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Original Article

Human knee joint sound during the Lachman test: Comparison between healthy and anterior cruciate ligament-deficient knees

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ABSTRACT

Background: The Lachman test is clinically considered to be a reliable physical examination for anterior cruciate ligament (ACL) deficiency. However, the test involves subjective judgement of differences in tibial translation and endpoint quality. An auscultation system has been developed to allow assessment of the Lachman test. The knee joint sound during the Lachman test was analyzed using fast Fourier transformation. The purpose of the present study was to quantitatively evaluate knee joint sounds in healthy and ACL-deficient human knees.
Methods: Sixty healthy volunteers and 24 patients with ACL injury were examined. The Lachman test with joint auscultation was evaluated using a microphone. Knee joint sound during the Lachman test (Lachman sound) was analyzed by fast Fourier transformation. As quantitative indices of the Lachman sound, the peak sound (Lachman peak sound) as the maximum relative amplitude (acoustic pressure) and its frequency were used.
Results: In healthy volunteers, the mean Lachman peak sound of intact knees was 100.6 Hz in frequency and −45 dB in acoustic pressure. Moreover, a sex difference was found in the frequency of the Lachman peak sound. In patients with ACL injury, the frequency of the Lachman peak sound of the ACL-deficient knees was widely dispersed. In the ACL-deficient knees, the mean Lachman peak sound was 306.8 Hz in frequency and −63.1 dB in acoustic pressure. If the reference range was set at the frequency of the healthy volunteer Lachman peak sound, the sensitivity, specificity, positive predictive value, and negative predictive value were 83.3%, 95.6%, 95.2%, and 85.2%, respectively.
Conclusion: Knee joint auscultation during the Lachman test was capable of judging ACL deficiency on the basis of objective data. In particular, the frequency of the Lachman peak sound was able to assess ACL condition.

1. Introduction

The anterior cruciate ligament (ACL) is located within the knee joint space surrounded by synovial fluid, and plays an important role in knee joint stability. The ACL restrains the anterior tibial translation with respect to the femur, and maintains the rotational stability of the knee [1]. When the ACL is subjected to loading that exceeds its physiologic range, microfracture takes place even before the yield point is reached. When the yield point is exceeded, the ACL begins to undergo gross rupture, and the knee joint begins to show abnormal displacement [1]. This abnormality can affect sports activities, and result in damage to the meniscus and articular cartilage [2]. Therefore, early diagnosis and treatment are important for ACL injury.

Clinical history and findings are important key factors for accurate diagnosis of ACL injury. Most knee joints with ACL injury exhibit hemarthrosis that occurs within a few hours after injury [3]. ACL injury also causes an audible pop or crack at the moment of ligament rupture. However, physical examination of the ACL-deficient knee in the acute phase is often difficult, because swelling and pain lead to guarding by the patient. Therefore, the anterior drawer test involving 90 degrees of knee flexion is

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considered to be a poor examination of ACL injury in the acute phase [4]. The sensitivity of the anterior drawer test has been reported to range from 22.2% to 41% when performed in alert patients [4–7]. Further, the Lachman test with 10–20 degrees of knee flexion has been shown to be the most reliable test for diagnosis of ACL injury in the acute phase. In the Lachman test, differences in anterior tibial translation or feeling of a soft endpoint may indicate an ACL tear. The sensitivity of the Lachman test has been reported to range from 80% to 99%, with a specificity of 95% [6–10]. However, the Lachman test involves subjective judgement of differences in tibial translation and endpoint quality, and inexperienced clinicians and residents may experience some difficulties in both performance and interpretation of the Lachman test.

