# A study of analyzing end-plate and conducting waves using multi-channel surface EMG

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# 多チャンネル表面筋電図を用いた**end-plate**と伝播波の解析に関する研究

Marzieh Aliabadi Farahani

## 和文要旨

身体運動のリハビリテーションにおいて、筋電図は身体運動に伴う筋収縮の回復状況を判断する重要な情報である。本論文では、多チャンネル表面筋電図から伝播波を抽出する方法を用いて、end-plateから対称的に伝播する伝播波を新たに解析し、上腕二頭筋におけるend-plate分布や筋収縮制御等を考察した。また、利き腕と非利き腕の上腕二頭筋の伝播波を比較することで、両筋肉の筋線維組成や筋収縮制御の違いを考察した。その結果、遠位側にend-plateが広く分布することや、非利き腕に比べて、よく使う利き腕の筋収縮では伝播波の種類が均一化されること等がわかった。筋収縮の訓練で伝播波が均一化する現象もあることから、伝播波の種類の均一性から筋収縮の回復状況を判断できる可能性を示した。

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## Abstract

There are 3 different types of muscles in human body that are 1) smooth muscle 2) cardiac muscle and 3) skeletal muscle. In this research, we mainly focused on skeletal muscle.

Rehabilitation is a kind of training that people need to get back, keep or improve their abilities in daily life and it helps people get their abilities back to be independent again. For rehabilitation, it is important to know the mechanism of muscle contraction and how muscles are controlled be able to help people. In rehabilitation, Electromyography (EMG) is important to achieve some information about the recovery process of the muscle. In this research, multi-channel surface EMG had been used to achieve the data of muscle and multi-channel method could newly analyze the waveforms conduct from end-plate to the both directions of tendon. The test muscle was biceps brachii muscle and the distribution of end-plate and control of muscle contraction had been considered.

In addition, by comparing the conducting waves of the biceps brachii in the dominant arm and non-dominant arm, the differences in muscle fiber composition and control of muscle of both arms had been considered. As a result, it was found that the end-plate is widely distributed on the distal side. Also, according to results of muscle contraction of both arms, dominant arm has the same type of motor units that cause the conduction than the non-dominant arm. Since there is a phenomenon that the conducting waves become uniform by the training of muscle, the possibility that the recovery process of the muscle can be judged by the uniformity of the type of the motor units that cause the conduction was shown.

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# 1. INTRODUCTION

There are 3 different types of muscles in the human body that are 1) smooth muscle 2) cardiac muscle and 3) skeletal muscle. Smooth muscle is like our stomach, cardiac muscle is like our heart that they can be active in our body involuntary. In this research, we mainly focus on skeletal muscle that is like our hand or leg and they make a movement under our control and are voluntary.

A skeletal muscle is a striated type of muscle attached to the skeleton and used to facilitate movement by applying a force to the bones and joints via contraction. Skeletal muscles are composed of thousands of parallel muscle fibers running through the length of the muscle. Each muscle fiber contains several parallel contractile units called myofibrils, which extend through the length of the muscle fiber. Motor Unit is comprised of a motor neuron and the skeletal muscle fibers that often team up and work together to coordinate the contractions of a muscle. When the action potential happens, a signal travels from the brain or the spinal cord to make the contraction of skeletal muscles happen. The site where a motor neuron excites a skeletal muscle fiber is called neuromuscular junction. It is a chemical synapse consisting of the points of contact between the axon terminals of motor neurons and the end-plate of a skeletal muscle fiber. The end-plate is responsible for starting action potentials across the muscle surface. In end-plate, action potentials move to both sides of the tendon and make the muscle contraction happens.

Rehabilitation is a kind of training that people need to get back, keep or improve their abilities in daily life and it helps people get their abilities back to be independent again. For rehabilitation, it is important to know the mechanism of muscle contraction and how muscles are controlled to be able to help people.

For the mechanism of muscle contraction, there are some researches about the composition of muscles and they investigated the effect of training on muscles. Furthermore, it is also important to have more information about end-plate and its effects on different conducting waves because it is responsible for starting action potentials across the muscle surface. Furthermore, it is required to record the electrical activity of skeletal muscle. Electromyography (EMG) is an electro-diagnostic technique for evaluating and recording the electrical signals of the body and there are 2 ways to measure the signals: 1) intramuscular EMG and 2) surface EMG. Intramuscular EMG has the needles that hurt the patients and put a lot of stress on them. On the other hand, surface

EMG is more widely used, because it contacts the muscle indirect and does not cause any pain and it is used more often than intramuscular EMG [1-4].

The muscle fiber conduction velocity is the conduction velocity of an action potential along a muscle fiber and in previous researches, it had been achieved by different methods as zero-crossing method [5] and cross-correlation method [6-7].

In surface EMG, the changes during muscle fatigue had been analyzed by integrated electromyography (i-EMG) [8-9] or frequency analysis [10-11]. However, it can measure the conduction velocity of action potentials between only 2 channels. In these analyses, only a single velocity, amplitude or frequency had been considered per analysis section. Furthermore, it is thought that there are a large number of motor units in the muscle with different action potentials. So, it is necessary to consider all the motor units and their velocity.

The multi-channel surface EMG is made up of several electrodes arranged in a row and it is able to measure the action potential of several channels. The multi-channel surface EMG developed in the previous research has the ability to examine the characteristics of conducting waves individually and quantify them. Thus, making it possible to simultaneously analyze and individually identify a large number of motor units. Since the waves are conducted in both directions of the tendon, the characteristics of pairs of symmetric conducting waves which conduct symmetrically in opposite directions to the tendon had not been clarified in the previous study. Additionally, the characteristics of waveforms conducted near the end-plate have not been elucidated and the effect of the end-plate on them was not clear. Furthermore, it is necessary to analyze these features to understand the detailed mechanism of muscle contraction.

The **first purpose** of this study is to clarify the characteristics of pairs of symmetric conducting waves that conduct symmetrically in opposite directions to the tendon, elucidate the characteristics of waveforms conducted near the end-plate and clarify the effect of the end-plate on conducting waves.

Further, there are few studies on dominant and non-dominant arms using integrated EMG and they had been considered just on amplitude and there is no consideration about the surface EMG [12]. Besides, by comparing the conducting waves of the biceps brachii in the dominant arm and non-dominant arm, the differences in muscle fiber composition and control of muscle of both arms had been considered.

The **second purpose** of this study is, analyzed the difference of muscle fibers composition and influence of cortex and spinal cord in dominant and non-dominant arms by applying different loads and using multi-channel surface EMG.

Chapter 2 is the explanation about how the human body works. It is explained that movements are divided to 2 groups of voluntary and involuntary and muscles work in pairs of flexors and extensors to be able to make a movement. Further, the meaning of rehabilitation is explained and it is important for people that lost their abilities in daily life and need to get back. Additionally, it describes about the goal of rehabilitation that is to help people to get their abilities back to be independent again. For rehabilitation, there are 2 ways to measure the electrical signals of the body that are intramuscular and surface EMG. Intramuscular EMG has recently fallen out of favor, because it hurts the patient and puts a lot of stress on them but, surface EMG is more widely used, because it contacts with the muscle indirect and does not cause any pain.

Chapter 3 is the explanation of types of muscle in human body, their structures and functions. Muscles are roughly classified into 3 categories of smooth muscle, skeletal muscle and cardiac muscle. Skeletal muscles are striated and voluntary. Smooth muscles are controlled by nervous system automatically and they take a long time to contract compare to skeletal muscles but they can stay contracted for a longer time. Cardiac muscle are striated as skeletal muscles but they are involuntary as smooth muscles. In this chapter, structure of muscle fibers have been introduced. Skeletal muscle are composed of thousands of muscle fibers that are divided to slow-twitch and fast-switch. Neuromuscular junction is a chemical synapse consisting of the points of contact between the axon terminals of motor neurons and the motor end-plate of a skeletal muscle fiber. Further, the muscle fiber conduction velocity is explained.

In Chapter 4, the analysis methods used in this study have been introduced. Multi-channel method, symmetric conduction method and conduction source method had been used and each method has different condition for waveforms to be accepted as a conducting wave according to conduction judgement. By applying these 3 methods, end-plate was estimated.

In Chapter 5, the first experiment of this study has been introduced and the results have been proved. In this experiment, 4 healthy male participated the experiment and they were asked to keep the elbow of their right hand at a 90 degree angle for 1 minute while carrying a load with 40% of their maximum voluntary contraction (MVC). The relationship between amplitude, conducting velocity (CV) and spatial wavelength of waves and their changes over the time have been examined. In this chapter, the characteristics of pairs of symmetric conducting waves that conduct symmetrically in opposite directions to the tendon had been clarified, the characteristics of waveforms conducted near the end-plate had been elucidated and the effect of the end-plate on conducting waves got cleared.

In Chapter 6, the second experiment of this study has been introduced and the results have been proved. In this experiment, the method was same as the previous experiment but dominant and non-dominant arms were tested. There were 2 different conditions: 40% MVC for 10 sec and 10 % MVC for 30 sec. The relationship between amplitude, CV and spatial wavelength of waves and their changes over the time have been examined. In this chapter, the difference of muscle fibers composition and influence of cortex and spinal cord in dominant and non-dominant arms had been analyzed by applying different loads and using multi-channel surface EMG.

Chapter 7 is about the conclusion. The relation between experiment 1 and 2 and the results achieved from them had been compared.

Chapter 8 is about the future work. The future of this research and the possibilities to be able to continue it had been discussed.

Chapter 9 is about the references. All the references that had been used in this research are mentioned in this chapter.

The flowchart of this research had been shown below in Figure 1.

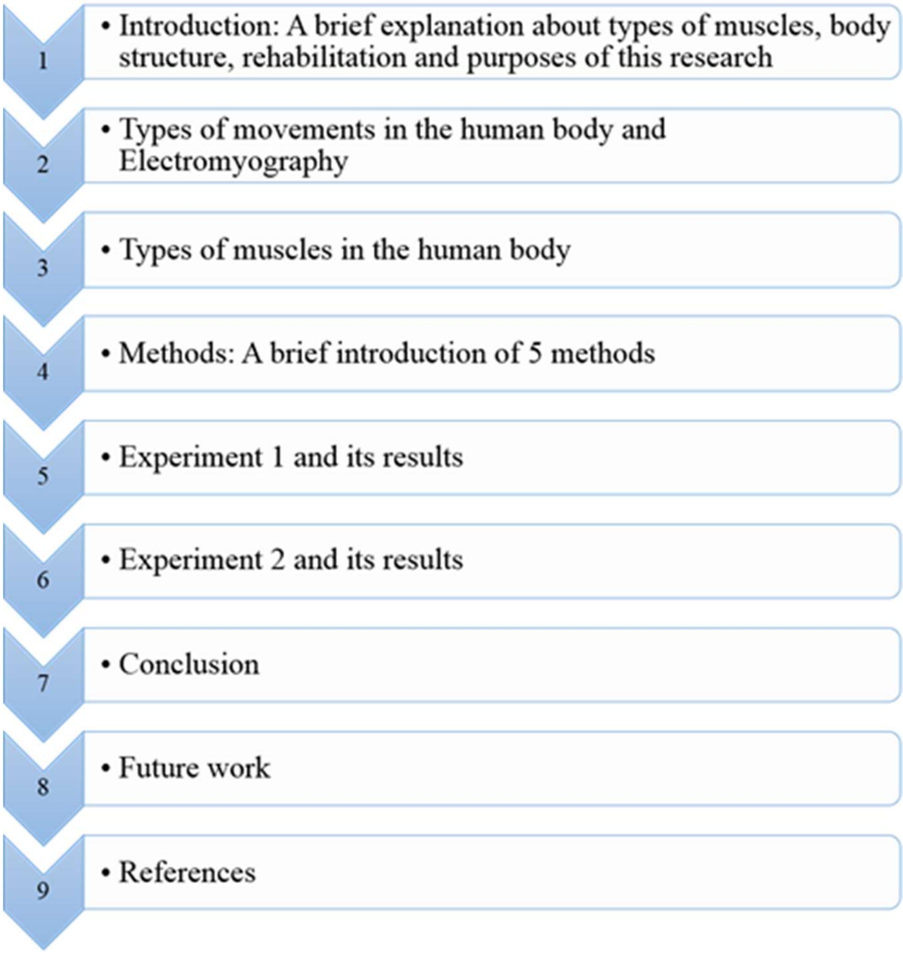

**Figure 1. Flowchart of this research**

# 2. REHABILITATION AND IT'S GOALS

## 2.1. How do muscles work?

The movements of muscles in the human body are coordinated by the brain and the nervous system. There are two types of muscle in the body: involuntary and voluntary. The involuntary muscles are controlled by structures deep within the brain and upper part of the spinal cord. The voluntary muscles are regulated by the parts of the brain. [13]

When a person decides to move, the motor cortex sends an electrical signal to the muscles through the spinal cord and nerves and makes the muscles contract. The motor cortex located on the left side of the brain controls the muscles on the right side of the body and the sensory cortex located on the right side of the brain controls the muscles on the left side.

Muscles are able to move the parts of the body by contracting and then relaxing. They have the ability to pull the bones but they are not able to push and return them to the original position. Therefore, they work in pairs of flexors and extensors.

Flexor muscles contract to bend a limb at a joint. When the bonds are pulled and the movement is completed, flexors relax and extensors contract to extend or straighten the limb at the same joint. The biceps muscle which is in front of the upper arm is a flexor and the triceps which is at the back of the upper arm is extensor. They work together as a pair and when someone bends the elbow, first, the biceps contract. Next, the biceps relax and the triceps contract to straighten the elbow.

## 2.2. Rehabilitation

Rehabilitation is the care that people need to get back, keep or improve their abilities in daily life. These abilities might be physical, mental or even cognitive [14-15]. There are several reasons to need rehabilitation. Some people might lose their abilities because of one of the reasons like: Injuries, spinal cord injuries, side effects from medical treatments, chronic pain including back and neck pain.

## 2.3. The goal of rehabilitation

The goal of rehabilitation is to help people get their abilities back to be independent again. But the specific goals for each person depend on what caused the problem, whether the cause is temporary or not, and how people lost their abilities.

It is also important to know the mechanism of muscles and detailed information about them. Moreover, it is necessary to achieve information about muscle contraction and the way it works. When people get rehabilitation, they often have a team of different health care providers helping them.

## 2.4. Electromyography (EMG)

Electromyography (EMG) is an electrophysiological method that is based on scanning the electrical manifestation of muscle tissue. There are two ways to measure the electrical signal of the action potential If the electrodes are placed directly into the muscle, it is known as intramuscular EMG [21-22] (Figure 2). If the electrodes are placed on the body surface, it is known as surface EMG [16-20] (Figure 3).

