Differences in acoustic parameters of hammering sounds between successful and unsuccessful initial cementless cup press-fit fixation in total hip arthroplasty

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Aims

It is important to analyze objectively the hammering sound in cup press-fit technique in total hip arthroplasty (THA) in order to better understand the change of the sound during impaction. We hypothesized that a specific characteristic would present in a hammering sound with successful fixation. We designed the study to quantitatively investigate the acoustic characteristics during cementless cup impaction in THA.

Methods

In 52 THAs performed between November 2018 and April 2022, the acoustic parameters of the hammering sound of 224 impacts of successful press-fit fixation, and 55 impacts of unsuccessful press-fit fixation, were analyzed. The successful fixation was defined if the following two criteria were met: 1) intraoperatively, the stability of the cup was retained after manual application of the torque test; and 2) at one month postoperatively, the cup showed no translation on radiograph. Each hammering sound was converted to sound pressures in 24 frequency bands by fast Fourier transform analysis. Basic patient characteristics were assessed as potential contributors to the hammering sound.

Results

The median sound pressure (SP) of successful fixation at 0.5 to 1.0 kHz was higher than that of unsuccessful fixation (0.0694 (interquartile range (IQR) 0.04721 to 0.09576) vs 0.05425 (IQR 0.03047 to 0.06803), $p < 0.001$). The median SP of successful fixation at 3.5 to 4.0 kHz and 4.0 to 4.5 kHz was lower than that of unsuccessful fixation (0.0812 (IQR 0.05631 to 0.01161) vs 0.1233 (IQR 0.0730 to 0.1449), $p < 0.001$; and 0.0891 (IQR 0.0526 to 0.0891) vs 0.0885 (IQR 0.0716 to 0.1048); $p < 0.001$, respectively). There was a statistically significant positive relationship between body weight and SP at 0.5 to 1.0 kHz ($p < 0.001$). Multivariate analyses indicated that the SP at 0.5 to 1.0 kHz and 3.5 to 4.0 kHz was independently associated with the successful fixation.

Conclusion

The frequency bands of 0.5 to 1.0 and 3.5 to 4.0 kHz were the key to distinguish the sound characteristics between successful and unsuccessful press-fit cup fixation.

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Take home message

- The frequency bands of 0.5 to 1.0, and 3.5 to 4.0 kHz were the key to distinguish the sound characteristics between successful and unsuccessful press-fit cup fixation in cementless total hip arthroplasty.
- There was an obvious positive relationship between body weight and sound pressure at 0.5 to 1.0 kHz.

Introduction

The cementless cup has long been a major component in total hip arthroplasty (THA) because of its excellent long-term durability.[1-3] Recent advances in surface manufacturing have led to a higher coefficient of friction, making it easier to achieve initial press-fit mechanical fixation.[4] However, acetabular fracture or failure of initial press-fit fixation still occurs because the hammering procedure to implant the cup in the acetabulum depends largely on the surgeon's skill and judgement.[5,6]

Insufficiently forceful hammering may result in inadequate initial fixation, leading to early cup loosening, while excessive hammering may cause intraoperative acetabular fracture. Several mechanical tests are available to confirm the cup stability intraoperatively, including the torque test,[4,7] lever-out test,[8-10] and hands-free test. Although these tests are useful, they are invasive and potentially destructive to surrounding tissue. Additionally, although surgeons have advocated that it is important to listen to the changes in the hammering sounds that occur during cup impaction, this hearing-based evaluation is completely subjective. Clinical experience is required to understand the hammering sounds that occur during cup impaction, and judge the initial fixation based on these hammering sounds.

Recent research has revealed objective characteristics of hammering sound in broaching procedure and stem insertion.[11,12] It is important to unveil the objective value of hammering sound for cup press-fit procedure so that it might help surgeons to understand the sound change easily during the THA. Moreover, it may be possible to develop an innovative surgery assisting system using the hammering sound if those objective values in the hammering sound for the cup insertion were revealed. Therefore, we hypothesized that a specific characteristic would present in a hammering sound with successful cup press-fit, and that certain patient factors would have an effect on the sound characteristics. We set out to answer the following two questions: first, how do the acoustic characteristics of the hammering sounds during cementless cup impaction differ between successful and unsuccessful initial press-fit fixation?; and second, which patient factors influence the acoustic characteristics during cementless cup impaction? We designed the present study to quantitatively investigate the differences in acoustic characteristics during cementless cup impaction between successful and unsuccessful cases of initial press-fit fixation, and to identify which patient characteristics contribute to the acoustic characteristics during cementless cup impaction.

