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Research article

The effects of multiple drilling of a bone with the same drill bit: thermal and force analysis

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ABSTRACT

Repeated use of the same drill bit during drilling wears off the cutting edges, which can lead to a significant increase in heat as a result of friction, which is harmful to a bone above 55 °C. Few previous studies have examined the effects of using the same drill bit several times, on temperature. The objective of this study was to determine the effect of each drilling on temperature and force. 72 trials were performed. A total of 24 stainless steel drill bits of ∅3.2 mm were used to drill bovine bone samples. Each drill bit was used at least 3 times. T thermocouples were used to measure temperatures during each drilling test. Possible correlations of cutting parameters were studied. Tests were performed on a test rig measuring forces and temperatures during drilling. Effects of spindle speed (N), feed rate (V_f), and several trials (E) on temperature and forces were measured. Images of the drill bits were analyzed by digital microscopy before and after the drilling series for signs of wear. Temperatures increased significantly from E_1 to E_3. They decreased moderately with V_f. The best cutting conditions were at N = 200 rpm for V_f = 60 mm/min and N = 100 rpm for V_f = 30 mm/min drilling. At N > 200 rpm, they were very high. Temperature rise is significantly related to number of drilling (E), spindle speed (N), and inversely to feed rate (V_f). Analysis of images by digital microscopy confirmed drill bits wearing off, following the number of trials.

1. Introduction

Bone drilling consists in perforating a bone with a drill bit using a manual or motorized drill. It is the most common and most discussed procedure in literature (Pandey and Panda, 2013; Singh et al., 2020). It is used in several surgical techniques, including arthroplasty, locked nailing, screw plate osteosynthesis, external fixation (Lee et al., 2018) During drilling, temperature rise due to friction of drill bit on bone is common and depends on several factors such as bone strength, drilling depth and cutting parameters (Alam et al., 2011; Augustin et al., 2012; Singh et al., 2015).

Necrosis due to abnormal increase in bone temperature has been reported (Augustin et al., 2012; Timon and Keady, 2019; Tsiagadigui et al., 2013). Eriksson and Albrektsson, applied implants heated to 50 °C to rabbit tibias for one minute and noted progressive bone resorption of about 30%. Temperatures between 47 and 50 °C caused significant decrease in callus volume around implant (Eriksson and Albrektsson, 1983, 1984). Other studies have confirmed that an abnormal rise in bone temperature is likely to cause irreversible cell necrosis after exposure to 43 °C for one hour, 47 °C for one minute (Augustin et al., 2012; Tahmasbi et al., 2017), 55 °C for 30 s (Berman et al., 1984; Pandey and Panda, 2013). Osteosynthesis failures and implant loosening due to bone resorption have been reported (Dolan et al., 2012; Singh et al., 2015). Salimov et al. found that repeated use of same drill bit had a detrimental effect on osseointegration and consequently led to failure of the implanted system (Salimov et al., 2020).

The main factors contributing to high temperature in bone drilling are axial thrust force, drill bit diameter, drilling speed, and drill bit edge roughness (Augustin et al., 2012). Repeated use of same tool leads to wear of the cutting edges, requiring higher forces to achieve same results (Mediouni et al., 2019). It has been shown that a used drill bit can induce more heat in the bone, high magnitude of drilling forces and significant

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drilling depth difference compared to new drill bits (Alajmo et al., 2012; Bertollo and Walsh, 2011; Koo et al., 2015; Oliveira et al., 2012; Staroveski et al., 2015). Allan et al. found that temperature rise was 7.5 °C for a new drill bit, 13.4 °C for a drill bit that had completed about 600 holes, and 25.4 °C for a drill bit that had been used for several months (Allan et al., 2005).

Jochum and Reichart also found that drills used more than 40 times led to significant increase in temperature (Jochum and Reichart, 2000). Influence of deviant high forces during bone drilling has been studied. They can provoke a break in drill bit, the fragment of which is very difficult to remove, and which prevents the placement of implants. Microcracks can be generated from the bone surface. If they propagate, they may converge and develop into macroscopic cracks. Unusual high temperatures have also been observed (Augustin et al., 2008; Bassi et al., 2008; Jantunen, 2002; Kasiri et al., 2010; Lee et al., 2011; Staroveski et al., 2015). From the above, force control is essential to ensure good drilling.

Due to economic constraints, surgeons empirically use the same drill several time, and the number of times a drill is used is generally not specified in the operating room. Besides in low-income countries where technology is limited, it is not easy to renew tools in the operating room. This is why it would be important to set out a limit for the reuse of the same drill.

The studies cited above, even though relevant, did not analyze variation in temperature and force by repeated use of the same drill and do not recommend a specific number of times for reuse of the same drill, and do not set out parameters for drilling. In addition, bit wear imaging by digital microscopy is poorly documented in orthopaedic literature.

In the present study, the effect of the number of drillings on temperature was investigated. The aim was to determine under which cutting conditions the same drill bit can be reused without inducing a rise in temperature and forces, which is harmful to the bone. As specific objectives, the study aimed at: measuring the temperature in the bone while it is close to the drill bit during each drilling attempt; calculate the average temperature increase on the basis of the number of attempts; identifying under which conditions the measured temperatures remain below 55 °C; and determining whether there is a correlation between the drilling parameters when reusing the same drill bit several times.

2. Materials and methods

2.1. Preparation of bone samples

One-year-old bovine tibiae were obtained from butchers, mechanically de-periosted, and preserved in 9:1000 saline for three days, at 10 °C. Cortical bone samples of 40 × 50 mm cross-section were considered, whose thickness varied between 5 and 9 mm ± 0.02.

