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Research article

Soft material drilling: A thermo-mechanical analysis of polyurethane foam for biomimetic bone scaffolds and optimization of process parameters using Taguchi method

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ABSTRACT

Drilling is a widely employed technique in machining processes, crucial for efficient material removal. However, when applied to living tissues, its invasiveness must be carefully considered. This study investigates drilling processes on polyurethane foam blocks mimicking human bone mechanical properties. Various drill bit types (118° twist, 135° twist, spherical, and conical), drilling speeds (1000–1600 rpm), and feed rates (20–80 mm/min) were examined to assess temperature elevation during drilling. The Taguchi method facilitated systematic experiment design and optimization. Signal-to-noise (S/N) ratio and analysis of variance (ANOVA) identified significant drilling parameters affecting temperature rise. Validation was conducted through confirmation testing. Results indicate that standard twist drill bits with smaller point angles, lower drilling speeds, and higher feed rates effectively minimize temperature elevation during drilling.

1. Introduction

The growing elderly population is contributing to a constant global trend of rising osteoporosis rates and chronic illness rates. Simultaneously, there is an increasing number of bone injuries and bone diseases being reported [1–4]. As a result of these patterns, there is an increasing demand for materials that can substitute bones, particularly within the domains of contemporary traumatology, orthopedics, and oncology [5,6]. Moreover, the extensive application of bone plastics materials in craniofacial surgery and dentistry cannot be overlooked [7–9].

Bone is a composite material composed of inorganic minerals, primarily hydroxyapatite (HA), which contributes mechanical strength to the bone structure as shown in Fig. 1. It also includes an organic collagenous matrix made of type I. Although bone may regenerate itself, when there is a large loss of bone, the natural healing process is not as effective [10,11]. In these cases, medical implants are typically used to replace the damaged bone. According to the bone tissue engineering method, the temporary 3D scaffold is essential in the regeneration of new bone into desired forms and significantly influence osteoblast functions [12,13].

Bone tissue engineering has seen extensive research into several biodegradable synthetic polymers, including polylactic acid (PLA),

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polycaprolactones (PCL), polyglycolide (PGA), and polylactic-co-glycolic acid [10,14,15]. However, striking the right balance between tissue regeneration and in vivo degradation proves challenging when using these artificial biodegradable polymers. As a result, there's growing interest in exploring alternative materials, particularly polyurethanes, for creating scaffolds to support bone tissue regeneration [16,17]. The utilization of polyurethane in scaffold construction offers a broader spectrum of morphological and mechanical properties compared to other biodegradable polymers [18–20].

Polyurethane (PUR) foam blocks have become a common choice in research experiments [11,21,22], serving as a substitute for cadaver or animal bone specimens. According to Jiao [15] and Muhayudin [14], polyurethane foam proves to be a viable alternative to human cancellous bone, with similar mechanical properties and suitability for testing implants. Feldmann [20], and several other researchers [23,24,25], conducted experiments to assess its mechanical characteristics, including temperature, strain, and density, highlighting its applicability not only in mechanical investigations but also in studies involving surgical instruments that generate heat. Furthermore, meeting ASTM F-1839-08 standards, this rigid polyurethane foam offers a controlled environment for mechanical testing of bone screws, medical devices, and instruments. This consistency ensures reliable comparisons between different products [4,20,26,27]. Table 1 presents a comparative analysis of the thermos-mechanical characteristics of commonly used materials simulating bone structures.

The objective of this study was to examine polyurethane (PU) material as a substitute for bone and evaluate thermal damage during drilling procedures of an implant site preparation. As a result, the objective was to assess the impact of drill bit geometrical shapes in conjunction with the parameter effects of drill speed and feed rate. Experimental procedures were carried out using solid rigid polyurethane foam materials as a substitute for human bone. T-type thermocouples were instrumented into the foams to measure temperature elevation during the drilling process. A thermal camera was utilized to simultaneously measure the temperature distribution on the surface of the polyurethane block and the exterior surface of the drill bit.

2. Materials and methods

2.1. Synthetic bone (PUR) model

In this study, the test sample employed was a synthetic bone created from polyurethane foam, obtained from Scalebone at the Research Laboratories of Universiti Teknologi Malaysia. Polyurethane synthetic bones are widely accepted in the research community for their ability to mimic the mechanical properties of natural bone [32,33], making them an excellent choice for pre-clinical testing and evaluation of orthopedic procedures and devices. The use of standardized synthetic materials allows for a controlled study environment, minimizing the variability that can arise from using natural bone, which can differ significantly in properties from sample to sample [14,34].

Specifically designed for drilling experiments, the specimens depicted in Fig. 2 were provided in a rectangular form, measuring 60 mm in length, 30 mm in width, and 20 mm in height. Vickers hardness tests were conducted on polyurethane synthetic bone using a Matsuzawa DVK-2 tester. The Vickers hardness values for the tested PUR bone samples ranged from 19.4 HV to 25.1 HV, with an average hardness of around 22.4 HV. This average hardness value reflects the material's overall resistance to indentation. The material

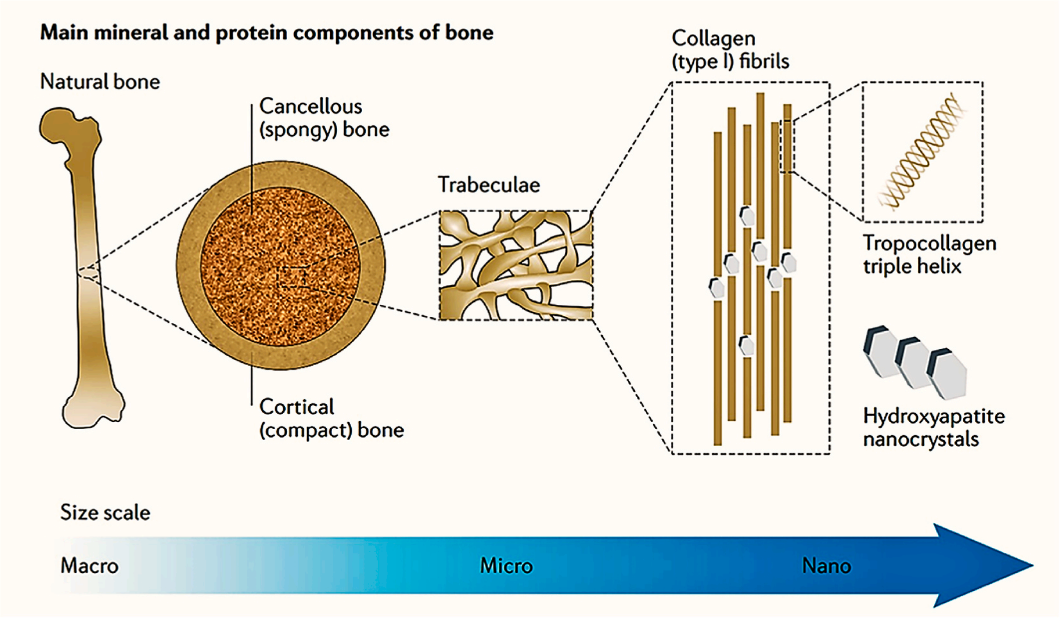

Fig. 1. Natural bone hierarchical structure to fabricate bone scaffolds using polymer nanocomposites [10].

