




# Angle and Load Measurement Method for Ankle Joint Using Active Bone-Conducted Sound Sensing

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**Abstract.** In this paper, we present a kinematic and dynamic measurement method of an ankle using an active bone-conducted sound sensing system. This sensing method is minimally invasive because the vibration which is propagated in a leg, mainly a tibia, is only used. First, we describe about the active bone-conducted sound sensing system. Second, we show the best measurement setup using proposed system. Then the relationships between the load on the leg, the ankle joint angle and the frequency characteristics of the vibration are presented. The experimental results show that the vibration characteristics are changed in heavy load and extension condition.

**Keywords:** Active bone-conducted sound sensing · Ankle biomechanics · Internal measurement

## 1 Introduction

Measurement and analysis techniques of the gait become important clinical tools for the quantitative evaluation of human locomotion ability. Both the kinematic and the dynamic measurement are necessary for understanding of the mechanical function of the feet and the legs.

Three dimensional motion capture system is widely employed for the kinematic measurement of the gait in the research field (joint angle, stride, swing speed and so on). However, accurate motion capture systems are costly and need large space and a lot of setup time. The Microsoft Kinect (Microsoft) also applies for kinematic measurement of gait. Pfister et al. were reported accuracy comparison between the Microsoft Kinect and Vicon motion capture system (Vicon) during sagittal plane gait kinematics [1]. They said that the Microsoft Kinect has basic motion capture capabilities but still needs improvements of the software and the hardware before it is used in clinical field. Hondori et al. were reported the technical and the clinical impacts of the Microsoft Kinect in physical therapy and rehabilitation fields [2]. In this paper, the number of the rehabilitation system using the Microsoft Kinect is increased. Also, many papers which are reported evaluation of the Microsoft Kinect's accuracy and

reliability were published. Müller et al. were presented the high accuracy motion capture system using multiple the Microsoft Kinect v2 [3]. They said that the proposed motion capture system is easy to setup, flexible with respect to the sensor locations and delivers high accuracy for the gait measurement.

These motion capture systems are using the Microsoft Kinect/v2 provide low cost and accurate measurement environment in the clinical field. However, the measurement range of the sensor and the system setup is still need some improvements before using clinicians.

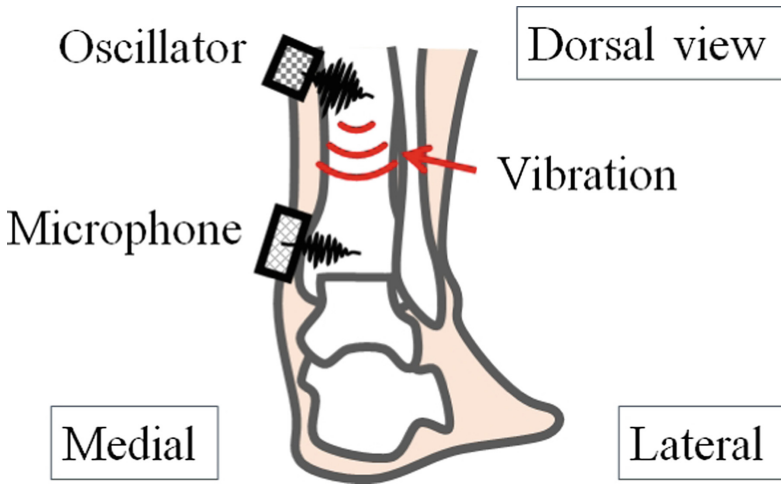
Various sensors are proposed to measure the contact force between the foot and the floor during the gait. Taborri et al. were reported the review paper of a variety of sensors for the gait phase partitioning [4]. These sensors can be classified into the two types, wearable or non-wearable. Foot switches or insole pressure sensors are standard for the wearable type sensing system, but the wearable type sensors have some inherent limitations. Therefore, inertial measurement systems were presented instead. Valuable results are reported using the electromyography, electroneurography and ultrasonic sensors. However, the internal measurement methods are necessary to improve for clinical applications.

The force plate with the optical three dimensional motion capture system, the most accurate system for the gait analysis, is widely used in an indoor environment. However, subject is required to step on the force plate for the contact force measurement during gait motion. This causes difficulties or unnatural motion for the subjects.

