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Factors Influence on the Broaching Hammering Sound during Cementless Total Hip Arthroplasty

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ABSTRACT

Background: The aim of this study is to identify the factors influence on the broaching hammering sound character during cementless total hip arthroplasty. Methods: We analyzed frequency spectrum of the hammering sound for 49 cases of uncomplicated cementless THAs using two types of proximal-coated stem performed by experienced surgeons. Normalized sound pressure (NSP) of each 0.5 kHz frequency band in final stage of broach procedure was determined by the fast Fourier transform analysis. The relationships between those sound characteristics and femoral morphology such as canal calcar ratio (CCR), Canal flare index (CFI), morphological cortical index (MCI) and femoral shaft length (FSL) in different cementless stem were investigated. Results: In Accolade 2, CCR was positively related to NSP in several bands [Frequency band (kHz); r: 2.0 - 2.5; 0.37, 4.5 - 5.0; 0.37, 9.5 - 10.0; 0.44], and negatively related to 7.5 - 8.0 kHz (r = −0.39). Negative correlations were observed among CFI and MCI in specific frequency bands (4.5 - 5.0, 5.0 - 5.5, and 7.5 - 8.0 kHz). In Taperloc Microplasty, strong correlations were found between FSL and the NSP of 7.5. - 8.0 kHz (r = 0.78) and CCR and the 7.5 - 8.0 kHz bands. There was significant difference of NSPs between high and low group divided by morphological parameters. Acoustic characteristics of NSPs between Accolade 2 and Microplasty were significantly different in 9 frequency bands. Conclusions: The hammering sound correlated with four parameters of the femoral morphology and differed in different types of proximal-coated stem. Those novel five factors are important to consider when to predict complications using acoustic

analysis.

1. INTRODUCTION

Total hip arthroplasty (THA) is one of the most successful surgical treatments and is reported to greatly reduce pain and restore hip function and the quality of life of patients with end-stage hip disease in both short-term and long-term follow-up [1, 2]. As the population ages, the demand for primary THA and revision THA has been increasing rapidly in recent years [3].

Although the use of cementless fixation in THA has gained its popularity, complications, such as intraoperative femoral fracture and implant subsidence, can occur after stem size mismatch and insufficient initial stem stability [4, 5]. These complications can compromise the surgical effect and increase the risks of dislocation, aseptic implant loosening and revision surgery [6, 7].

New technologies, such as preoperative three-dimensional (3D) templating, intraoperative navigation have been used to avoid inadequate stem selection and achieve better stem position [8, 9]. Vibration analysis has demonstrated the possibility to monitor the intraoperative femoral fracture and initial stem stability [10]. In addition to those, because experienced surgeons use the auditory sensation of a hammering sound during stem insertion to determine proper/improper stem sitting, researchers have attempted to analyze these changes to evaluate the implant insertion [11, 12]. Morohashi *et al.* reported an acoustic frequency patterns that 7 kHz was the most prominent frequency in patients without post-operative complication [11]. Sakai *et al.* reported frequency around 2 kHz and 3 kHz had highest peaks when proximal femoral fracture occurred [12, 13]. McConnell *et al.* reported that a frequency around 1 kHz could better predict an adequately sized stem using spectrographs [14]. Goossens *et al.* reported that frequency below 2 kHz was crucial to reflect the process of implant insertion [15]. And our previous study demonstrated a successful result that used both low and high range frequency acoustic parameters to predict postoperative stem subsidence [16].

Although these studies demonstrated that acoustic analysis has a great potential to help surgeons to make decision on the implant insertion, questions have been raised about why the essential frequency band that had been reported are different and what causes the difference. By following reasons, we hypothesized that four femoral morphological parameters such as canal calcar ratio and the usage of different femoral implant affect the process of implant insertion causing the various results of essential frequency. Because, from acoustical point of view, those factors could change a vibration mode of implant-femur composite and might lead different results. Indeed, the femoral morphology is different among races, and the shape and weight of instrument differ among industries. Therefore, we asked one question: Is the hammering sound affected by the femoral morphology and type of femoral implant?

This study was conducted to objectively analyze the relationship among the broaching hammering sound characteristics and femoral morphology and different usage of femoral implant.

2. METHODS

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The study protocol was approved by the Institutional Ethics Committee. Informed consent was obtained in a manner approved by the Ethics Committee from all individual participants included in this study. From November 2018 to July 2021, 116 patients (124 hips) undergone Primary THA for osteoarthritis (OA) and femoral head necrosis (FHN) who agreed to participate to this study were initially included (**Figure 1**). Exclusion criteria were 1) the surgery used prosthesis other than Accolade II femoral hip stem (Accolade II, Stryker, Tokyo, Japan) and Taperloc Complete Microplasty stem (Taperloc, Biomet, Tokyo, Japan), 2) the surgery was performed by a junior surgeon, 2) the surgery used different surgical instruments, 4) patients had stem subsidence (>3 mm) at one month post-operation and 5) and patients who lost to follow-up. After reviewing the inclusion and exclusion criteria, 35 patients (average age: 66.0 ± 11.3 years) who received the Accolade II stem and 14 patients (average age: 72.4 ± 7.4 years) who received the Taperloc stem were included in this study (Table 1).