Instrumented arthrometers, such as KT-1000 arthrometer, KT-2000 arthrometer and Rolimeter etc. can be used in the diagnosis of ACL injury. KT-1000 arthrometer is the most widely used in clinical settings because of reference instrument in the many literatures. Early studies concerning with reliability of KT-1000 arthrometer showed a high degree of consistency between the two examiners, resulting in high inter-examiner reliability [11]. However, KT-1000 arthrometer are operator-dependent with approximately 1 mm increments of precision [12]. Therefore, the examiner experience may influence the degree of error associated with the arthrometers. Jardin et al. compared the results of KT-1000 arthrometer with radiographic measurements of the knee after an ACL reconstruction. They indicated that the arthrometer did not agree with the radiographic measurements or clinical outcome [13]. Holt et al. showed that KT-1000 arthrometer had a significant inbuilt error and functioned with a significant hysteresis effect [14]. Notwithstanding the studies above-mentioned authors, KT-1000 arthrometer is commonly used as main outcome measurement of AP laxity in various clinical studies.

A new auscultation system has been developed to allow assessment of the Lachman test and analysis of knee joint sounds using fast Fourier transformation. Using porcine knee joints, the system was demonstrated to facilitate accurate evaluation of knee joint sounds during the Lachman test [15]. The purpose of the present study was to quantitatively evaluate knee joint sounds in healthy and ACL-deficient human knees. The goal of the study was to confirm objective performance of the Lachman test using joint auscultation, which would be useful for diagnosis in patients with ACL injury.

2. Methods

The present study was carried out according to a protocol approved by our Institutional Review Board. The protocol consisted of two separate phases. The first phase involved 60 healthy volunteers (30 males and 30 females) with no history of knee injury. The volunteers had a mean age of 22.4 (range: 15–35) years in males and 22.3 (range: 13–34) years in females. There was no significant difference in the age distribution between males and females. Each volunteer was brought to a private examination room, where the study was conducted. The volunteer lay in the supine position on an examination table and underwent knee joint sound (hereinafter described as the Lachman sound) analysis of the right knee during the Lachman test (Fig. 1). The Lachman sound of the right knee was recorded and analyzed using the methods described below. The Lachman tests of all volunteer knee joints were performed by a specialist in orthopedic surgery approved by the Japanese Orthopaedic Association (one of the authors).

The second phase involved 24 patients who underwent ACL reconstruction between May 2013 and March 2014. The characteristics of the patients are shown in Table 1. All patients were diagnosed with ACL injury on the basis of clinical findings, magnetic resonance imaging, and arthroscopic observation. No patients had a history of opposite knee injury or abnormality. Preoperatively, the Lachman test was performed on both the ACL-deficient and contralateral healthy knees. During the Lachman test, the Lachman sounds of the ACL-deficient and contralateral healthy knees were recorded and analyzed by the methods described below. The Lachman test was performed by a single orthopedic surgeon who specialized in knee surgery (one of the authors). Next, all patients underwent an arthrometry test on both the ACL-deficient and contralateral healthy knees using a KT-1000 system (MedMetric; San Diego, CA). The examiner strapped the KT-1000 onto the patient's legs and utilized the manual maximum force to pull the tibia forward on the femur. The anterior tibial translation

