebese PFA. Implant failure in osteosynthesis of fractures of long bones. J Biomed Sci 2006;5:75–8.
[7] Kim YY, Choi WS, Rhyu KW. Assessment of pedicle screw pullout strength based on various screw designs and bone densities – an ex vivo biomechanical study. Spine J 2012;12:164–8. doi:10.1016/j.spinee.2012.01.014.
[8] Esenkaya I, Denizhan Y, Kaygusuz MA, Yetmez M, Keleştemur MH. Comparison of the pull-out strengths of three different screws in pedicular screw revisions: a biomechanical study. Acta Orthop Traumatol Turc 2006;40:72–81.
[9] Chen L-H, Tai C-L, Lai P-L, Lee D-M, Tsai T-T, Fu T-S, et al. Pullout strength for cannulated pedicle screws with bone cement augmentation in severely osteoporotic bone: Influences of radial hole and pilot hole tapping. Clin Biomech 2009;24:613–18. doi:10.1016/j.clinbiomech.2009.05.002.
[10] Tsai W-C, Chen P-Q, Lu T-W, Wu S-S, Shih K-S, Lin S-C. Comparison and prediction of pullout strength of conical and cylindrical pedicle screws within synthetic bone. BMC. Musculoskelet Disord 2009;10:44. doi:10.1186/1471-2474-10-44.
[11] Bertollo N, Milne HRM, Ellis LP, Stephens PC, Gillies RM, Walsh WR. 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 2010;25:613–17. doi:10.1016/j.clinbiomech.2010.02.007.
[12] Carter DR, Caler WE, Spengler DM, Frankel VH. Fatigue behavior of adult cortical bone: the influence of mean strain and strain range. Acta Orthop Scand 1981;52:481–90. doi:10.3109/17453678108992136.
[13] Vashishth D, Behiri JC, Bonfield W. Crack growth resistance in cortical bone: concept of microcrack toughening. J Biomech 1997;30:763–9. doi:10.1016/S0021-9290(97)00029-8.
[14] Burr DB, Turner CH, Naick P, Forwood MR, Ambrosius W, Sayeed Hasan M, et al. Does microdamage accumulation affect the mechanical properties of bone. J Biomech 1998;31:337–45. doi:10.1016/S0021-9290(98)00016-5.
[15] Barak MM, Currey JD, Weiner S, Shahar R. Are tensile and compressive Young's moduli of compact bone different. J Mech Behav Biomed Mater 2009;2:51–60. doi:10.1016/j.jmbbm.2008.03.004.
[16] Wang Y, Cao M, Zhao Y, Zhou G, Liu W, Li D. Experimental investigations on microcracks in vibrational and conventional drilling of cortical bone. J Nanomater 2013;2013:6.
[17] Singh G, Jain V, Gupta D. Comparative study for surface topography of bone drilling using conventional drilling and loose abrasive machining. Proc Inst Mech Eng Part H J Eng Med 2015;229:225–31. doi:10.1177/0954411915576945.
[18] Brien FJO, Taylor D, Lee TC. The effect of bone microstructure on the initiation and growth of microcracks. J Orthop Res 2005;23:475–80.
[19] Taylor D, Kuiper JH. The prediction of stress fractures using a "stressed volume" concept. J Orthop Res 2001;19:919–26. doi:10.1016/S0736-0266(01)00009-2.
[20] Li X, Yang Y, Fan Y, Feng Q, Cui FZ, Watari F. Biocomposites reinforced by fibers or tubes as scaffolds for tissue engineering or regenerative medicine. J Biomed Mater Res – Part A 2014;102:1580–94. doi:10.1002/jbm.a.34801.
[21] Li X, Huang Y, Zheng L, Liu H, Niu X, Huang J, et al. Effect of substrate stiffness on the functions of rat bone marrow and adipose tissue derived mesenchymal stem cells in vitro. J Biomed Mater Res – Part A 2014;102:1092–101. doi:10.1002/jbm.a.34774.
[22] Li X, Wang L, Fan Y, Feng Q, Cui FZ, Watari F. Nanostructured scaffolds for bone tissue engineering. J Biomed Mater Res – Part A 2013;101:2424–35. doi:10.1002/jbm.a.34539.

[23] Li X, Gao H, Uo M, Sato Y, Akasaka T, Feng Q, et al. Effect of carbon nanotubes on cellular functions in vitro. J Biomed Mater Res – Part A 2009;91:132–9. doi:10.1002/jbm.a.32203.

[24] Taylor D, O'Brien F, Prina-Mello A, Ryan C, O'Reilly P, Lee TC. Compression data on bovine bone confirms that a "stressed volume" principle explains the variability of fatigue strength results. J Biomech 1999;32:1199–203. doi:10.1016/S0021-9290(99)00112-8.

[25] Alam K, Mitrofanov AV, Silberschmidt VV. Experimental investigations of forces and torque in conventional and ultrasonically-assisted drilling of cortical bone. Med Eng Phys 2011;33:234–9. doi:10.1016/j.medengphy.2010.10.003.