In the muscle, there are 2 types of Motor Units: Kinetic Motor Units and Tonic Motor Units which are mixed. Tonic Motor Units have low voltage but they Keep the rhythm of contraction and they are fatigue resistant. Compare to them, Kinetic Motor Units have high voltage but short duration and get fatigued very quickly [39-41] (Figure 4).

Spinalization happens when the interval of action potentials is shorter and they have smaller variance. Corticalization happens when the interval of action potentials longer and they have larger variance [39-41] (Figure 5).

According to above information, Spinalization has similar reaction as Tonic Motor Units and it is related to Dominant parts of the body. On the other hand, Corticalization has similar reaction as Kinetic Motor Units and it is related to Non- dominant parts of the body [39-41]

In rehabilitation, electrography is used mainly for biomechanical analysis of muscles. It is used as:

- Indicator of muscle coordination
- Indicator of force developed by a muscle contraction
- Indicator of the level of muscle fatigue

In all these scenarios, the preference is using surface EMG because it is less invasive than intramuscular EMG. Intramuscular EMG is painful, hurts the patients and puts a lot of stress on them. Further, it is not appropriate for dynamic motions. On the other hand, surface EMG does not make any pain since it will place on the body surface. But, it can evaluate the rough muscle contraction between only 2 points.

Surface electrodes can be either dry or floating. Dry electrodes are in direct contact with the skin, whereas floating electrodes use an electrolytic gel as a chemical interface between the skin and the metallic part of the electrode. In needle EMG, the signals will be transmitted from the needles through a wire to a receiver or an amplifier.

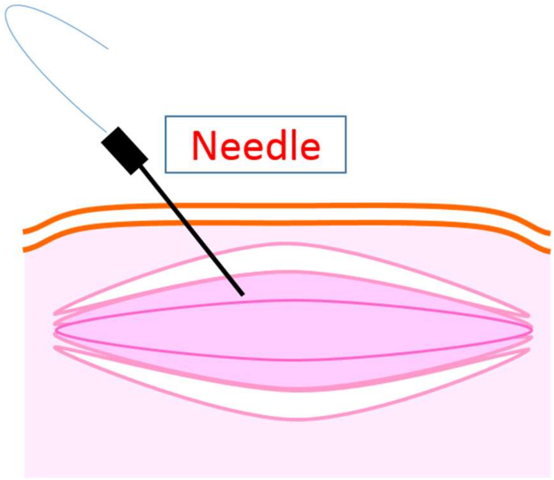

Figure 2. Intramuscular EMG

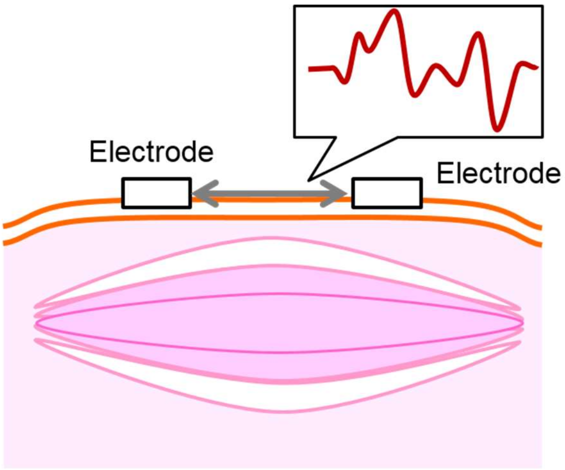

Figure 3. Surface EMG

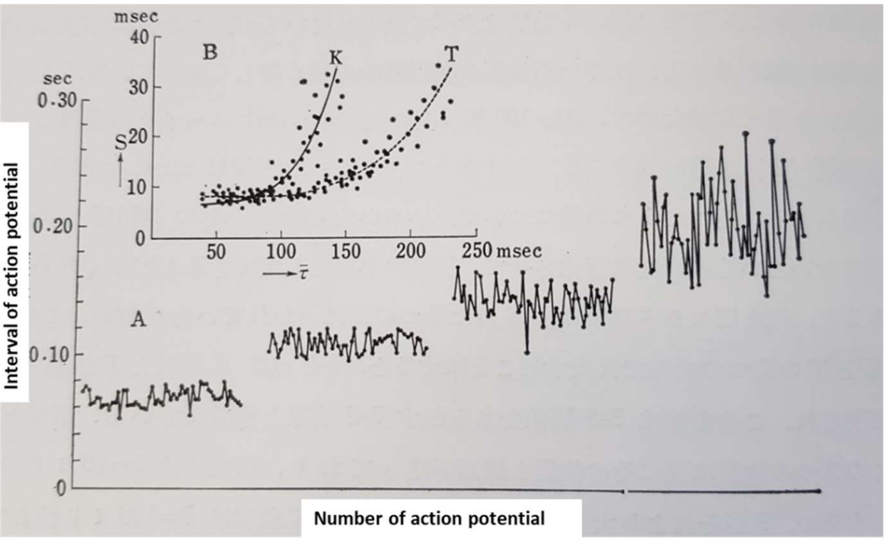

Figure 4 The relationship between number and interval of action potential

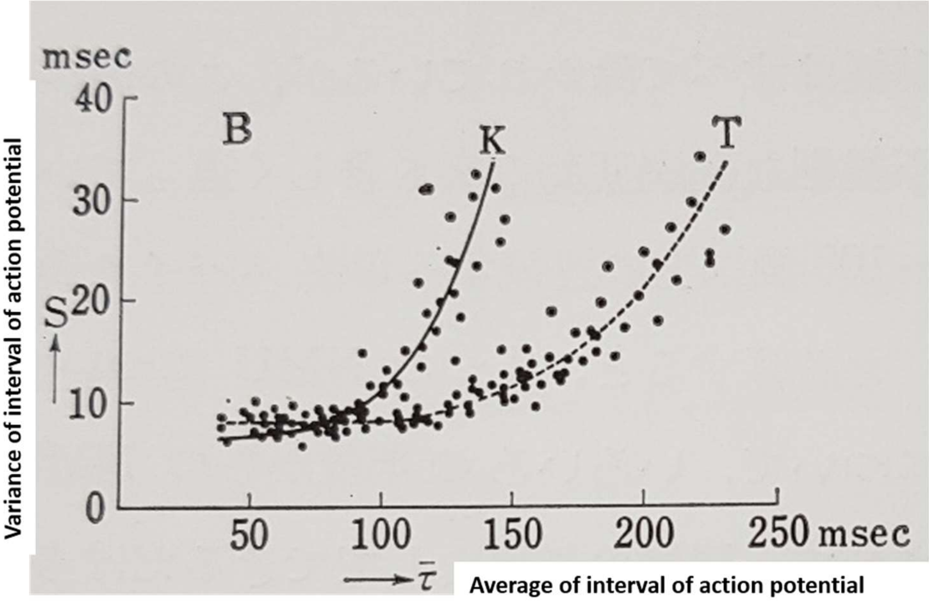

Figure 5. The relationship between average and variance of interval of action potential

## 2.5. Multi-channel Surface EMG

Multi-channel surface EMG designed in the previous work of this research, has the ability to examine the characteristics of conducting waves individually and quantify them, simultaneously analyze and individually identify a large number of motor units and evaluate muscle contraction. For this study, a 17-electrode array was used and 16 channels were measured. The electrodes were made of pure silver wire, and were 1mm in diameter and 10mm in length. The distance between the central part of each electrode was 5mm. The Multi-channel surface EMG used in this research is shown in Figure 6.

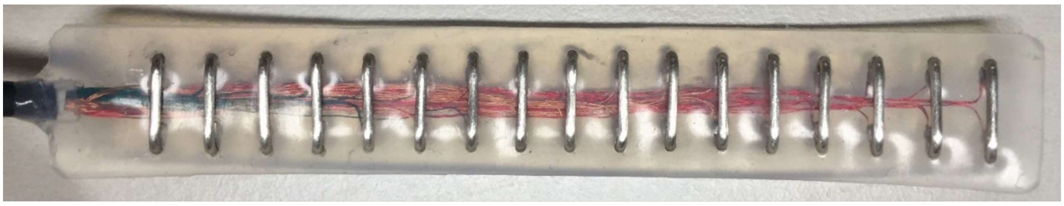

**Figure 6. Multi-Channel Surface EMG**

# 3. SKELETAL MUSCLE OF HUMAN BODY

## 3.1. Skeletal system, Bones, Joints, Muscles

The skeletal system is the organ system of the body composed of bones and cartilage that provides for movement, support, and protection. Bones can provide enough support for the body and help to form the shape. They are light but strong to be able to support the entire weight of the body [23]. Joints are where 2 bones are connected to each other to make the skeleton flexible. Muscles pull on the joints and facilitate the movements. [13]

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## 3.2. Types of muscle in human body

Muscles in the human body can be roughly classified into 3 categories of smooth muscle, skeletal muscle, and cardiac muscle according to their location and function. At the same time, muscles are able to be divided into 2 groups of involuntary and voluntary muscles. They are shown in Figure 7.

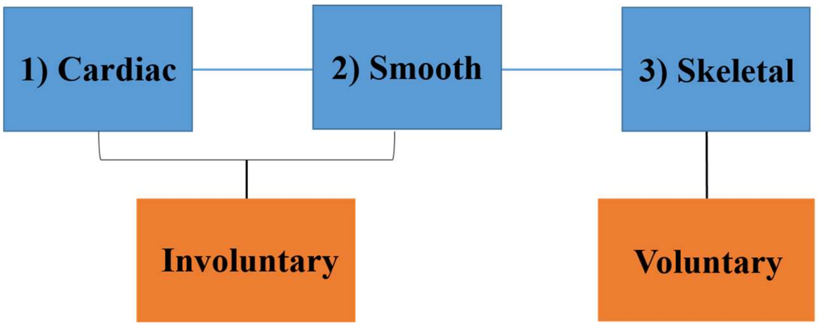


**Figure 7. Classification of muscles**

It shows different types of the muscles.

### 3.2.1. Skeletal muscle

They are attached to the bones by tendons. They are made up of several fibers that have horizontal stripes when viewed under a microscope and that is the reason they are called striated. They help hold the skeleton together and give shape to the body and they have different shapes and sizes. They are voluntary and able to contract quickly and powerfully but they are easy to tire. The percentage of body weight of skeletal muscle is 40-50%. For example leg and hand.

### 3.2.2. Smooth muscle

They are made of several layers of fibers with one layer behind the others which they look smooth, not striated. They are controlled by the nervous system automatically and it is the reason that they are called involuntary. They take a long time to contract compare to skeletal muscles but they can stay contracted for a longer time. For example internal organs such as blood vessel wall, stomach, intestine, bladder, and uterus.

### 3.2.3. Cardiac muscle

They are involuntary and make up the heart. Same as smooth muscles, they are controlled automatically and are involuntary. Their common fact with skeletal muscle is that they are striated muscle. They pump the blood out and make the blood circulation. For example heart.

## 3.3. Skeletal muscle structure and function

A skeletal muscle is a striated type of muscle attached to the skeleton. It is used to facilitate movement by applying a force to the bones and joints via contraction. Skeletal muscles are composed of thousands of parallel muscle fibers running through the length of the muscle.

Each muscle fiber contains several parallel contractile units called myofibrils, which extend through the length of the muscle fiber. The structure of the muscle is shown in Figure 8. An action potential of muscle fibers originates from a brain signal and occurs when the membrane potential of a specific axon location rapidly rises and falls [24]. This is communicated to the "end-plate" of a muscle fiber; the neuromuscular junction between a motor neuron and the muscle fiber. The action potential is conducted from the end-plate to both sides of the tendon.

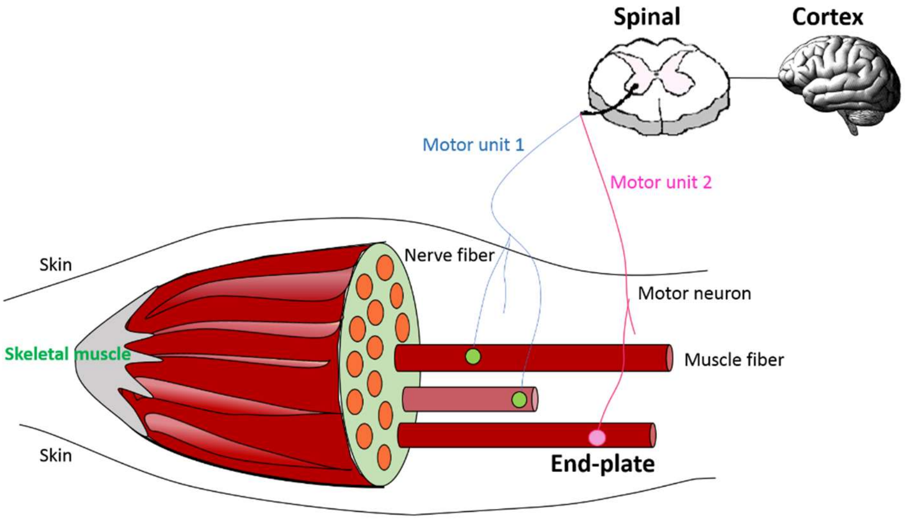


**Figure 8. The structure of skeletal muscles**

It shows different parts of skeletal muscle.

### 3.3.1. Motor Unit

Motor Unit is comprised of a motor neuron and the skeletal muscle fibers that are innervated by the axonal terminals of the Motor Neuron [25-26]. Motor Units often team up and work together to coordinate the contractions of a muscle. When Motor units receive a signal from the brain for contracting, all of the muscle fibers within the Motor Unit contract at the same time with full force.

### 3.3.2. Motor Neuron

Motor Neuron is a special type of brain cell that is called neurons and they are located within the spinal cord and the brain. There are 2 main types of Motor Neurons, upper motor neurons, and lower motor neurons. Axons from upper motor neurons synapse onto interneurons in the spinal cord and occasionally directly onto lower motor neurons [27].

### 3.3.3. Muscle fiber

It is generally accepted that humans have two main types of muscle fiber: slow-twitch (type I) muscle fibers and fast-twitch (type II) muscle fibers. Fast-twitch muscle fibers can be further categorized into type FT-A and type FT-B [28]. (Table 1).

#### 3.3.3.1. Slow-Twitch Muscle Fibers (ST)

The slow-twitch muscle fibers are identified by a quick contraction time and slow resistance to fatigue. They are more efficient at using oxygen to generate more adenosine triphosphate (ATP) fuel for continuous, extended muscle contractions over a long time. They fire more slowly than fast-twitch fibers and can go for a long time before they fatigue. Therefore, slow-twitch fibers are great at helping athletes run marathons and bicycle for hours [29].