Methods

Study participants

From November 2018 to April 2022, 457 THA procedures were performed in our hospital. Institutional review board approval was obtained before initiation of the study, and written informed consent was obtained from all included patients. Among these procedures, we included 56 hips of 54 patients who underwent primary THA using the Trident HA acetabular system (Stryker, USA) for osteoarthritis and osteonecrosis of the femoral head, and who agreed to participate in this study (Figure 1). Patient characteristics are shown in Table I.

Because use of the Trident PSL shell (Stryker) was our first-choice protocol, and the Trident hemispheric multi-hole cup was used with a different operative protocol (2 mm under-reaming) when the surgeons judged the patient to be at high risk of initial fixation failure, hips that underwent treatment with the Trident hemispheric multi-hole cup were excluded from this study. Moreover, any hips in which press-fit fixation was reattempted after initial failure were excluded from the analysis because of the possibility of procedural heterogeneity.

Operative procedure and definitions

Several surgeons (YH, TW, KH, and TB) were involved in each procedure. The surgery was performed via the direct anterior approach with the patient in a supine position on a surgical traction table.[13] All surgeries were performed using identical surgical instruments and the same surgical techniques. The same hammer was used by every surgeon. After exposure on the acetabular side, line-to-line reaming was used in all cases. Fluoroscopy was used to verify the position of the acetabular reamer and cup orientation at the time of cup insertion. All patients underwent standardized postoperative rehabilitation with full weightbearing on the first postoperative day.

A single attempt of press-fit fixation was defined as the entire hammering procedure with multiple impacts, which was performed until application of the intraoperative press-fit test. In each attempt, the last five consecutive hammering impact sounds were recorded in all patients except for one, in whom only four hammering impact sounds were performed and recorded. Then, those sounds were labelled as a success or failure of the initial press-fit attempt.

The press-fit fixation was defined as successful if the following two criteria were met, and as unsuccessful if either criterion was not met: intraoperatively, the stability of the cup was retained after manual application of the torque test, lever-out test, or hands-off test accordingly to the surgeon's preference; and the cup showed no translation on radiograph examination within one month postoperatively.

In the event of a failed cup press-fit fixation, the surgeon would routinely remove interposed soft-tissue from around the acetabular edge and repeat the reaming with the same-size reamer. Cup fixation was attempted again, but only the failed attempts were recorded and analyzed for this study.

Sound data acquisition and analysis

All hammering sounds that occurred during cup insertion were recorded using a highly sensitive sound level metre (LA-7500; Ono Sokki, Japan) set on a tripod mounted one metre above from the floor and two metres away from the surgical table. Recordings were made in the range of 40 to 110 dB using a flat weighted filter and fast time-weighting at a 64 kHz sampling rate and a 16-bit sampling depth.

Sound analysis was performed using O-solution software (Ono Sokki). As previously described,[12] the last five consecutive hammering sounds were recorded in each