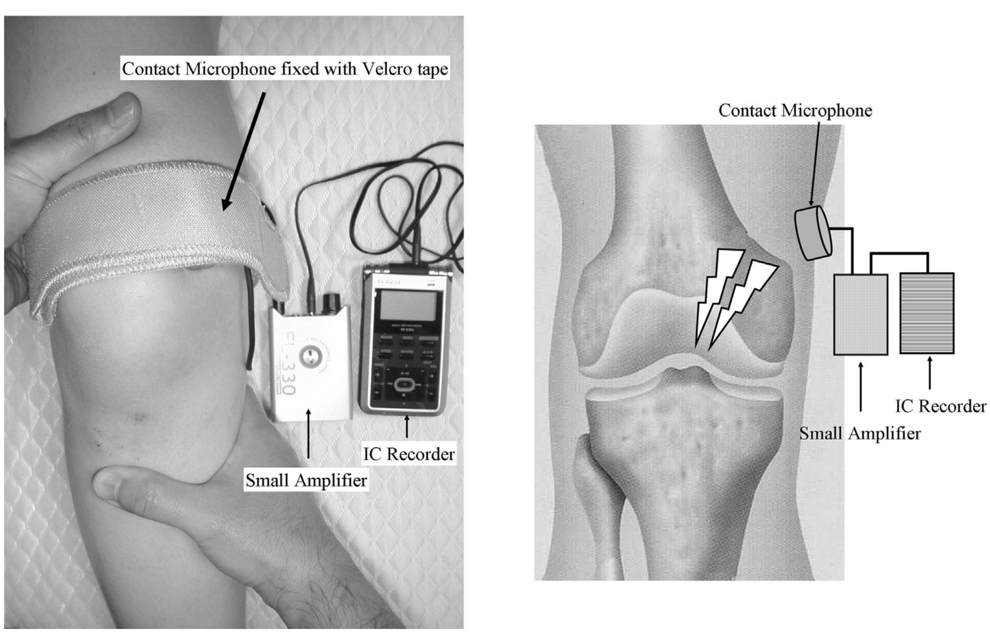

Fig. 1. Configuration of the knee joint auscultation system.

Table 1
Details of the 24 patients with anterior cruciate ligament injury.

Case	Age at surgery (years)	Gender	Knee	ACL Scar pattern (Cram EH et al.)	Meniscus tear	Cartilage damage	Side to side difference in KT1000 (mm)
1	19	M	Rt	Group 1	+	–	6.5
2	19	F	Rt	Group 2	+	+	5.5
3	18	M	Rt	Group 1	–	–	6.0
4	22	M	Lt	Group 3	–	+	5.0
5	26	F	Rt	Group 3	–	+	4.0
6	15	F	Rt	Group 4	–	–	10.0
7	15	M	Rt	Group 4	+	–	4.0
8	17	F	Rt	Group 3	–	+	5.0
9	14	F	Lt	Group 1	+	–	8.0
10	19	F	Rt	Group 3	+	+	12.0
11	29	M	Rt	Group 2	–	+	6.5
12	16	F	Lt	Group 1	–	–	9.5
13	38	F	Lt	Group 4	–	+	3.0
14	50	F	Lt	Group 2	–	+	8.5
15	17	F	Lt	Group 2	+	–	9.0
16	17	M	Lt	Group 4	+	–	6.0
17	22	M	Lt	Group 3	–	–	8.0
18	18	F	Lt	Group 2	–	+	7.0
19	52	F	Lt	Group 4	–	+	9.0
20	16	M	Rt	Group 4	–	+	6.0
21	20	M	Rt	Group 1	–	+	2.0
22	20	M	Rt	Group 2	–	–	6.5
23	23	F	Lt	Group 3	–	–	5.5
24	16	M	Lt	Group 4	–	–	10.0

was recorded in millimeters. The manual maximum side-to-side difference was used to assess the ACL deficiency. Patients with severe joint swelling that could influence the measurements of KT-1000 and Lachman sound analysis were omitted from the subjects of the study. Regarding joint effusion, the knee joint aspiration was performed before the measurements. Before ACL reconstruction, arthroscopic evaluation of the ACL remnant, meniscus tear and articular cartilage damage were performed. The configuration of the ACL remnant and its attachments to the femur and tibia were assessed using the classification of Crain et al. [16]. Briefly, the classification was as follows: group 1, ligament scarring to the posterior cruciate ligament; group 2, scar tissue appearing to extend from the ACL fibers to the roof of the notch; group 3, ACL remnants appearing to have healed to the lateral wall of the notch or the medial aspect of the lateral femoral condyle in a position anterior and distal to the ACL anatomic footprint; group 4, no identifiable ligament tissue remaining.