#### 3.3.3.2. Fast-Twitch Muscle Fibers (FT)

The fast-twitch muscle fibers are identified by a quick contraction time and low resistance to fatigue. Because they use anaerobic metabolism to create fuel, they are better at generating short bursts of strength or speed than slow muscles. However, they fatigue more quickly. Fast-twitch fibers generally produce the same amount of force per contraction as slow muscles, but they get their name because they are able to fire more rapidly. Having more fast-twitch fibers can be an asset to sprinters since they need to quickly generate a lot of force [30].

### 3.3.3.3. Fast-Twitch Muscle Fibers (FT-A)

These fast-twitch muscle fibers are also known as intermediate fast-twitch fibers. They can use both aerobic and anaerobic metabolism almost equally to create energy. They have a moderate resistance to fatigue and represent a transition between the two extremes of type I and type II muscle fibers.

### 3.3.3.4. Fast-Twitch Muscle Fibers (FT-B)

These fast-twitch fibers are very sensitive to fatigue and are used for short anaerobic, high force production activities. They have the highest rate of contraction of all the muscle fiber types, but it also has a faster rate of fatigue and cannot last as long before it needs rest. Therefore, these muscle fibers are great at helping athletes sprinting, hurdling and jumping.

### 3.3.3.5. Aerobic metabolism

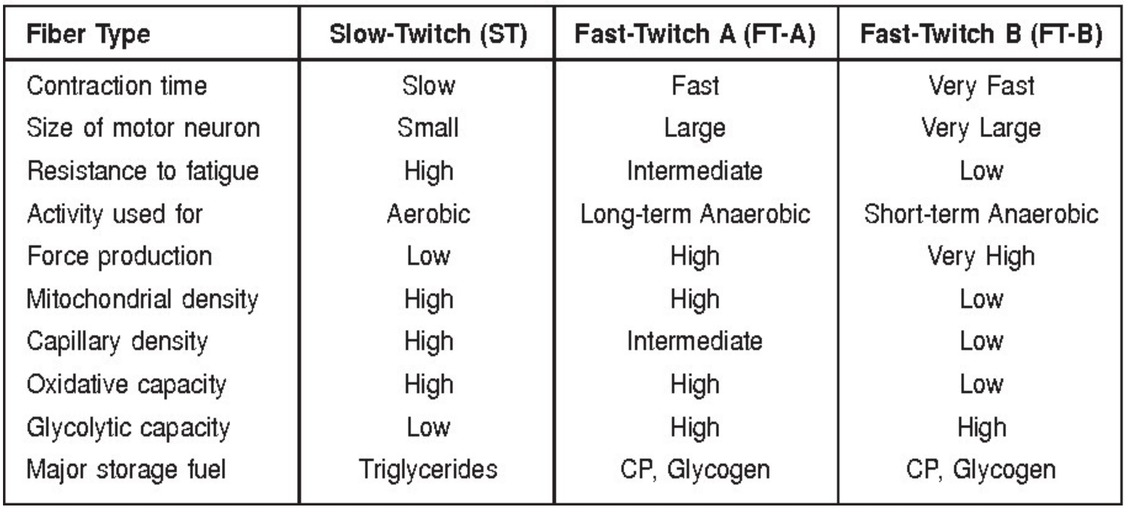
It is the way that the body creates energy through the combustion of carbohydrates, amino acids, and fat in the presence of oxygen.

### 3.3.3.6. Anaerobic metabolism

It is the creation of energy through the combustion of carbohydrates in the absence of oxygen.

**Table 1. Characteristics of muscle fibers [31]**

This table shows the difference between slow-twitch, fast-twitch A and fast-twitch B.



| Fiber Type | Slow-Twitch (ST) | Fast-Twitch A (FT-A) | Fast-Twitch B (FT-B) |
|---|---|---|---|
| Contraction time | Slow | Fast | Very Fast |
| Size of motor neuron | Small | Large | Very Large |
| Resistance to fatigue | High | Intermediate | Low |
| Activity used for | Aerobic | Long-term Anaerobic | Short-term Anaerobic |
| Force production | Low | High | Very High |
| Mitochondrial density | High | High | Low |
| Capillary density | High | Intermediate | Low |
| Oxidative capacity | High | High | Low |
| Glycolytic capacity | Low | High | High |
| Major storage fuel | Triglycerides | CP, Glycogen | CP, Glycogen |

## 3.4. Neuromuscular junction and end-plate

The nerve impulses, also known as action potentials, travels from the brain or the spinal cord to trigger the contraction of skeletal muscles. An action potential conducts down a motor neuron to the skeletal muscle fiber. This site where a motor neuron excites a skeletal muscle fiber is called neuromuscular junction. It is a chemical synapse consisting of the points of contact between the axon terminals of motor neurons and the motor end-plate of a skeletal muscle fiber. Synapse is the junction between two neurons where the electrical activity of one neuron is transmitted to the others. The motor end plate is, in fact, the highly excitable region of muscle fiber plasma membrane and it is responsible for initiating action potentials across the muscle surface. This effect ultimately results in muscle contraction. The neuromuscular junction is composed of three parts: synaptic end bulbs, motor end-plate, and synaptic cleft.

### 3.4.1. Synaptic end bulbs

As the axon of the motor neuron enters the skeletal muscle, it forms many branches called axon terminals. At the end of each axon terminal, there is a bulbous swelling called "synaptic end bulb". Each synaptic end bulb contains many synaptic vesicles. These vesicles contain all the important neurotransmitter substances such as acetylcholine. These neurotransmitter substances are responsible for the transmission of an impulse from axon to muscle fiber through the synapse.

### 3.4.2. Motor end-plate

It is the part of the sarcolemma of the muscle cell, which is in closest proximity to the synaptic end bulb.

### 3.4.3. Synaptic cleft

It is the space between the motor end-plate (muscle fiber part) and synaptic end bulb (motor neuron part) of the neuromuscular junction. It is from 20 to 30 nanometers wide. Because of this cleft, the connection between the motor neuron and the muscle fiber is not continuous and there is a break. This break is traversed by the neurotransmitters.

## 3.5. MFCV

The muscle fiber conduction velocity (MFCV) [32-34] is the velocity at which muscle fibers transmit action potentials before muscle contraction. Primarily, action potentials generated in endplates are propagated toward the muscle fiber terminal. In general, a surface EMG is used to simultaneously measure the action potential of a large number of motor units [35] in the muscle.

The relationship between MFCV and muscle dynamic characteristics has been reported for voluntary contractions of the tibialis anterior muscle. When MFCV increases, muscle dynamic characteristics are improved; conversely, when MFCV decreases, muscle dynamic characteristics deteriorate.

# 4. METHODS

The analysis methods are Multi-channel method [36-38], Symmetric conduction method, Conduction source method, End-plate estimation method and Spatial wavelength.

## 4.1. Multi-channel method

In this method, the interval where the zero crossing occurs twice was defined as the analysis unit, and the channel with the analysis unit was defined as the conduction source. The adjacent channels around the conduction source that were within 10 ms before or after the starting point of the conduction were defined as the conduction destination. To obtain acceptable data using the waveform conduction method, a correlation coefficient of 0.9 or more, amplitude ratio of 0.7 dB or more and wavelength ratio of 0.9 Hz or more were needed.

However, since the wavelengths were different, resampling was performed on two zero crossing intervals according to the sampling theory of Eq. (1). In this equation, $\Delta t$ is the sampling interval; $x_a(k\Delta t)$ represents the sampling data; $x_a(\mathrm{t})$ is the analog signal restored from the sampling data.

$$x_a(\mathrm{t}) = \sum_{k=-\infty}^{+\infty} x_a\,(k\Delta t) \cdot \frac{\sin\left[\frac{\pi}{\Delta t}(t - k\Delta t)\right]}{\frac{\pi}{\Delta t}(t - k\Delta t)}. \qquad (1)$$

According to Eq. (1), the original analog signals are theoretically able to be restored by achieving the conditions of the sampling theory. Thus, only the sampling numbers can be approached because the amount of data is not infinite. Resampling the data can help to analyze the action potential of muscle at any resolution and calculate a correlation coefficient for two zero crossing intervals with differing interval lengths (Figure 9).

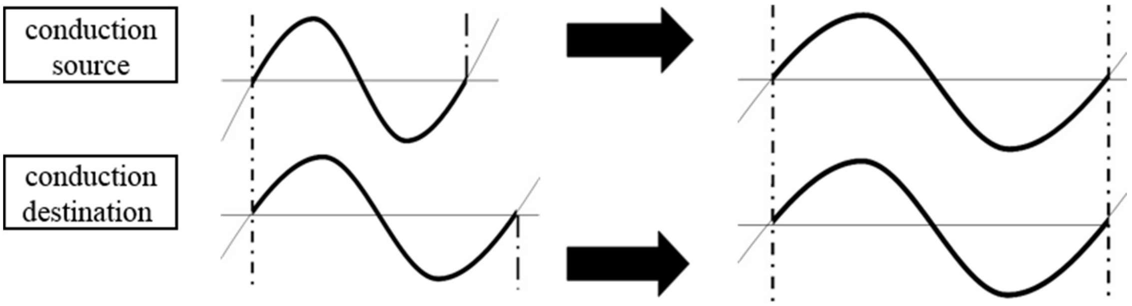


**Figure 9. Multi-channel method**

It shows the process of resampling in multi-channel method.

To quantitatively evaluate the similarity in shape of two zero crossing intervals that have been resampled, the similarity ratio $\mathrm{R}_{xy}$ was used as a conduction condition. The similarity ratio $\mathrm{R}_{xy}$ is given by Eq. (2), where $m_x$ and $m_y$ are the average of action potential; φ is the correlation function ($\varphi_x$ and $\varphi_y$ are the autocorrelations) and $\varphi_{xy}(\tau) = E\ [x(\tau)y(t+\tau)]$ is the cross correlation.

$$R_{xy}(\tau) = \frac{\{\varphi_{xy}(\tau) - m_x m_y\}}{\sqrt{\{\varphi_x(0) - m_x^2\}\{\varphi_x(0) - m_x^2\}}}. \tag{2}$$

The denominator of $\mathrm{R}_{xy}$ in Eq. (2) represents the width of the zero crossing intervals in the conduction source and conduction destination channels. Differences in wave amplitude are not reflected in the similarity ratio $\mathrm{R}_{xy}$ in Eq. (2). Therefore, the following amplitude ratio $\mathrm{G}_{xy}$ was another component used in the conduction conditions:

$$G_{xy} = \frac{\sqrt{\{\varphi_x(0) - m_x^2\}}}{\sqrt{\{\varphi_y(0) - m_y^2\}}}. \tag{3}$$

Furthermore, the wavelength ratio was also needed during conduction to evaluate the wavelength similarity. The wavelength ratio $\mathrm{L}_{xy}$ is given by Eq. (4). It was utilized as a component of the conduction conditions; Lx and Ly are the zero crossing interval lengths of the conduction source and destination channels.

$$L_{xy}$$

$$= \frac{L_x}{L_y}. \tag{4}$$

The coefficient of variation of the conducting velocity (CV) was calculated as below in Eq. (5).

$$\text{Coefficient of Variation of Conducting Velocity (\%)}$$
$$= \frac{standard\ \ deviation\ \ of\ \ CV}{average\ \ deviation\ \ of\ \ CV} \times 100 \tag{5}$$

In order to be considered as a conducting wave based on the similarity of waves among multiple channels, this study proposed a more reliable conduction judgment by searching for waveforms conducted over multiple channels as shown in Figure 10.

The conduction velocity can be calculated by resampling and considering the partial expansion and contraction. As shown in Figure 10, the accepted conducting waves were based on the similarity of waves and then divided into two. The delay time was calculated as explained below.

First, the conduction source and conduction destination waveforms were divided by the midpoint. The conduction source waveform was divided into the back waveform and the front waveform without moving the midpoint. Next, the waveforms were searched while changing the position of the midpoint of the conduction destination. The point that the correlation coefficient of the conduction source and conduction destination waveforms became the highest, was set as the midpoint of the conduction destination. Additionally, it was divided into the back waveform and the front waveform.

$\Delta t_1$ is the difference between the midpoints of the back waveforms while $\Delta t_2$ is the difference between the midpoints of the front waveforms in both the conduction source and destination.

Furthermore, D1% and D2% were derived from the conduction source, weighted, and the delay time Δt was calculated. Calculation of Δt was performed as shown in Eq. (6) (Figure 11).

$$\Delta \mathrm{t} = \Delta t_1 D_1 \ + \ \Delta t_2. \tag{6}$$

The conduction velocity was calculated using the delay time Δt as shown in Eq. (7).

$$\mathrm{CV} = \frac{Distance\ \ between\ \ electrodes\ \ (D)}{Delay\ \ time\ \ (\Delta t)}\ . \tag{7}$$