Table 1
Mechanical properties of bone and substitutes materials [16,28,29–31].

Mechanical property		Human bone	Human cortical bone	Polyurethane (PU)	PMMA	Artificial bovine bone	Bovine bone
Density	Kg/m^3	1780–2200	1640	1700	1190–1400	600–1800	4490
Vickers hardness	Kgf/mm^2	24.46–43.82	–	19.4–25.1	19.9–35.67	–	–
Young's modulus	GPa	0.5–17	17	0.4	–	–	22
Poisson's ratio	–	0.4	0.4	0.33	–	–	0.3
Specific heat	J/kg°C	1150–1300	1640	1250	1400–1470	–	~1600
Thermal conductivity	W/m.K	0.1–0.35	0.452	0.47	0.15–0.4	0.3–0.4	0.54 (cancellous = 0.3)

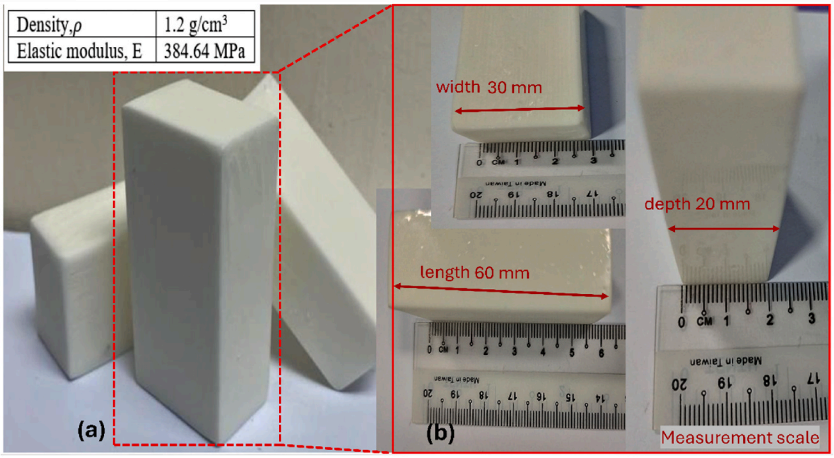

Fig. 2. Material properties and dimensions of polyurethane blocks, (a) provides the density and elastic modulus of the test specimens and (b) shows the dimensions of the test specimens

possesses a closed-cell structure with a density of 1.2 g/cm^3, thermal conductivity of 0.47 W/m.K, Specific heat of 1250 J/kg°C and a Young's modulus of 0.4 GPa. The Young's modulus, which indicates how readily the material can stretch and deform, is a crucial parameter for simulating the mechanical behavior of natural bone during drilling.

2.2. *Experimental setup and equipment*

The experimental process commences with the preparation of a rigid synthetic bone block made of polyurethane foam (PUR) to investigate the impact of various geometrical shapes of drill bits on temperature changes during drilling. This block is equipped with a T-type thermocouple for internal temperature measurement and a thermal camera to monitor the temperatures of both the drill bit and the surface.

The thermocouple was carefully inserted into the polyurethane block by drilling a precise, small hole to accommodate the sensor with a diameter of 1 mm and a depth of 8 mm, positioned 0.5 mm distant from the drilling site's edge, as shown in Fig. 3. Precision drilling ensured a snug fit without deforming the surrounding material, while minimized disturbance and controlled temperature during drilling prevented any alteration to the polyurethane's properties. The thermocouple was aligned flush with the inner surface, and post-insertion inspections confirmed that the mechanical and thermal properties of the polyurethane remained unchanged.

All the experiments were conducted in the laboratory at 21 °C. The operating room environment typically has a lower temperature range 20–24 °C, which can influence heat dissipation during bone drilling [35,36]. This effect arises because the patient's flesh, in contact with the bone, can alter heat dissipation. To simulate these conditions accurately, we maintain a laboratory temperature of 21 °C, replicating the temperature of an actual operating room. Temperature monitoring within the synthetic bone block is carried out throughout the machining process using a data logging thermometer (Appellant Instruments AT4808 Handheld Multi-channel Thermometer).

A Thermal Imaging Camera (FLIR E6) with emissivity $\varepsilon = 0.97 \pm 0.01$, calibrated at the factory, was securely affixed to a tripod positioned 0.2 m away from the drilling area. It captured two thermal images during each drilling occurrence, with the initial image captured just before the commencement of drilling and the second image taken when the drill bit reached a depth of 8 mm. The comprehensive experimental arrangement is illustrated in Fig. 4.

The study assessed the impacts of drill speed, feed rate, and drill bit geometry (shape) on hole creation, using a constant drilling depth of 8 mm throughout. The drill bits utilized were all made of high-speed steel (HSS) and featured varying point angles and shapes,

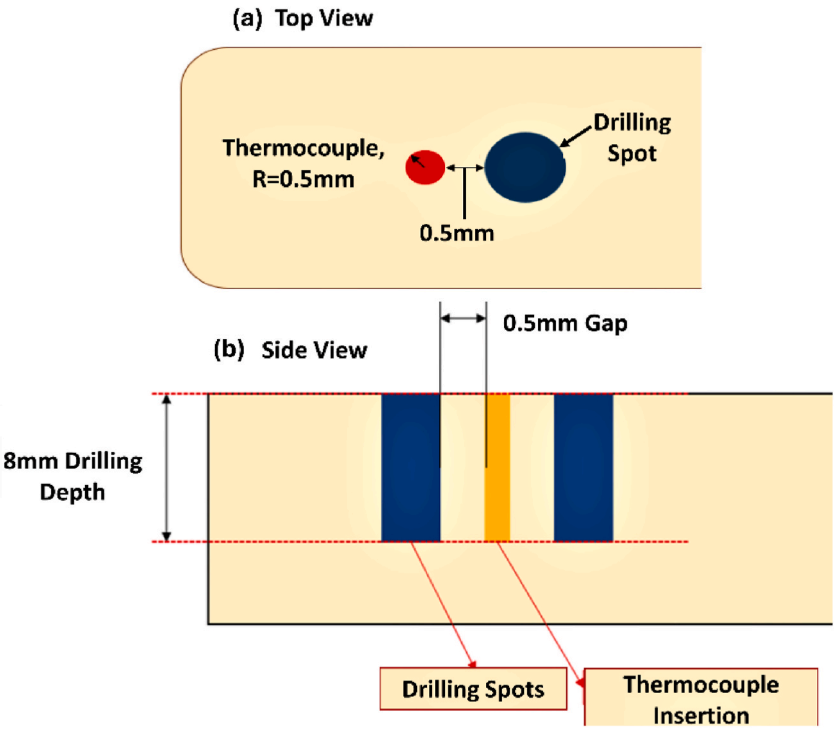

Fig. 3. Schematic of the polyurethane block workpiece during the drilling process (a) top view: shows the arrangement of the thermocouple (R = 0.5 mm) and drilling spot, with a 0.5 mm gap between them and (b) side view: Illustrates the 8 mm drilling depth, with the thermocouple insertion and drilling spots aligned with a 0.5 mm gap