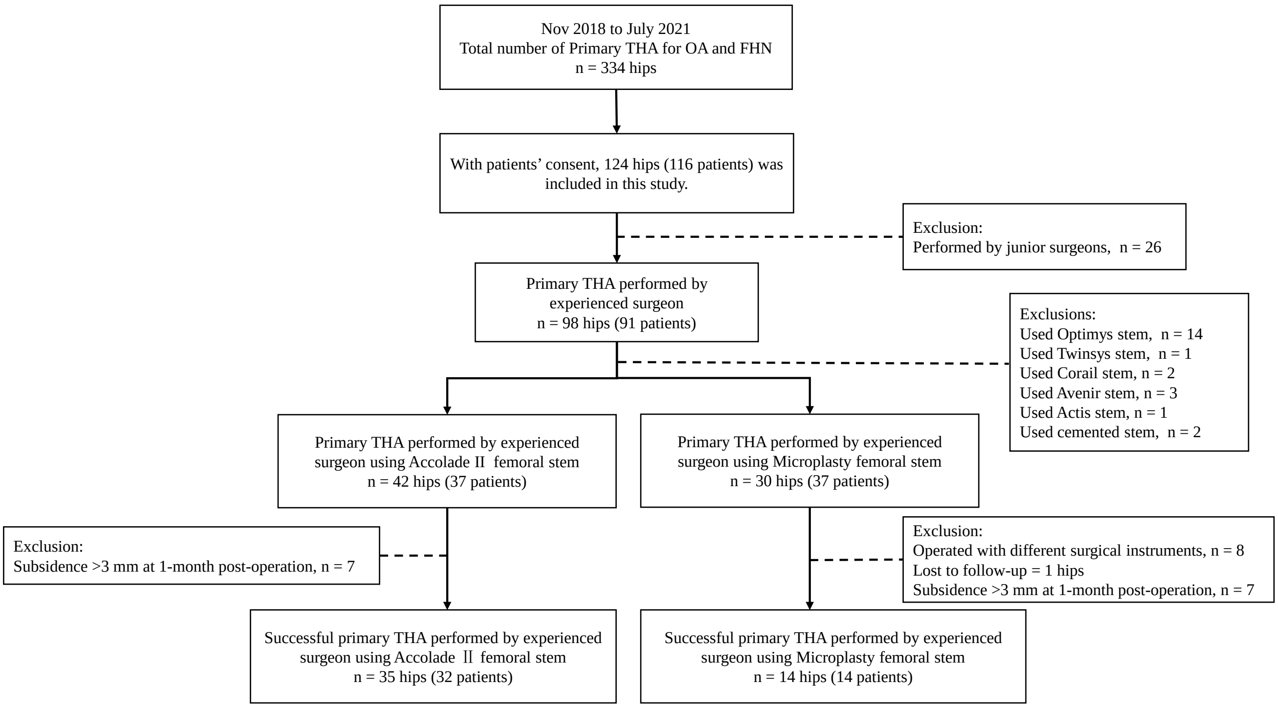

Figure 1. Study flowchart. THA, total hip arthroplasty; OA, osteoarthritis; FHN, femoral neck necrosis.

Table 1. Patient characteristics and femoral morphology.

Variable	Accolade II	Taperloc Microplasty	
Basic characteristic			P value
Number	35	14	
Age	65.7 ± 11.3	72.4 ±7.4	0.048*
Female sex, n (%)	29 (83)	12 (86)	
Height, m	1.55± 0.07	1.54 ± 0.11	0.602
Weight, kg	58.38± 11.71	54.77 ± 11.46	0.345
BMI, kg/m^2	24.04 ± 3.69	22.89 ± 2.71	0.305
Femoral morphology			
Canal-Calcar Ratio	0.46 ± 0.09	0.48 ± 0.14	0.397
Canal Flare Index	3.68 ± 0.70	3.50± 1.02	0.497
Morphologic Cortical Index	2.94 ± 0.36	2.92 ± 0.68	0.873
Canal-Bone Ratio	0.46 ± 0.06	0.49 ± 0.90	0.222
Femoral shaft length, m	330.9 ±19.2	332±24.9	0.848

BMI: Body Mass Index, LT: Lesser Trochanter. * Significant difference.

These surgeries were performed by four experienced orthopedic surgeons via the direct anterior approach using the distal part of the Smith-Petersen approach with the patient in the supine position on a surgical traction table [17]. All surgeries were performed using the corresponding surgical instruments provided by the manufacturers except the surgical hammer, which we used a lightweight hammer (Stainless hammer 01-412-01 Large, Mizuho Medical, Tokyo, Japan) to achieve better control of the hammer blows. And all surgeons followed same impaction technique of delivering a rapid series of light blows to insert the broach. All patients underwent standardized postoperative rehabilitation with full weight bearing one-day post-surgery.

A highly sensitive sound level meter (LA-7500, Onosokki, Kanagawa, Japan) was used to record the hammering sound of the broach and stem insertion. In all cases, the sound level meter was set on a tripod mount at 1 m high and 2 m away from the surgical table in the same operating room (**Figure 2**). Recordings were made in the range of 40 - 110 dB using Z frequency weighting (flat-weighted filter) and fast time weighting at a sampling rate of 64 kHz and a 16-bit sampling depth.