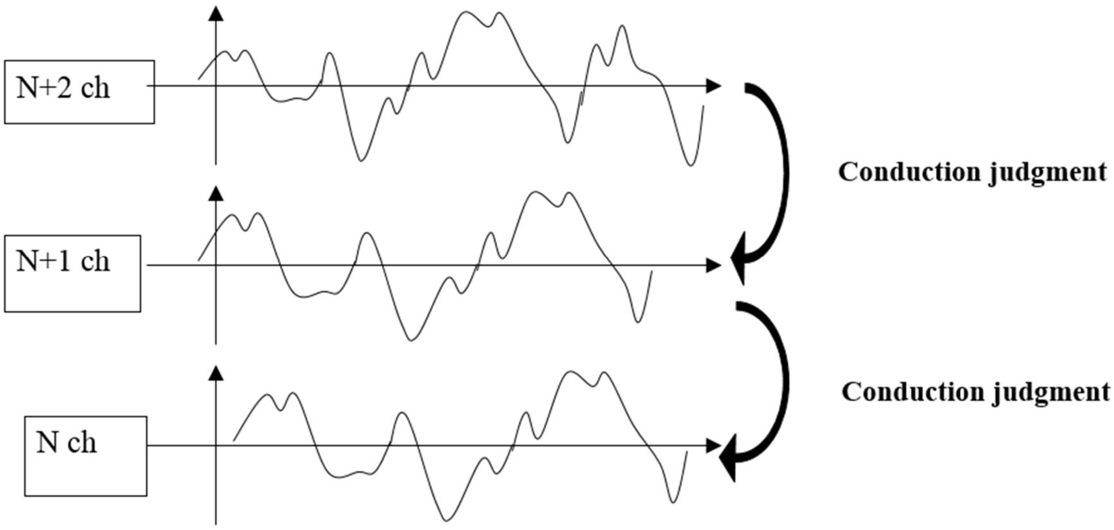


**Figure 10. Multi-channel method**

It shows the process of multi-channel method regarding to conduction judgement

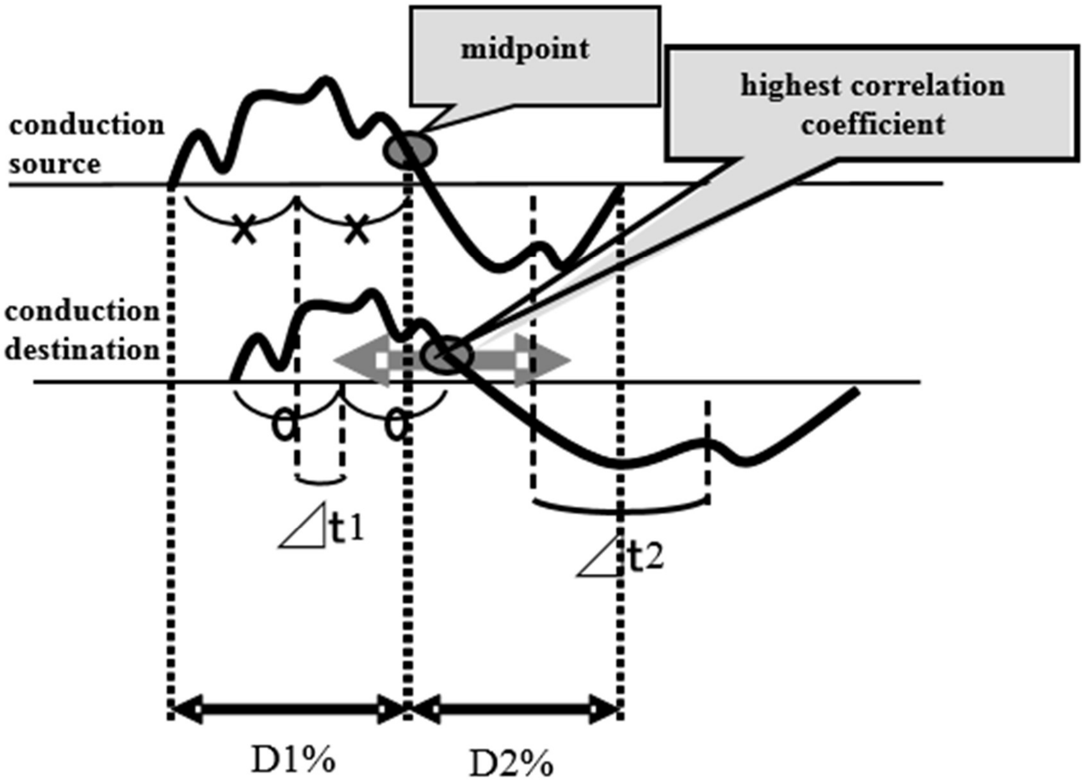


**Figure 11. Calculation of delay time**

It shows hot it is possible to calculate the delay time($\Delta t$)

## 4.2. Symmetric conduction method

In this method, symmetric conducting waves moved in the opposite direction from the end-plate with the same but reversed shape. The symmetric conduction method was performed using a correlation coefficient of -0.9 or less, the amplitude ratio of 0.7 dB or more, and wavelength ratio of 0.9 Hz or more for each antiphase analysis unit obtained in method 4.1. Note that when the conducting waves moved further from the conduction source, the interval time increased. When the channels that analysis units are taken, are far from each other, the position of end-plate would not be in the center anymore. Therefore, time will help to have an accurate answer. Accordingly, 10 ms will be added to the result per each channel between analysis units (Figure 12).

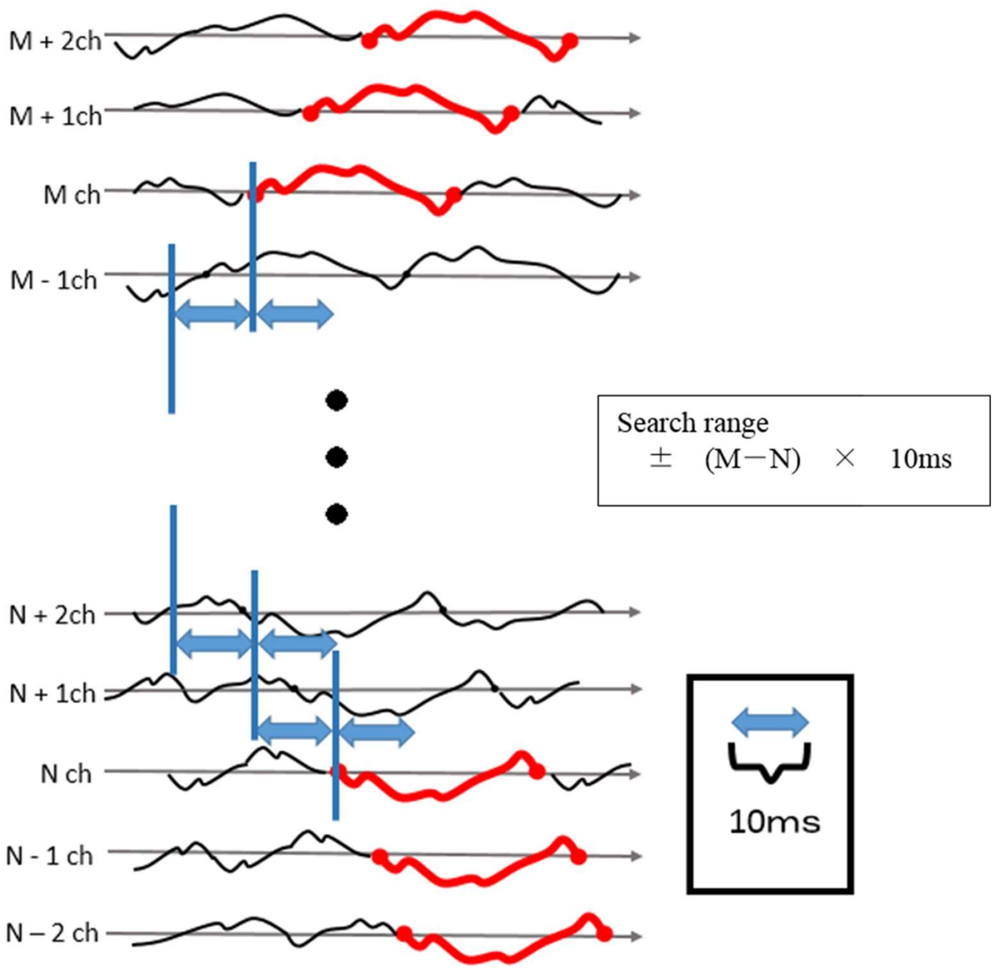


**Figure 12. Symmetric conduction method**

## 4.3. Conduction source method

For conditions in method 4.2, where it was not possible to find any symmetric conducting waves, the waves with a correlation coefficient of 0.9 or more and conduction velocity within ±50 m/s, moving along the direction of conduction were identified (Figure 13).

To be able to find out the shape of a wave before considering it as a conducting wave, looking for conduction source wave was necessary. Accordingly, a wave that was considered as a conducting wave according to the Multi-channel method was taken as a test model. Between adjacent channels in the direction of conduction source, the waves with 2 zero crossings and starting within ±10 ms of our test model are considered as conduction source method. In the case of finding several channels as the conduction source, the waves were compared and the one with the highest percentage of similarity to conducting wave was chosen as the conduction source. By repeating the process which was mentioned above, we were able to find the conduction source of all the channels of a conducting wave.

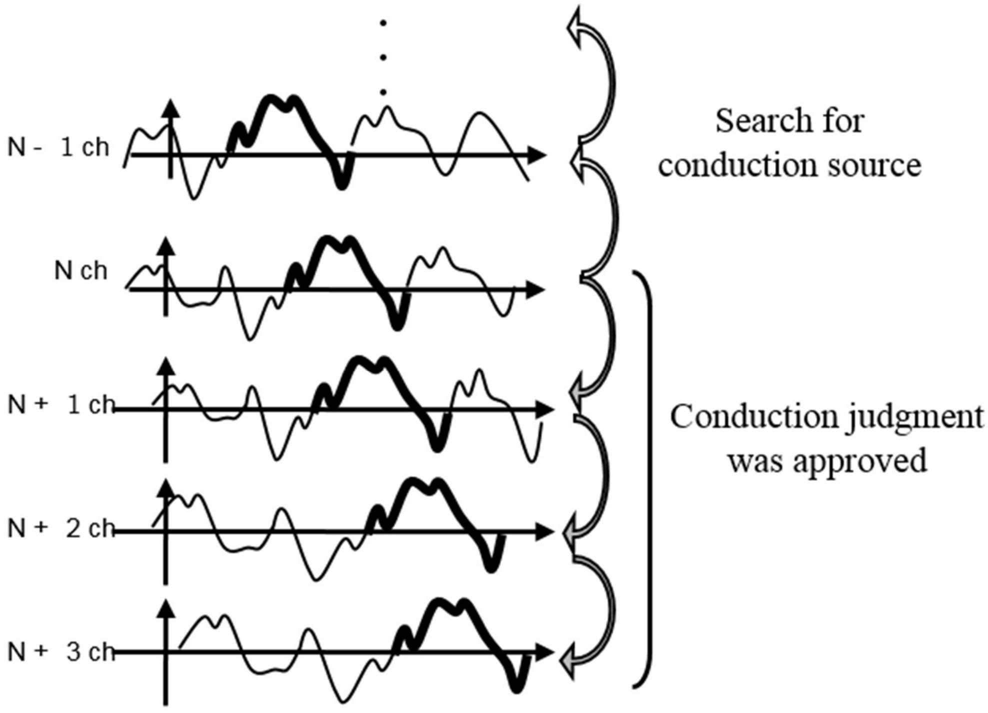


**Figure 13. Conduction source method**

It shows how to search for conduction sourch wave.

## 4.4. End-plate estimation method

End plate was estimated by analyzing the waves in order of methods 4.1, 4.2 and 4.3.

In 4.1, first, conduction judgment was performed by using a multi-channel method and conducting waves with plus and minus analysis unit was extracted.

In 4.2, next, by using the symmetric conduction method among the channels with an analysis unit that had found in 1, the pairs of symmetric conducting waves that could have the end-plate in between were extracted.

In 4.3, finally, by using the conduction source method, among the channels with pairs of symmetric conducting waves that could have the end-plate in between that had found in 2, the area that no symmetric analysis unit had found, we looked for waves with a correlation coefficient of 0.9 or more (Figure 14).

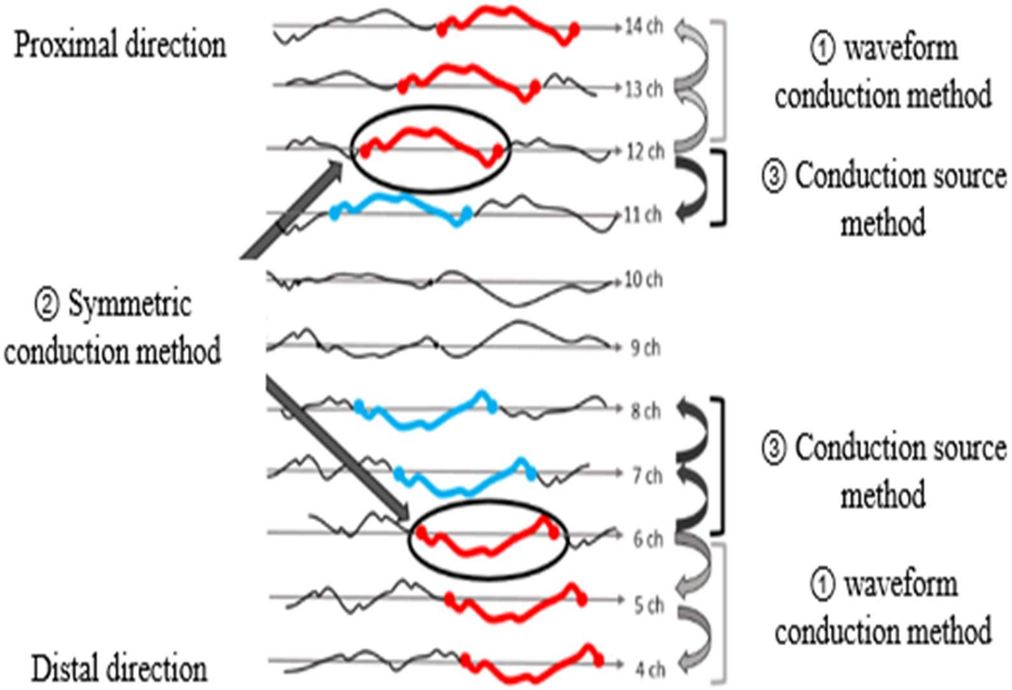


**Figure 14. End-plate estimation method**

It shows that how it is possible to find the end-plate.

## 4.5. Spatial wavelength

For conducting waves, usually, the distance that waves pass according to time (wavelength), is considered more often as a key point. But, it is not only the distance which is important but also the speed of the wave should be considered. The wave which is taking more time to pass has a slower speed compared to the wave which passes faster within a shorter time. Accordingly, the spatial wavelength is considered as the speed and distance that a wave is able to pass (Figure 15).

In this research, the relation between wavelength and spatial wavelength is shown as below.

Spatial wavelength (m) = wavelength(s) × CV(m/s)

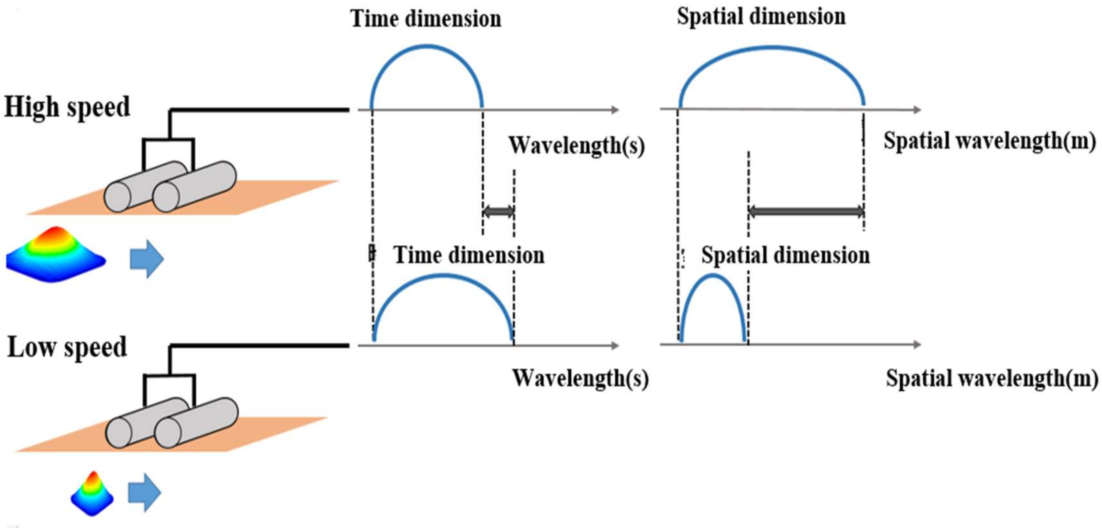


**Figure 15. Spatial wavelength and wavelength**

It shows the relationship between spatial wavelength and wavelength and the difference of them.