Using AutoCAD® drawing software, a hollow circle of 3.2mm was drawn on a label, corresponding to the diameter of the drill bit. At 0.5mm from this first circle, a 0.5mm indentation corresponding to the diameter of the thermocouple was drawn. The label was affixed to the outer surface of each bone sample. A 2mm deep hole was drilled at each of the 0.5mm points using a 0.5mm high-speed steel twist drill (HSS) (Figure 1). Tests were performed on fresh cortical bones, but without additional irrigation.

2.2. Measurement of bone sample hardness

To ensure homogeneity of mechanical characteristics of the bone sample surface, the hardness was determined using a mobile « Leeb Hardness Tester ®» on 15 × 15 × 5 mm specimens, for each bone sample. Leeb Hardness is a dynamic rebound test procedure. The hardness value of the test sample is determined by measuring the velocity of a moving impact body before and after impact. The ratio of impact velocity to rebound velocity provides the dynamic Leeb hardness of the test specimen. The impact velocity commonly used varies between 1.4 and 3.0 m/s depending on the method. The moving impact body is a ball-shaped indenter, made of tungsten carbide cobalt, ceramic, or diamond. They are of different forces and shapes.

Values were obtained from an average of five tests.

2.3. Measurement of temperature and force

Temperatures and forces were measured on a test bench (Figure 2). The test bench consisted of the following elements:

- a STONIC-35® CNC milling machine with 1/1000mm precision and SIEMENS 802D control director;
- two 0.5mm T-type thermocouples (T1 and T2) MESUREX®;
- a PICO TECHNOLOGY TC-08® data acquisition device

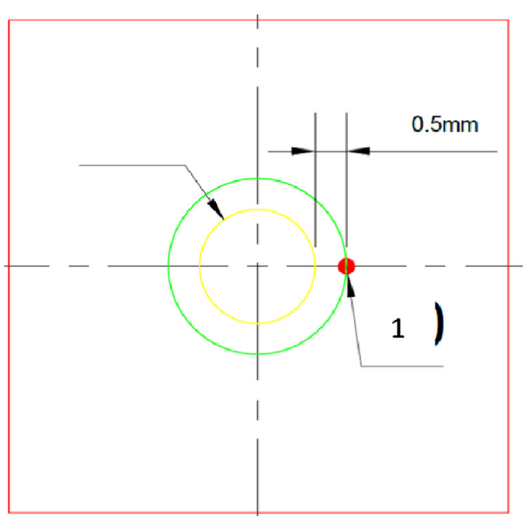

Figure 1. Drilling template. a: scheme. b: bone template.

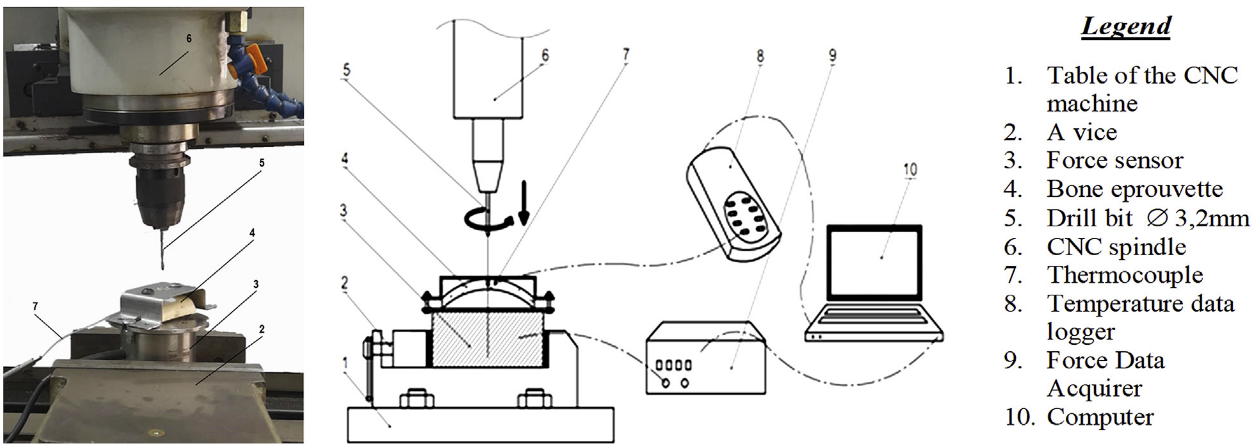

Figure 2. Test bench.

- a laptop computer;
- ME-K6D40® 06-axis force sensor;
- GSV-8DS® data acquisition device;
- a ∅3.2 mm 316L stainless steel drill bit. Cutting angle 118°, helix angle 30°, 2 flutes

2.4. Calibration of the thermocouple

The process consists in comparing and matching the temperature of the probe to be calibrated with the temperature of the test probe. It is carried out at several points corresponding to different temperature levels always including 0 °C and 100 °C.

A standard thermocouple is inserted into a standard oven heated to 100 °C. The standard thermocouple enables the reading of the real temperature, which is not always 100 °C. The thermocouple to be calibrated is inserted into the same oven and its temperature is measured and compared to that of the standard thermocouple.

When the temperature of the standard thermocouple and that of the thermocouple to be calibrated are different, the difference is recorded. This difference can be used to refine the measurement. If the difference is too large, the thermocouple is considered out of tolerance and discarded. This process is performed at several predetermined temperature levels.

For calibration at 0 °C, the thermocouple to be calibrated is placed in a bucket filled with ice and pure water. Water must not exceed the ice level. The thermostat is set so that the bucket always contains a mixture of ice and water. The temperature is then considered to be stabilized at O°C. Adjustments are made in the same way.