Therefore, accurate and simple measurement technique which is easily use for clinicians is needed. In vibrational science field, the nondestructive inspection method is widely used to measure the internal condition of a building construction [5]. We use this methodology to human gait measurement. In this paper, we present the relationship between the ankle joint angle, the load on the leg and the frequency characteristics of propagating vibration.

Figure 1 shows a conceptual image of proposing sensing method. We actively add vibration to a leg and measure propagated vibration at other point of the leg. This sensing method is minimally invasive because vibration which is propagating in a leg, mainly the tibia, is only used. Kato et al. were presented the hand pose estimation method using the active bone-conducted sound sensing and the support vector machine to classify the hand pose [6]. Funato et al. were proposed the three axis contact force estimation method using the active bone-conducted sound sensing and a support vector regression [7]. The vibration which is propagated in-vivo tissue can be used for the joint angle estimation and the force estimation of the end-effector. However, it is still unclear the possibility of the joint angle and the force estimation at the same time.

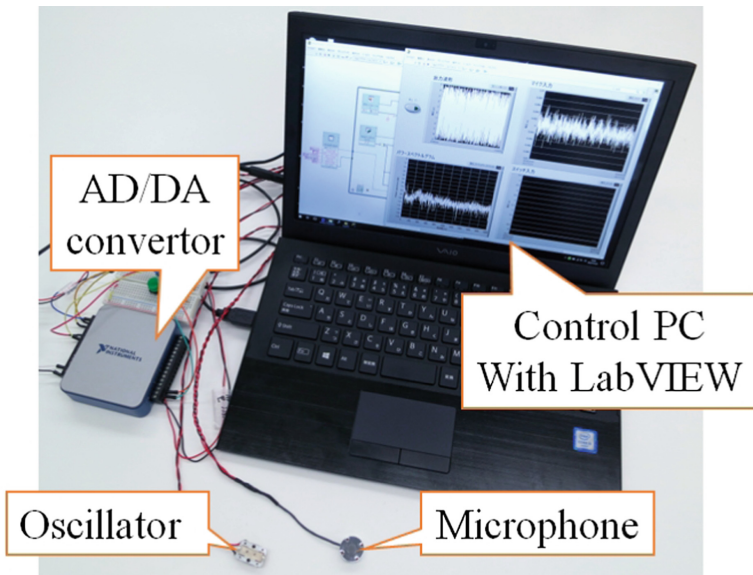
In this paper, we present measurement method of the propagated vibration in the leg under different the ankle joint angle and the loading force on the ankle. Firstly, we compare the sensor position and the distance between the oscillator and the microphone for stable measurement of the vibration. Then the frequency characteristics of the propagated vibration under different condition are analyzed. We discuss the experimental result from the view point of biomechanics.



**Fig. 1.** Internal propagation of the vibration using active bone conducted sound sensing system on the leg (the tibia)

## 2 Measurement System

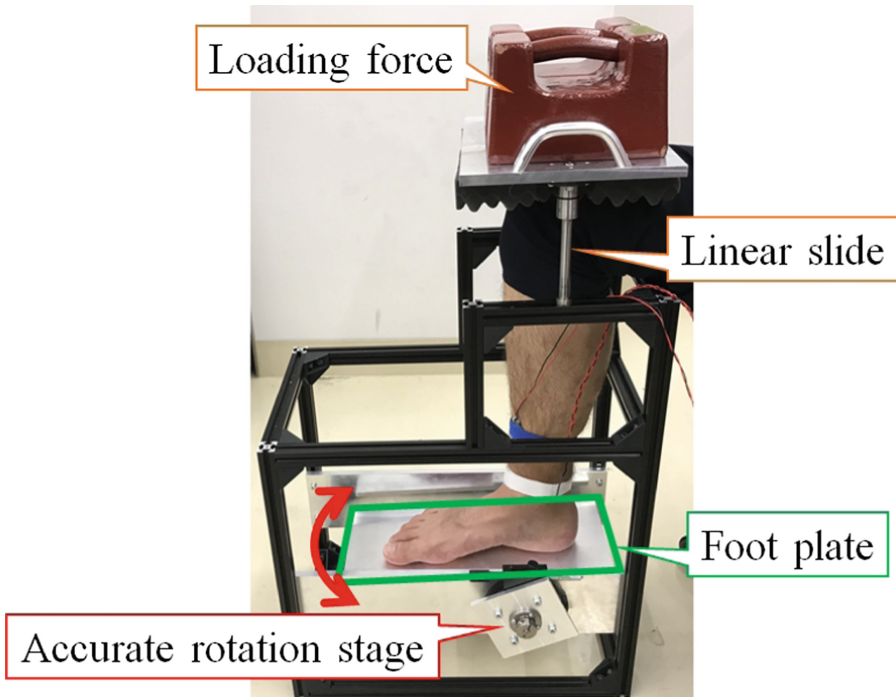
The active bone-conducted sound sensing system is consisting from three components which are a control PC, an oscillator and a microphone. Figure 2 shows the measurement system which we use in this paper.