# 5. EXPERIMENTS (PART1)

## 5.1. Electrode

For this study, a 17-electrode array was used and 16 channels were measured. The electrodes, which are shown in Figure 16, were made of pure silver wire, and were 1 mm in diameter and 10 mm in length. The distance between the central part of each electrode was 5 mm.

For the cutoff frequency, the high-pass filter (HPF) was set to 5 Hz and the low-pass filter (LPF) was set to 1 kHz. The amplification factor was 80 dB and the sampling frequency was 5 kHz. All data was saved to a computer for analysis. Data were collected for 10 minutes and analyzed with HPF at 5 Hz, along with the finite impulse response (FIR) filter added. C-Logger was used to monitor the data and collect signals while the data were processed in Visual Studio by C#.

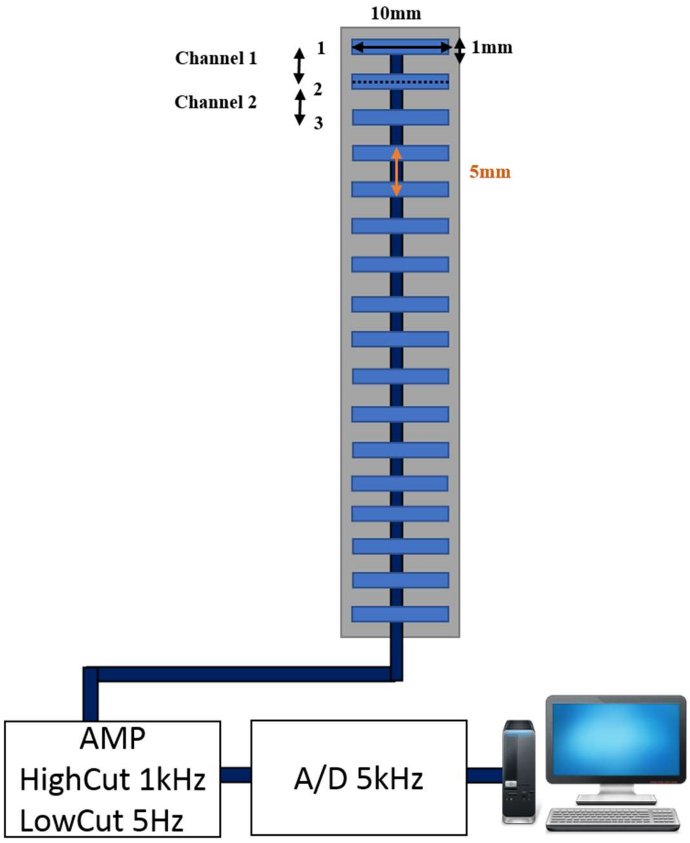


**Figure 16. Electrode array**

It is the surface electrode used in this research and it can measure 16 channels.

## 5.2. Experiment 1 (40% MVV for 60 seconds)

Four healthy, adult male university students, aged between 22 and 27 years, participated in this experiment. The test muscle was the brachii muscle of the right arm. First, 100% maximum voluntary contraction (MVC) was measured to calculate the maximum muscular strength of each participant. For this purpose, participants were asked to sit on a chair with a small back and keep their elbows at a 90-degree angle. Next, a hanging scale attached to a fixed object on one side with a band on the other side was attached to the arms of the participants (about 5 cm from the wrist, Figure 17). Participants were asked to pull the scale up, three times with the highest level of their power, for 10 seconds each time. Following this, the average was calculated and used as 100% MVC. After calculating the 100% MVC of each participant, the experiment was conducted using 40% MVC in the same position, but for 60 seconds. During the experiment, an electrode array consisting of 16 channels was used.

For the experiment, both the electrode array and brachii muscle of each participant was disinfected with alcohol. Next, the electrode array was covered with a special gel to ensure a better connection between the skin and electrodes to achieve more accurate data. The brachii muscle of each participant was then scrubbed to ensure better results. Next, the gel was applied on the skin above the brachii muscle and the electrode array was placed vertically on the right arm of each participant in the same direction as the muscle fibers and fixed with tape.

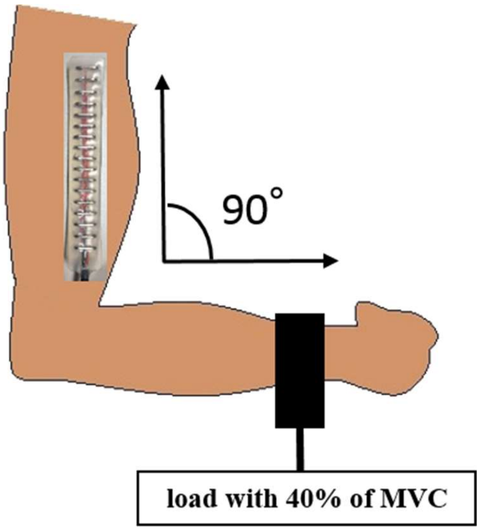


**Figure 17. Experiment 1**

In this experiment, participants were asked to sit on a chair and keep their elbows at a 90-degree angle.

## 5.3. Characteristics of pairs of symmetric conducting waves

There are two different directions in the body, the proximal direction, and the distal direction. The proximal direction is closer to the point of attachment, i.e., closer to the shoulder. The distal direction has the opposite meaning, i.e., farther from the point of attachment

To determine the characteristics of pairs of symmetric conducting waves, the relationship between amplitude and CV, spatial wavelength and CV, amplitude and spatial wavelength of 4 different subjects of this study were examined (Figures 18 to 29).

As it is shown in Figures 18, 21, 24, there was not any differences in the appearance pattern of amplitude.

As shown in Figures 18, 19, 21, 22, 24 and 25, the waves with higher CV were found in the distal direction and had a different start compared to waves in the proximal direction.

As shown in Figures 19, 22, 25, the distal side shifts to a larger value of spatial wavelength compared to the proximal side.

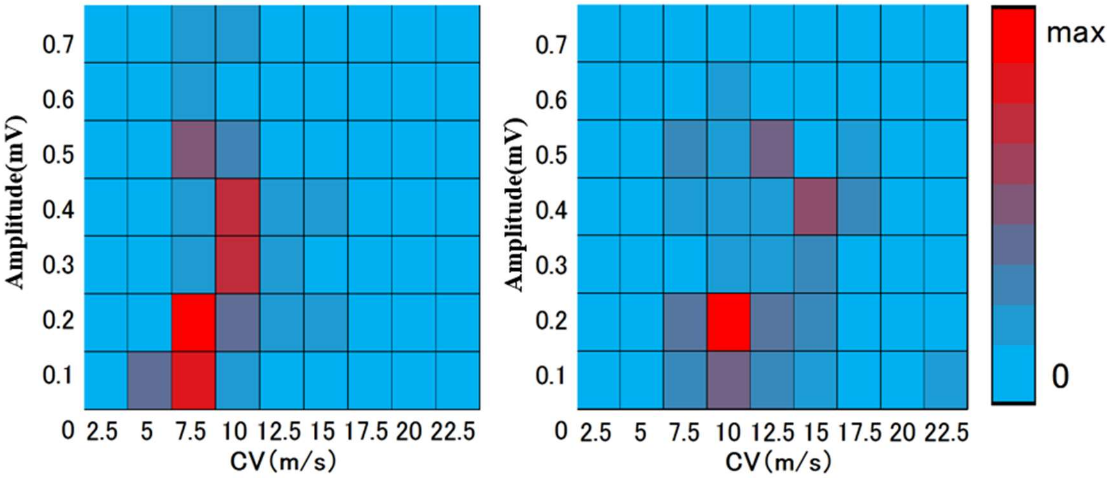
As shown in Figures 20, 23, 26, amplitude and spatial wavelength would not have large values at the same time.

It is suggested that the influence of end-plate may affect not only CV but also other elements of the conducting waves. Since there is a difference in the trend of CV and spatial wavelength between the distal direction and the proximal direction, it will be necessary to analyze the difference in characteristics depending on the conduction direction in future analysis. Notably, there were some subjects where pairs of symmetric conducting waves were not seen.

Next, we checked the relationship between the CV, wavelength and Amplitude over time (Figure 30 to 41).

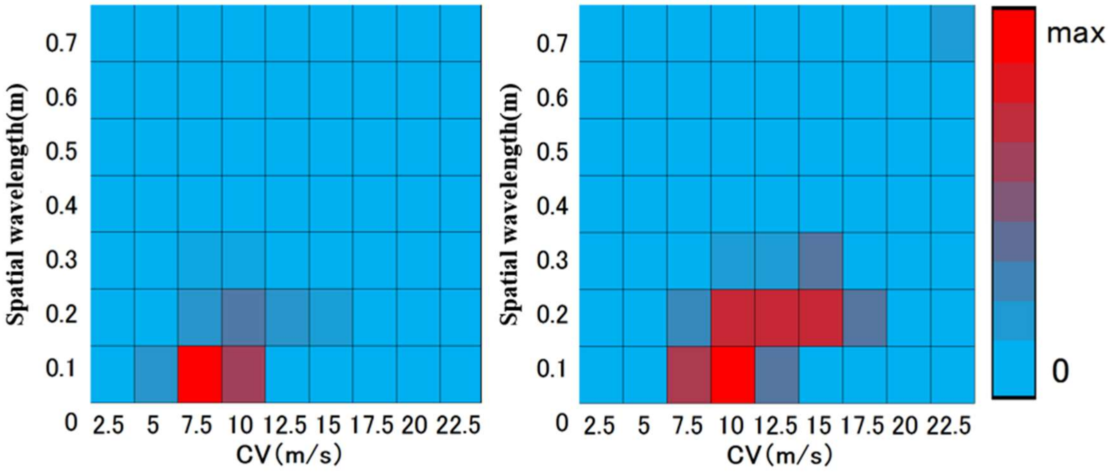
It is known that conducting waves start to move when muscle activity starts, but in the case of pairs of symmetric conducting waves, there was a delay, which means the waves started to move slightly after muscle activity started. The pairs of symmetric conducting waves are considered to be a phenomenon that occurs when muscle contraction is continued for a certain period of time. Thus, it was thought that it would be necessary to monitor the changes within a certain amount of time to see the effect of the end-plate on the waveforms.

Figures 30, 32, 33, 35, 36, 38, 39, 41 suggest that CV and wavelength were not particularly affected by time. However, Figures 31, 34, 37, 40 show that the amplitude of the pairs of symmetric conducting waves increased widely and at some point, and it decreased from the point of occurrence by passing time. The cause of this change in amplitude is thought to be an effect of fatigue or training. The amplitude changes when the muscle is tired.



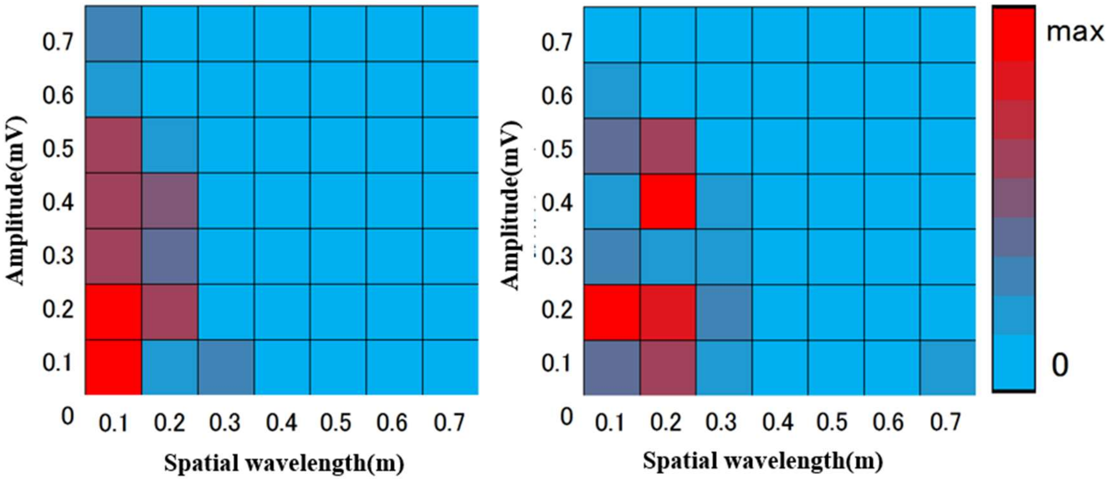
(a) proximal (b)distal

Figure 18. Distribution of Amplitude and CV (sub1)



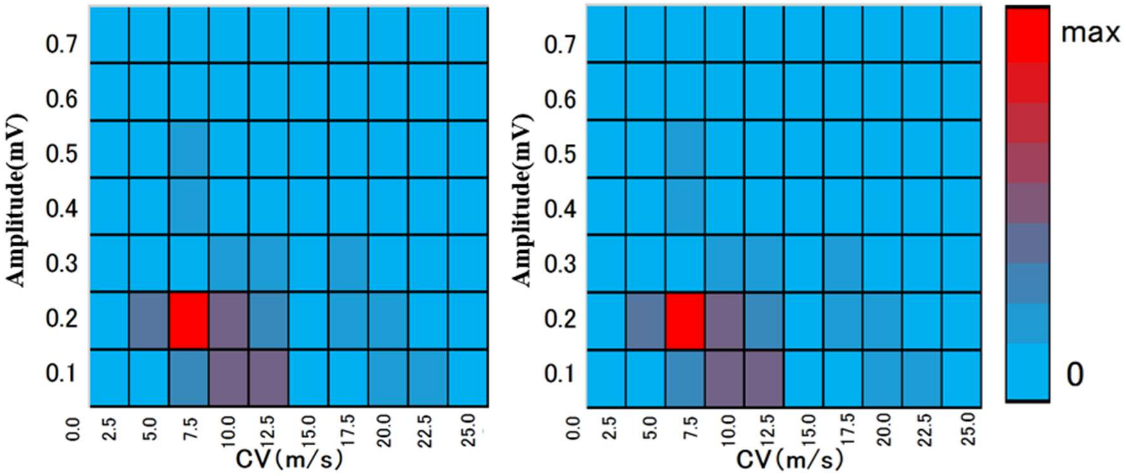
(a) proximal (b)distal

Figure 19. Distribution of Spatial wavelength and CV (sub1)