2.5. Procedure

Bone sample (4), fitted on T-type thermocouple (7) connected to PICOLOG® temperature data logger (8) was held in isostatic position in center of ME-K6D40® dynamometer (3) connected to GSV-8DS® data logger (9), using GSVMulti Version 1.42® software. Set was clamped to CNC machine table (1) using a vice (2). ∅3.2mm 316L stainless steel drill bit (5) was secured in drill chuck (6). Computer (10) enhanced spontaneous reading and recording of forces and temperatures in GSV-8DS® and PICOLOG® respectively.

The bone sample was clamped with one or more thermocouples and stabilized on the stress sensor with the screws so that the drill bit passed through the centerline of the sensor fixed on the milling machine table during drilling with a vise. The forces and temperatures were measured and recorded in real-time during the tests. To avoid damages to electronic components of the dynamometer, irrigation was not performed.

2.6. Test parameters

The following parameters were used:

- Bone type: bovine tibia cortex,
- Diameter of the drill bit ∅3.2mm,
- Spindle speed of the drill (N) 100rpm, 200rpm, 300rpm and 500rpm,
- Feed rate (V_f) 30 and 60 mm/min.

Bovine tibial cortex was taken because of its mechanical properties close to those of human cortical bone (Lee et al., 2012a; Liao and Axinte, 2016; WangYu et al., 2013) Each bone specimen was drilled on its centre with a ∅3.2mm stainless steel drill bit, which is indicated in the surgical technique for femoral and tibial shaft osteosynthesis.

The spindle speeds were 100, 200, 300, and 500 rpm, and the feed rates were 30–60 mm/min. Other authors have used these same parameters (Alam et al., 2011; Augustin et al., 2008; Lee et al., 2012a).

For each ∅3.2 mm drill bit, at least three trials (E_1, E_2, E_3, E_n) were performed. Three drills (O_1, O_2, O_3) were used for each type of test. Thus, a test could be labeled as follows: N = 100rpm, V_f = 30 mm/min, O1, E3. Tests were grouped following the indices E_1, E_2, E_3, E_n.

A total of 24 drill bits were used to drill 72 bone specimens. Temperature and force curves for each test were recorded in line with spindle speed (N), feed rate (V_f), and test number (E_i).

The average maximum temperature of the trials (TMMEi) corresponded to the average of the cumulative maximum temperatures for each drill bit of the same trial number: $TMME_i = \sum_{n}^{k} TMME_iO_k/n$ (k < 1, 2, 3>) with i = trial number and k = drill bit sequence number.

The average maximum force of the trials was the average of the cumulative maximum forces for each bit of the same trial number.

Figure 3 shows the general pattern of the evolution of the axial drilling force and temperature for a validated test. Tests with curves different from those shown in Figure 3 were excluded.

Each test group corresponded to the combination of the parameters spindle speed (N), feed rate (V_f), and test number (E_i).

The calculation of the average temperature increase for each test group was performed as follows: for each wick, at least three trials (E1, E2, E3, En) were performed; for each test group, the initial mean temperature (TMI) and the maximum mean temperature (TMM), which is the average of the maximum temperatures, were calculated. The average temperature rise (ΔTMM) given by the formula ΔTMM = TMM-TMI was calculated. Differences in temperature rise per test group were expressed by the formula $\Delta Tj/i = \Delta TMMj - \Delta TMM_i$ where i and j denote the test numbers with $i \neq j$.

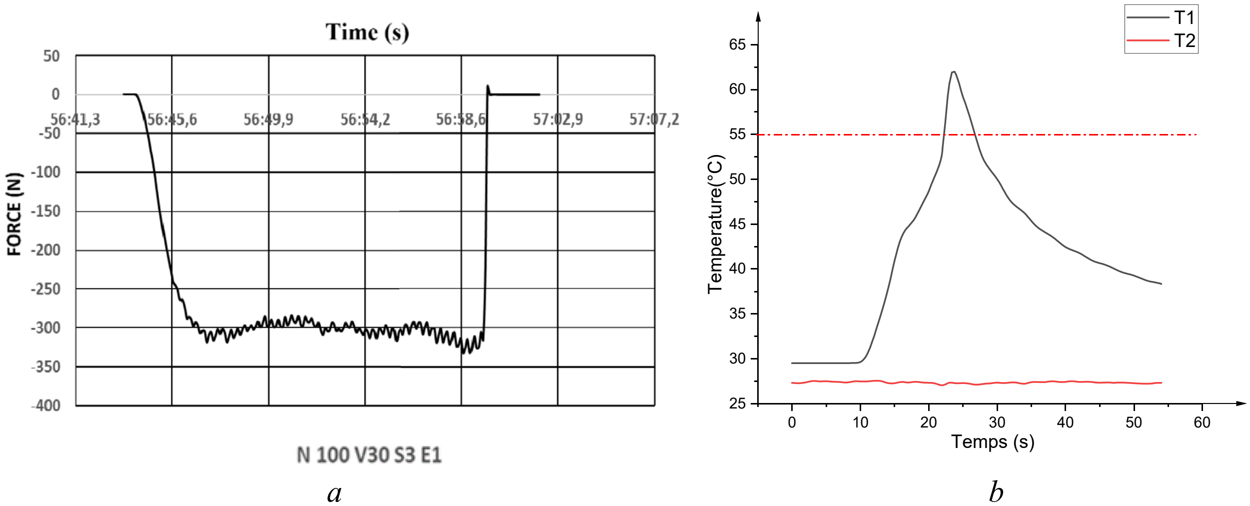

Figure 3. Evolution of the parameters during a test. a: Force. b: Temperature.