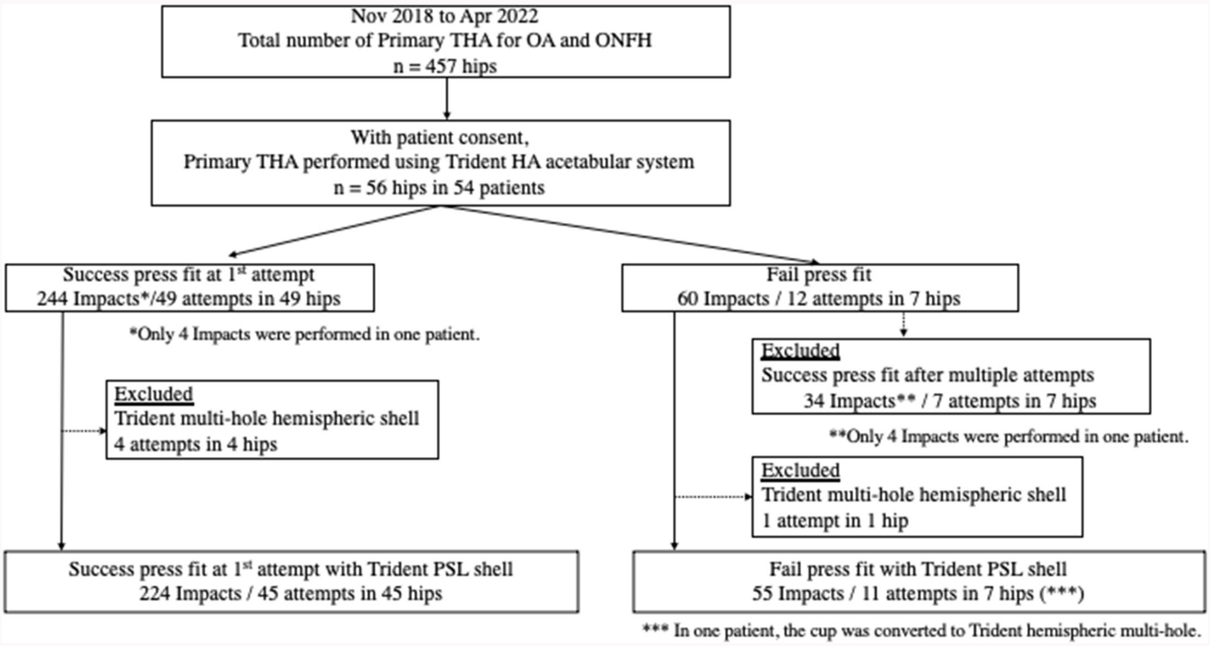

Fig. 1

Study flowchart. A single attempt of press-fit fixation was defined as the entire hammering procedure with multiple impacts, which was performed until application of the intraoperative press-fit test. In each attempt, the last five consecutive hammering impacts sounds were recorded. Then, those impact sounds were labelled as either success or failure of the press fit. The press-fit fixation was defined as successful if the following two criteria were met, and as unsuccessful if either criterion was not met: intraoperatively, the stability of the cup was retained after manual application of the torque test, lever-out test, or hands-off test according to the surgeon's preference; and the cup showed no translation on radiograph examination within one month postoperatively. OA, osteoarthritis; ONFH, osteonecrosis of the femoral head; THA, total hip arthroplasty.

Table I. Patient baseline characteristics.

Characteristic	Total
Number of hips	52
Sex, n	Male: 9, Female: 43
Mean age, yrs (SD)	64.7 (11.02)
Mean height, m (SD)	1.57 (0.09)
Mean weight, kg (SD)	60.54 (13.56)
Mean BMI, kg/m^2 (SD)	24.32 (4.26)
Aetiology, n	OA: 49, ON: 3
Mean cup size (range)	47.8 (44 to 52)

OA, osteoarthritis; ON, osteonecrosis; SD, standard deviation.

attempt before the intraoperative stability test was performed. The first 0.1 seconds of each hammering sound was used for analysis. In this 0.1 second period, the hammer made contact with the impaction handle and immediately caused a composite vibration that generated a soundwave at full amplitude without obvious sound attenuation, allowing us to record the hammering sound while the cup was still vibrating. A noise check was performed before the analysis of the selected hammering sounds; if background noises were detected along with the selected hammering sounds on the spectrogram, the recording with these noises was replaced by the previous or next recording.

First, the recorded hammering sounds were analyzed using a rectangular weighted window at a maximum range of 12.5 kHz via fast Fourier transform analysis. The frequency spectrum of the hammering sounds was divided into 25 frequency bands at 0.5 kHz intervals. The sound pressure (SP) was assessed for each frequency band. The 0.0 to 0.5 kHz frequency band was excluded from the analysis because it was inevitably mixed with background noises, such as the air conditioning and voices. Second, an analysis was performed to address outliers using a quantile range control approach (tail quantile: 1, Q: 3), and the outlier data were not used for the analysis. Finally, the SP (Pa) without the outliers in 24 bands was analyzed in this study.

The SP (Pa) was compared between successful and unsuccessful press-fit fixation procedures. Distinctive frequency band with statistically different SP was defined as a key band in this study. The patients' baseline characteristics, such as age, sex, height, body weight, and cup size, were assessed with regard to their effect on the SP in the key band. Finally, multivariate analysis was performed to determine which sound characteristics in the key bands were associated with successful or unsuccessful press-fit fixation.

Statistical analysis

Patient demographics are expressed as mean and standard deviation (SD). The Mann-Whitney U test was used to compare continuous independent data. Spearman's rank correlations were performed to assess the linear relationship between continuous variables. Differences were considered statistically significant at $p < 0.01$. Post hoc power analysis was performed to determine if the power (1-β) was more than 0.8 ($\alpha = 0.01$). Statistical analysis was performed using JMP Pro software, version 16.0 (SAS Institute, USA).