**Fig. 2.** Active bone-conducted sound sensing system

The control PC generates a waveform to drive the oscillator and records propagated vibration through the microphone. We use LabView (National Instruments) for the programming. White noise is employed as the waveform. The white noise is outputted to the oscillator through the multi-function I/O device (USB-6002, National Instruments). We insert a voltage follower circuit between the I/O device and the oscillator to stabilize the operation of the oscillator. The propagated vibration is received by the microphone and recorded in the control PC with 4 [kHz]. We use COM-10917 (SparkFun) as the oscillator and CM-01B (TE connectivity) as the microphone. These devices have enough frequency response characteristic.

Figure 3 shows the measurement stage. A subject put the right bare foot on the foot plate. Ankle joint angle of the subject is adjusted mechanically by the accurate rotation stage. Then foot is adjusted to a position where the tibia is in a vertical posture. In this paper, we assume that the vertical posture of the tibia is the medial condyle and the medial malleolus are on the vertical line. Two linear guides which are installed on the upper part can control the loading force along the gravity direction.



**Fig. 3.** Adjustable stage for stable measurement

The oscillator and the microphone are attached on skin where the subcutaneous tissue is thin with several centimeters of gap. This means the vibration of the oscillator is transmitted not only in the skin but also in the bone and other tissues.

### 3 Sensor Position Comparison

#### 3.1 Sensor Position Patterns

First, we compare the sensor positions to find the best measurement setup. Figure 4 and Table 1 describe the sensor position patterns. Again, we focus on an ankle joint mechanical property. Therefore, we try to measure directly an ankle joint mechanical property with the pattern A. However, there are many tissues, skin, the bones, the tendons, the cartilage, etc., in an ankle joint. There is a possibility of that these tissues affect as a noise to the measurement.

The pattern B is most close to the contact area during gait motion. And the area around the heel has the smallest organization type, almost the bone (the calcaneu) and skin. This means that a noise from tissues is less than the other patterns.

In the pattern C, the sensors are attached on the tibia which is one of the most important bones to support the weight. The tibia is also important for the power transmission during gait. The vibration by the oscillator easily propagates in the tibia because the shape of the tibia is long and thin.

We use a hook-and-loop fastener band to fasten the sensors in the pattern A and C. In the pattern B, we use an extensionless taping tape to avoid the ankle joint movement limitation.