Thrust force was recorded for each trial. The averages of maximum forces were averages obtained for each trial group. Plots boxes were generated on the basis of the spindle speed (N), the trial number (E_i) and the feed rate.

Maximum temperatures, as well as the calculated variations, were plotted on figures, and a threshold at 55 °C was determined as threshold temperature. Drilling parameters that keep temperatures below 55° were selected.

Temperature variations and forces were compared under the same drilling conditions for each type of trial. Correlations were sought.

To evaluate the degree of wear of wicks, a SOMIKON® USB 50-500X digital microscope with a resolution of 640 × 480 pixels (VGA) was used. Images of the wicks before and after trials series were compared.

Mean values calculated from data of different trials are presented in tables, graphs, and curves. OriginLab 2019b® software was used to plot the curves. Student's t test® was used for comparison of means. One-, two-, and three-factor analysis of variance was performed (see Table 1).

3. Results

3.1. Measurement of temperature

Table 2 shows the observed temperatures and means. The mean initial temperature for all trials was 29.24 °C (min 28.00 °C, max 31.00 °C, SD 0.79). The differences observed were not statistically significant: $p = \pm 0.86$. The mean maximal temperature was 68.08 °C (min 46.38 °C; max 99.06 °C, SD 15.76). The differences observed were highly significant: $p < 0.0001$.

Considering 55 °C as the critical temperature threshold for bone tolerance, it was observed that:

- at spindle speed N = 100 rpm, cortical bone can be drilled twice with the same drill at feed rates V_f = 30 mm/min and V_f = 60 mm/min without reaching the critical temperature;
- at spindle speed N = 200 rpm, the cortical bone can be drilled with the same drill once at feed speed V_f = 30 mm/min, and twice at feed speed V_f = 60 mm/min without reaching the critical temperature;
- at spindle speeds N = 300 rpm and N = 500 rpm, the critical temperature was largely exceeded regardless of feed speed or number of trials (Figure 4).

Table 1. Summarizes all the parameters used for the tests.

Variables	Symbols	Values used
Spindle speed	N (rpm)	100, 200, 300, 500
Feed speed	V_f (mm/min)	30 et 60
Drill bit diameter	∅ (mm)	3,2
Drilling tools	O_k	O_1, O_2, O_3
Tests	E_i	E_1, E_2, E_3

Figure 4 shows the evolution of the average maximal temperatures at different spindle speeds depending on the number of trials and feed rate. It can be noted that these temperatures increase with number of trials.

Variations of temperature have been calculated. In all cases, they increase with number of trials. For example, at N = 100rpm and feed rate of V_f = 60 mm/min, variation of temperature is 17.28 °C during the 1st trial, 26.41 °C during the 2nd trial and 31.53 °C during the 3rd trial. The difference in temperature variations related to the number of trials was recorded. Thus, between the 1st and 2nd trial, and under drilling conditions of N = 100 rpm and V_f = 60 mm/min, the difference is 9.13 °C. In other words, when drilling the cortex twice, and under the same conditions, heat generated is about 9.13 °C higher. No correlation was observed in these variations, with trials number.

3.2. Measurement of force

Table 3 Summarizes forces measured according to spindle speed, number of trials, and feed rate.

Forces vary between 60.57N and 604.54N. They are highest at spindle speed N = 100 rpm and gradually decrease up to N = 500 rpm. The feed speed has a significant influence on the force magnitude. However, there is no linear correlation between recorded forces and the feed rate values. Force magnitude increases with number of tests, whatever drilling parameters.

Figure 5 enables an evolution of forces in line with speed, number of trials, and feed rate.

At feed rate 30 mm/min, it can be observed that thrust force varies between 60.57 and 368.66N. The lower the speed, the higher the thrust force. Thrust force does not vary enough in trials where the spindle speed is greater than or equal to 200 rpm. On the other hand, it varies significantly at 100 rpm.

When the feed rate rises to 60 mm/min, thrust force is found to vary between 81.53 and 604.54N. The lower the feed speed, the higher the thrust force. This thrust force does not vary enough from one group of trials to another, which means that in a group of trials with same spindle speed, thrust force is almost similar.

Table 2. Average temperature values and variations for each test group according to drilling conditions.

N (rpm)	Vf (mm/min)	N° Essai	N° Drilling tools	Mean Forces	TMI (°C)	TMM (°C)	ΔTMM (°C)	$\Delta T_{2/1}$ (°C)	$\Delta T_{3/2}$ (°C)	$\Delta T_{3/1}$ (°C)
100	30	1	03	262,48	29,69	48,51	18,82	3,48	6,03	9,51
		2	03	337,23	29,76	52,06	22,30			
		3	03	368,66	29,78	58,11	28,33			
	60	1	03	547,34	29,10	**46,38**	17,28	9,13	5,12	14,25
		2	03	580,68	29,20	55,61	26,41			
		3	03	**604,54**	29,30	60,83	31,53			
200	30	1	03	154,64	29,83	50,72	20,89	13,73	6,90	20,63
		2	03	166,15	29,52	64,14	34,62			
		3	03	178,24	29,55	71,07	41,52			
	60	1	03	226,25	28,00	50,27	22,27	3,20	4,18	7,38
		2	03	242,30	28,30	53,77	25,47			
		3	03	287,54	28,40	58,05	29,65			
300	30	1	03	94,66	29,76	65,00	35,24	21,05	13,65	34,70
		2	03	110,62	29,52	85,81	56,29			
		3	03	128,43	28,57	98,51	69,94			
	60	1	03	170,73	28,20	59,48	31,28	12,68	4,55	17,23
		2	03	210,95	28,00	71,96	43,96			
		3	03	231,15	28,10	76,61	48,51			
500	30	1	03	**60,57**	29,20	78,28	49,08	6,77	14,11	20,88
		2	03	71,37	29,50	85,35	55,85			
		3	03	85,68	29,10	**99,06**	69,96			
	60	1	03	81,53	29,84	77,55	47,71	2,42	4,95	7,37
		2	03	98,48	30,50	80,63	50,13			
		3	03	118,90	31,00	86,08	55,08			