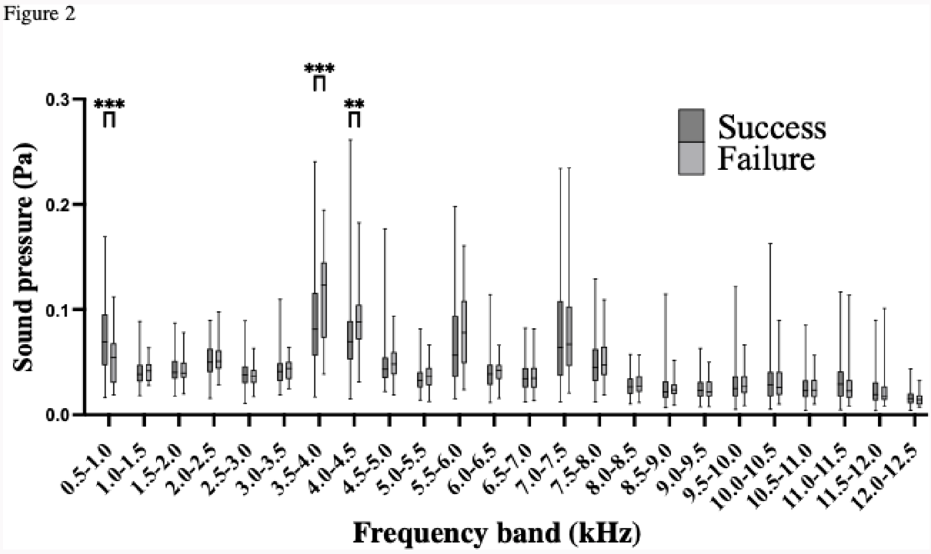

Fig. 2
The sound pressure (Pa) in different frequency bands (kHz) of successful and unsuccessful press-fit fixation.

Results

There were no outliers in the SP in 24 bands. Among the 56 hips, the sound of 244 impacts of 49 successful attempts in 49 hips, and the sound of 60 impacts of 12 unsuccessful attempts in seven hips, were recorded. Among these, hips in which a Trident hemispheric multi-hole cup was used were excluded. Finally, the sound of 224 impacts of successful press-fit fixation and 55 impacts of unsuccessful press-fit fixation were analyzed.

Figure 2 shows the SP (Pa) in different frequency bands (kHz) of successful and unsuccessful press-fit fixation. The median SP of successful fixation at 0.5 to 1.0 kHz was higher than that of unsuccessful fixation (0.0694 (0.04721 to 0.09576) vs 0.05425 (0.03047 to 0.06803), $p < 0.001$). The median SP of successful fixation at 3.5 to 4.0 kHz and 4.0 to 4.5 kHz was lower than that of unsuccessful fixation (0.0812 (0.05631 to 0.01161) vs 0.1233 (0.0730 to 0.1449), $p < 0.00\ 1$ and 0.0891 (0.0526 to 0.0891) vs 0.0885 (0.0716 to 0.1048); $p < 0.001$, respectively, all Mann-Whitney U test). The post hoc powers analysis ($\alpha = 0.01$, number of successful fixations = 224, unsuccessful fixations = 55) revealed that the power (1-β) in those comparisons with statistical difference were more than 0.8 (0.96, 1.0, and 0.82, respectively). No difference in the median SP was observed in other frequency bands. Those bands with a p value of < 0.01 were considered the key bands for differentiation of the sound characteristics between successful and unsuccessful press-fit fixation.

Next, the relationship between the key bands and the patients' baseline characteristics was investigated. A small difference in the median SP between the two sexes was observed (Figure 3). Plot graphs of the results of simple linear regression of SP and age, height, body weight, and cup size are shown in Figure 4. There was a statistically significant relationship between body weight and SP at 0.5 to 1.0 kHz ($p < 0.001$). This statistically significant positive relationship was not seen at 3.5 to 4.0 kHz or 4.0 to 4.5 kHz. Moreover, a larger

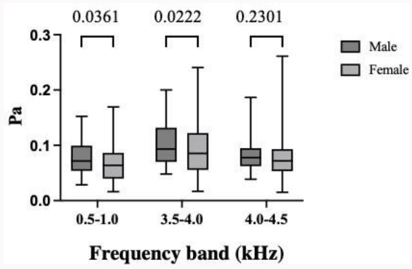

Fig. 3
Comparison of the median sound pressure in three key frequency bands between the two sexes.

cup size and higher SP in the key bands were observed with a p-value of < 0.001. Spearman's rank correlations with 95% confidence intervals are shown in Table II.

Univariate and multivariate analyses were performed to determine the effect of SP in the key bands on the success or failure of press-fit cup fixation (Table III). As shown in Table IV, two models with different variables (model 1 adjusted for SP in the key bands, and model 2 adjusted for model 1 plus age, height, body weight, and cup size) indicated that the SP at both 0.5 to 1.0 kHz and 3.5 to 4.0 kHz was independently associated with the success or failure of press-fit cup fixation. Addition of the patients' basic information contributed to an increase in the area under the curve.