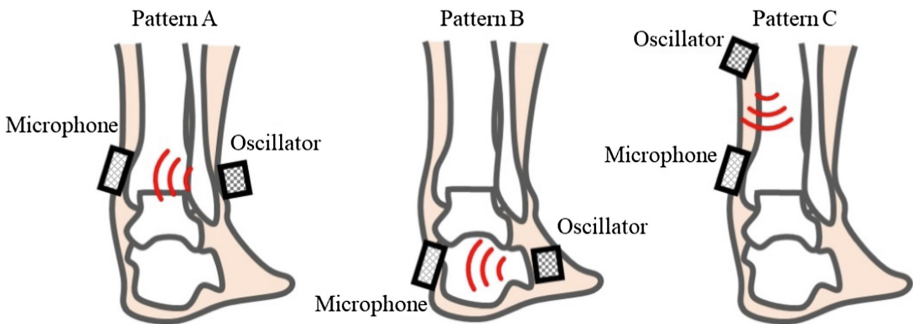


Fig. 4. Sensor position patterns

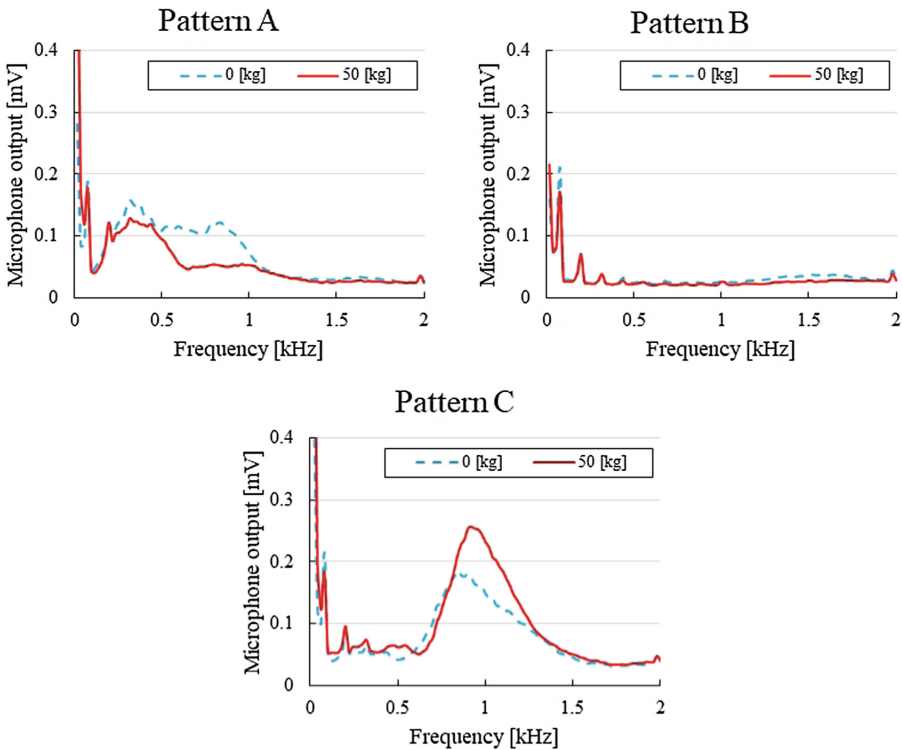
Table 1. Sensor attached bones

	Oscillator	Microphone
Pattern A	Lateral malleolus	Medial malleolus
Pattern B	Lateral process	Medial process
Pattern C	Tibia (medium)	Medial malleolus

One healthy subject volunteered to participate the sensor comparison experiment. The subject was received the explanation of the detail of this research and gave written informed consent before the experiment. We measure the vibration under the two load condition, 0 [kg] and 50 [kg], in each pattern. The ankle joint angle was kept 0 [deg]. We did five trials under respective conditions.

### 3.2 Result

Recorded voltage data from the microphone were fast Fourier transformed (FFT) for the frequency analysis. Figure 5 shows the average FFT data of pattern A, B and C. The blue dash line means the no-load condition (no weight) and the red line means the maximum load condition (the log + 50 [kg] weight).



**Fig. 5.** Frequency characteristics under different loading conditions (Color figure online)

We cannot observe any significant change of the frequency characteristics in the pattern B. In pattern A, the frequency components from 600 to 1000 [Hz] are decreased when the weight was loaded. In pattern C, the frequency components from 800 to 1300 [Hz] are increased the weight was loaded. Also, the peak frequency was changed from 840 [Hz] to 920 [Hz] when the weight was loaded.

We observe the biggest difference of the frequency characteristics between the no-load condition and the maximum load condition in the pattern C. This means that the mechanical characteristics of the tibia is most.

### 3.3 Distance Between Sensors

Second, we compare the distance between the oscillator and the microphone. The sensor's relative distance affect the strength and the path of the vibration. If the sensors attached close place, we can observe the strong vibration signal. However, the vibration mostly path through the surface of the body. On the other hand, the signal strength become weaker according to the sensor's relative distance. In this case, the vibration signal includes a lot of noise.

