Selection of Hammering Sound Collection Devices for the Development of Total Hip Arthroplasty Support Systems

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ABSTRACT

In total hip arthroplasty, intraoperative femoral fractures can be avoided by analyzing the hammering sounds from the stem inserted into the femur. This procedure is based on a hammering test that makes use of the fact that sound depends on the stability of the object. This technique is generally used in engineering. A system designed to avoid excessive stem hammering by predicting the intraoperative fracture risk based on this technique and software for real-time spectra analysis has been developed with repetitive improvements. The remaining technical challenge lies in selecting an appropriate sound collection device and building a compact and easy unit for use. This study reviewed the types of directional microphones suitable for the sound collection system to develop a practical THA support system. Four types of microphones based on selected methods were used to collect and compare the peak frequencies of the hammering sounds and make comparisons between them, and the built system was used to conduct clinical trials. For miniaturization and operational ease of the unit, plug-in unidirectional microphones are appropriate. However, no laboratory-level data has been collected, and thus, further data accumulation is necessary.

1. INTRODUCTION

Total hip arthroplasty (THA) is a surgical procedure to replace a hip joint, with hip prostheses, that

has lost its functionality. The developments in hip arthroplasty over recent years have aimed to improve outcomes, reduce complications [1-3]. However, it has been reported that during surgery, serious intra-operative fractures occur at a rate between 0.4% and 4.9% [3-5].

One of the causes of intraoperative femoral fracture is the fact that no criterion is available for deciding whether the stem is sufficiently stable [6]. Currently, surgery is dependent on the surgeon's experience and sense without being based on the objective data. An insufficiently fixation stem results in insufficient stability. A stem excessively fix to increase stability causes intraoperative fracture; this means that it is possible to avoid intraoperative fracture by appropriate fixation the stem during surgery based on scientific grounds (see Figure 1).

Research till date indicates that with a focus on the fact that the sound depends on the object's stability, it is possible to avoid intraoperative fracture by analyzing hammering sounds from the stem being fix into the femur [7, 8]. A system has been built to avoid intraoperative fractures, and software for fast Fourier analysis has been developed with repetitive improvements [9, 10]. The remaining technical challenge is to select an appropriate sound collection device and build a compact unit that is easy to use.

To develop a practical THA support system, this study focused on the following three points, particularly those associated with the selection of sound collection systems. First, the type of directional microphone suitable for a sound collection system was reviewed. Next, four types of microphones based on the selected methods were used to collect and compare the peak frequencies of the hammering sounds and make comparisons between them. Finally, the built system was used to conduct clinical trials.

2. MATERIALS AND METHODS

Selection of microphones

The THA support system for preventing intraoperative fractures consists of a dual-channel sensor amplifier (SR-2200 from Ono Sokki, Japan), a digital storage scope (DSO-2250 USB from Hantek Electronic Co. Ltd., China), and a laptop computer (Endeavor NJ1000 from Epson, Japan). To select the most suitable directional microphone to be incorporated into this support system, comparisons were made among the electret-condenser, dynamic, and DC-biased condenser types. Table 1 lists the types, output levels, noise levels, sensitivity levels, and sound qualities of the microphones.
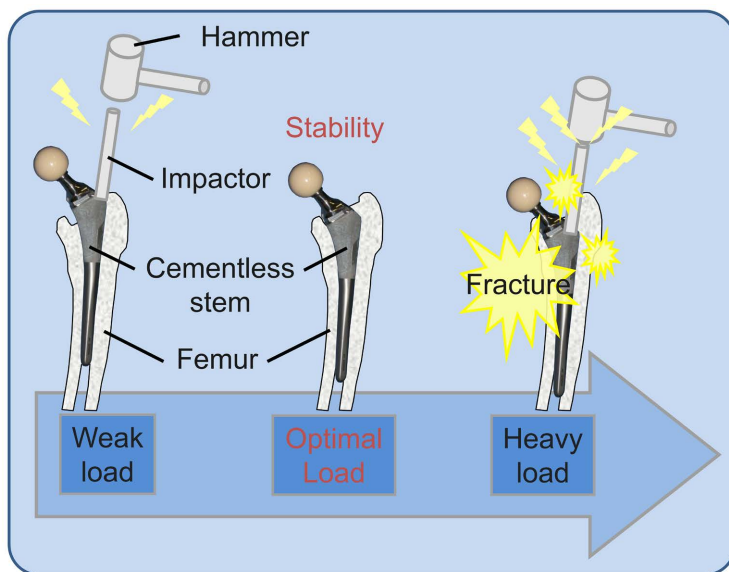

Figure 1. If the force is not enough or the number of hits is insufficient, the stem will loosen. Excessive striking of the stem causes intraoperative fractures.