including (a) a 118° twist drill bit, (b) a 135° twist drill bit, (c) a spherical drill bit, and (d) a conical drill bit (as depicted in Fig. 5). It is important to note that the diameters of the drill bits were not equal, as the focus of the study was on the heat generation pattern, not the diameter.

Selecting initial bone drilling process parameters based on existing literatures were four drill bit types with a drilling speed set at 1000 rpm and a feed rate of 20 mm/min. The advantage of reducing the rotation speed lies in reducing friction. However, it's crucial to avoid decreasing the rotational speed below 1000 RPM due to the substantial increase in both thrust force and torque, which rises exponentially. The permissible range for the drilling variables was established by adjusting the speed within the range of 1000–1600 rpm and the feed rate within the range of 20–80 mm/min [26,37]. The drilling parameters, defined as drill bit types (A), drilling speed (B), and feed rate (C), were identified as controlling factors influencing temperature, and their respective levels were specified as detailed in Table 2.

2.3. *Taguchi method*

The advocate of the Taguchi method is Genichi Taguchi, and R.A. Fisher contributed to the development of the experimental design method in 1922 [38], offers a direct and effective approach for designing parameters and planning experiments. In this method, the word 'signal' defines the desired value (mean) for the output, while 'noise' signifies the undesired value, specifically the standard deviation for the output. Consequently, the Signal-to-Noise (S/N) ratio is derived by dividing the mean by the standard deviation. There are three main categories for interpreting S/N ratios based on the desired outcome: lower-the-better, higher-the-better, and nominal-the-better [7,39,40]. The Taguchi method utilizes these categories to optimize quality characteristics through parameter design. The summarized steps for this process are illustrated in Fig. 6.

3. Result and discussion

In this section, we examine how orthogonal arrays effectively decrease the number of drilling experiments needed to determine the most successful drilling configurations. The drilling experiment results are investigated using response mean values, signal-to-noise (S/N) ratios, and ANOVA. Using the outcomes from this analysis, we identify and validate the ideal drilling parameters that result in the lowest temperature.

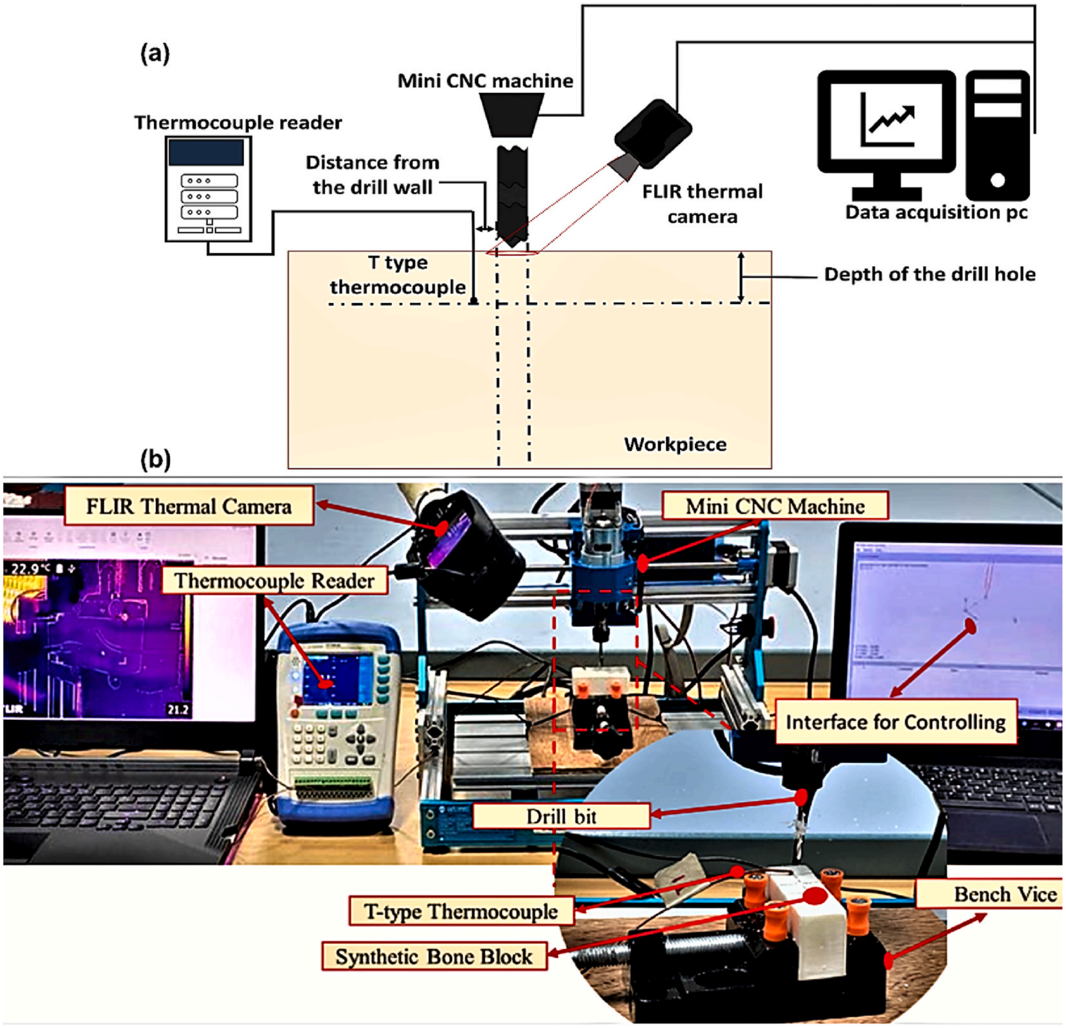

Fig. 4. (a) Schematic of experiment setup and (b) real setup for polyurethane synthetic bone drilling