Oscope ver 2.1, (Onosokki, Kanagawa, Japan) was used for the sound analysis. Recorded sound data were analyzed using a rectangular weighted window and 50% overlap at a maximum range of 10.0 kHz via fast Fourier transform (FFT) analysis. The second to fourth hammering sounds from the end were defined as hammering sounds of broaching procedure. If noises were mixed in with these hammering sounds, or an improper hammer blow, such as slipping off the broach handle or double hammering caused by hammer bounce, was detected on the spectrogram, those hammering sound would be switched to the previous or next one.

The frequency spectrum of the hammering sounds in broaching procedure was first divided into 19 frequency bands in the range of 0.5 kHz from 0 to 10.0 kHz. Then each frequency band was measured in two ways: sound pressure (SP) and normalized sound pressure (NSP). SP quantifies the exact value of each frequency band. NSP is calculated as the ratio of the SP of each frequency band over the total frequency spectrum, which reflects spectral power distribution of the hammering sound independent on the strength of hammering blow. The 0 - 0.5 kHz frequency band was excluded from the analysis because this frequency band was inevitably mixed with noises in the operating room, such as the noise of air conditioner and speaking voice, etc. Next, correlations were determined between the femoral morphology, NSP of the hammering sound of broaching procedure. Lastly, the parameters of femoral morphology had been divided into two groups based on low and high value from the median value, the NSP of these groups was compared according to those two groups.

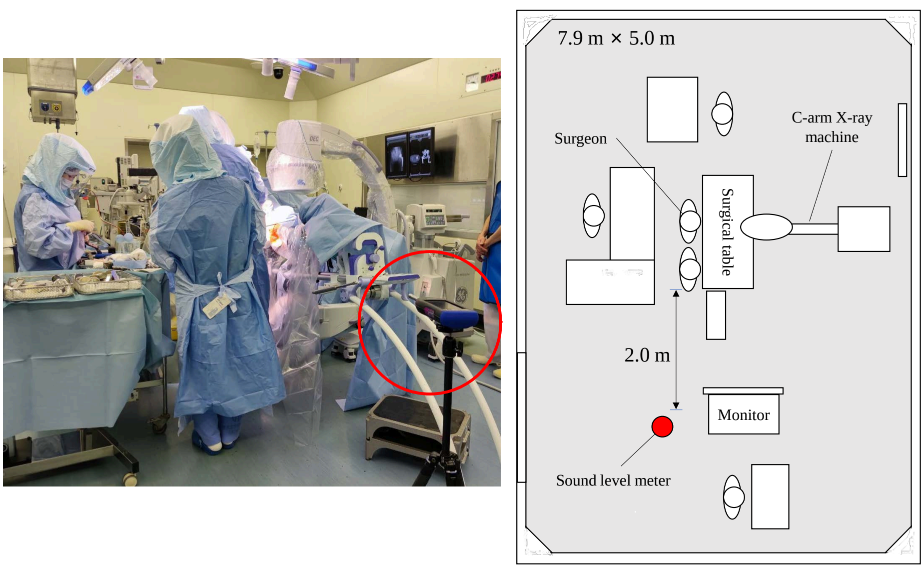

Figure 2. Recording environment. The sound level meter was set 2 m away from the surgical table.

Radiographs of the femoral morphology were assessed using the final preoperative and immediate postoperative Anterior Posterior hip radiographs. Preoperative radiographs were used to analyze 4 morphologic parameters as follows [18]. 1) Canal-calcar ratio (CCR): ratio of the intracortical diameter of the femoral canal isthmus at 10 cm below the lesser trochanter to the intracortical diameter of the proximal femur at the medial tip of the lesser trochanter. 2) Canal-flare index (CFI): ratio of the intracortical diameter of the proximal femoral isthmus at 2 cm above the lesser trochanter to the intracortical diameter of the femoral canal isthmus at 10 cm below the lesser trochanter. 3) Morphologic cortical index (MCI): ratio of the extracortical diameter of the femur at the medial tip of the lesser trochanter to the intracortical femoral diameter at 7 cm below the lesser trochanter. 4) Femoral shaft length (FSL): the distance from the level of midpoint between great trochanter and lesser trochanter to the intercondylar fossa [19].

A single observer (S.I) who was not involved in the sound analysis analyzed the measurements. Radiographs were assessed using the ruler function of the Picture Archiving and Communication System at our institution (Fujifilm Synapse 3.2.1 SR-356; Fujifilm Corp, Tokyo, Japan).

The natural frequencies (<10 kHz) of surgical instruments (**Figure 3**) used in THA surgery, including femoral broach, broach handle, femoral stem, stem impactor and surgical hammer were analyzed in an anechoic room using a previously described method [11].

Statistical analysis was performed using JMP Pro 16. Patient demographics are expressed as the mean ± standard deviation. Wilcoxon signed-rank tests were used to compare paired data. Mann whitney U tests were used to compare independent data. Spearman rank correlation and univariate linear regression were used to evaluate relationships between variables. Differences and correlations were considered statistically significant if $p < 0.05$.