The details of the Lachman sound assessment system are shown in Figs. 1 and 2. The microphone (FL-330; Sun-Mechatronics, Tokyo, Japan) was placed on the medial suprapatellar area, which was coated with ultrasound transmission gel (Sono Jelly; Toshiba Medical Supply Co. Ltd., Tokyo, Japan). The gel was used to effectively eliminate skin friction noises caused by slight movement of the microphone during tibial translation in the Lachman test. The microphone was fixed with Velcro tape. The microphone was connected an IC recorder (R-05; Roland, Hamamatsu, Japan) through an equipped small amplifier. The Lachman sound was recorded and the sound data were converted into a spectrogram by fast Fourier transformation. Fig. 2 shows typical digitized audio data of the Lachman sound (upper) and the corresponding spectrogram (lower). The spectrogram of the Lachman sound was obtained as a two-dimensional map with the x-axis and y-axis representing time and frequency, respectively, and the relative amplitude representing acoustic pressure, as indicated by the gray scale. As quantitative indices of the Lachman sound, the peak sound of tibial translation (hereinafter described as the Lachman peak sound) was measured as the maximum relative amplitude (acoustic pressure) and its frequency. The Lachman peak sound of the third tibial translation (white arrow in Fig. 2) was selected and five measurements were taken and the average was calculated.

3. Statistical analysis

Differences in the Lachman peak sound data were analyzed by the nonparametric Mann–Whitney U-test. Statistical analyses were performed using Excel Statistical Program File Statcel (developed by Yanai H, OMS syuppan Co., Ltd., Saitama Japan). The significance level was set at $P < 0.05$.

4. Results

4.1. Lachman peak sound in healthy volunteers

All of the Lachman peak sounds of the healthy volunteers' knees had a similar frequency and acoustic pressure. All volunteers' knees had a firm endpoint feeling during the Lachman test. The frequency of the Lachman peak sound was 100.6 ± 16.2 Hz (mean ± SD), and the acoustic pressure of the Lachman peak sound was −45 ± 8.9 dB. Regarding sex differences, the frequency of the Lachman peak sound was 93 ± 15 Hz in males and 108.2 ± 13.7 Hz in females, and the acoustic pressure of the Lachman peak sound was −47.2 ± 10.2 dB in males and −42.8 ± 6.8 dB in females (Fig. 3). The difference in frequency between males and females was significant ($P = 0.016$).

4.2. Lachman peak sound in patients with ACL injury

The distribution charts of the Lachman peak sounds in the patients with ACL injury are shown in Fig. 4. The Lachman peak sounds of the ACL-deficient knees exhibited a large range of frequency. The distribution pattern of the data for the ACL-deficient knees showed a spindle-shaped mode along the x-axis. In the ACL-deficient knees, the frequency of the Lachman peak sound was 306.8 ± 413.3 Hz, and the acoustic pressure of the Lachman peak sound was −63.1 ± 8.2 dB. The Lachman peak sounds of the contralateral intact knees were centered around 100 Hz. In the contralateral intact knees, the mean frequency of the Lachman peak