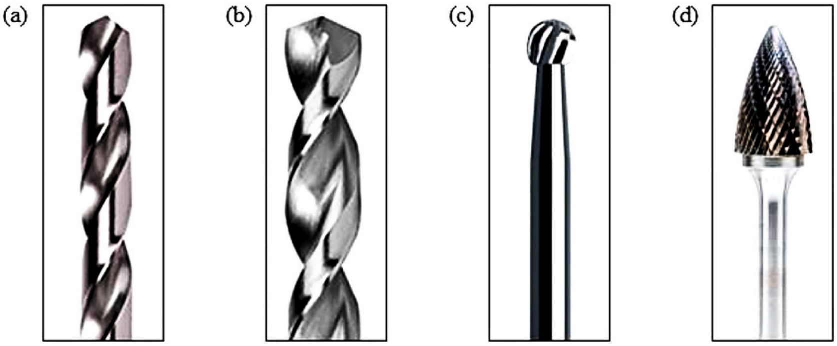

Fig. 5. Types of drill bits used in bone drilling experiments (a) 118° Twist drill bit, (b) 135° Twist drill bit, (c) Spherical drill bit, and (d) Conical drill bit

3.1. Selection of orthogonal array

Selecting the appropriate orthogonal array for experimental design is essential, and a critical step in this process is calculating the total degrees of freedom. Degrees of freedom represent the number of independent comparisons required among process parameters to

Table 2
Drilling conditions and levels

Symbol	Drilling parameters	Levels			
		1	2	3	4
A	Drill bit type	118° Twist	135° Twist	Spherical	Conical
B	Drilling speed (rpm)	1000	1200	1400	1600
C	Feed rate (mm/min)	20	40	60	80

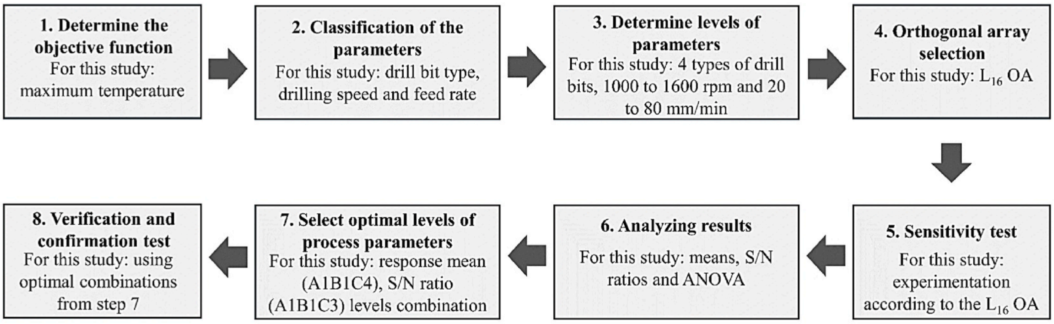

Fig. 6. Taguchi methodology flow process

evaluate the influence of each level and quantify the magnitude of improvement [41–43]. For instance, a process parameter characterized by four levels involves three degrees of freedom. Ideally, the orthogonal array's degrees of freedom should either higher or at least equal to those attributed to the process parameters [44,45]. For this study, we utilized an L16 orthogonal array design, resulting in a total of sixteen experiments as outlined in Table 3.

3.2. *Signal-to-noise (S/N) ratio and mean temperature analysis*

The temperature-associated heat generation was recorded in each experimental trial using a T-type thermocouple. The Taguchi method utilizes the Signal-to-Noise (S/N) ratio to evaluate experimental design robustness against external factors [46,47]. As previously outlined, there are three performance characteristic categories: the lower-the-better, nominal the-better, and the higher-the-better.

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^{2}\right) \tag{1}$$

In this study, we employed the "smaller-the-better" concept as shown in Equation (1) where y represents the response variable, n is the total number of observations, and y_i signifies the individual response measurements. By using these measurements, we calculated the Signal-to-Noise (S/N) ratio, as depicted in Table 4. The main aim was to attain the lowest temperature, which served as the optimal

Table 3
L_{16} orthogonal array and parameters level combinations

Trial no. L_{16}	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	1	4	4
5	2	1	2
6	2	2	1
7	2	3	4
8	2	4	3
9	3	1	3
10	3	2	4
11	3	3	1
12	3	4	2
13	4	1	4
14	4	2	3
15	4	3	2
16	4	4	1

Table 4
Temperature observed in case of drilling PUR synthetic bone block

Trial no.	A	B	C	Temperature (°C)	S/N ratio (dB)
	Drill bit type	Drilling speed (rpm)	Feed rate (mm/min)		
1	118° Twist	1000	20	32.5	−30.2377
2	118° Twist	1200	40	35.7	−31.0534
3	118° Twist	1400	60	38.6	−31.7317
4	118° Twist	1600	80	41.0	−32.2557
5	135° Twist	1000	40	36.5	−31.2459
6	135° Twist	1200	20	38.2	−31.6413
7	135° Twist	1400	80	41.7	−32.4027
8	135° Twist	1600	60	44.0	−32.8691
9	Spherical	1000	60	34.9	−30.8565
10	Spherical	1200	80	36.4	−31.222
11	Spherical	1400	20	39.5	−31.9319
12	Spherical	1600	40	42.0	−32.465
13	Conical	1000	80	38.9	−31.799
14	Conical	1200	60	43.0	−32.6694
15	Conical	1400	40	46.7	−33.3863
16	Conical	1600	20	51.0	−34.1514

outcome for assessing the effect of drilling parameters on the Polyurethane (PUR) synthetic bone block. A higher S/N ratio signifies superior performance, reflecting lower variability and smaller undesirable responses. Table 5 provides the average S/N ratios and mean temperature values corresponding to each level of drilling parameters. The data from Table 4 were employed to generate line graphs in Fig. 7, demonstrating the influence of drilling speed and feed rate on temperature rise using four different drill bit shapes.

Overall, an increase in drilling speed correlates with a rise in temperature. However, the response of feed rate varies with drill bit shapes. Twist drill bits in Fig. 7 (a) and (b) exhibit higher temperatures with increased feed rates, whereas spherical and conical drill bits in Fig. 7 (c) and (d) demonstrate an inverse relationship, indicating that lower feed rates result in higher temperatures. According to the line graphs, 118° twist drill bit with 80 mm/min and 135° twist drill bit with 60 mm/min feed rate produce high temperatures of 41 °C and 44 °C respectively. However, spherical and conical drill bit with lower feed rate of 40 mm/min and 20 mm/min experienced 42 °C and 51 °C respectively. Forty-eight experiments were conducted in total, with each combination repeated three times.