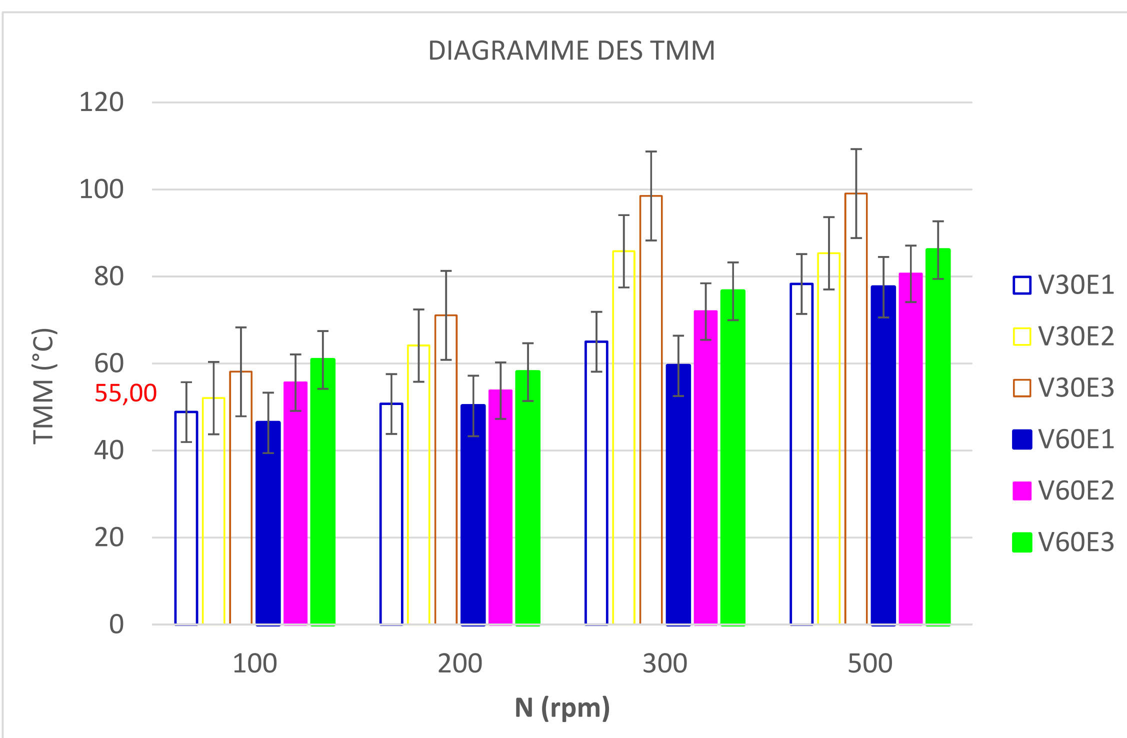

Figure 4. Evolution of TMM over T_1, corresponding to N, V_f and trial number.

3.3. Determination of drill bit wear by digital microscopy

Figure 6 shows the filtered images of an unused drill bit (a) compared to a used drill bit (b). The filter removes noise cloud to improve visualization. It can be observed that the tip of the used drill bit is blunt and its apex angle is greater than that of the new drill bit. Careful observation reveals an abrasion of the material.

The same images obtained by segmentation study the variation of black (0) or white (1) pixels, which defines contours of images. Wear burrs are highlighted in the segmented image s1 (Figure 7). A

Table 3. Average force values for each test group.

		100	200	300	500
$V_f = 30$	E1	262,48	154,64	94,66	60,57
	E2	337,23	166,15	110,62	71,37
	E3	368,66	178,24	128,43	85,68
$V_f = 60$	E1	547,34	226,25	170,73	81,53
	E2	580,68	242,30	210,95	98,48
	E3	604,54	287,54	231,15	118,90

magnification of the areas of interest reveals a smoothing of the surface and appearance of material abrasion areas on the used drill bit.

On histograms corresponding to the equalized images (o0 and s1), an abrupt variation and a strong brightness of the surface of the used drill bit are observed. This is materialized by the increase in the number of pixels whose gray level is close to white, corresponding to 255 on the drill bit used (Figure 8).

4. Discussion

4.1. Influence of spindle speed and feed rate on temperatures

Drilling resulted in rise in temperature during all tests. This temperature rise would be linked to quantity of bone material removed and to the friction-induced following the number of revolutions of the drill bit through bone, especially since bone conductivity is low (Calttenburg et al., 1975). Maximum temperatures quickly exceeded the 55 °C thresholds. Temperatures below 55 °C were observed in the tests with spindle speeds N = 100 rpm and N = 200 rpm. For the tests with spindle speeds N = 300 rpm and N = 500 rpm, the maximum average temperatures were above 55 °C. This phenomenon could be explained by cutting