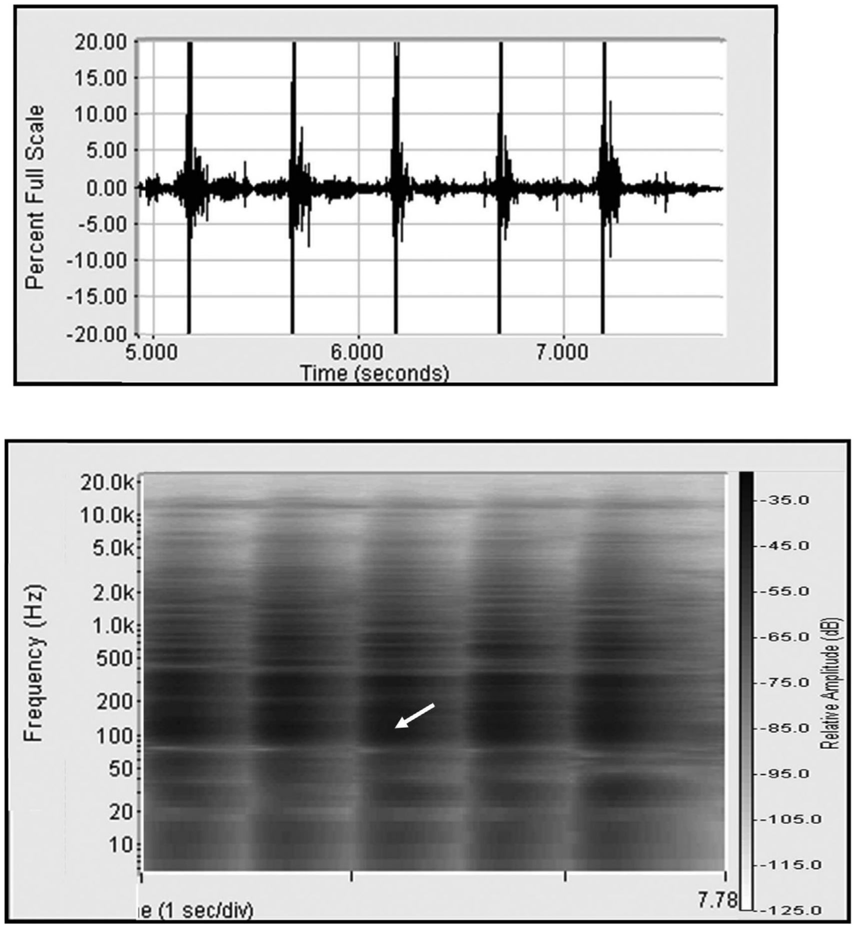

Fig. 2. Knee joint sound (Lachman sound) in a healthy volunteer during the Lachman test. Digitized audio data (upper panel) were converted into a spectrogram (lower panel) by fast Fourier transformation. The spectrogram is shown as a two-dimensional map with the x-axis and y-axis representing time and frequency, respectively, and the relative amplitude representing acoustic pressure, as indicated by the gray scale. The white arrow shows the Lachman peak sound as the maximum relative amplitude (acoustic pressure) and its frequency.

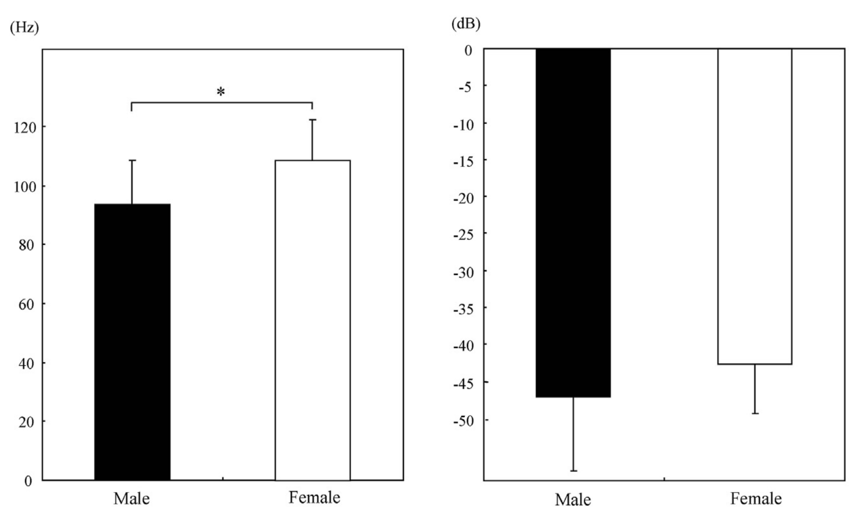

Fig. 3. Lachman peak sounds in the knees of healthy males and females. The values are means ± SD. *P < 0.05 by the Mann–Whitney U-test.

sound was 95.3 ± 12.9 Hz, and the mean acoustic pressure of the Lachman peak sound was −48.6 ± 6.3 dB. The difference in acoustic pressure between the ACL-deficient knees and the contralateral intact knees was significant (P = 0.019).

