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# Measurement and Estimation of the Wave Propagation in Human Body using Multi-Sensory System and 3-D Simulation

# マルチセンサシステムと３次元シミュレーションを用いた人体の音波伝搬計測と推定

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## 1. Introduction

A precise method for quantitative estimation of rehabilitation or exercise is required to improve the QOL in this aging society. However, it is not realistic to measure the mechanical stress or the acoustic vibration inside human body directly.

Therefore, instead of the direct measurement, we estimated the amount of the propagating wave in inferior limb of human bodies using contact sensors and a three-dimentional human body model for acoustic simulation when a single pulse was impress to their heel [1-3]. As a result, clear wave separation caused by multi-path effect in bone portion and soft tissue portion was observed. The fastest wave mainly propagated in bone portion. This interesting behavior was expected to be a good estimation parameter of rehabilitation or exercise because the the fastest wave reflects the amount of the stimulation to the bone.

However, the investigation was performed when the participants were standing motionless. Therefore, in this study, we tried to estimate the wave propagation inside human inferior limb while walking or running.

## 2. Method

We proposed a simple measurement system using pressure sensors and a acceleration sensor. **Figure 1** shows the measurement system. Two pressure sensors (Interlink Electronics, 402) are inserted on the insole of right foot and one contact acceleration sensor (Ono Sokki, NP-3211) was sealed on the skin over the greater trochanter of the participant. The received waveform was amplified 40 dB by an amplifier (Ono Sokki, SR-2200). The derived waveforms from these sensors were recorded by a data logger (NI, USB6212) connected to a PC. The sampling rate of data logging was fixed at 4 kHz.

In addition, the numerical investigation was performed using three-dimensional simulation model in order to assess the path of wave propagation. As the model, the male data in the "*Realistic High-Resolution Whole-Body Voxel Models*" constructed by Nagaoka *et al.* was used [4]. The model describes consisting tissues of normal Japanese person with the resolution of 2.0 mm$^3$. Using this model, elastic properties of the tissues are assigned to water, fat, cortical bone, bone marrow, and air. As the elastic coefficients of cortical bone and bone marrow, experimentally measured values are used [5,6]. As an initial waveform, a single sinusoidal pulse at 20 kHz was virtually impressed to the right heel of the model. The wave propagation was calculated by three-dimensional elastic FDTD (finite-difference time-domain) method. The software was developed by our team [7].

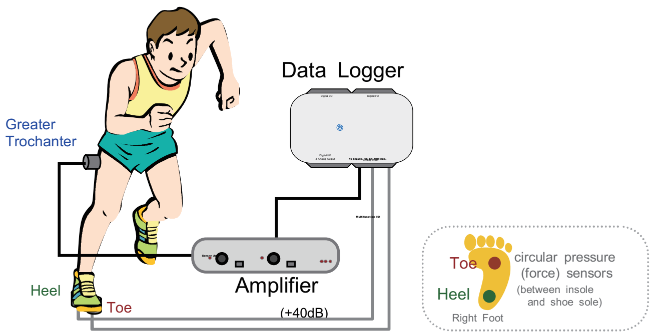


Fig.1 Measurement system.

## 3. Results and Discussion

**Figure 2(a)** shows the examples of the observed pressure waveforms while walking. As shown in Fig 2(a), the mechanical pressure at heel rises rapidly preceding the pressure at toe. The pressure at toe rises moderately compared to that at heel. This interesting behavior tells that a strong pulse wave is impressed to heel part (calcaneus). **Figure 2(b)** shows the acceleration waveform observed on greater trochanter. Clear periodical pulse wave, whose observed time is just after the each rising time of the pressure wave at heel, can be seen. This implies that the pulse wave impressed to heel evoke an acoustic wave (or mechanical vibration) that propagates through inferior limb, then finally it is observed as an acceleration wave at greater trochanter.

**Figures 3(a)** and **(b)** show the examples of the results when the participant was running. In addition to the reasonable fact that the interval of the periodic pattern is shorter than the data of walking, the peak pressure observed at heel was much higher. This tells that much stronger pulse is impressed to the heel while running. The derived data by acceleration sensor also showed a supporting tendency: The peak value of the pulse wave just after the timing of step on heel at greater trochanter was higher than that of walking.