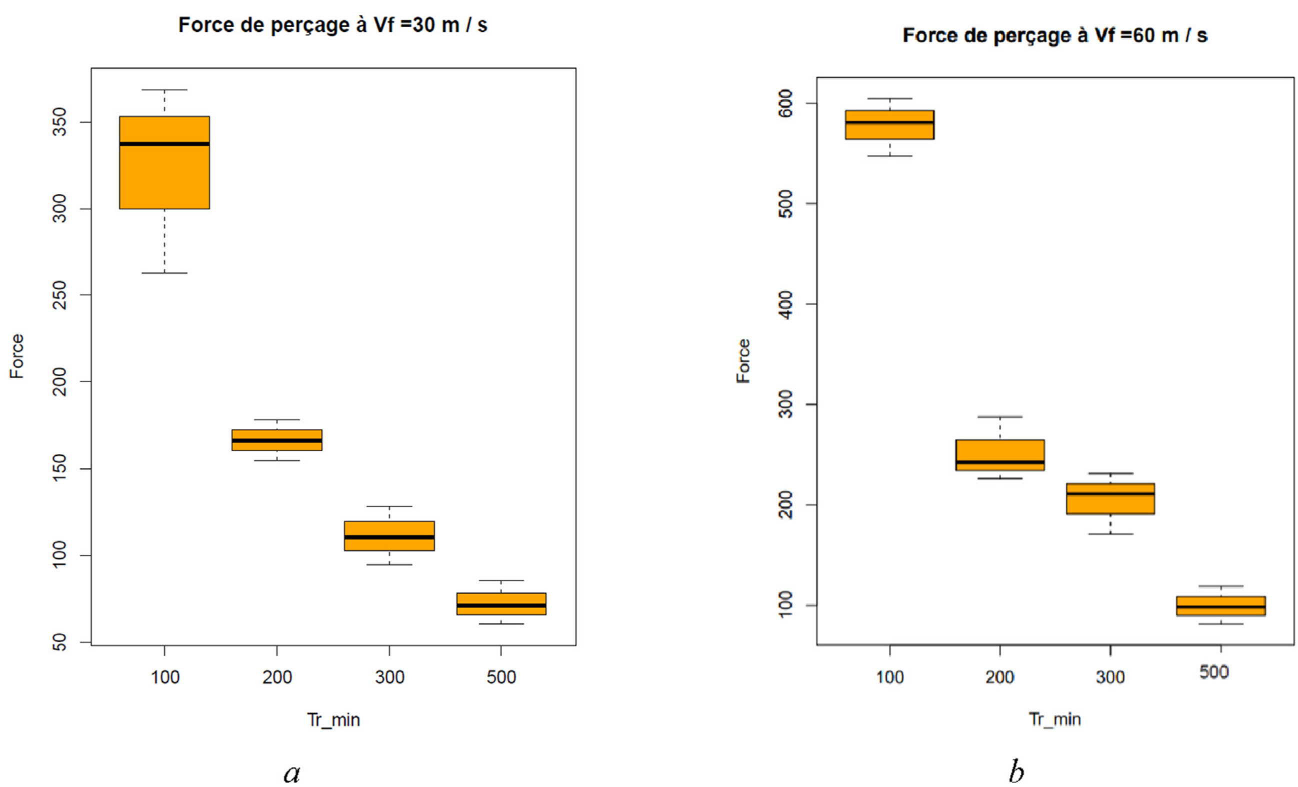

Figure 5. Variations in average maximum temperatures. a: $V_f = 30$ mm/min. b: $V_f = 60$ mm/min.

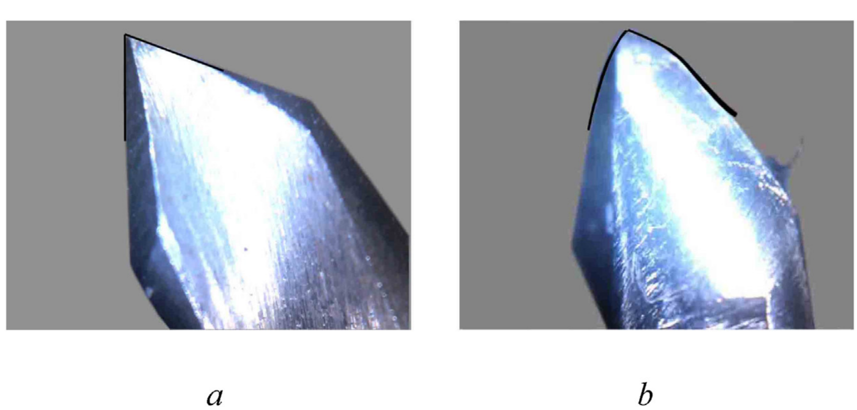

Figure 6. Filtered image of a drill bit under the digital microscope. a: unused drill bit, the apex angle is acute. b: used drill bit, the apex angle is blunt and greater than the unused one.