On the basis of the healthy volunteers' Lachman peak sound, the reference range for the frequency was set at 63.7–122.4 Hz in males and 81.2–135.1 in females (mean ± 1.96 SD). In the patients with ACL deficiency, 20 ACL-deficient knees were true positives and 4

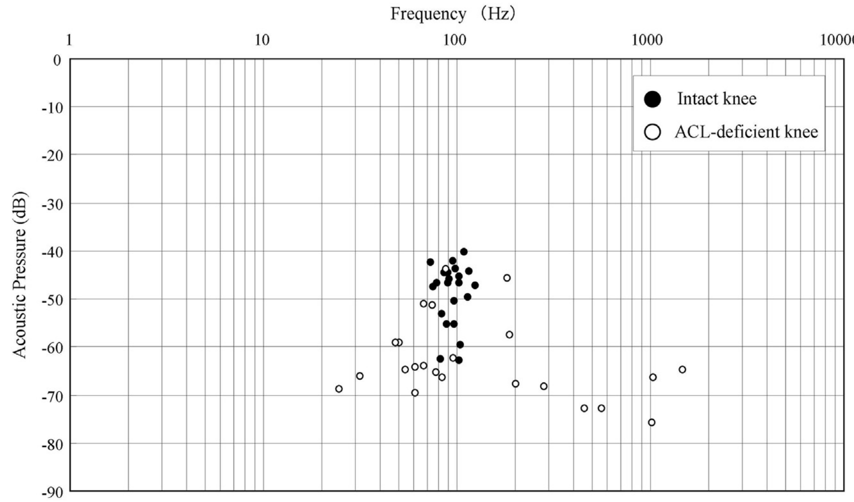

Fig. 4. Distribution charts of the Lachman peak sounds obtained from patients with ACL-deficient knees (open circles) and contralateral healthy knees (filled circles).

were false negatives, while 23 contralateral intact knees were true negatives and 1 were false positives. The sensitivity, specificity, positive predictive value, and negative predictive value were 83.3%, 95.6%, 95.2%, and 85.2%, respectively.

5. Discussion

In the present study, ACL-deficient and intact knees were evaluated quantitatively using the joint peak sound during the Lachman test, defined as the Lachman peak sound. Our findings demonstrate the ability of joint auscultation to support the judgement of the Lachman test, which involves feeling a proprioceptive mushy or firm endpoint. In particular, two interesting results were obtained in this study. First, the Lachman peak sounds were centered around 100 Hz in frequency and −45 dB in acoustic pressure in the healthy volunteer group, but a sex difference was found in the frequency. Second, almost all ACL-deficient knees had different Lachman peak sounds from those of the contralateral intact knees. On the basis of these experimental results, we consider the meaning of knee joint auscultation during the Lachman test below.

Auscultation is a popular method for clinical diagnosis. According to the research of Steindler [17], Heuter used a stethoscope to localize loose bodies in knee joints. To improve knee joint sound detection, Blodgett developed a specially designed stethoscope with a rubber diaphragm to prevent skin friction noise [18]. Subsequently, many researchers used a microphone for joint auscultation to reduce the subjective nature of knee joint analysis [19,20]. Oehl et al. used the word "phonoarthrography" to describe joint sound examination using a microphone [21]. However, the microphone system had some flaws for joint auscultation, i.e. signal distortion caused by background noise and poor response to low-frequency signals [22,23]. To overcome the shortcomings of the microphone system, a vibration-sensitive sensor (accelerometer) has been used for joint auscultation. McCoy et al. proposed the term "vibration arthrography" for joint auscultation using an accelerometer [22]. Most studies have used an accelerometer in the mainstream of joint auscultation [22–24]. Vibration arthrography relies on an acceleration sensor used to collect the mechanical vibrations generated by movement of the articular surface. Therefore, vibration arthrography can directly evaluate the quality of joint motion. The vibration magnitude increases in relation to articular cartilage degeneration and meniscal damage. In the present study, we combined joint auscultation with the Lachman test, as a physical test for ACL deficiency. During tibial translation in the Lachman test, the knee is shaken intensely and a louder knee joint sound occurs from restraints to anterior tibial translation. Therefore, we were able to record and analyze the knee joint peak sound using a microphone without being troubled by background noise and poor response to low-frequency signals. Nevertheless, it remains unknown whether vibration arthrography can be used for assessment of the Lachman test.