Discussion

Achievement of adequate mechanical stability of the cup, so-called 'press fit', is essential in cementless THA. Although various techniques are available to evaluate the initial stability of the cup, listening to the change in the hammering sound is one way to assess cup stability. However, this is a highly subjective evaluation. In the present study, we assessed the acoustic characteristics of cup impaction and identified acoustic parameters that influenced the status of

Table II. The relationship between the key bands and the patients' basic characteristics, presented as Spearman's rank correlations with 95% confidence intervals.

	0.5 to 1.0 kHz	3.5 to 4.0 kHz	4.0 to 4.5 kHz	Age	Height	Weight	Cup size
0.5 to 1.0 kHz	1.0	0.1347 (0.0362 to 0.2657)	0.0109 (-0.1505 to 0.0841)	-0.0165 (-0.1481 to 0.0865)	0.1320 (0.0305 to 0.2604)	0.3923* (0.3336 to 0.5247)	0.2944* (0.2024 to 0.4146)
3.5 to 4.0 kHz	-	1.0	0.6665* (0.6370 to 0.7570)	0.0406 (-0.1358 to 0.0989)	0.1318 (-0.0010 to 0.2308)	0.1508 (0.0243 to 0.2546)	0.2570*(0.1026 to 0.3265)
4.0 to 4.5 kHz	-	-	1.0	0.1217*(-0.0046 to 0.2273)	0.0456 (-0.0816 to 0.1530)	0.2005 0.0100 to 0.2411	0.1800* (0.0424 to 0.2714)
Age	-	-	-	1.0	-0.3437* (-0.4527 to -0.2469)	-0.0765 (-0.2284 to 0.0035)	-0.1727* (-0.3762 to -0.1585)
Height	-	-	-	-	1.0	0.4679* (0.3772 to 0.5600)	0.5018* (0.4635 to 0.6278)
Weight	-	-	-	-	-	1.0	0.5181* (0.4495 to 0.6169)
Cup size	-	-	-	-	-	-	1.0

*p < 0.01.

Table III. Univariate analyses performed to determine the effect of sound pressure in the key bands on the success or failure of press-fit cup fixation (279 impacts in total).

Factors	Odds ratio	p-value
Sound pressure (mPa)		
0.5 to 1.0 kHz	0.776	< 0.001*
3.5 to 4.0 kHz	1.276	< 0.001*
4.0 to 4.5 kHz	1.095	0.010

* p < 0.01.

cup impaction: successful or unsuccessful press-fit fixation. It is important for surgeons to understand the acoustic characteristics of the hammering sounds that occur during cup impaction.

Our data suggest that objective hammering sounds can help surgeons to judge whether press-fit fixation has been achieved. The SP in several frequency bands showed distinctive peaks, such as within bands 0.5 to 1.0, 3.5 to 4.5, 5.5 to 6.0, and 7.0 to 7.5 kHz. The presence of these peaks indicates that there is a specific vibration mode in the objects, referred to as the natural frequency. Although the 7.0 to 7.5 kHz showed a peak, the median SP was similar in both groups. We assumed that the peak in this band came from the hammer itself and was not influenced by the status of the cup press fit, since the natural frequency of the hammer was reported as 7 kHz in a previous study.[14] Furthermore, the hammer remains sufficiently independent from the objects such as bone and cup connection to the impactor handle. In contrast, other peaks (0.5 to 1.0, 3.5 to 4.5 kHz) associated with the key bands represent the press-fit status, because those peaks demonstrate a difference in the median SP, which suggests a dissimilar vibration mode of the bone-cup-impactor composite between successful and unsuccessful press-fit fixation. Although the torque test, lever-out test, and hands-off test are frequently used to assess the initial fixation stability, they are invasive and destructive to surrounding tissue: adding physical pressure when performing these tests might lead to unnecessary disruption of the press-fit fixation that has already been achieved. By contrast, the assessment of hammering sounds is a non-destructive test and might be useful as a screening tool.

A possible explanation for the increased SP at 0.5 to 1.0 kHz and decreased SP at 4 kHz in successful press-fit fixation is as follows. Because the cup is well fixed to the acetabulum, the vibrating objects change from the cup and impactor to the bone-cup-impactor composite. Because this composite becomes heavier than the cup and instruments themselves, the frequency decreases. As a result, the frequency range drops lower, leading to 0.5 to 1.0 kHz as a dominant key band in successful press-fit fixation. This theory is supported by our finding that augmentation of the low-frequency band (0.5 to 1.0 kHz) in successful press-fit fixation was