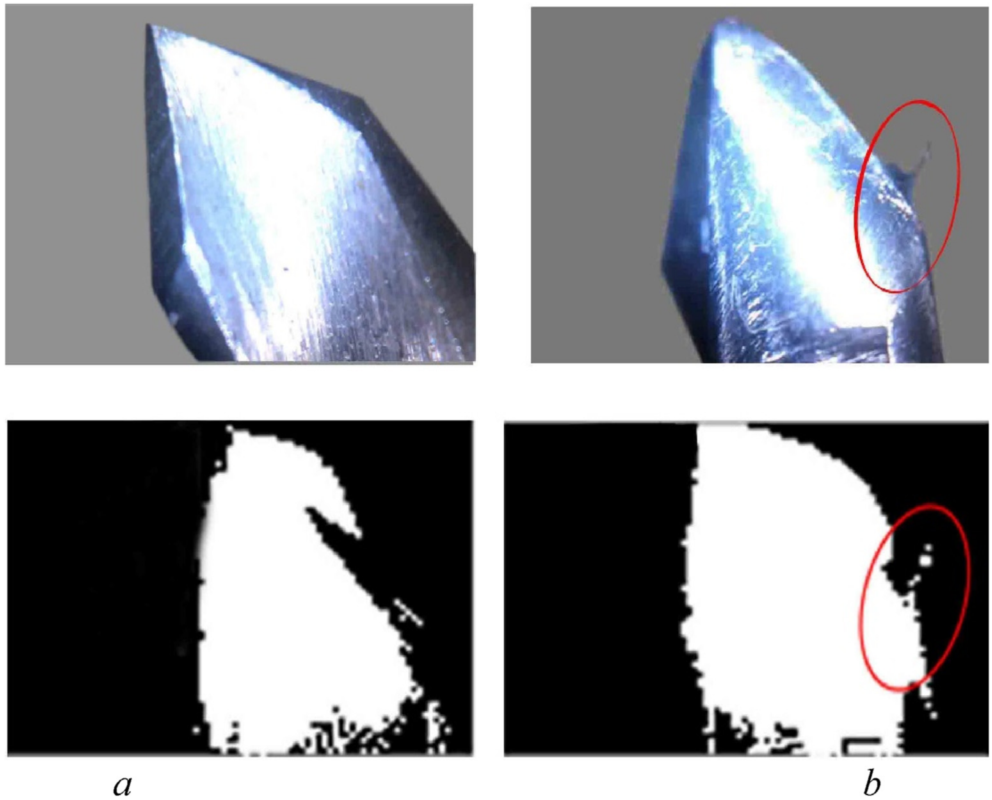

Figure 7. Comparison of filtered images (top, blue variation) with segmented images (bottom, grey variation) of the same drill bit. a: unused drill bit. b: used drill bit, confirmation of the abrasion of the material.

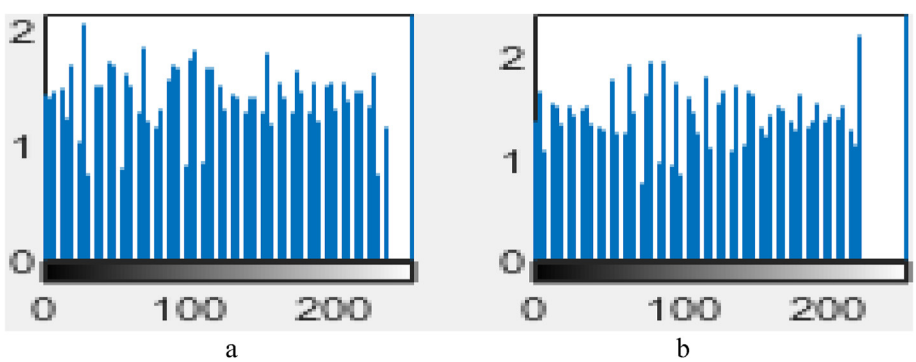

Figure 8. Comparison of histograms corresponding to the equalized images. a: unused drill bit. b: used drill bit.

force which increases with the cutting speed. Many authors have found that the temperature increases proportionally with spindle speed (Allan et al., 2005; Augustin et al., 2008, 2012; Bachus et al., 2000; Bertollo et al., 2010; Natali et al., 1996; Reingewirtz et al., 1997).

Temperatures measured at 60 mm/min were relatively lower than those measured at 30 mm/min, certainly because of the shorter drilling time. For example, the lowest temperature (46.38 °C) was recorded at 60 mm/min and the highest (99.06 °C) at 30 mm/min. Experimental studies have shown that increasing feed rate results in a relative decrease in temperature rise. Results of this experiment are consistent with these data (Augustin et al., 2008, 2012; Bachus et al., 2000; Bertollo et al., 2010). Nevertheless, in some conditions, temperatures were found higher at a feed rate of 60 mm/min (N = 100 rpm, E2). Others found that an increase in spindle speed associated with a decrease in feed rate increases temperature (Augustin et al., 2012; Hillery and Shuaib, 1999; Lee et al., 2018). This was not verified in this experiment.

Apparently, for a maximum of 3 cortical drillings with the same tool, the best drilling parameters are at $N \leq 200$rpm where temperatures are lower than 55 °C, irrespective of the feed rate.

4.2. Influence of the number of trials on the temperatures

In this study, the results differ from those obtained by other authors, because of the experimental conditions. 72 trials were performed at lower spindle speeds with a total of 24 drill bits. Considering the 1st trial (E_1), the maximum temperatures are close to the results observed by some authors (Allan et al., 2005; Augustin et al., 2008). During 2nd and 3rd trials, the maximum temperatures were significantly higher, which supports the theory of wear as a function of the number of trials (Allan et al., 2005; Jochum and Reichart, 2000; Lee et al., 2012b).

A progressive increase in temperature rise corresponding to the number of trials was observed. For example, for the spindle speed N =

100 rpm, and a feed speed $V_f = 30$ mm/min, the temperature variation increases from 18.82 °C during the 1st trial, to 22.30 °C in the 2nd trial and 26.29 °C in the 3rd trial (Table 2). The differences in the average maximum temperature rise increase progressively with the number of trials. They were higher for the feed $V_f = 60$ mm/min. The difference in average maximum temperatures was significant for TE2- TE1 ($p = 0.016$). It was higher and more significant for TE3- TE1 ($p < 0.001$). In other words, each new drilling with the same tool corresponds to an increase in temperature rising (Figure 5). This data confirms the effect of drill wear on the temperature rising and has been observed by Allan et al. (2005).