Next, we consider the sex difference in the Lachman peak sound of intact knees. Specifically, the Lachman peak sound had a lower frequency in males than in females. Here, we try to explain the sex difference using Mersenne's law, which indicates the frequency of oscillation of a stretched string, and some previous literature describing sex differences in the ACL. Mersenne's law is expressed as:

$$f = \frac{1}{2L}\sqrt{\frac{F}{\mu}},$$

where f is the frequency, L is the length, F is the force, and μ is the linear density.

In cadaveric studies, Chandrashekar et al. reported that the length of the ACL in females was 90–91.3% of that in males [25,26]. Similarly, Stijak et al. measured the cadaveric ACL length, and revealed that the length of the ACL in females was 85.1% (anteromedial bundle) and 92.2% (posterolateral bundle) of that in males [27]. Based on Mersenne's law and these findings, the frequency of the Lachman peak sound is 1.08 $\left(=\frac{1}{0.922}\right)$ – 1.18$\left(=\frac{1}{0.851}\right)$ times higher in females than in males. With regard to the linear density of the ACL, Hashemi et al. investigated the existence of sex differences in the ultrastructural characteristics of the human ACL [28]. They reported that the collagen fibril fraction was 41% in females and 45% in males. Consequently, the linear density of the ACL in females was 91.1% of that in males. Therefore, the frequency of the Lachman peak sound is 1.05 $\left(=\sqrt{\frac{1}{0.911}}\right)$ times higher in females than in males. Regarding the tensile force of the ACL during the Lachman test, few studies have focused on sex differences. If the same tibial translation load was applied for both males and females, the ACL tensile force in females would be greater than that in males. Lipps et al. revealed that during pivot shift loading, the female knee experienced greater ACL strain than the male knee because of anatomical differences in the ACL [29]. However, in our study, it was unknown whether the same translation load was applied to both male and female tibias during the Lachman test. In our joint sound analysis, differences were not found in the acoustic pressure of the Lachman peak sound between males and females. Therefore, we speculated that the ACL tensile force during the Lachman test did not differ between males and females.

Taking the above factors into consideration, 93 Hz (measured value for frequency of male Lachman peak sound) multiplied by 1.08–1.18 (sex difference in length) and 1.05 (sex difference in linear density) equals 105.5–115.2 Hz (theoretical value for frequency of female Lachman peak sound). The theoretical value for the frequency in females is in agreement with the measured value in females (108.2 ± 13.7 Hz). Therefore, the frequency of the Lachman peak sound contains information on the physical properties of the ACL. In addition, the frequency analysis has a potential to diagnose partial tear of ACL.

Based on the frequency of the Lachman peak sound in the healthy volunteers' knees, the frequency in the ACL-deficient knees and contralateral intact knees could be estimated. In the present study, four ACL-deficient knees (Cases 1, 3, 8, and 17) were false negatives. In the false-negative cases, the scar patterns in the knees were either group 1 (ligament scarring to the PCL) or group 3 (ACL remnants appearing to have healed to the lateral wall of the notch or the medial aspect of the lateral femoral condyle in a position anterior and distal to the ACL anatomic footprint). That is, the ACL remnants in groups 1 and 3 have the potential to become restraints in tibial anterior translation. As a result, it was speculated that these four cases would show negative findings for ACL deficiency from the frequency analysis of the Lachman peak sound.