3. RESULTS

Several weak correlations were observed between the femoral morphological parameters and NSP of broaching procedure in Accolade II hip system (**Table 2**). CCR was positively related to NSP in several bands [Frequency band (kHz); r: 2.0 - 2.5; 0.37, 4.5 - 5.0; 0.37, 9.5 - 10.0; 0.44], and negatively related to 7.5 - 8.0 kHz ($r = -0.39$). Negative correlations were observed among CFI and MCI in specific frequency bands (4.5 - 5.0, 5.0 - 5.5, and 7.5 - 8.0 kHz). Result of univariate linear regression is shown in **Table 3**.

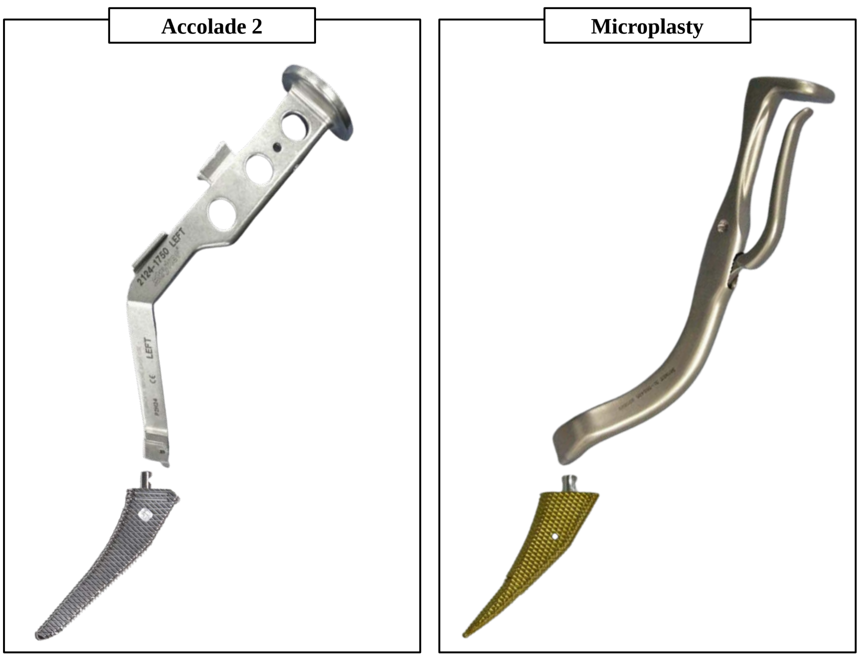

Figure 3. Photograph of the instruments used in this surgery.

Table 2. Correlations between the femoral morphology and the NSPs. Correlations between the femoral morphology and the NSPs in each frequency band of hammering sounds in the final stage of final broaching using Accolade II and Taperloc hip system were demonstrated.

Frequency (kHz)	Broach – SP ratio							
	Accolade II				Taperloc Microplasty			
	CCR	CFI	MCI	FSL	CCR	CFI	MCI	FSL
0.5 - 1.0	0.04	−0.17	−0.11	−0.27	0.03	−0.25	−0.04	−0.45
1.0 - 1.5	0.23	−0.25	−0.24	−0.36*	−0.15	0.12	0.42	−0.28
1.5 - 2.0	−0.09	0.02	0.15	−0.29	−0.48	0.43	0.26	−0.05
2.0 - 2.5	0.37*	−0.31	−0.32	−0.25	−0.21	0.08	0.21	−0.12
2.5 - 3.0	0.06	−0.05	0.11	−0.11	−0.03	0.11	0.44	0.19
3.0 - 3.5	−0.06	0.08	0.11	0.08	−0.53*	0.55*	0.48	−0.34
3.5 - 4.0	0.04	−0.09	0.15	−0.09	−0.33	0.31	0.13	0.35
4.0 - 4.5	0.13	−0.26	−0.15	0.04	−0.12	0.1	−0.15	0.08
4.5 - 5.0	0.37*	−0.42*	−0.38*	0.06	0.06	−0.08	−0.06	−0.25
5.0 - 5.5	0.2	−0.35*	−0.38*	−0.08	−0.47	0.33	0.24	−0.48
5.5 - 6.0	0.02	0.01	−0.04	−0.2	0.14	−0.12	−0.07	−0.14
6.0 - 6.5	−0.31	0.3	0.12	0.2	0.24	−0.13	−0.21	−0.04
6.5 - 7.0	−0.16	0.16	0	0.11	0.05	−0.13	−0.4	0.21
7.0 - 7.5	−0.27	0.29	0.23	0.09	0.2	−0.12	−0.24	0.78**
7.5 - 8.0	−0.39*	−0.40*	0.33	0.32	0.72**	−0.67**	−0.54*	−0.08
8.0 - 8.5	−0.28	0.29	0.23	0.09	0.02	0.05	−0.27	0.44
8.5 - 9.0	−0.24	0.2	0.24	0.12	−0.08	0.09	−0.23	−0.02
9.0 - 9.5	0.07	0.11	−0.01	0.19	−0.12	0.23	0.43	0.01
9.5 - 10.0	0.44**	−0.23	−0.31	0.06	0.02	−0.01	0.18	0.12

*. Correlation is significant at the 0.05 level. **. Correlation is significant at the 0.01 level.