Repeated use of the same drill bit leads to wearing out of the cutting edges, which affects the drilling properties. The drill may show macroscopic deformation (alteration of the angle at the top) and induce an abnormal temperature rise during drilling, as a result of wear (Burny et al., 2007). It should be noted that in current bone surgery, osteosynthesis is performed with at least 3 screws on either side of a fracture site, i.e. 12 cortices. It would be interesting to study the bone temperatures under the same conditions to determine the degree of wear of the drill bit after 12 cortical drillings and possibly the wear coefficient.

However, the surgical conditions of bone drilling in orthopedics differ from those of this experiment because of the normal temperature of the tissues (37 °C initial temperature), regardless of air conditioning, ambient temperature, and the possibilities of irrigating a bone during drilling. It would be also interesting to get closer to these conditions during the further experiments.

4.3. Influence of speeds and number of trials on forces

In current practice, the surgeon empirically adapts the drilling force and the spindle speed according to the penetration resistance of the drill bit. These tests enabled us to measure the axial force during drilling under extreme conditions.

Increasing spindle speed was associated with a significant decrease in force regardless of the number of trials. Forces were higher in the 3rd trial than in the 1st. The forces were higher at the feed rate $V_f = 60$ mm/min. Mean values ranged from 60.57N (N = 500 rpm, $V_f = 30$ mm/min, E_3) to 604.54N (N = 100 rpm, $V_f = 60$ mm/min, E_1).

A gradual decrease in force was observed correlating with spindle speed, and there was a significant increase that was consistent vis-à-vis the feed rate. At feed rate $V_f = 30$ mm/min, these forces were 262.48, 154.64, 94.66, and 60.57N respectively for spindle speeds N = 100, 200, 300, 500 rpm in the 1st trial. At feed rate $V_f = 60$ mm/min, these forces were 547.34, 226.25, 170.73, and 81.53N respectively for spindle speeds of 100, 200, 300, 500 rpm for the same trial.

This decrease in force with spindle speed has been observed in other studies (Xu et al., 2014; Yang et al., 2010). The difference in force magnitude observed in the present study is most likely due to the cutting parameters, especially higher spindle speeds used in the other experiments. Dedong et al. (2019) measured and then developed a predictive model of forces from the cutting parameters. In addition to the inverse effect of spindle speed on force magnitude, they observed a decrease in force magnitude in older, certainly osteoporotic, bone samples (Dedong et al., 2019).

4.4. Drill bit wear

Wear of the drills was studied by digital microscopy and numerical analyses were performed before and after drilling. All drills were used at least 3 times. The image analysis showed blunting of the tip, smoothing of the material, and abrasion of the steel. These defects were observed on almost all the drills after the 3 tests. The comparison was not made on the rotation speeds or the feed rates, but only on the number of trials.

Numerically, we observed a significant increase in the number of white pixels on the wicks used, which correlates with the polishing of the wick by friction. A relationship between the increase in temperature, the number of trials, and the wear of the wicks could therefore be established. A specific protocol would allow the quantitative study of the effect of rotation speed, feed rate, and number of trials on wick wear. The present analysis only points to the conclusion that the wear is related to the number of cycles of use and leads to an increase in temperature.

Not much data are available on objective studies of drill bit wear in bone surgery. Alam et al. performed an experimental study of the effect of drill bit wear on bone drilling performance. In this study, surface roughness of the bone, bone delamination around the hole, and roughness of the drill bits were measured. Wear of the drill was strongly related to drilling force, torque, temperature, and surface roughness of the drilled hole. Favorable conditions for bone drilling were obtained with feed rate, drill speed, and roughness of the drill bit cutting edge at 30 mm/min, 2000 rpm and up to 2 mm, respectively (Alam et al., 2020).

Augustin et al., compared unused drill bits with those used 600 times or in service for 20 years using standard photography (Augustin et al., 2012). Although interesting, images obtained do not appreciate the follow-up of drill bits after few trials.

In this study, image digitization led to the detection of macroscopically invisible defects. It was possible to confirm that even minimal use of the same drill bit alters its surface, with significant modification of maximal temperature.

5. Conclusion

Temperatures were measured in the bone in the vicinity of the drills used repeatedly and at programmed rotation and feed rates on a CNC milling machine. The results showed that repeated trials with same drill and increase in spindle speed significantly affected the temperature (making it to rise). Although temperature differences were observed in line with feed rate V_f, these differences were not statistically significant. These parameters should be strictly controlled during drilling. Best conditions for bone drilling were at spindle speeds of 100 and 200 rpm with feed rates of 30 and 60 mm/min respectively. Under these drilling conditions and considering critical threshold of 55 °C, we should use the ∅ 3.2-mm drill bit twice at $N \leq 200$ rpm. However, in routine practice, the majority of fractures are treated by drilling at least 12 cortices and probably at higher spindle speeds. Therefore, it would be interesting to study the cooling curve to determine the duration of the temperature rise, which should not exceed 55 °C beyond 30 s.

The number of times the same drill bit is used certainly has an impact on the degradation of the cutting edge of the cutting tool. It would be necessary for the surgeon to be able to control the cutting parameters during drilling and monitor for the number of times, the drill bit is used. The study of drill bit cutting edge wear in bone surgery remains an area to be explored.

Declarations

Author contribution statement

Jean Gustave Tsiagadigui, Benoit Ndiwe, Marie-Ange Ngo Yamben, Nzogning Fotio, Fabrice Ella Belinga, Ebenezer Njeugna: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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No data was used for the research described in the article.

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The authors declare no conflict of interest.

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