In our preliminary experiment, the relative distance around 6 to 12 [cm] performed better signal-to-noise ratio. Accordingly, we compare three relative distance of the sensors. Figure 6 shows the sensor attached position with the relative distance 6, 9 and 12 [cm]. The sensor positions are as same as the pattern C in the previous subsection. The microphone is attached on the medial malleolus (the white band in Fig. 6) and the oscillator is attached on the tibia (the blue band in Fig. 6).

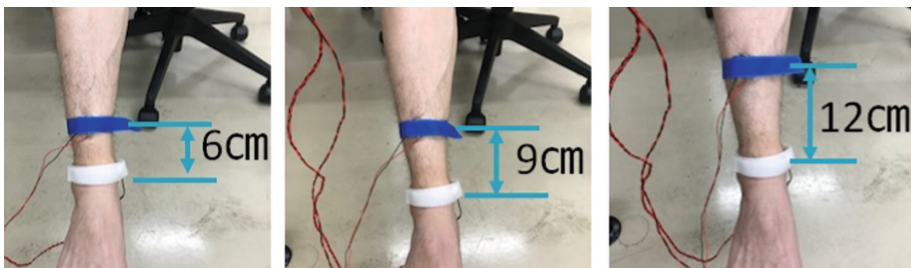


Fig. 6. Distance between the oscillator and the microphone (Color figure online)

In this experiment, we participate other healthy subject. The subject was received the explanation of the detail of this research and gave written informed consent before the experiment. We measure the vibration under the two load condition and the one ankle joint angle condition as same as previous subsection. We did three trials under respective conditions.

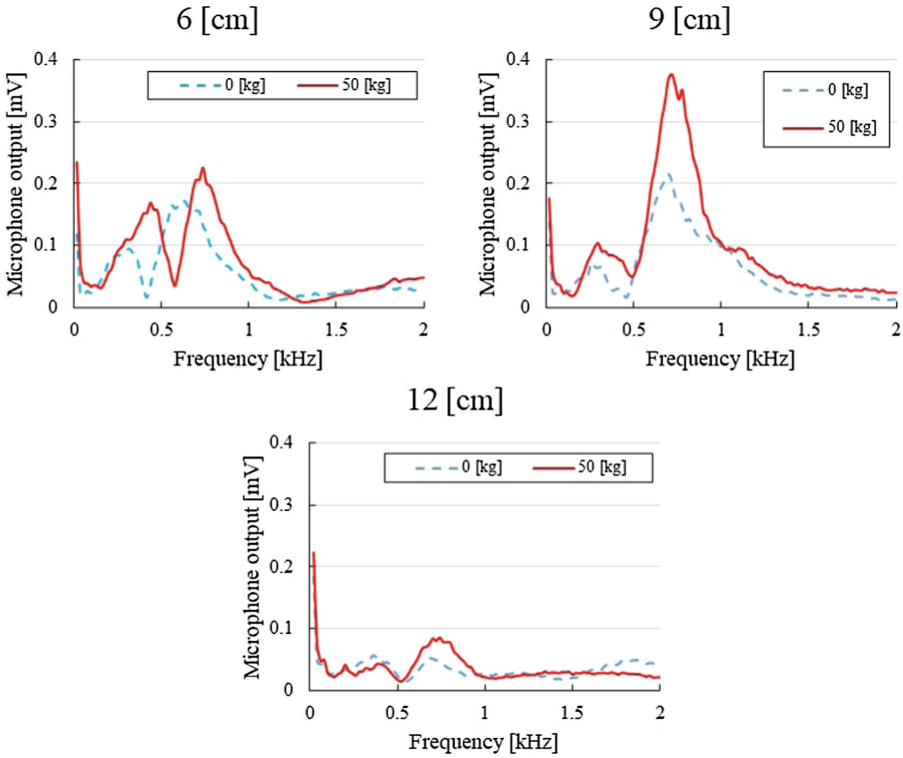
### 3.4 Result

Recorded voltage data from the microphone were fast Fourier transformed for the frequency analysis. Figure 7 shows the average FFT data of three relative distances. The blue dash line means the no-load condition (no weight) and the red line means the maximum load condition (the log + 50 [kg] weight).