Table 3. Univariate linear regression: Curve is fitted by an ordinary least squares regression. Univariate linear regression between the femoral morphology and the NSPs in each frequency band of hammering sounds in the final stage of final broaching using Accolade II and Taperloc hip system were demonstrated.

Frequency	Broach – SP ratio															
(kHz)	Accolade II								Taperloc Microplasty							
	CCR		CFI		MCI		FSL		CCR		CFI		MCI		FSL	
	β	p value	β	p value	β	p value	β	p value	β	p value	β	p value	β	p value	β	p value
0.5 - 1.0	0	0.97	−0.47	0.53	−0.14	0.72	−22.53	0.29	0.12	0.46	−1.02	0.39	−0.44	0.58	−48	0.1
1.0 - 1.5	0.07	0.59	−1.09	0.25	−0.68	0.16	−50.86	0.05	−0.05	0.74	0.4	0.7	0.81	0.23	−12.56	0.65
1.5 - 2.0	−0.12	0.26	0.46	0.55	0.45	0.26	−35.75	1	−0.27	0.22	2.25	0.16	1.03	0.35	9.98	0.84

Continued

2.0 - 2.5	0.09	0.17	−0.72	0.16	−0.51	0.05*	−13.78	0.33	−0.15	0.32	0.31	0.78	0.53	0.49	0.14	1
2.5 - 3.0	0	1	−0.19	0.66	0.11	0.63	−2.55	0.83	−0.06	0.66	0.35	0.72	0.46	0.47	14.66	0.55
3.0 - 3.5	−0.03	0.5	0.21	0.55	0.2	0.29	−3.97	0.69	−0.28	0.07	2	0.08	1.15	0.14	−15.29	0.63
3.5 - 4.0	−0.02	0.73	−0.12	0.72	0.15	0.41	−8.85	0.38	−0.04	0.74	0.23	0.77	0.02	0.97	15.17	0.44
4.0 - 4.5	0.01	0.74	−0.34	0.25	−0.09	0.55	0.24	0.98	−0.06	0.62	0.35	0.68	−0.04	0.94	3.58	0.87
4.5 - 5.0	0.1	0.06	−0.95	0.01*	−0.44	0.03*	−0.65	0.95	0.08	0.54	−0.1	0.95	−0.14	0.83	−24.37	0.36
5.0 - 5.5	0.03	0.25	−0.47	0.03*	−0.23	0.04*	−0.45	0.94	−0.15	0.22	1.01	0.25	0.65	0.27	−14	0.57
5.5 - 6.0	−0.01	0.85	0.27	0.63	0.02	0.95	−19.65	0.2	0.1	0.17	−0.61	0.25	−0.41	0.24	−21.77	0.09
6.0 - 6.5	−0.11	0.13	1.1	0.04*	0.15	0.6	16.19	0.44	0.04	0.82	−0.6	0.6	−0.58	0.45	−3.33	0.92
6.5 - 7.0	−0.12	0.2	0.87	0.2	0.06	0.88	10.01	0.64	−0.04	0.82	−0.37	0.75	−0.79	0.29	23.57	0.49
7.0 - 7.5	−0.08	0.27	0.84	0.12	0.33	0.24	9.92	0.53	0.01	0.9	−0.28	0.68	−0.37	0.39	38.46	0.06
7.5 - 8.0	−0.05	0.2	0.62	0.05	0.24	0.14	14.91	0.09	0.3	0.01*	−2.28	0.01*	−1.3	0.04*	−9.04	0.72
8.0 - 8.5	−0.04	0.37	0.48	0.13	0.17	0.3	3.96	0.66	−0.03	0.9	0.52	0.73	−0.59	0.55	37.48	0.3
8.5 - 9.0	−0.03	0.46	0.28	0.3	0.19	0.17	5.35	0.49	0.05	0.7	0.05	0.96	−0.58	0.37	−1.15	0.96
9.0 - 9.5	0.11	0.33	0	1	−0.25	0.57	36.89	0.14	−0.09	0.57	1.07	0.36	1.44	0.05*	11.15	0.7
9.5 - 10.0	0.16	0.03*	−0.77	0.17	−0.53	0.07	2.35	0.88	0.04	0.83	−0.19	0.89	0.71	0.42	14.92	0.65

*. Significant at the 0.05 level. **. Significant at the 0.01 level.

Regarding the Taperloc Microplasty, strong correlations were found between FSL and the NSP of 7.5 - 8.0 kHz (r = 0.78) and CCR and the 7.5 - 8.0 kHz bands. Also, the band 7.5 - 8.0 kHz and 3.0 - 3.5 kHz band were correlated to the CCR, CFI and MCI. Result of univariate linear regression is shown in **Table 3**.

Compared the NSP of broaching hammering sound between low-value and high-value femoral morphology groups, the Accolade II cases with higher-value CFI had lower NSP in the 2.0 - 2.5 kHz (p = 0.013), 4.5 - 5.0 kHz (p = 0.002), and had higher NSP in the frequency band from 7.0 to 9.0 kHz (**Table 4**). Cases with higher-value CCR had a lower NSP in the 7.5 - 8.0 kHz, but a higher NSP in the 9.5 - 10.0 kHz frequency band. Cases with higher-value MCI had lower NSP in the 5.0 - 5.5 kHz frequency band.