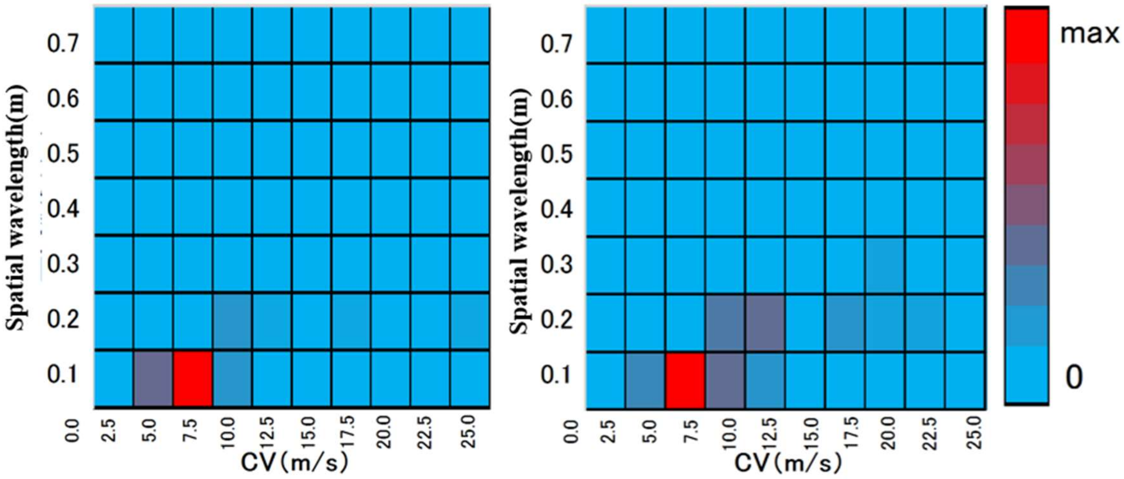
(a) proximal (b)distal

Figure 20. Distribution of Amplitude and Spatial wavelength (sub1)



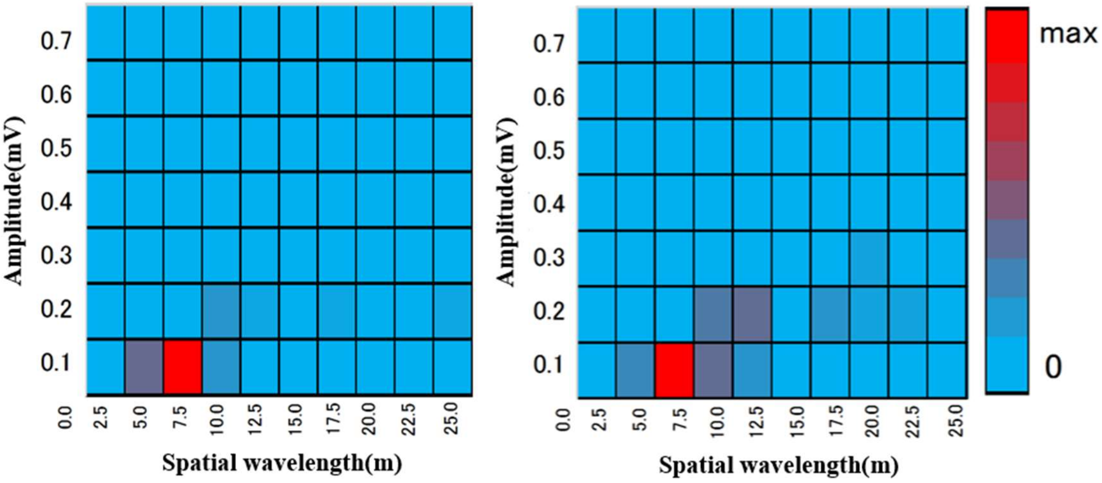
(a) proximal (b)distal

Figure 21. Distribution of Amplitude and CV (sub2)



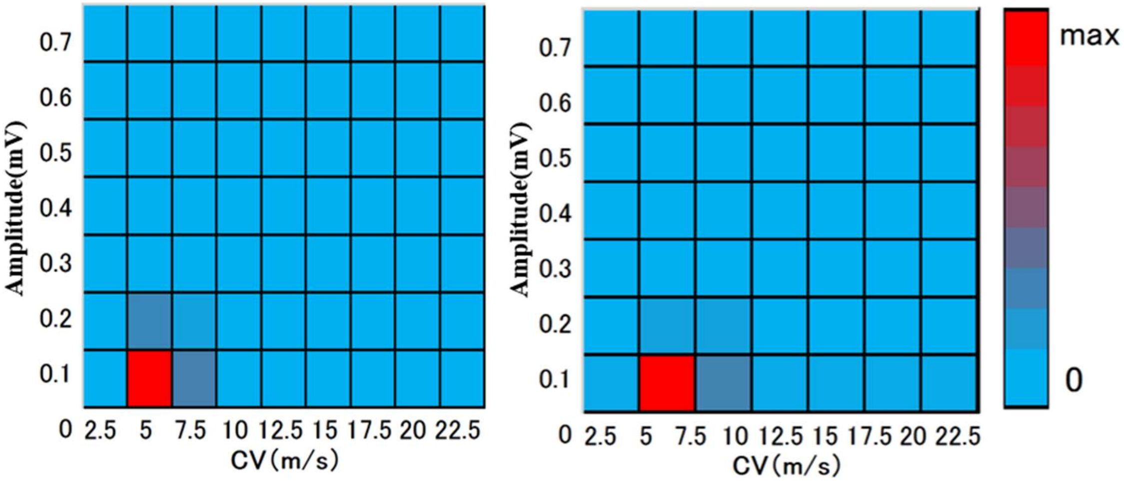
(a) proximal (b) distal

Figure 22. Distribution of Spatial wavelength and CV (sub2)



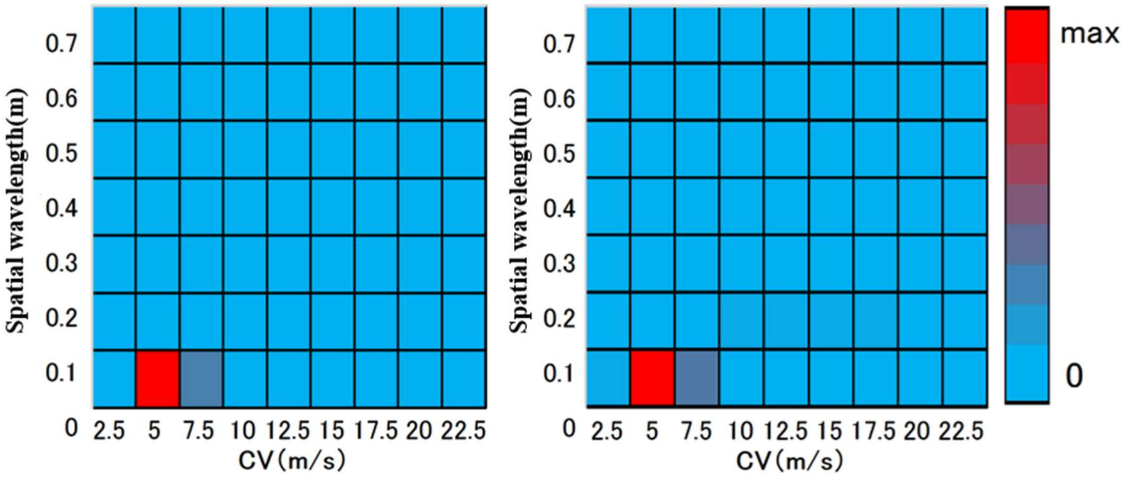
(a) proximal (b) distal

Figure 23. Distribution of Amplitude and Spatial wavelength (sub2)



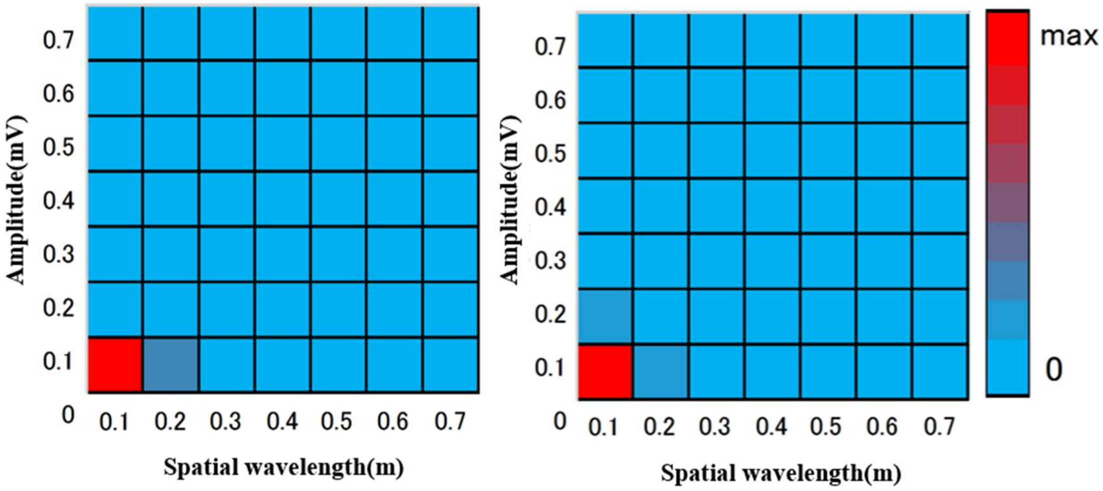
(a) proximal (b) distal

Figure 24. Distribution of Amplitude and CV (sub3)



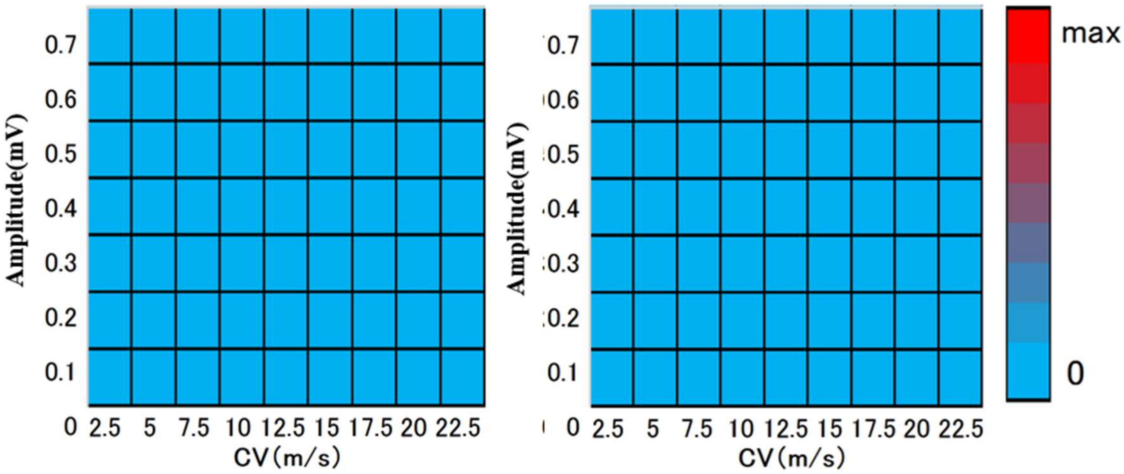
(a) proximal (b) distal

Figure 25. Distribution of Spatial wavelength and CV (sub3)



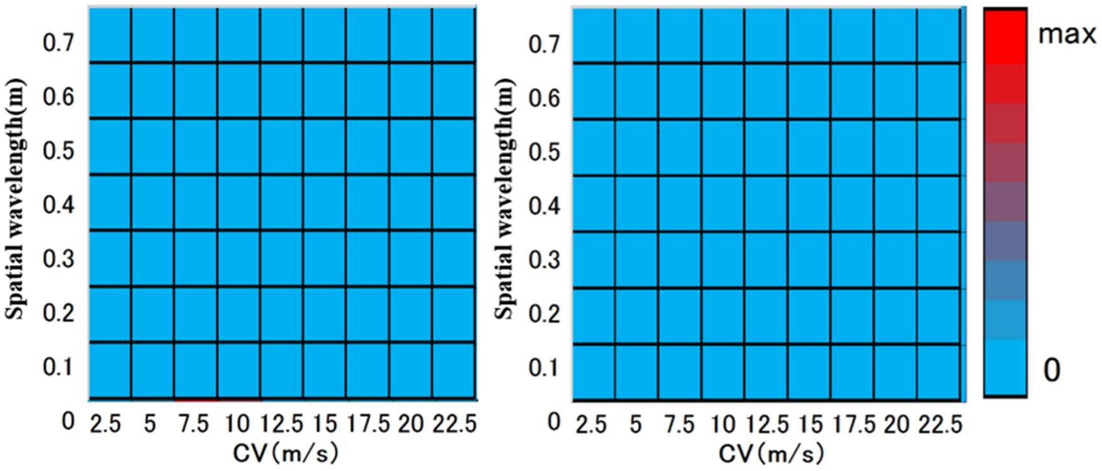
(a) proximal (b) distal

Figure 26. Distribution of Amplitude and Spatial wavelength (sub3)



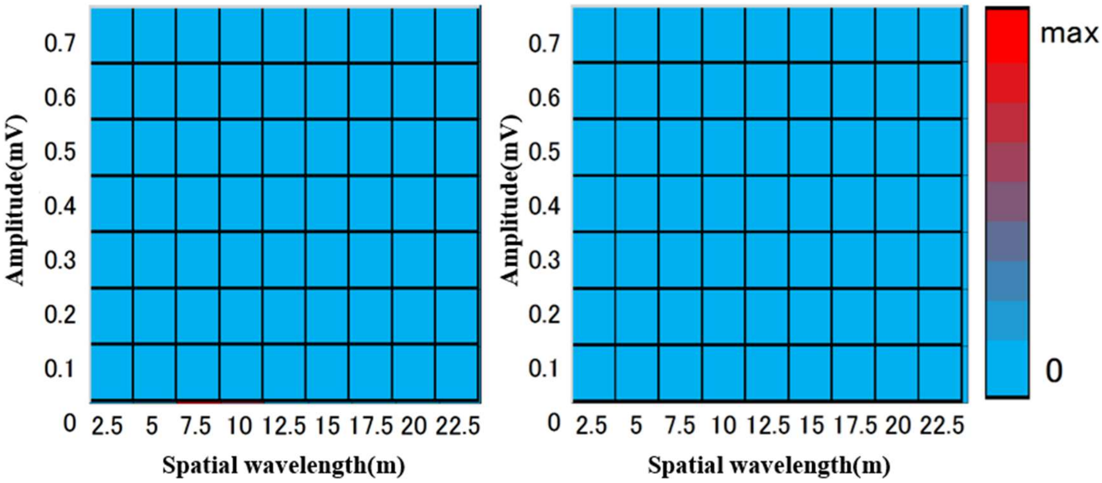
(a) proximal (b) distal

Figure 27. Distribution of Amplitude and CV (sub4)



(a) proximal (b) distal

Figure 28. Distribution of Spatial wavelength and CV (sub4)