We observe that the vibration signal of 12 [cm] much weaker than the other distance. Under the no-load condition, the waveforms of 6 and 9 [cm] have similar

shape and amplitude. When the maximum load condition, the vibration signal of 9 [cm] is much bigger than 6 [cm]. Also, the peak frequency is slightly increased.

These results indicates that the best distance between the oscillator and the microphone is around 9 [cm]. However, this result depends on the subject's physical parameter of the leg.



**Fig. 7.** Frequency characteristics with difference relative distance of the sensors (Color figure online)

## 4 Frequency Characteristics Under Different Load and Joint Angle Condition

### 4.1 Experimental Setup

In this experiment, we measure the vibration using proposed system under 30 different conditions. Experimental conditions are composed of combination of the joint angle ( $-10$  (plantar flexion),  $0$ ,  $10$ ,  $20$ ,  $30$  (dorsal flexion) [degree]) and the load ( $0$ ,  $10$ ,  $20$ ,  $30$ ,  $40$ ,  $50$  [kg]). We did three trials in each condition. One healthy subject volunteered for this experiment. The subject was given the experimental protocol information and he gave his consent to participate.



The subject was sitting and put the right foot on the foot plate then keep relaxing during the experiment. Recorded vibration data are transformed to frequency data by FFT.

### 4.2 Result

Figure 8 shows the average FFT data of different ankle joint angle under the no-load condition. We observe the biggest amplitude when the ankle joint angle is 10 [deg] flexion. The amplitude of the vibration signal is decreased according to the ankle joint bending or flexing. On the other hand, the frequency peak does not change dynamically.

This result indicates that the vibration frequency component from 700 to 1160 [Hz] are also changed according to the ankle joint angle.

Figure 9 shows the average FFT data of different load condition with the maximum flexion posture. We observe the same amplitude level under all load condition. On the other hand, the frequency peak is slightly increased according to the weight number.

Figure 10 shows the average FFT data of different load condition with the small flexion posture. We observe the same amplitude level under all load condition. On the other hand, the frequency peak is slightly increased according to the weight number.

These results show the different trend from the experimental result in the Sect. 3.

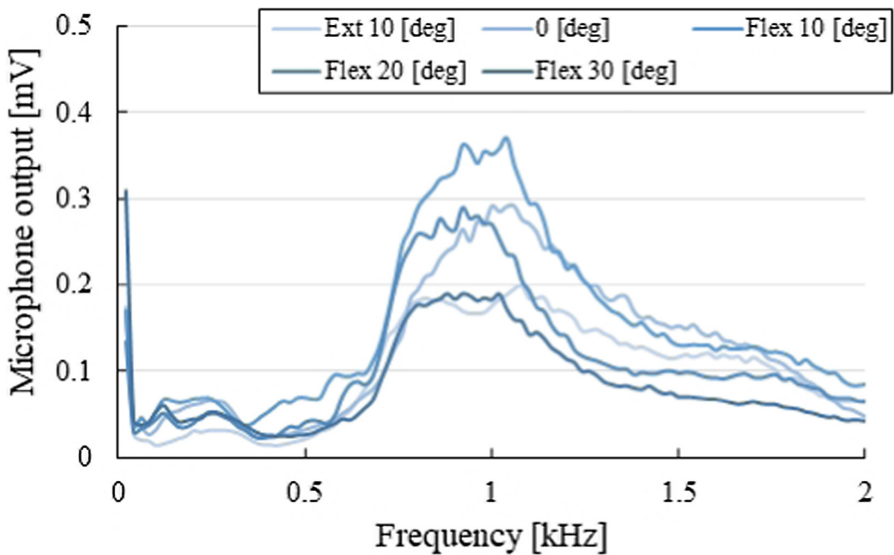


Fig. 8. Ankle joint angle comparison under the no-load condition (50 [kg])