**Figures 4** show the screenshots of the wave distribution in the 3-D human body model. In response to the initial pulse impressed to heel, discriminative wave propagation pattern inside inferior limb is seen: The fastest wave propagates in the bone part. This interesting result implies that the estimation of the amount of the acoustic wave inside bone is possible by monitoring the vibration on the skin near greater trochanter.

## 4. Conclusion

The received acceleration wave at greater trochanter corresponded to the motion (walking or running). On the other hand, simulation revealed that the fastest wave received on greater trochanter is the wave propagated in bone part of inferior limb. These interesting results imply that the estimation of the effect of exercising or practice may be possible by monitoring the amount of vibration on body surface, which may tell us the amount of osteoanagenesis (bone reconstruction). This hypothesis should be confirmed carefully in the future work.


## Acknowledgment

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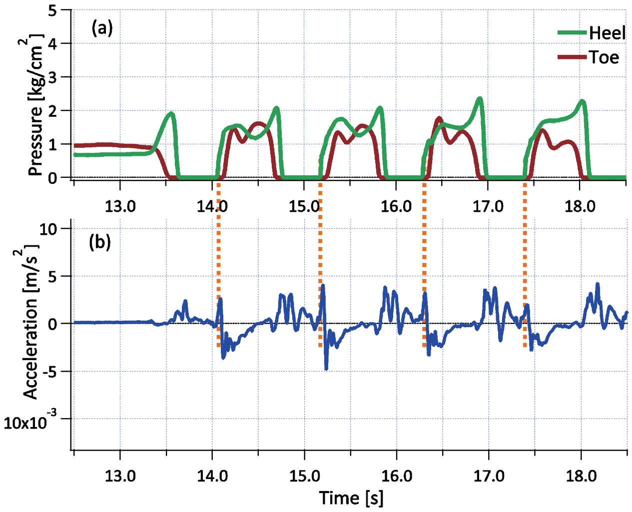


Fig.2 Observed waveform while walking.

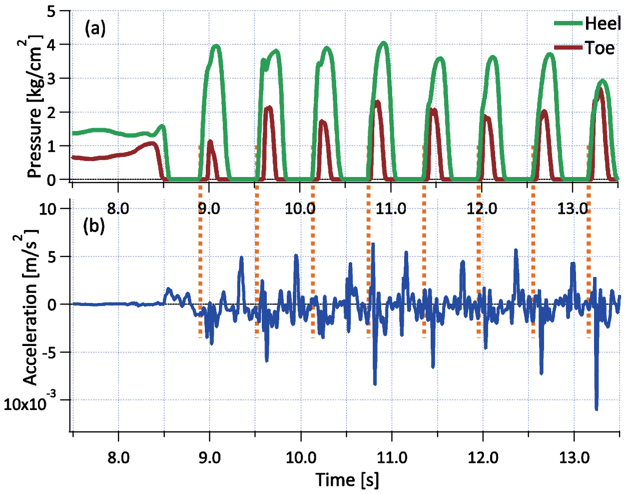


Fig.3 Observed waveform while running.

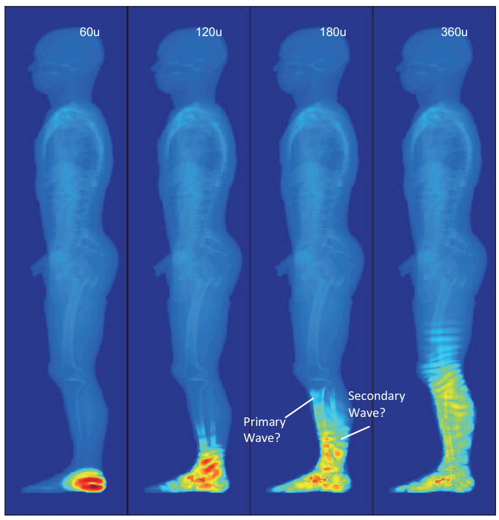


Fig.4 Wave distrubition inside 3-D human model.