Fig. 8 specifically shows the mean Signal-to-Noise ratio and temperature means graph for the maximum temperature rise, highlighting the minimized variability of output characteristics around the desired value as reflected in the Signal-to-Noise ratio.

3.3. Analysis of variance (ANOVA)

ANOVA is a statistical test that determines whether observed differences in an experiment's outcome due to different experimental factors are statistically significant. This involved studying the overall variability of Signal-to-Noise (S/N) ratios, which are indicators of performance, by measuring the sum of squared deviations from the average S/N ratio [37,48]. The purpose was to distinguish the effects of individual drilling parameters from any errors present. Initially, the total sum of squared deviations from the average S/N ratio, represented as y_m, was computed using Equation (2).

$$SS_T = \sum_{i=1}^{n} (y_i - y_m)^2 \tag{2}$$

In an orthogonal array, where 'n' denotes the number of experiments performed and y_i denotes the average Signal-to-Noise (S/N) ratio observed for the i-th experiment, the total sum of squared deviations (SS_T) is divided into two distinct components: SS_d, which captures the squared deviations attributed to individual process parameters, and SS_e, which represents the sum of squared errors. To compute

Table 5
Response of S/N ratios (dB) and temperature means

Parameters	Temperature (°C)					
	Level 1	Level 2	Level 3	Level 4	Max - Min	Rank
S/N ratios						
A	−31.32	−32.04	−31.62	−33.00	1.68	2
B	−31.03	−31.65	−32.36	−32.94	1.90	1
C	−31.99	−32.04	−31.03	−31.92	0.12	3
Means						
A	36.95	40.10	38.20	44.90	7.95	2
B	35.70	38.33	41.63	44.50	8.80	1
C	40.30	40.23	40.13	39.50	0.80	3

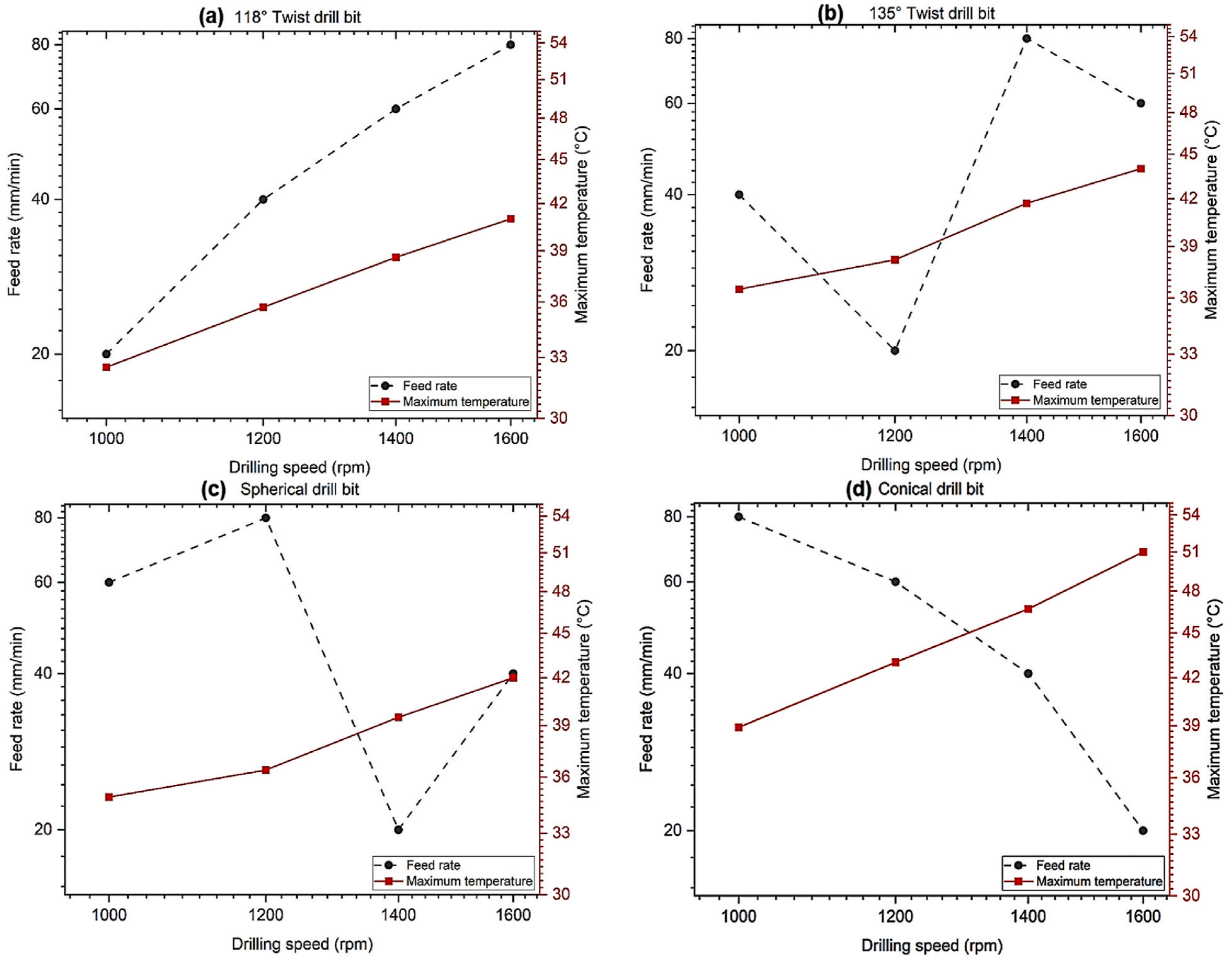

Fig. 7. Line plot for drilling speed vs feed rate and temperature ((a) 118° Twist Drill Bit, (b) 135° Twist Drill Bit, (c) Spherical Drill Bit, and (d) Conical Drill Bit)