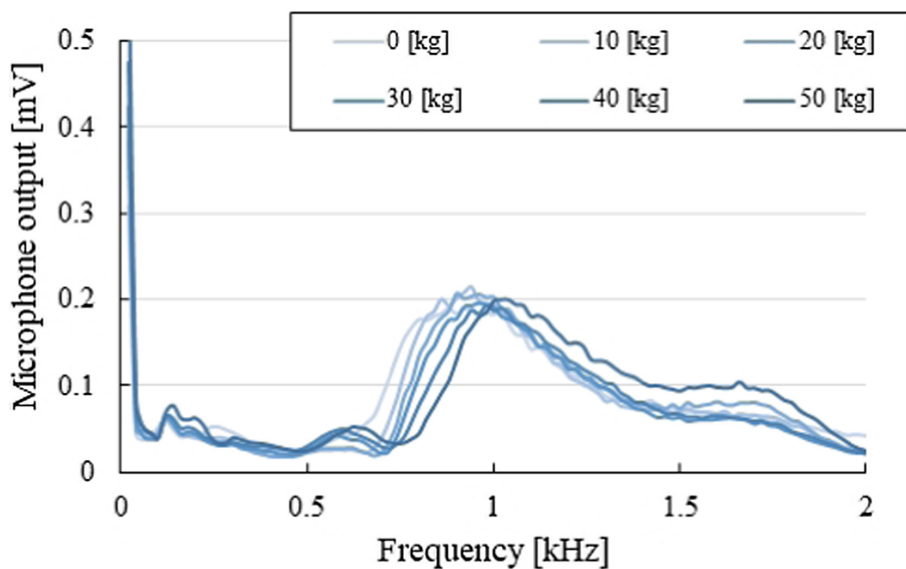


Fig. 9. Load comparison under the maximum flexion condition (30 [deg])

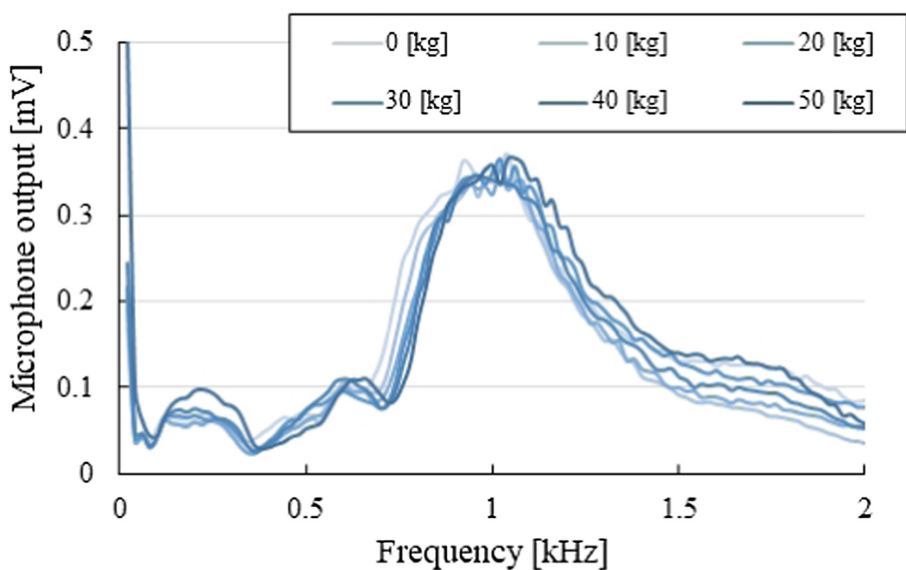


Fig. 10. Load comparison under the small flexion condition (10 [deg])

## 5 Discussion

According to the experimental results of the Sect. 3, the vibration amplitude of the middle range frequency (around 600 to 1200 [Hz]) are increased to depend on the load condition. However, the experimental results of the Sect. 4 shows the different trend. This difference of the data trend is caused by the difference between the subjects. Because the data of each experiment are very stable.

The data trend from one subject, we can observe the trend of the amplitude and the frequency peak according to the ankle joint angle and the load. We believe that the possibility of the estimation of the joint angle of the ankle and the load on the leg at the same time.

## 6 Conclusion

We propose the kinematic and dynamic measurement method for the ankle using the active bone-conducted sound sensing system. The relationships between the ankle joint angle, the load on the leg and the frequency components of the vibration are discussed. Future work will include correcting more data from variable subjects and compare the data trend.

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