The distribution pattern of the Lachman peak sound differed between intact and ACL-deficient knees. Previously, the distribution pattern of the Lachman peak sound was examined using experimentally ACL-deficient porcine knees. The distribution pattern in the ACL-deficient human knees showed some similarities to that in the ACL-deficient porcine knees [15]. In addition, the distribution pattern in the contralateral intact knees was similar to that in the healthy volunteers' knees. However, the acoustic pressure of the Lachman peak sound was lower in the ACL-deficient knees than that in the healthy volunteers' knees. One reason for the difference is that the Lachman test was performed under anesthesia in the patient group and without anesthesia in the healthy volunteer group. Another reason is that the Lachman tests were performed by different examiners. Therefore, further studies are needed to investigate the interobserver and intraobserver reliabilities of the Lachman sound analysis. From the view point of clinical setting, the other reason would be considered in this study as follows. If examiners cannot feel the firm endpoint in the adequate range of anterior tibial translation, they will gear down the force of tibial translation to preclude any possibility of cartilage and meniscal damage. As a result, acoustic pressure of the ACL-deficient human knees was lower than the porcine knees.

In considering the frequency of Lachman sound, Lachman peak sound of intact knees exhibited around 100 Hz, while those of ACL-deficient knees were a large range of frequency. Biomechanically ACL provides 86% of total resisting force against tibial translation and other ligaments, meniscus cartilage and capsular structure were the remaining secondary restraints [30]. Therefore, Lachman peak sound around 100 Hz occurred from ACL and differences in the main secondary restraint would cause the variety of Lachman peak sound with different frequencies in ACL-deficient knees. As for articular cartilage as the secondary restraint, previous studies indicated that high frequency peak sound (over 1000 Hz) occurred in a contact or a sliding of articular cartilage with each other [19]. In our study, the Lachman peak sounds of three ACL-deficient knees were over 1000 Hz. Regarding meniscus, five cases of ACL-deficient knees with meniscus tear showed the low frequency (under 80 Hz) of Lachman peak sound. Therefore, Lachman peak sound would help us finding out what is a main restraint of tibial translation of ACL-deficient knee.

Several limitations of our study should be considered. First, the Lachman tests were performed by single knee surgeon. Five joint sound measurements were taken and the average was calculated as a measurement value. Although, the measured variation was relatively small, we need to verify reproducibility over time and by different examiners. Therefore, we must investigate both inter-observer and intra-observer reliability for a further study. Second, limited statistical power because of the small population size in our study ($n = 60$ in healthy volunteers, $n = 24$ in patients with ACL deficiency) may have played a role in limiting the significance of some of the statistical comparisons conducted. A post hoc power analysis was conducted using G*Power 3 (developed by Faul F and Erdfelder E et al.) The statistical power was 0.95 in the frequency of healthy volunteers and 0.99 in the acoustic pressure of patients and the effect size d was 1.06 in the healthy volunteers and 1.98 in the patients. Third, we were unable to quantitatively analyze the histological and biomechanical properties of the ACL. As a result, our findings represent a qualitative study. Nevertheless, this method may contribute to progress in ACL treatments. We will continue to gather data from clinical and basic studies, with a view to establishing the present method for quantitative evaluation of the ACL and applying it to the evaluation of operative techniques for ACL reconstruction.

In conclusion, the knee joint auscultation used in the Lachman test was capable of judging ACL deficiency on the basis of objective data. The main finding of this study was that the frequency of the Lachman peak sound had the potential to indicate the ACL condition, including length, linear density, and strain during tibial translation. Therefore, the Lachman peak sound may be useful for not only supporting the judgement of the Lachman test, but also diagnosing the partial rapture of ACL and assessing the ligament condition after ACL reconstruction.

Conflict of interest

The authors declare that they have no conflict of interest.

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