(a) proximal (b) distal

Figure 29. Distribution of Amplitude and Spatial wavelength (sub4)

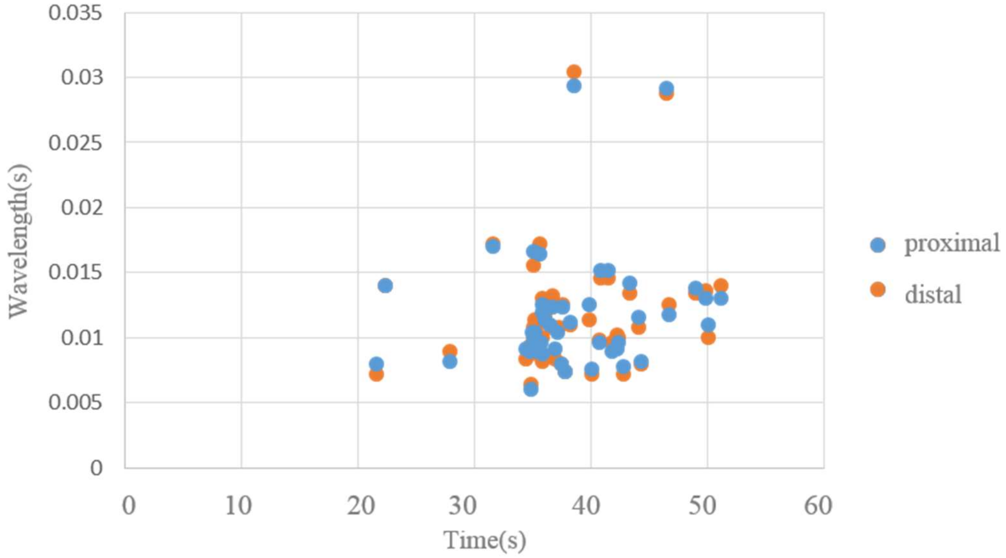


**Figure 30. The changes of wavelength by time (sub1)**

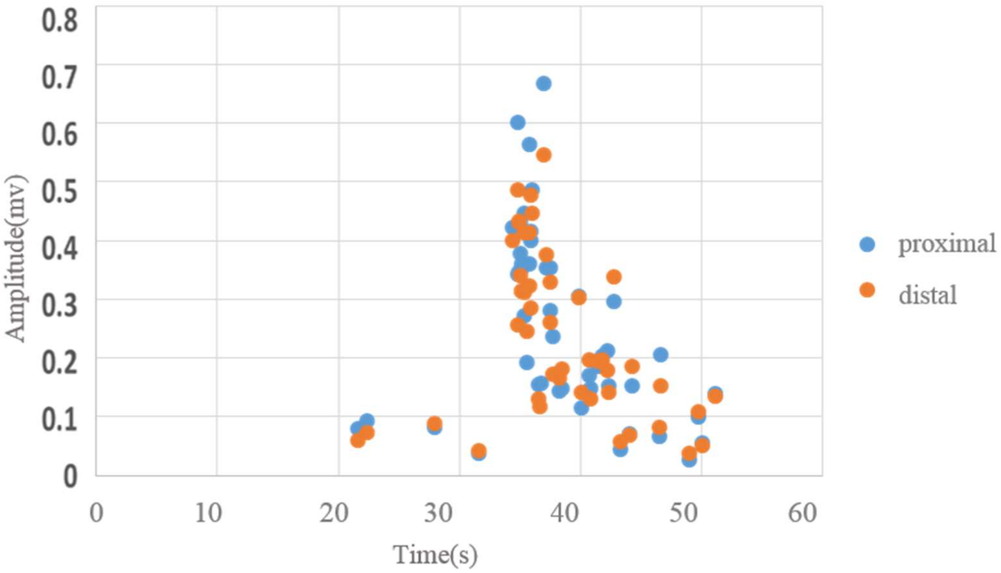


**Figure 31. The changes of amplitude by time (sub1)**

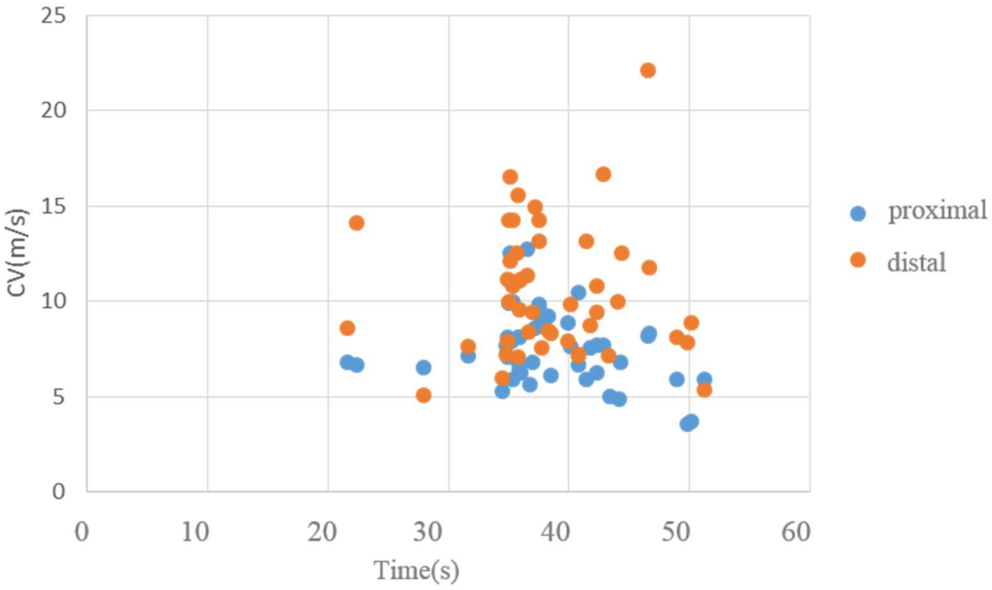


Figure 32. The changes of CV by time (sub1)

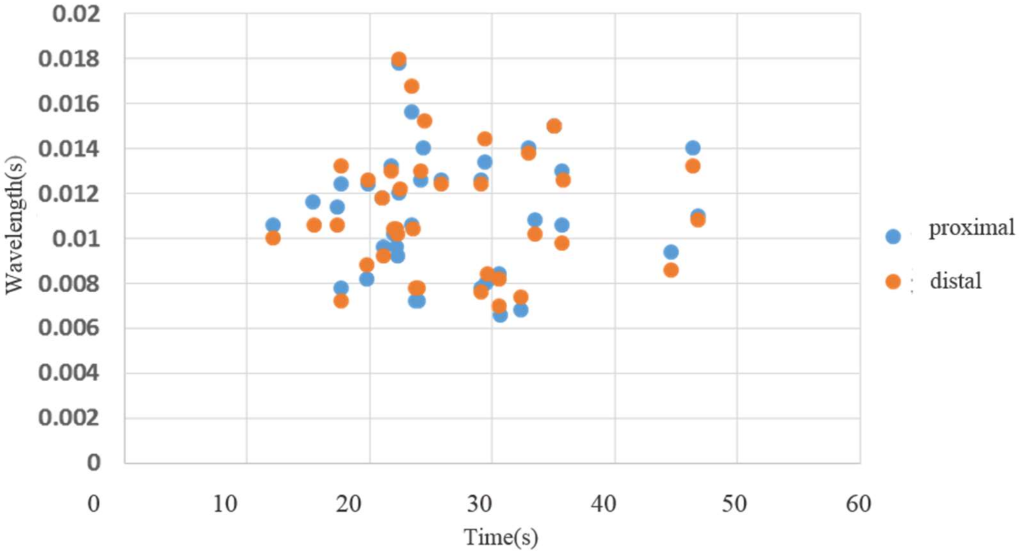


Figure 33. The changes of wavelength by time (sub2)

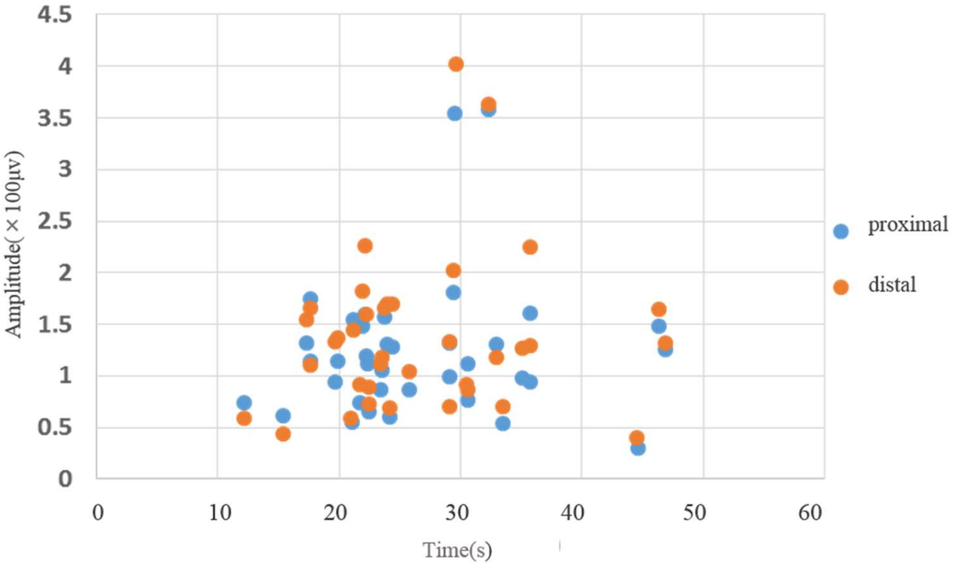


Figure 34. The changes of amplitude by time (sub2)

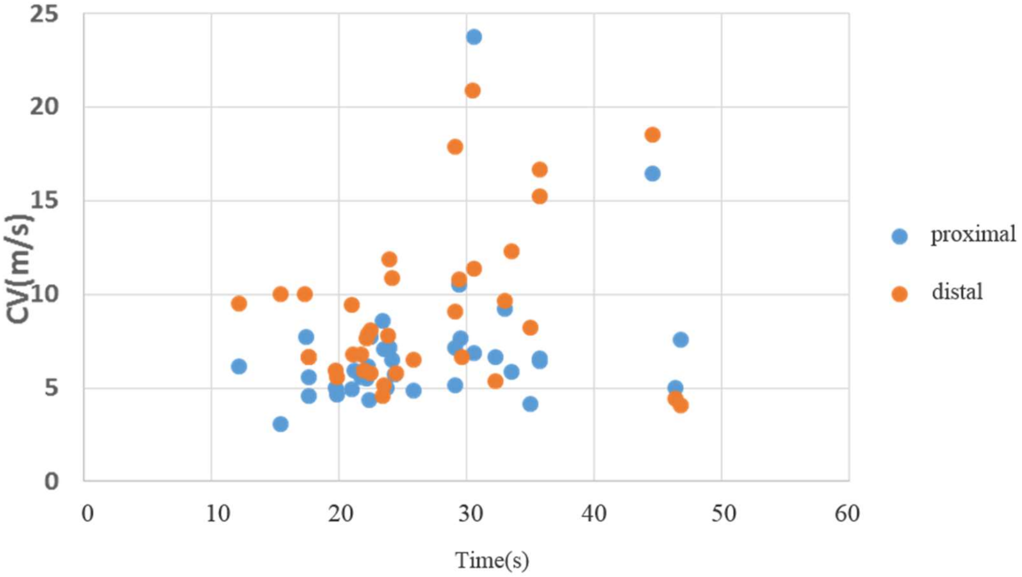


Figure 35. The changes of CV by time (sub2)