As to the cases received Taperloc stem, in the final broach insertion, the NSP of 3.0 - 3.5 kHz frequency band was significantly higher in the cases with higher-value MCI (p = 0.018). The NSP of 7.5 - 8.0 kHz frequency band was significantly higher in the cases with higher-value CCR (p = 0.048) and lower-value CFI (p = 0.048).

Acoustic characteristics of NSPs between Accolade 2 and Microplasty were significantly different in 9 frequency bands (**Figure 4**). The results obtained from the preliminary experiment of natural frequencies of the surgical instruments are shown in **Table 5**.

To summarize, four parameters of femoral morphology were influenced to the hammering sound. And the character of hammering sound in different surgical material was also differed. Thereby, a total of five factors were found to be important affecting the hammering sound.

4. DISCUSSION

In the present study, we performed a full-quantitative post-operative analysis using NSP to quantify the broaching hammering sound. We found that the broaching hammering sound characteristics was correlated with the femoral morphology and type of stem. Those factors should be considered when to predict to complications using the hammering sound analysis.

Table 4. **Comparisons of the NSP between different femoral morphology. Comparisons of the median and interquartile range of NSP of each frequency band of hammering sounds in the final stage of stem insertion between low value groups and high value groups of each femoral morphology.**

	Accolade II broach – SP ratio									Taperloc Microplasty broach - SP ratio								
	CCR			CFI			MCI			CCR			CFI			MCI		
Frequency (kHz)	Low	High	P value	Low	High	P value	Low	High	P value	Low	High	P value	Low	High	P value	Low	High	P value
0.5 - 1.0	0.79 (0.58)	0.82 (0.74)	0.947	0.83 (0.74)	0.77 (0.58)	0.137	0.82 (0.61)	0.79 (0.72)	0.531	0.92 (0.24)	0.91 (0.49)	0.749	0.99 (0.43)	0.86 (0.36)	0.749	0.91 (0.43)	0.92 (0.24)	0.848
1.0 - 1.5	0.70 (0.60)	0.77 (0.41)	0.448	0.80 (0.33)	0.70 (0.60)	0.092	0.76 (0.53)	0.71 (0.44)	0.291	1.16 (0.28)	0.77 (0.72)	0.338	0.94 (0.72)	1.1 (0.44)	0.338	0.94 (0.48)	1.16 (0.64)	0.406
1.5 - 2.0	0.75 (0.52)	0.73 (0.48)	0.531	0.79 (0.55)	0.70 (0.55)	0.448	0.74 (0.55)	0.74 (0.52)	0.468	1.01 (0.28)	0.85 (0.4)	0.18	0.85 (0.4)	1.01 (0.28)	0.18	0.89 (0.4)	0.98 (0.3)	0.482
2.0 - 2.5	0.88 (0.68)	0.92 (1.13)	0.248	0.98 (1.13)	0.80 (0.68)	0.013*	0.95 (1.13)	0.81 (0.63)	0.222	0.97 (0.58)	0.86 (0.23)	0.655	0.86 (0.23)	0.97 (0.58)	0.655	0.84 (0.19)	1.04 (0.58)	0.277
2.5 - 3.0	0.94 (0.77)	0.90 (1.20)	0.921	0.97 (1.2)	0.86 (0.77)	0.235	0.85 (0.96)	0.94 (1.2)	0.338	1.11 (0.25)	1.23 (0.74)	0.848	1.19 (0.31)	1.11 (0.72)	0.848	0.97 (0.28)	1.23 (0.61)	0.277