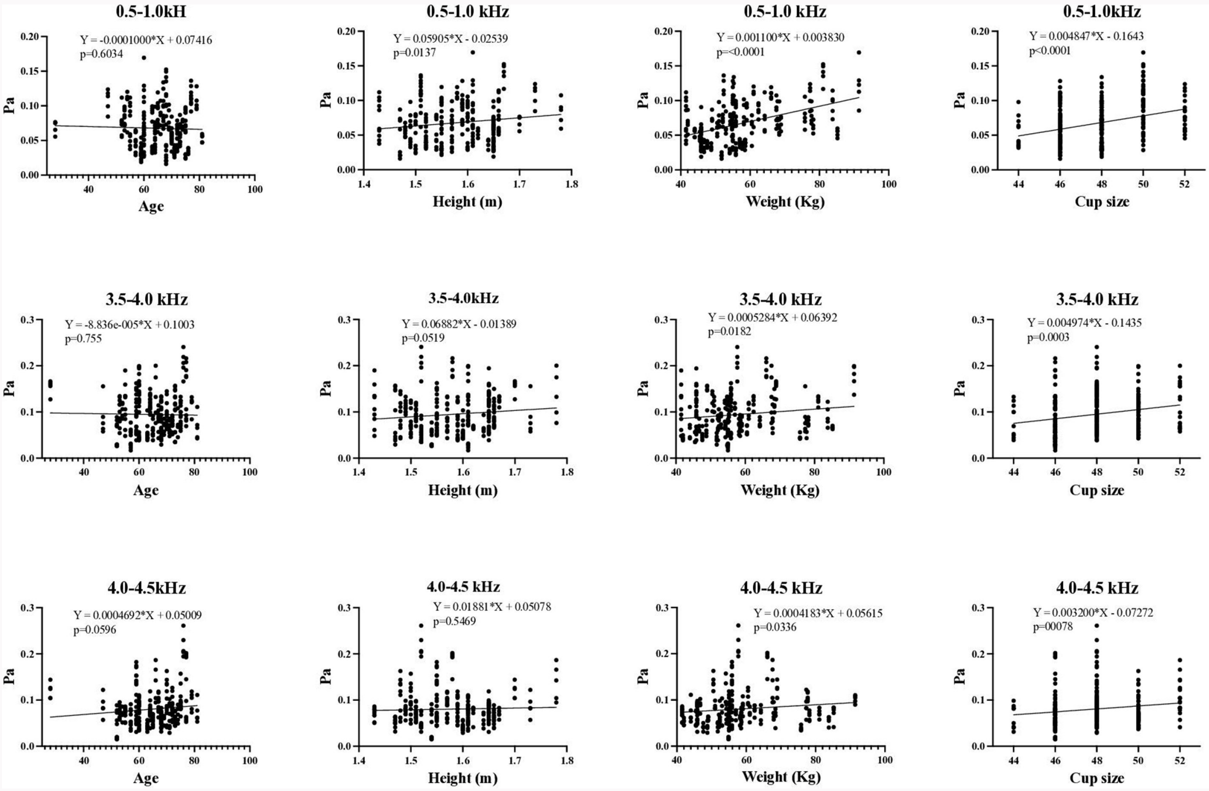

Fig. 4

Plot graphs of the results of simple linear regression of sound pressure and age, height, weight, and cup size are shown. There was an obvious positive relationship between weight and sound pressure at 0.5 to 1.0 kHz (p < 0.001, Spearman's rank correlation).

Table IV. Two models with different variables indicated that the sound pressure at both 0.5 to 1.0 kHz and 3.5 to 4.0 kHz was independently associated with the success or failure of press-fit cup fixation. Addition of the patients' baseline information contributed to an increase in the area under the curve.

Models	p-value	Goodness-of-fit test p-value	AUC	Factors	OR (95% CI)	p-value
				0.5 to 1.0 kHz	0.727 (0.637 to 0.830)	< 0.001
Model 1	< 0.001	0.96	0.77338	3.5 to 4.0 kHz	1.168 (1.086 to 1.257)	< 0.001
				0.5 to 1.0 kHz	0.700 (0.563 to 0.849)	< 0.001
				3.5 to 4.0 kHz	1.256 (1.126 to 1.416)	< 0.001
				Age	0.868 (0.811 to 0.919)	< 0.001
				Height	1.215 (1.123 to 1.333)	< 0.001
				Weight	0.882 (0.825 to 0.937)	< 0.001
Model 2	< 0.001	1.00	0.91445	Cup size	0.802 (0.517 to 1.199)	0.288

Model 1: adjusted model to Sound pressure (mPa) in two frequency bands (0.5 to 1.0 and 3.4 to 4.0 kHz).
Model 2: adjusted model to Model 1 plus age, height, body weight, and cup size.
AUC, area under the receiver operating characteristic curve; CI, confidence interval; OR, odds ratio.