[26] Alam K, Silberschmidt VV. Analysis of temperature in conventional and ultrasonically-assisted drilling of cortical bone with infrared thermography. Technol Heal Care 2014;22:243–52.

[27] Alam K, Hassan E, Bahadur I. Experimental measurements of temperatures in ultrasonically assisted drilling of cortical bone. Biotechnol Biotechnol Equip 2015;29:753–7. doi:10.1080/13102818.2015.1034176.

[28] Wang Y, Cao M, Zhao X, Zhu G, McClean C, Zhao Y, et al. Experimental investigations and finite element simulation of cutting heat in vibrational and conventional drilling of cortical bone. Med Eng Phys 2014;36:1408–15. doi:10.1016/j.medengphy.2014.04.007.

[29] Alam K, Mitrofanov AV, Silberschmidt VV. Measurements of surface roughness in conventional and ultrasonically assisted bone drilling. Am J Biomed Sci 2009:312–20. doi:10.5099/aj090400312.

[30] Augustin G, Zigman T, Davila S, Udilljak T, Staroveski T, Brezak D, et al. Cortical bone drilling and thermal osteonecrosis. Clin Biomech 2012;27:313–25. doi:10.1016/j.clinbiomech.2011.10.010.

[31] Wang W, Shi Y, Yang N, Yuan X. Experimental analysis of drilling process in cortical bone. Med Eng Phys 2014;36:261–6. doi:10.1016/j.medengphy.2013.08.006.

[32] Miller ER, Ullrey DE. The pig as a model for human nutrition. Annu Rev Nutr 1987;7:361–82.

[33] Aerssens J, Boonen S, Lowet G, Dequeker J. Interspecies differences in bone composition, density, and quality: potential implications for in vivo bone research. Endocrinology 1998;139:663–70. doi:10.1210/en.139.2.663.

[34] Tanck E, Homminga J, Van Lenthe GH, Huiskes R. Increase in bone volume fraction precedes architectural adaptation in growing bone. Bone 2001;28:650–4. doi:10.1016/S8756-3282(01)00464-1.

[35] Teo JCM, Si-Hoe KM, Keh JEL, Teoh SH. Relationship between CT intensity, micro-architecture and mechanical properties of porcine vertebral cancellous bone. Clin Biomech 2006;21:235–44. doi:10.1016/j.clinbiomech.2005.11.001.

[36] Abshire BB, McLain RF, Valdevit A, Kambic HE. Characteristics of pullout failure in conical and cylindrical pedicle screws after full insertion and back-out. Spine J 2001;1:408–14. doi:10.1016/S1529-9430(01)00119-X.

[37] Subramanian KN, Temple AJ, Evans S, John A. Pull-Out strength of a polished tapered stem is improved by placing bone cement over the shoulder of the implant. J Arthroplast 2009;24:139–43. doi:10.1016/j.arth.2008.05.029.

[38] Zhang Y, Tian L, Yan Y, Sang H, Ma Z, Jie Q, et al. Biomechanical evaluation of the expansive cannulated screw for fixation of femoral neck fractures. Injury 2011;42:1372–6. doi:10.1016/j.injury.2011.07.004.

[39] Erhart S, Schmoelz W, Blauth M, Lenich a. Biomechanical effect of bone cement augmentation on rotational stability and pull-out strength of the Proximal Femur Nail Antirotation^{TM}. Injury 2011;42:1322–7. doi:10.1016/j.injury.2011.04.010.

[40] Brasiliense LBC, Lazaro BCR, Reyes PM, Newcomb AGUS, Turner JL, Crandall DG, et al. Characteristics of immediate and fatigue strength of a dual-threaded pedicle screw in cadaveric spines. Spine J 2013;13:947–56. doi:10.1016/j.spinee.2013.03.010.

[41] Zhang QH, Tan SH, Chou SM. Effects of bone materials on the screw pullout strength in human spine. Med Eng Phys 2006;28:795–801. doi:10.1016/j.medengphy.2005.11.009.

[42] Costa F, Ortolina A, Galbusera F, Cardia A, Sala G, Ronchi F, et al. Pedicle screw cement augmentation. A mechanical pullout study on different cement augmentation techniques. Med Eng Phys 2016;38:181–6. doi:10.1016/j.medengphy.2015.11.020.

[43] MacAvelia T, Salahi M, Olsen M, Crookshank M, Schemitsch EH, Ghasempoor A, et al. Biomechanical measurements of surgical drilling force and torque in human versus artificial femurs. J Biomech Eng 2012;134:124503. doi:10.1115/1.4007953.

[44] Lughmani W, Bouazza-Marouf K, Ashcroft I. Drilling in cortical bone: a finite element model and experimental investigations. J Mech Behav Biomed Mater 2015;42:32–42. doi:10.1016/j.jmbbm.2014.10.017.

[45] Alam K, Ahmed N, Silberschmidt VV. Comparative study of conventional and ultrasonically-assisted bone drilling. Technol Heal Care 2014;22:253–62.