3.0 - 3.5	1.08 (1.35)	1.07 (0.99)	0.552	1.08 (1.33)	1.07 (1.22)	0.692	1.01 (1.33)	1.09 (1.22)	0.306	0.99 (0.4)	0.86 (0.24)	0.11	0.86 (0.22)	1.09 (0.41)	0.11	0.86 (0.2)	1.09 (0.41)	0.018
3.5 - 4.0	1.13 (1.68)	1.23 (0.96)	0.355	1.23 (1.55)	1.17 (1.08)	0.222	1.18 (1.57)	1.29 (1.09)	0.448	1.2 (0.37)	1.07 (0.75)	0.225	1.07 (0.38)	1.2 (0.48)	0.225	1.14 (0.22)	1.2 (0.49)	0.482
4.0 - 4.5	1.25 (1.39)	1.41 (1.65)	0.235	1.40 (1.65)	1.24 (1.39)	0.069	1.40 (1.64)	1.28 (1.64)	0.692	1.71 (0.41)	1.61 (0.79)	0.482	1.61 (0.73)	1.71 (0.44)	0.482	1.73 (0.67)	1.63 (0.57)	0.949
4.5 - 5.0	1.27 (0.97)	1.50 (1.07)	0.051	1.57 (0.81)	1.21 (0.97)	0.002*	1.50 (1.00)	1.30 (1.16)	0.065	1.42 (0.68)	1.3 (0.55)	0.749	1.38 (0.55)	1.3 (0.68)	0.749	1.38 (0.69)	1.3 (0.51)	0.655
5.0 - 5.5	1.79 (1.84)	1.96 (1.71)	0.306	2.08 (1.71)	1.83 (1.84)	0.166	2.21 (1.69)	1.62 (1.84)	0.009*	1.33 (0.59)	1.17 (0.32)	0.277	1.15 (0.32)	1.33 (0.59)	0.277	1.15 (0.34)	1.32 (0.59)	0.225
5.5 - 6.0	1.13 (0.97)	1.18 (0.86)	0.792	1.20 (0.57)	1.14 (1.00)	0.921	1.20 (0.84)	1.13 (0.97)	0.974	1.24 (0.47)	1.42 (0.88)	0.565	1.39 (0.77)	1.46 (0.76)	0.565	1.42 (0.77)	1.39 (0.76)	0.749
6.0 - 6.5	1.03 (1.21)	0.94 (0.58)	0.121	0.96 (0.58)	1.03 (1.21)	0.322	0.93 (0.73)	1.00 (1.21)	0.644	1.04 (0.48)	1.05 (0.3)	0.848	1.06 (0.27)	1 (0.5)	0.848	1.07 (0.51)	1 (0.13)	0.225
6.5 - 7.0	0.90 (0.72)	0.87 (0.49)	0.692	0.82 (0.49)	0.91 (0.72)	0.121	0.88 (0.6)	0.88 (0.74)	0.448	0.95 (0.56)	0.89 (0.36)	0.949	0.95 (0.35)	0.85 (0.56)	0.949	1.12 (0.49)	0.85 (0.25)	0.142
7.0 - 7.5	0.85 (0.85)	0.87 (1.03)	0.552	0.82 (0.56)	0.94 (0.98)	0.013*	0.82 (1.17)	0.94 (0.67)	0.075	1.1 (0.46)	1.26 (0.38)	0.565	1.26 (0.33)	0.98 (0.46)	0.565	1.28 (1.01)	0.98 (0.4)	0.142
7.5 - 8.0	1.39 (1.55)	1.02 (1.42)	0.044*	0.90 (1.09)	1.40 (1.13)	0.001*	1.07 (1.56)	1.24 (1.41)	0.198	0.96 (0.24)	1.35 (0.57)	0.048*	1.35 (0.41)	0.92 (0.17)	0.048*	1.09 (0.53)	0.92 (0.3)	0.085
8.0 - 8.5	1.40 (1.48)	1.10 (1.17)	0.08	1.09 (1.17)	1.44 (1.24)	0.006*	1.12 (1.11)	1.25 (1.54)	0.575	0.98 (0.22)	0.99 (0.42)	0.848	0.99 (0.42)	0.98 (0.22)	0.848	0.99 (0.28)	0.9 (0.32)	0.18
8.5 - 9.0	1.44 (1.41)	1.07 (1.39)	0.113	1.03 (1.39)	1.52 (1.41)	0.023*	1.12 (1.22)	1.32 (1.54)	0.509	1.08 (0.33)	1.1 (0.35)	0.655	1.1 (0.34)	0.9 (0.4)	0.655	1.1 (0.22)	0.84 (0.58)	0.225
9.0 - 9.5	0.78 (0.46)	0.82 (0.63)	0.717	0.74 (0.63)	0.84 (0.48)	0.235	0.81 (0.63)	0.81 (0.36)	0.531	0.85 (0.13)	0.85 (0.43)	0.848	0.85 (0.43)	0.85 (0.13)	0.848	0.85 (0.32)	0.85 (0.52)	0.655
9.5 - 10.0	0.86 (0.71)	0.95 (0.79)	0.019*	0.94 (0.79)	0.91 (0.71)	0.391	0.95 (0.73)	0.91 (0.79)	0.428	0.61 (0.39)	0.57 (0.3)	0.749	0.63 (0.28)	0.54 (0.39)	0.749	0.57 (0.23)	0.61 (0.57)	0.949