positively correlated with the patient's body weight. This speculation is also consistent with previous investigations of the femur.[11,12,15] Homma et al[11] reported that, as a cementless stem was inserted, there were notable changes in the normalized SP at 0.5 to 1.0 kHz. Moreover, they found in another study that the sound characteristics differed between cases with and without postoperative subsidence. Specifically, the normalized SP in the low-band area (0.5 to 2.0 kHz) in patients without postoperative subsidence was higher than that in patients with subsidence.[12] McConnell et al[16] found the emergence of a low-frequency band of sound in the 1 kHz range during final femoral broaching. Whitwell et al[15] reported that low-frequency (0.44 to 1.2 kHz) spectral peaks were not detected when using the first broach, but that such peaks were detected in the last broach and implant introduction.

To achieve highly accurate judgement of press-fit fixation by an artificial intelligence (AI)-based algorithm, it is important to identify the factors that influence the hammering sound characteristics during cup impaction. As our regression analysis demonstrated, basic patient information such as height and body weight may be related to objective sound characteristics. During cementless femoral implant initial fixation in THA, an interesting finding is that length of the femur, not body weight, influences the hammering sound in the femur,[17] whereas weight influences the hammering sound in the pelvis. This probably occurs because the femoral canal acts as an intensifier, but no such structure intensifies the sound in the pelvis. The weight of the pelvis is therefore more important in influencing the hammering sound. Homma et al[18] showed that adding patient information augmented the accuracy of predicting postoperative subsidence. With this in mind, it is necessary to identify additional features that may increase the accuracy of predicting cup fixation.

Our results will help surgeons to understand these hammering sounds, and allow investigators to develop AI-based algorithms to analyze them and assist surgeons in using them during THA. Approaches for healthcare using sound and AI have recently been developed.[18–21] These have been assessed not only in orthopaedics, but also a variety of medical fields. For example, a newborn cry-based diagnostic system to distinguish between sepsis and respiratory distress syndrome using combined acoustic features has been introduced.[19,20] Additionally, a swallowing sound evaluation in patients with amyotrophic lateral sclerosis, using an electronic stethoscope with AI analysis has been reported as a new useful tool.[21]

This study has several limitations. First, only one type of cementless cup was analyzed. Whether the same acoustic characteristics can be generalized to cups with other shapes, compositions, and deformation characteristics remains unclear. Second, all included patients were Japanese, and it is highly probable that they had smaller stature than patients from Western populations. Because body weight impacts the acoustic characteristics, the study findings might be altered in different populations. Third, we did not investigate the acetabular bone morphology and bone quality, parameters which might influence the hammering sound and contribute to the accuracy of binary judgement. It would be expected that the sound in patients with femoral neck fracture due to osteoporosis might differ. Fourth, the physical strength of different surgeons may affect results. However, the data in this study were generated by multiple surgeons. Moreover, those differences may affect the sound level, but these are expected to have a minimal effect on the sound characteristics. Finally, there are other several possible factors that affect the results, such as the approach and patient's position (supine or lateral decubitus), the acetabular reaming technique, and distance of the recording point. Although those factors were fixed in this study, further investigations into how they affect the results are necessary in the future.

In conclusion, hammering sounds differed between successful and unsuccessful press-fit cup fixation. The frequency bands of 0.5 to 1.0, and 3.5 to 4.0, were the key to distinguish the sound characteristics between whether the fixation was a success or a failure. Further investigation is needed to identify factors that may increase the prediction accuracy, such as patient body weight and bone characteristics.