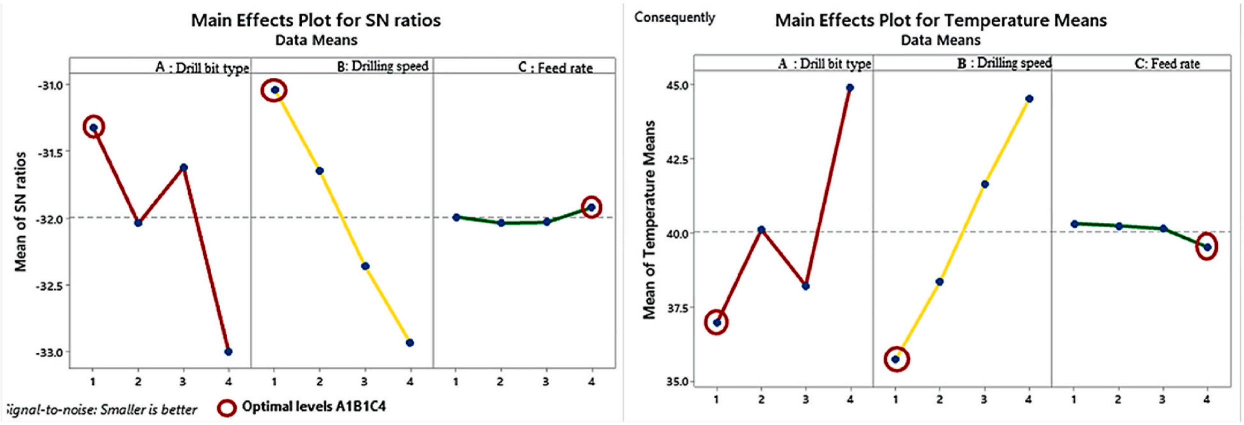

Fig. 8. Mean signal-to-noise ratios (a), and mean of temperature means (b)

the percentage contribution 'P' of each process parameter to the total SS_T, divide the sum of squared deviations (SS_d) associated with that parameter by the overall SS_T [49,50].

In statistical analysis, the F test is important for determining the impact of various process parameters on drilling quality attributes.

The F test requires computing the mean of squared deviations (SS_m) for each drilling parameter. SS_m is calculated by dividing the sum of squared deviations (SS_d) by the degrees of freedom associated with the specific drilling parameters. Following this computation, the F value for each process parameter is calculated by dividing SS_m by the mean squared error (SS_e). An F value greater than one numerical value indicates a significant impact of the process parameter variation on the quality features [51].

Table 6 shows the outcomes of the analysis of variance (ANOVA) for the drilling temperature of the polyurethane block. The findings indicate a notable impact of variations in drilling parameters, as specified in Table 2, on the temperature increase. This is substantiated by F values exceeding one for both drill bit type and drilling speed parameters. Consequently, with reference to Table 5 and Fig. 8, the most favorable drilling settings are identified as A1B1C4 for factors A, B, and C, respectively.

The ANOVA analysis indicates that among the considered drilling process parameters, drilling speed has the most significant impact on heat elevation characteristics, with a significant percentage contribution of 53.24 %. Table 6 provides additional insights, revealing a decreasing order of percentage contributions for other parameters, namely drill bit type (29.08 %) and feed rate (0.38 %).

3.4. Verification and confirmation test

After determining the most efficient combination for drilling process parameters, the subsequent phase entails verifying the percentage variation in temperature decrease between the predicted and observed values for this optimal set. Table 7 provides a comparative assessment of the results derived from confirmation experiments using the suggested drilling parameter combination is A1B1C4, that is, the drill bit type of the process parameters is 118° Twist drill bit, the drilling speed is 1000 rpm and feed rate is 80 mm/min acquired through the proposed methodology. Table 7 compares the initial and optimal drilling parameters, predicting and experimentally validating the impact on the maximum temperature reached during drilling. The initial drilling parameters refer to the starting values of the drilling parameters utilized in the initial experiments, which are denoted as A1B1C1. On the other hand, the optimal drilling parameters represent the levels of drilling parameters that have been found to be optimal and are denoted as A1B1C4. Predictions refer to the maximum temperature and S/N ratio that are predicted based on the optimal parameters. Lastly, the error range specifies the range of error for the S/N ratio between the prediction and the experimental results.

3.5. Limitations and future research directions

1 The primary aim of this study is to investigate the potential use of polyurethane foam as a substitute for human bone. Although it is commonly used as a testing material for orthopedic devices, the precise biomechanical properties of polyurethane have not been fully understood. Therefore, conduct experimental studies using real bone specimens to validate the findings obtained with polyurethane foam. This would provide a more accurate representation of the thermal effects during bone drilling in clinical settings.
2 Explore the impact of biological factors on the drilling process, including the influence of blood flow, tissue reactions, and the role of cells in bone regeneration. This would contribute to a more comprehensive understanding of bone drilling in a physiological context. However, this study focuses solely on the thermal aspects of bone drilling and does not consider biological responses or interactions with living tissues.
3 Synthetic bones are designed to mimic the mechanical properties of natural bones, but their microhardness may differ. This difference can influence the drilling process, as harder materials typically generate more heat. The microhardness of natural bones varies depending on their type (cortical vs. cancellous) and location. This variability can affect drilling outcomes, including heat generation and tool wear.
4 An interesting topic for further research is to develop and integrate computational models that simulate the thermo-mechanical behavior of bone during drilling. This could allow for a more detailed analysis of complex scenarios and facilitate the optimization of drilling parameters in silico before experimental validation.

4. Conclusion

This work describes an experimental approach for thermo-mechanical damage during the polyurethane synthetic bone drilling process, which employs various drill bit shapes. The inquiry also looked into how the Taguchi method may be utilized to optimize the process parameters involved in drilling operations. As previously stated, the Taguchi method's parameter design part provides a simple, methodical, and successful technique to improving parameter impact. Drilling parameters such as speed, feed, and drill bit shape all have an impact on the maximum temperature rise when drilling polyurethane synthetic bone blocks, which are used to

Table 6
ANOVA analysis for drilling parameters

Symbol	Drilling parameters	DF	Sum of square	Mean of square	F value	P value	Contribution %
A	Drill bit type	1	96.360	96.360	20.16	0.001	29.08
B	Drilling speed	1	176.418	176.418	36.91	0.000	53.24
C	Feed rate	1	1.250	1.250	0.26	0.618	0.38
Residual Error	–	12	57.349	4.779	–	–	17.30
Total	–	15	331.378	–	–	–	100

Table 7
Verifications and confirmation of the results

	Initial drilling parameters	Optimal drilling parameters		
		Prediction	Experiment	Error range
Level	A1B1C1	A1B1C4	A1B1C4	–
Maximum Temperature (°C)	32.5	32.0	29	–
ΔT (°C) = $T_{optimal}$ - $T_{initial}$	29–32.5 = −3.5 °C			–
S/N ratio (dB)	−30.2377	−30.2844	−30.2800	±0.0044

The analysis shows that the maximum temperature decreased from 32.5 °C to 29 °C with optimal parameters, resulting in a ΔT of −3.5 °C. The negative sign signifies a reduction in temperature. The S/N ratio slightly differed, with initial parameters at −30.2377 dB, predicted optimal at −30.2844 dB, and experimental optimal at −30.2800 dB, within an error range of ±0.0044 dB, demonstrating improved temperature control and prediction accuracy. These findings demonstrate that the optimal configuration (A1B1C4) of the drilling process parameters is effective in lowering the temperature during the drilling of polyurethane (PUR) synthetic bone blocks.

replace human bone.