*. Correlation is significant at the 0.05 level. Data was expressed as median (Inter quartile range).

Table 5. Natural frequency of the surgical instruments used in the surgery.

Surgical instruments	Natural frequencies (kHz)						
Accolade II							
Femoral stem	2.7,	4.1,	6.4,	9.2			
Stem inserter	1.0,	2.0,	2.9,	5.2,	7.7,	9.0	
Broach	3.0,	5.0,	6.4,	9.0			
Broach with Broach handle	0.5,	3.1,	5.0,	8.5,	9.7		
Surgical hammer	2.1,	4.4,	8.2				
Taperloc Microplasty							
Femoral stem	4.0,	6.5,	7.5				
Stem inserter	1.0,	2.5,	4.0,	5.5,	8.5		
Broach	4.0,	7.5,	9.5				
Broach with Broach handle	1.5,	2.6,	5.1,	5.9,	7.0,	8.4,	9.5
Surgical hammer	2.1,	4.4,	8.2				

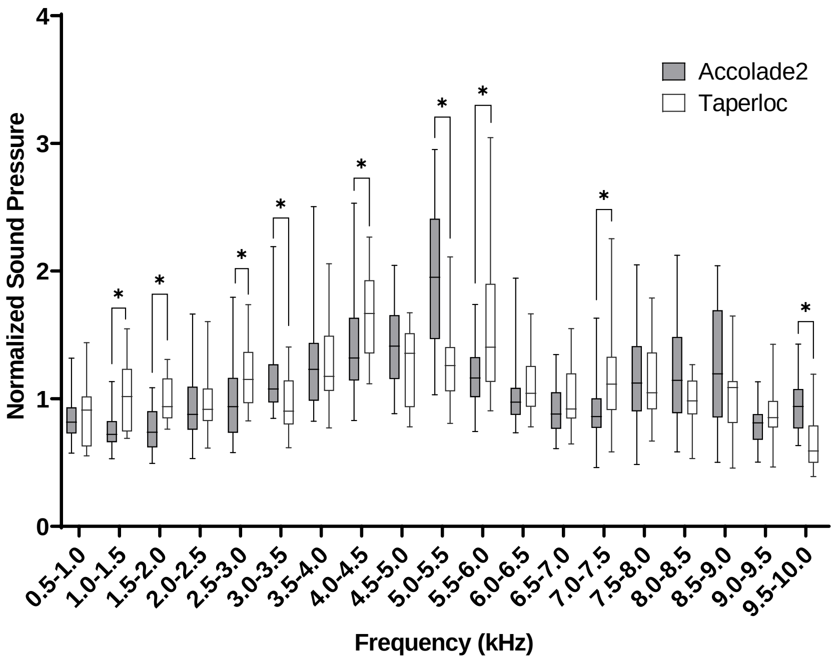

Figure 4. Comparison results of normalized sound pressure between Accolade II and Taperloc Microplasty hip system. Comparison of NSP in the final stage of broaching of procedure between Accolade II and Taperloc Microplasty hip system was made. In specific bands, NSP was significantly different between two groups.

Our study suggest that novel two principals are important for understanding the hammering sound and further study of the sound frequency to assist the surgery. First, femoral morphology affects the hammering sound. In the cases using Accolade II hip system, that NSP of the frequency around 5.0 and 7.5 kHz of broaching had negative correlations with the CFI and MCI. Ideally, a high CFI/MCI indicates that the intracortical diameter of the proximal femoral canal isthmus will be relatively large, and the stem will be less likely to be fixed at the proximal femur which could cause fixation instability. It is highly possible that the difference of femoral morphology may change the vibration mode of stem-femur composite, which lead to altered sound characteristics. The second, sound characteristics differ among different proximal-coated cementless implant types, even though it shares some similarities in common. This difference is explained by two following reasons. One is that each implant system had different instruments having different natural frequency (**Table 4**), which created different sound characteristics. The shape of broaching is also different among different types of stems, which demonstrated different vibration mode of broach-femur composite.

We believe that the NSP could be a useful method to assess the hammering sound, because it reflects the spectral power distribution of each frequency not depending on the strength of hammer blow. An object that vibrates freely produces sound waves that correspond to its natural frequencies. This could also assist in identifying the mode of vibration. Therefore, finding the SP is crucial to acoustic analysis, and applicated to the research in hip arthroplasty field [13-15, 20, 21]. Although the evaluation of SP during implant insertion has been mainstream so far, this method has a major drawback, which the SP could be affected not only by the vibration mode change, but also the strength of a hammer blow. This bias makes difficult to analyze the sound. On the other hand, considering the NSP, it makes us possible to compare the sound characteristics by normalized method independent on the surgeon's hammering manner.

This study had several limitations. First, the sample size was relatively smaller than those in other papers that demonstrate the clinical outcomes. However, this paper is not one that reports clinical outcomes. Despite the number of patients in this study, the statistic methodology was adequate to objectively analyze for sound characteristic data with significant differences. Second, this is a vivo study; the hammering force could not be standardized. Although we averaged the data and used NSP to quantify sound changes, this method still required a baseline of the average overall frequency spectrum. Thus, the frequency range should be chosen carefully. Third, noises in the operating environment, such as suction noise, the electrocardiograph monitoring alarm, could inevitably affect the recorded sound quality. Although the hammering sounds with obvious background noise were excluded, and the noises were minimalized using our analysis method. It is important to find better ways to reduce the noise effect. Moreover, we verified the possibility of clinically use of the acoustic analysis in the most practical sitting environment with noises from the operating field. Further study will be performed to evaluate practicability using acoustic analysis in real-time monitoring.

5. CONCLUSION

This study revealed the quantitative broaching hammering sound correlated with four parameters of the femoral morphology and different types of proximal-coated stem. Those novel five factors should be considered when to predict to complications using the hammering acoustic analysis.

DECLARATIONS

Ethical Approval and Consent to Participate

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The study protocol was approved by the Juntendo University Hospital Ethics Committee. Informed consent was obtained in a manner approved by the Ethics Committee from all individual participants included in this study.

Consent for Publication

Written informed consent was obtained from the patient for publication of this study and any accompanying images and audio files or any other types of file.

Availability of Supporting Data

All data generated or analyzed during this study are included in this published article.

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Authors' Contributions

YH conceived and designed research. YH and TB obtained the data. YH, TS, IM, TS and XZ analyzed data. XZ wrote the initial manuscript. YH revised the manuscript. YH, IM, KK and IM interpretated the data. All authors read and approved the manuscript.

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Authors' Contributions

YH conceived and designed research. YH and TB obtained the data. YH, TS, IM, TS and XZ analyzed data. XZ wrote the initial manuscript. YH revised the manuscript. YH, IM, KK and IM interpretated the data. All authors read and approved the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest regarding the publication of this paper.

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