References

1. **Lunz A**, **Von Falkenhayn M**, **Jaeger S**, **et al**. Minimum 20-year follow-up of a press-fit acetabular cup in cementless total hip replacement in young patients. *Acta Orthop*. 2023;94:321–327.
2. **Ben-Shlomo Y**, **Blom A**, **Boulton C**, **Clark E**, **et al**. National Joint Registry Annual Reports. The National Joint Registry 19th Annual Report 2022, London: National Joint Registry. 2022.
3. **Roedel GG**, **Kildow BJ**, **Sveom DS**, **Garvin KL**. Total hip arthroplasty using highly cross-linked polyethylene in patients aged 50 years and younger. *Bone Joint J*. 2021;103-B(7 Supple B):78–83.
4. **Kobayashi H**, **Homma Y**, **Tanabe H**, **et al**. Objective evaluation for initial stability of highly porous cup without screws in total hip arthroplasty for femoral neck fracture. *J Orthop*. 2020;17:97–100.
5. **Dammerer D**, **Putzer D**, **Glodny B**, **et al**. Occult intra-operative periprosthetic fractures of the acetabulum may affect implant survival. *Int Orthop*. 2019;43(7):1583–1590.
6. **Yamamuro Y**, **Kabata T**, **Kajino Y**, **Inoue D**, **Hasegawa K**, **Tsuchiya H**. Does intraoperative periprosthetic occult fracture of the acetabulum affect clinical outcomes after primary total hip arthroplasty? *Arch Orthop Trauma Surg*. 2022;142(11):3497–3504.
7. **Kaneko K**, **Inoue Y**, **Yanagihara Y**, **Uta S**, **Mogami A**, **Iwase H**. The initial fixation of the press-fit acetabular shell--clinical observation and experimental study. *Arch Orthop Trauma Surg*. 2000;120(5–6):323–325.
8. **Kanda A**, **Kaneko K**, **Obayashi O**, **Mogami A**, **Iwase H**. Limitation of total hip arthroplasty of the acetabular roof by press-fit without screw fixation: discussion of a biomechanical study. *Eur J Orthop Surg Traumatol*. 2013;23(4):417–424.
9. **Schulze C**, **Vogel D**, **Mallow S**, **Bader R**. Comparison of test setups for the experimental evaluation of the primary fixation stability of acetabular cups. *Materials (Basel)*. 2020;13(18):3982.
10. **Ruhr M**, **Huber G**, **Niki Y**, **Lohner L**, **Ondruschka B**, **Morlock MM**. Impaction procedure influences primary stability of acetabular press-fit components. *Bone Joint J*. 2023;105-B(3):261–268.
11. **Homma Y**, **Zhuang X**, **Yanagisawa N**, **Ishii S**, **Baba T**, **Ishijima M**. Patients with shorter stature exhibit minimal hammering sound changes during cementless stem insertion in total hip arthroplasty. *Arthroplasty Today*. 2023;21:101136.
12. **Zhuang X**, **Homma Y**, **Ishii S**, **et al**. Acoustic characteristics of broaching procedure for post-operative stem subsidence in cementless total hip arthroplasty. *Int Orthop*. 2022;46(4):741–748.
13. **Banno S**, **Baba T**, **Tanabe H**, **et al**. Use of traction table did not increase complications in total hip arthroplasty through direct anterior approach performed by novice surgeon. *J Orthop Surg (Hong Kong)*. 2020;28(2):230949902092309.
14. **Morohashi I**, **Iwase H**, **Kanda A**, **et al**. Acoustic pattern evaluation during cementless hip arthroplasty surgery may be a new method for predicting complications. *SICOT-J*. 2017;3:13.
15. **Whitwell G**, **Brockett CL**, **Young S**, **Stone M**, **Stewart TD**. Spectral analysis of the sound produced during femoral broaching and implant insertion in uncemented total hip arthroplasty. *Proc Inst Mech Eng H*. 2013;227(2):175–180.
16. **McConnell JS**, **Saunders PRJ**, **Young SK**. The clinical relevance of sound changes produced during cementless hip arthroplasty: a correctly sized femoral broach creates a distinctive pattern of audio frequencies directly related to bone geometry. *Bone Joint J*. 2018;100-B(12):1559–1564.
17. **Zhuang X**, **Homma Y**, **Sato T**, **et al**. Factors influence on the broaching hammering sound during cementless total hip arthroplasty. *J Biomedical Science and Engineering*. 2022;15(9):229–240.
18. **Homma Y**, **Zhuang X**, **Ohtsu H**, **et al**. Highly accurate acoustical prediction using support vector machine algorithm for post-operative subsidence after cementless total hip arthroplasty. *Int Orthop*. 2023;47(1):187–192.
19. **Khalilzad Z**, **Hasasneh A**, **Tadj C**. Newborn cry-based diagnostic system to distinguish between sepsis and respiratory distress syndrome using combined acoustic features. *Diagnostics*. 2022;12(11):2802.

20. **Khalilzad Z**, **Tadj C**. Using CCA-fused cepstral features in a deep learning-based cry diagnostic system for detecting an ensemble of pathologies in newborns. *Diagnostics*. 2023;13(5):879.
21. **Nakamori M**, **Ishikawa R**, **Watanabe T**, **et al**. Swallowing sound evaluation using an electronic stethoscope and artificial intelligence analysis for patients with amyotrophic lateral sclerosis. *Front Neurol*. 2023;14:1212024.

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Data sharing

The datasets generated and analyzed in the current study are not publicly available due to data protection regulations. Access to data is limited to the researchers who have obtained permission for data processing. Further inquiries can be made to the corresponding author.

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Ethical review statement

This study was conducted in accordance with the principles of the Declaration of Helsinki. Institutional review board approval was obtained before initiation of the study, and written informed consent was obtained from all included patients.

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