The results of the investigation can be outlined in the following manner.

- Out of the four types of drill bits mentioned (twist 118°, twist 135°, spherical, and conical), the conical shape produces the highest drilling temperature. This could be due to factors such as the increased friction and contact area of the conical shape with material being drilled, leading to more heat generation.
- The highest temperature increase occurs when drilling speed is high and feed rate is low, which means that when the drilling tool moves quickly through the material but takes longer to advance, it generates more heat. This combination leads to the maximum temperature rise during the polyurethane synthetic bone drilling process.
- To minimize drilling temperature, it is recommended to utilize a standard twist drill bit with smaller cutting point angle in conjunction with slower drilling speed and a faster feed rate.
- The drilling speed contributes 53.24 %, the drill bit type contributes 29.08 %, and the feed rate contributes 0.38 % to the temperature rise during drilling. This means that the drilling speed has the highest impact on temperature rise, followed by the drill bit type, while the feed rate has the least impact.

This study helps in enhancing the safety and quality of drilling surgeries. Also contribute to the substitution of actual bone in initial clinical trials and provide support to specialists or surgical robot systems in their automated assistance solutions.

CRediT authorship contribution statement

Md Ashequl Islam: Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nur Saifullah Kamarrudin:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Muhammad Farzik Ijaz:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tatsuya Furuki:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Khairul Salleh Basaruddin:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ruslizam Daud:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Muhammad Farzik Ijaz reports administrative support and article publishing charges were provided by Researchers Supporting Project number (RSPD2024R1072), King Saud University, Riyadh, Saudi Arabia. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Y. Dong, et al., Global incidence, prevalence, and disability of vertebral fractures: a systematic analysis of the global burden of disease study 2019, Spine J. 22 (5) (2022) 857–868.
[2] G. Adami, et al., Osteoporosis in 10 years time: a glimpse into the future of osteoporosis, Ther. Adv. Musculoskelet. Dis. 14 (2022) 1–14.

[3] F.D. Al-Shalawi, et al., Biodegradable synthetic polymer in orthopaedic application: a review, Mater. Today Proc. 74 (2023) 540–546.

[4] H. Tian, X. Dang, D. Meng, B. Tian, J. Li, Influence of drilling parameters on bone drilling force and temperature by FE simulation and parameters optimization based Taguchi method, Alex. Eng. J. 75 (2023) 115–126.

[5] M.E. Cooke, et al., 3D printed polyurethane scaffolds for the repair of bone defects, Front. Bioeng. Biotechnol. 8 (October) (2020) 1–10.

[6] M. Fernandes, E. Fonseca, T. Teixeira, R. Jorge, Dynamic numerical simulation of different drill bit diameter on the polyurethane foams drilling, MATTER Int. J. Sci. Technol. 3 (3) (2017) 1–12.

[7] N.S. Patel, P.L. Parihar, J.S. Makwana, Parametric optimization to improve the machining process by using Taguchi method: a review, Mater. Today Proc. 47 (2021) 2709–2714.

[8] N.E. Putra, J. Zhou, A.A. Zadpoor, Sustainable sources of raw materials for additive manufacturing of bone-substituting biomaterials, Adv. Healthcare Mater. 2301837 (2023).

[9] B. Naureen, A.S.M.A. Haseeb, W.J. Basirun, F. Muhamad, Recent advances in tissue engineering scaffolds based on polyurethane and modified polyurethane, Mater. Sci. Eng. C 118 (August 2020) (2021) 111228.

[10] D. Cao, J. Ding, Recent advances in regenerative biomaterials, Regen. Biomater. 9 (December) (2022).

[11] S.D. Mustafov, F. Sen, M.O. Seydibeyoglu, Preparation and characterization of diatomite and hydroxyapatite reinforced porous polyurethane foam biocomposites, Sci. Rep. 10 (1) (2020) 1–9.

[12] M.I. Echeverria Molina, K.G. Malollari, K. Komvopoulos, Design challenges in polymeric scaffolds for tissue engineering, Front. Bioeng. Biotechnol. 9 (June) (2021) 1–29, https://doi.org/10.3389/fbioe.2021.617141.

[13] A. Bharadwaz, A.C. Jayasuriya, Recent trends in the application of widely used natural and synthetic polymer nanocomposites in bone tissue regeneration, Mater. Sci. Eng. C 110 (January) (2020) 110698.

[14] N.A. Muhayudin, K.S. Basaruddin, F. McEvoy, A. Tansey, Evaluating compressive properties and morphology of expandable polyurethane foam for use in a synthetic paediatric spine, J. Mater. Res. Technol. 9 (2) (2020) 2590–2597.

[15] Z. Jiao, S. Lyu, L. Wang, C. You, M. Chen, Improving the mechanical properties and corrosion resistance of biodegradable Mg-Zn-Ca-Mn alloy bone screw through structural optimization, J. Mater. Res. Technol. 21 (2022) 1442–1453.

[16] J. Szalma, B.V. Lovász, L. Vajta, B. Soós, E. Lempel, S.C. Möhlhenrich, The influence of the chosen in vitro bone simulation model on intraosseous temperatures and drilling times, Sci. Rep. 9 (1) (2019) 1–9.

[17] A. Ho-Shui-Ling, J. Bolander, L.E. Rustom, A.W. Johnson, F.P. Luyten, C. Picart, Bone regeneration strategies: engineered scaffolds, bioactive molecules and stem cells current stage and future perspectives, Biomaterials 180 (2018) 143–162.

[18] N.C. Deresse, V. Deshpande, I.W.R. Taifa, Experimental investigation of the effects of process parameters on material removal rate using Taguchi method in external cylindrical grinding operation, Eng. Sci. Technol. an Int. J. 23 (2) (2020) 405–420.

[19] X. Feng, S. Zhang, Z. Luo, H. Liang, B. Chen, F. Leung, Development and initial validation of a novel thread design for nonlocking cancellous screws, J. Orthop. Res. 40 (12) (2022) 2813–2821.

[20] A. Feldmann, M. Schweizer, S. Stucki, L. Nolte, Experimental evaluation of cortical bone substitute materials for tool development, surgical training and drill bit wear investigations, Med. Eng. Phys. 66 (2019) 107–112.

[21] A. Kirillova, et al., Fabrication of biomedical scaffolds using biodegradable polymers, Chem. Rev. 121 (18) (2021) 11238–11304.

[22] N. Bertollo, H.R.M. Milne, L.P. Ellis, P.C. Stephens, R.M. Gillies, 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 (6) (2010) 613–617.