Table 1. Type of microphones, output, noise, sensitivity and sound quality.

Type	Output	Noise	Sensitivity	Sound quality
Electret condenser type	Normal	Normal	Normal	Versatile and delicate. Compared to the DC bias type, it cannot pick up minute level sound.
Dynamic type	Low	Normal	Low	Suitable for high volume recording
DC bias capacitor type	High	Low	High	Delicate and smooth. Abundant information at a minute level.

Four types of dynamic and DC-biased condenser directional microphones, namely, Type A (F-P5500 from Sony, Japan), Type B (BETA58A from Shure Inc., IL, USA), Type C (C391 from Harman International Japan Co. Ltd., CT, USA), and Type D (BP4073 from Audio-Technica Corporation, Japan), were incorporated into the THA support system to collect hammering sounds under the same conditions. Types A and B are dynamic microphones, and Types C and D are DC-biased condenser microphones. Table 2 lists the directivities and frequency responses of microphones.

In the laboratory, systems (VerSys from Zimmer, USA) were implanted into simulated femurs (Sawbones Medium Left Femur 1121-19: Pacific Research Laboratory, WA, USA). With the surgical equipment used in clinical trials, the systems were fixed using the same procedure as that of the THA using a hammer (VerSys from Zimmer, USA) through an inserter (VerSys from Zimmer, USA). Directional microphones were placed approximately 1 m away from the simulated femurs. Six simulated femurs were used for each microphone. An FFT analyzer (DS-3000, Onosokki, Japan) was used to perform short-time Fourier transformations to calculate the peak frequencies at which the amplitudes were maximized.

Clinical trials

This study was approved by the ethics commission of the organization to which the author belongs (B16-239). Clinical trials were conducted on 12 joints in 12 cases of total hip replacements (for four male patients and eight female patients, with a mean age of 70.1 years old), conducted from June to December 2017 at Kitasato University Hospital. The surgery was performed by an orthopedic surgeon specializing in the hip joint, with more than 20 years of clinical experience.

As equipment to be carried into operating rooms, the system had to be a compact, easy-to-use unit. Microsoft Visual Studio 2010 was used as the development platform, and Microsoft Visual C# 2010 was used as the programming language to develop an application. The application normally runs on a PC Miix 2 8 (from Lenovo Corporation, China), a tablet PC equipped with Windows as the operating system (OS).

Changes were made to the software and hardware of the THA support system; thus, microphones were selected again. Comparisons were made between Microphone A (F-P5500 from SONY, Japan), a handheld unidirectional microphone that exhibited the best performance in the laboratory; microphone E (i266 from MI Seven Japan Inc., Japan), a plug-in unidirectional cordless microphone that directly connects to a tablet; and microphone F, a plug-in super-directive small microphone (AT9913 from Audio-Technica Corporation, Japan) (Table 3). With the microphones placed 2 m away from the surgical field, one microphone and the system were used to analyze each case. Each microphone was randomly allocated to four of the 12 cases. Table 3 lists the directivities and frequency responses of the microphones.

3. RESULTS

The four types of directional microphones A, B, C, and D exhibited peak frequencies of 0.70 ± 0.03 kHz, 0.30 ± 0.09 kHz, 0.72 ± 0.01 kHz, and 0.67 ± 0.05 kHz, respectively. Unlike the other microphones, microphone A clearly exhibited its peak frequency (Figure 2(A)). Microphone B exhibited a peak frequency more than 1 kHz, which was lower than the peak frequencies of the other microphones (see Figure 2(B)). Microphone C exhibited a smooth waveform, but its peak frequencies, the most critical data, were scattered (Figure 2(C)). Microphones B and D were characterized by picking up low-frequency sounds (Figure 2(D)).

Table 2. Characteristics of the microphones used in the laboratory.

Type	Product	Directivity		Frequency characteristics
Dynamic type	A	Unidirectional		50 Hz - 20 kHz
	B	Super directional		50 Hz - 16 kHz
DC bias capacitor type	C	Unidirectional		20 Hz - 20 kHz
	D	Super directional		20 Hz - 20 kHz

Table 3. Characteristics of the microphones used in the operating room.

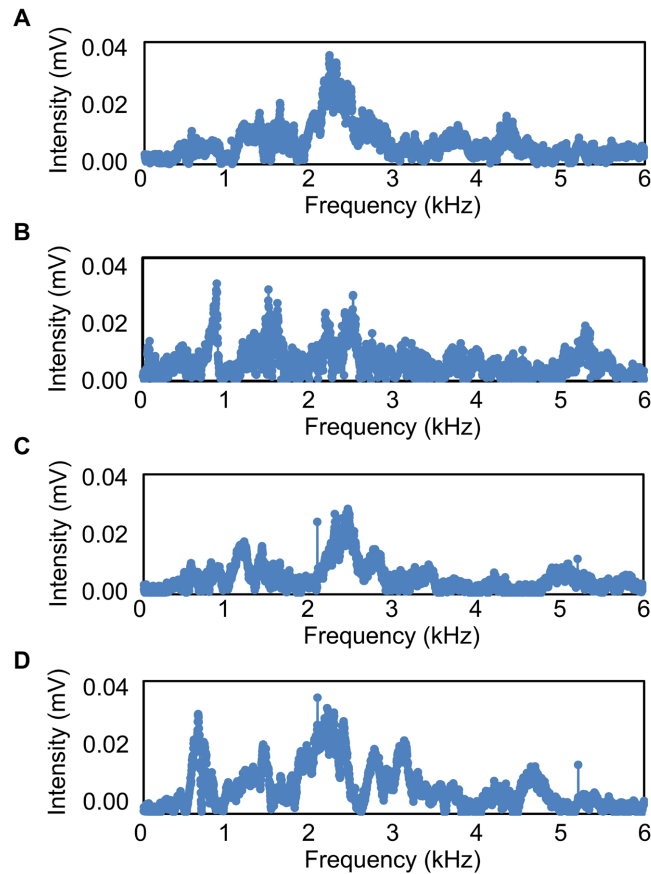| Type	Product	Directivity		Frequency characteristics
Dynamic type	A	Unidirectional		50 Hz - 20 kHz
Plug in type	E	Unidirectional		20 Hz - 20 kHz
	F	Super directional		70 Hz - 15 kHz

Figure 2. Frequency and intensity of each microphone. (A) Microphone A showed a remarkable peak. (B) The peak frequency of microphone B was lower than that of other microphones by 1 kH or more. (C) The peak frequency of microphone C varied. (D) Microphone D had the characteristic of picking up low frequency information.

In the clinical trials, microphone A failed to detect one hammering sound in one of the four cases. The x plot in **Figure 3(A)** shows the undetected data that is one miscounted hammering sound out of a series of 58 hammering sounds collected by microphone A. Microphone B did not fail to detect any hammering sounds in all cases. Microphone C failed to detect hammering sounds in all cases, with 4 ± 3.16 counting errors per case. **Figure 3(B)** shows one of the four cases where microphone C was used, with five counting errors observed out of 96 hammerings performed.