[23] L. Comuzzi, M. Tumedei, A. Piattelli, G. Iezzi, Osseodensification drilling vs. Standard protocol of implant site preparation: an in vitro study on polyurethane foam sheets, Prosthesis 2 (2) (2020) 76–86.

[24] M.A. Islam, N.S. Kamarrudin, R. Daud, I. Ibrahim, Z.M. Razlan, M.F.H. Rani, Drill bit design and its effect on temperature distribution and osteonecrosis during implant site preparation: an experimental approach, J. Phys. Conf. 2643 (1) (Nov. 2023) 012020.

[25] M.G. Fernandes, E.M.M. Fonseca, R.N. Jorge, M. Vaz, M.I. Dias, Thermal analysis in drilling of ex vivo bovine bones, J. Mech. Med. Biol. 17 (5) (2017) 1750082.

[26] K. Alam, A. Al-Ghaithi, S. Piya, A. Saleem, In-vitro experimental study of histopathology of bone in vibrational drilling, Med. Eng. Phys. 67 (2019) 78–87.

[27] M.A. Islam, N.S. Kamarrudin, R. Daud, S.N.F.M. Noor, A.I. Azmi, Z.M. Razlan, A review of surgical bone drilling and drill bit heat generation for implantation, Metals 12 (11) (2022) 1900.

[28] M.F.A. Akhbar, A.R. Yusoff, Comparison of bone temperature elevation in drilling of human, bovine and porcine bone, Procedia CIRP 82 (July) (2019) 411–414, https://doi.org/10.1016/j.procir.2019.03.220.

[29] W.W. Wu, Y.B. Zhu, W. Chen, S. Li, B. Yin, J.Z. Wang, Y.Z. Zhang, Bone hardness of different anatomical regions of human radius and its impact on the pullout strength of screws, Orthop. Surg. 11 (2) (2019) 270–276.

[30] S. Li, J.Z. Wang, B. Yin, Z.S. Hu, X.J. Zhang, W. Wu, Y.Z. Zhang, Atlas of human skeleton hardness obtained using the micro-indentation technique, Orthop. Surg. 13 (4) (2021) 1417–1422.

[31] M. Mathew, K. Shenoy, K.S. Ravishankar, Vickers hardness and specifi c wear rate of poly propylene reinforced PMMA, Int. J. Sci. Stud. 2 (3) (2014) 71–75.

[32] S. Fernando, M. McEnery, S.A. Guelcher, Polyurethanes for bone tissue engineering, Advances in polyurethane biomaterials (2016) 481–501.

[33] M.J. Smith, S. James, T. Pover, N. Ball, V. Barnetson, B. Foster, V. Walton, Fantastic plastic? Experimental evaluation of polyurethane bone substitutes as proxies for human bone in trauma simulations, Leg. Med. 17 (5) (2015) 427–435.

[34] P.S.D. Patel, D.E.T. Shepherd, D.W.L. Hukins, Compressive properties of commercially available polyurethane foams as mechanical models for osteoporotic human cancellous bone, BMC Muscoskel. Disord. 9 (2008) 5–11.

[35] F.P. Ellis, The control of operating-suite temperatures, Occup. Environ. Med. 20 (4) (1963) 284–287.

[36] P.G. Kapse, K.S. Thakare, R.K. Yeltiwar, S.R. Parwani, M.A. Ashtankar, N.B. Rathi, Thermal effect of operatory room temperature, surgical drill diameter, and temperature of irrigants at different depths of implant site preparation–thermographic analysis on goat mandible, J. Indian Soc. Periodontol. 26 (1) (2022) 32–36.

[37] K. Alam, et al., Effect of drill quality on biological damage in bone drilling, Sci. Rep. 13 (1) (2023) 1–13, https://doi.org/10.1038/s41598-023-33381-y.

[38] R.A. Fisher, Statistical Methods for Research Workers, Springer, New York, NY, 1992, pp. 66–70.

[39] W.H. Chen, et al., A comprehensive review of thermoelectric generation optimization by statistical approach: Taguchi method, analysis of variance (ANOVA), and response surface methodology (RSM), Renew. Sustain. Energy Rev. 169 (September) (2022) 112917.

[40] P. Antil, S. Kumar Antil, C. Prakash, G. Królczyk, C. Pruncu, Multi-objective optimization of drilling parameters for orthopaedic implants, Meas. Control 53 (9–10) (2020) 1902–1910.

[41] J.E. Manikanta, B.N. Raju, N. Ambhore, S. Santosh, Optimizing sustainable machining processes: a comparative study of multi-objective optimization techniques for minimum quantity lubrication with natural material derivatives in turning SS304, Int. J. Interact. Des. Manuf. (2024) 1–12.

[42] J. Sui, C. Wang, N. Sugita, Experimental study of temperature rise during bone drilling process, Med. Eng. Phys. 78 (2020) 64–73.

[43] M.A. Islam, N.S. Kamarrudin, R. Daud, I. Ibrahim, S.A. Bakar, S.N.F.M. Noor, Quantifying the impact of drilling parameters on temperature elevation within bone during the process of implant site preparation, Journal of Advanced Research in Applied Mechanics 116 (1) (2024) 1–12.

[44] A.R. Vazquez, P. Goos, E.D. Schoen, Constructing two-level designs by concatenation of strength-3 orthogonal arrays, Technometrics 61 (2) (2019) 219–232.

[45] N. K., M. Sugiyama, The degrees of freedom of partial least squares regression, Taylor Fr 1 (494) (2016) 1–23.

[46] J. Sui, N. Sugita, Experimental study of thrust force and torque for drilling cortical bone, Ann. Biomed. Eng. 47 (3) (2019) 802–812.

[47] M.A. Islam, N.S. Kamarrudin, M.F.F. Suhaimi, R. Daud, I. Ibrahim, F. Mat, Parametric investigation on different bone densities to avoid thermal necrosis during bone drilling process, J. Phys. Conf. 2051 (1) (2021).

[48] V. Gupta, P.M. Pandey, Experimental investigation and statistical modeling of temperature rise in rotary ultrasonic bone drilling, Med. Eng. Phys. 38 (11) (2016) 1330–1338.

[49] S. Athreya, Y.D. Venkatesh, Application of Taguchi method for optimization of process parameters in improving the surface roughness of lathe facing operation, Int. Ref. J. Eng. Sci. 1 (3) (2012) 13–19.
[50] K. Krishnaiah, P. Shahabudeen, Applied Experimental Design and Taguchi Method, 2012.
[51] A.N. Siddiquee, Z.A. Khan, P. Goel, M. Kumar, G. Agarwal, N.Z. Khan, Optimization of deep drilling process parameters of AISI 321 steel using Taguchi method, Procedia Mater. Sci. 6 (Icmpc) (2014) 1217–1225.