4. DISCUSSION

The frequency components that constitute the hammering sound are the characteristic frequencies of the hammer and the inserter [11]. Zhuang *et al.* stated that the frequency components of the hammering sound are almost independent of the manufacturers of the inserter and hammer [1]. Based on previous research, we reported that the peak frequency is approximately 3 kHz [10]. Microphone A exhibited a peak frequency near this value, which did not scatter significantly. Dynamic microphones are inexpensive and suitable for collecting large amount of sound [12]. We believe that dynamic microphones are suitable for bone fracture prevention devices because they are tolerant to rough handling in clinical practice and are easy to handle.
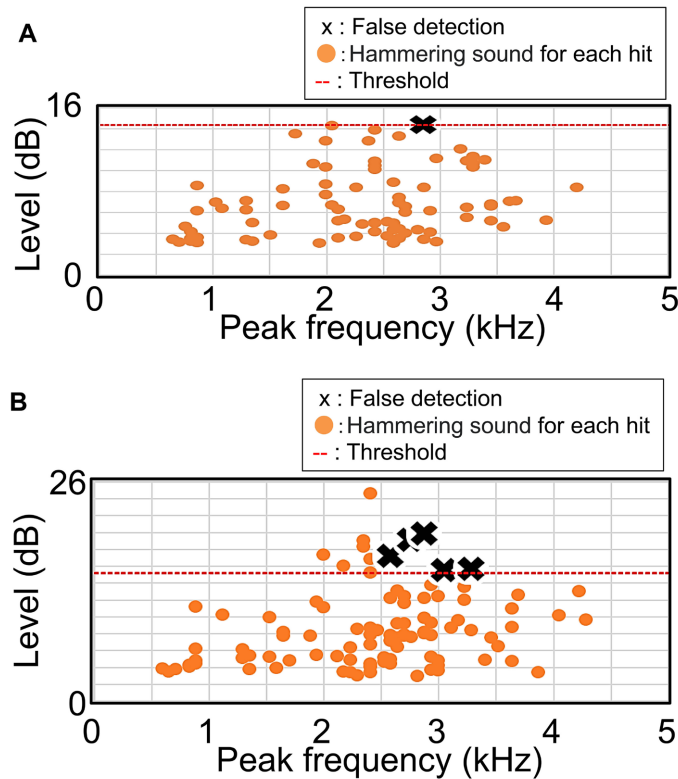
Figure 3. Peak frequency and level of each microphone. The orange plot shows the hammering sound, and the x plot shows the undetected data. (A) A counting error occurs once in 58 times of hammering collected by microphone A. (B) Microphone C was hammered 96 times, and 5 count errors occurred and the data was not detected.

Dynamic microphones are disadvantageous because their output and sensitivity levels are low, although the dynamic microphone is cheap enough for collecting of sound [12]. DC-biased condensers exhibited high output and sensitivity levels. However, they are precision optical instruments that are expensive and require careful handling (for example, exposure to high temperatures and humidity must be avoided). For these reasons, we believe that they are inappropriate as devices used in operating rooms. With their excellent collection of low-pitched sounds, DC-biased condensers can collect abundant micro-information. However, hammering sounds are high-pitched and not delicate; thus, the microphone does not need to be of a DC-biased condenser type [13]. Electret condenser microphones provide fine sound quality because they include batteries and an electronic circuit. However, demerits of electret condenser microphones may cause battery leakage because batteries are always kept inside them and are thus excluded from the selection [14].

Although the laboratory study revealed that Microphone A, a handheld unidirectional type, performed excellently, we thought that the microphone should be smaller in size as it must be carried into operating rooms. Microphone A, E, and F are handheld unidirectional, plug-in unidirectional, and plug-in superdirective type, respectively, and the frequency responses cover the frequency range of the hammering sound. The microphone cannot be placed near the sound source, that is, the surgical field; therefore, we expected that the superdirective type would be suitable for collecting sounds. However, the results showed that the unidirectional types were excellent. We found that the unidirectional types collected sound in a wider area than the superdirective types and thus picked up sounds that came around the barrier, the operator, and from the sound source [15].

Given that the first prerequisite for the sound collection device was compactness, we determined that microphone E was appropriate. However, the amount of data is insufficient, and thus must be increased so that statistics can be maintained. In clinical trials, ossein is not consistent; thus, it is difficult to handle the obtained qualitative data. Therefore, laboratory-level data was collected again. If the microphone is required not to make many misdetections, it may be deemed that Microphone A, a dynamic handheld unidirectional type, or the plug-in unidirectional microphone, is appropriate as a sound collection device for the THA support system. As a limitation, we considered the material of the microphone did not influence the results. We have not confirmed whether there is a difference between gender and age in the collected data.

5. CONCLUSION

It is necessary to discuss the criteria for determining whether the stem is sufficiently stable. As one approach, intraoperative fractures can be avoided by analyzing the hammering sound from the stem inserted into the femur. A system was built to avoid intraoperative fracture risk based on this technique, and software for real-time analysis has been developed with repetitive improvements in the THA support system. The remaining technical challenge is to select an appropriate sound collection device. This study revealed that dynamic handheld unidirectional microphones are suitable for collecting sounds. To achieve miniaturization and operational ease of the THA support system, plug-in unidirectional microphones are found to be appropriate. However, no laboratory-level data has been collected for plug-in unidirectional microphones; therefore, data collection must be increased in the future.

CONFLICTS OF INTEREST

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

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