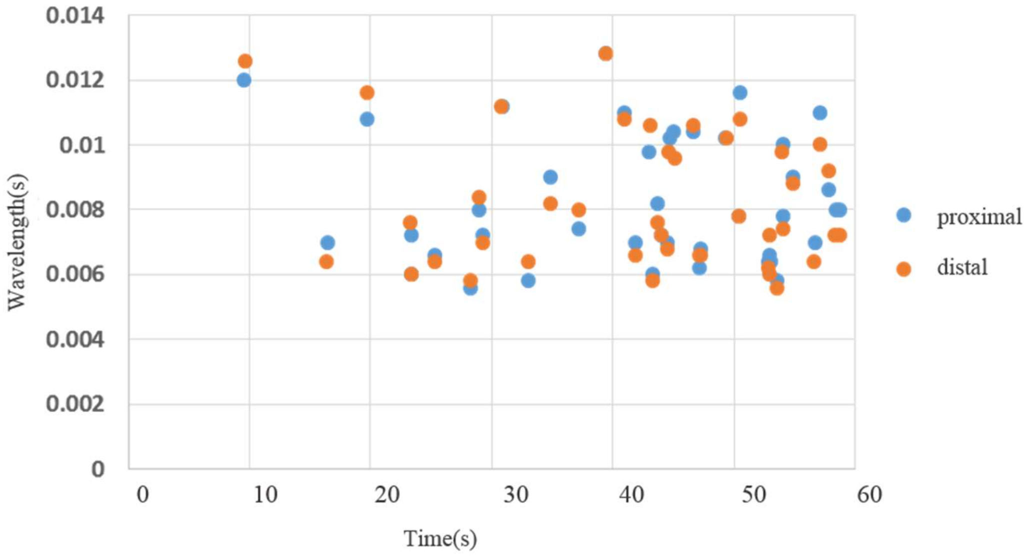


**Figure 36. The changes of wavelength by time (sub3)**

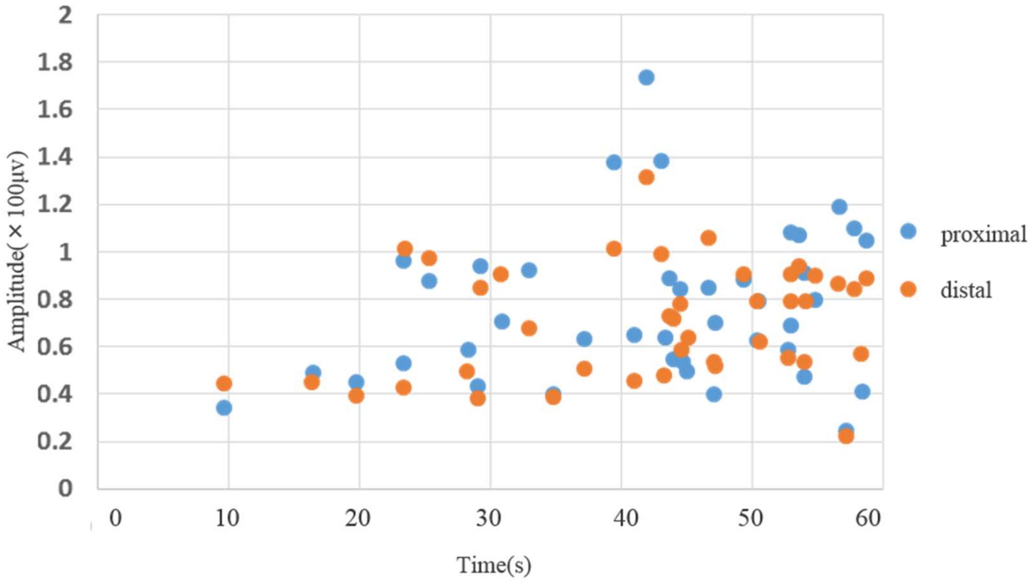


**Figure 37. The changes of amplitude by time (sub3)**

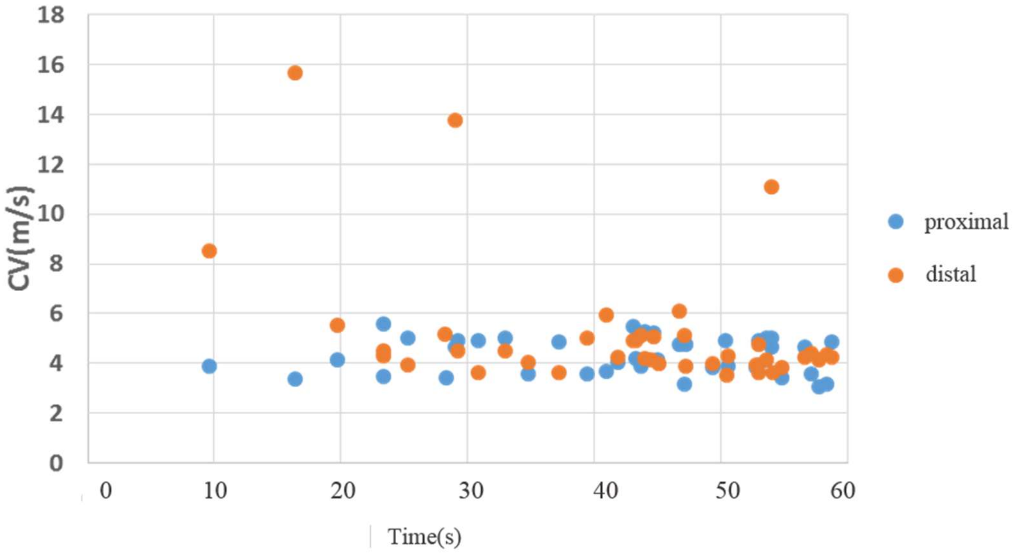


Figure 38. The changes of CV by time (sub3)

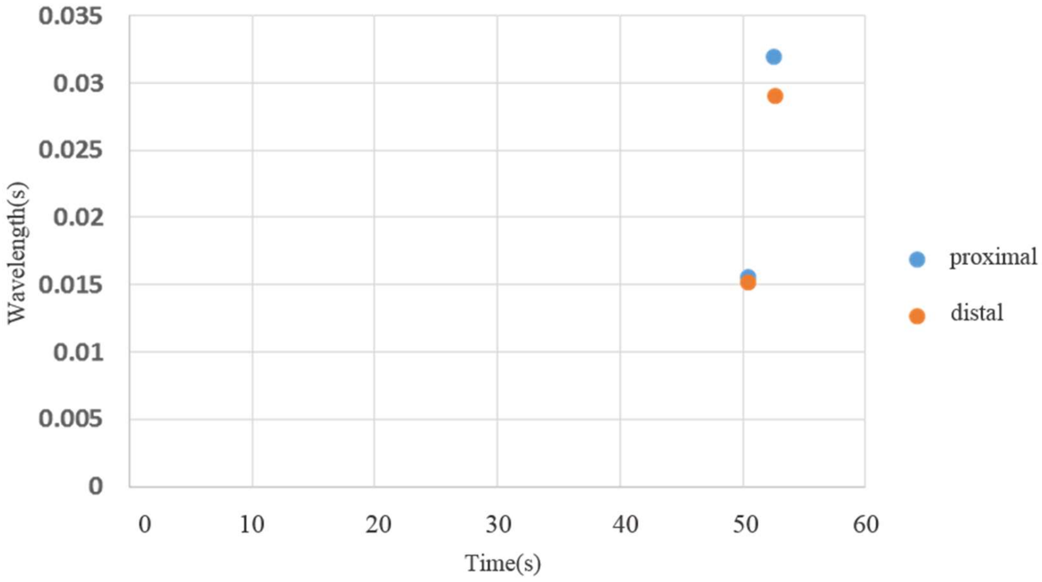


Figure 39. The changes of wavelength by time (sub4)

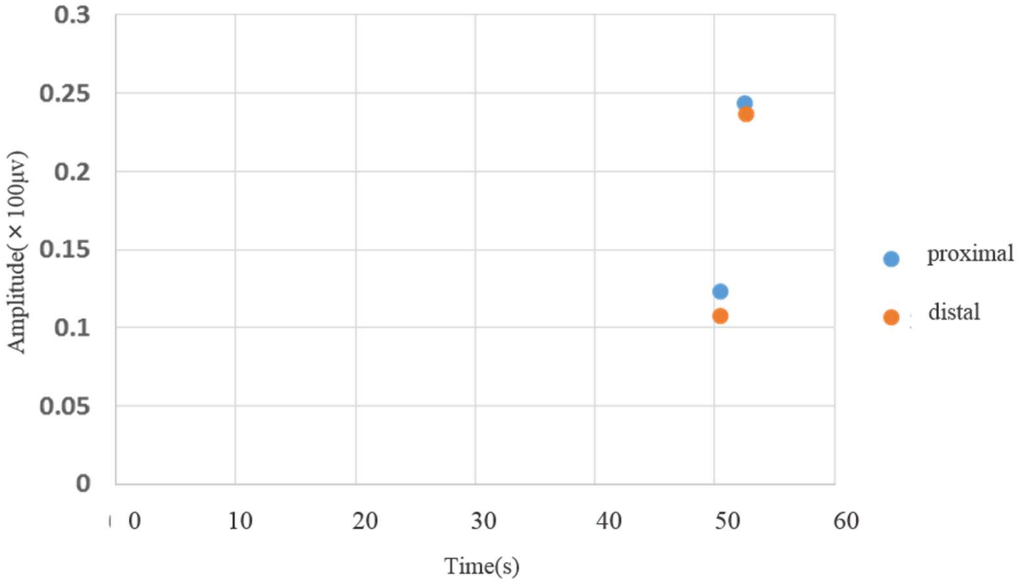


Figure 40. The changes of amplitude by time (sub4)

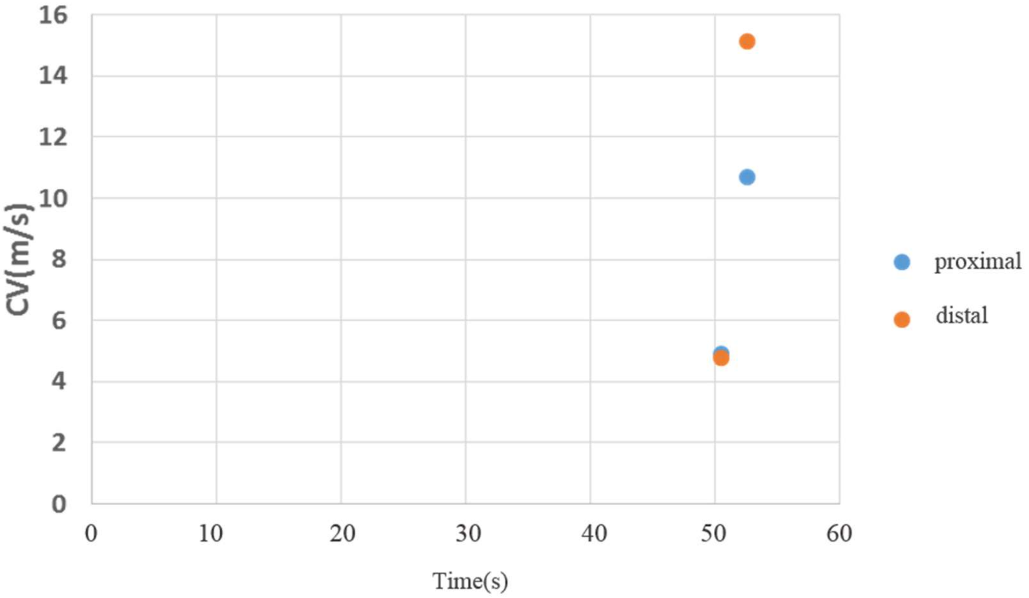


Figure 41. The changes of CV by time (sub4)

## 5.4. Characteristic of the waveform traced from pairs of symmetric conducting waves

Generally, it was thought that the waveform generated from the end-plate tended to increase in amplitude. However, by examining the characteristics of pairs of symmetric conducting waves, various waveforms with different characteristics were found, as shown in section 5.3.

Therefore, Table 2 shows the amplitude of the waveform before it became a conducting wave.

It was confirmed that the waveforms generated from the end-plate had monotonous change of amplitude, and included waveforms with increasing amplitude and waveforms with decreasing amplitude. As an example, in the case of subject 2 in Table 1, more than 50% of the waveforms were monotonically increasing in amplitude. However, for other subjects, the monotonically increasing waveform was not seen as much as in subject 2. There were also waveforms that did not show a monotonous changes of amplitude, and those waveforms tended to occur more in the distal direction.

These data suggest that the waveforms generated from the end-plate conducted with various amplitudes. Additionally, in the case of pairs of symmetric conducting waves, the wave in the distal direction was affected more by the end-plate than the other waves.

| Tendency | sub1 | | sub2 | | sub3 | |
|---|---|---|---|---|---|---|
| | proximal | distal | proximal | distal | proximal | distal |
| Monotonically increasing | 35% | 30% | 76% | 60% | 10% | 50% |
| Monotonically decreasing | 22% | 24% | 18% | 20% | 86% | 11% |
| Others | 43% | 45% | 6% | 20% | 5% | 39% |

**Table 2. Tendency of the waveforms**

# 6. EXPERIMENTS (PART2)

## 6.1. Experiment 2 (10% MVC for 30 seconds and 40% MVC for 10 seconds)

In the experiment, the biceps brachii muscle of the left and right hands was used as the test muscle. The subjects were 5 healthy adult males with an average age of 22. The subjects were asked to keep the elbow joint angle at 90 degrees in the sitting position to measure 100% of their maximum voluntary contraction (MVC); maximum muscular strength. After that, the subjects were asked to keep the same posture for 2 different experiments.

- 30 seconds with 10% of MVC of each arm
- 10 seconds with 40% of MVC of each arm

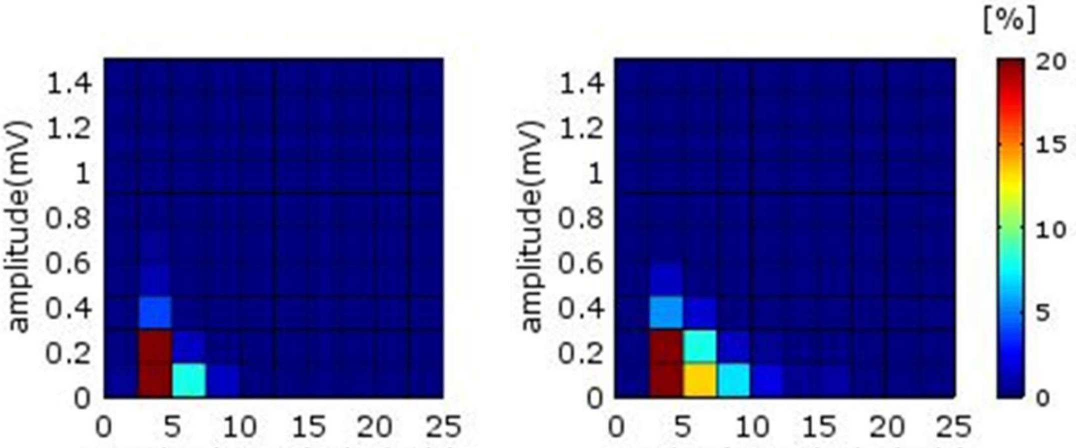
And data were acquired.

## 6.2. Result and discussion

### 6.2.1. Changes of Amplitude and CV in dominant an dnon-dominant arms

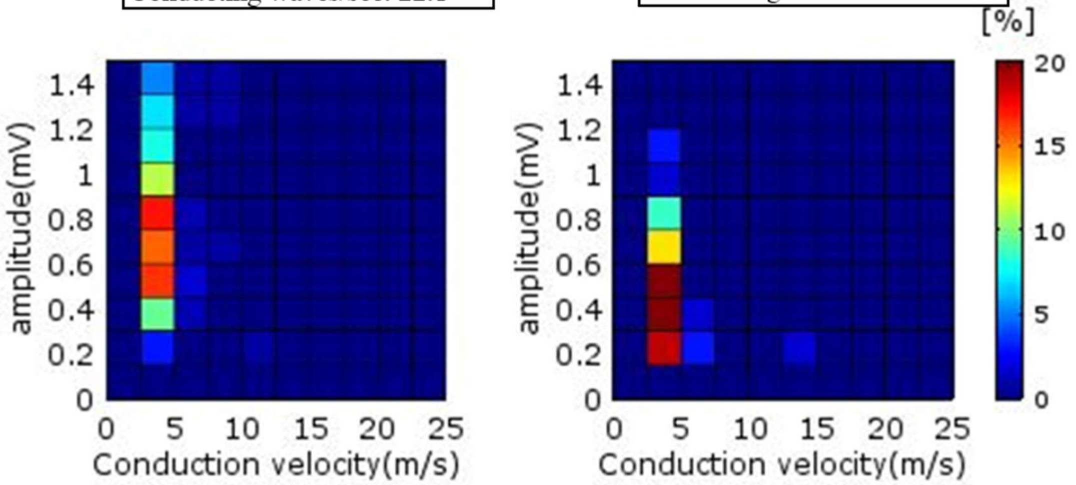
It can be seen that by increasing the load from 10% MVC to 40% MVC, conducting waves with high amplitude values for both dominant and non-dominant arms were extracted. It is shown in Figures 42 to 46 from a to b and from c to d. On the other hand, the number of conducting waves extracted per second from the dominant and non-dominant arms were different depending on the load applied. For a load with 10% MVC, the number of propagating waves in the dominant arm was extracted more than in the non-dominant arm. On the other hand, when the load is 40% MVC, the number of propagating waves in the non-dominant arm was more than the dominant arm.

For 10% MVC, which is likely similar to a load that will be used even in daily life, it is speculated that there are many motor units of the dominant arm that participate in the contraction activities compare to the non-dominant arm. For 40% MVC, which is an extraordinary load, in the non-dominant arm, it is considered that more motor units ignite than the dominant arm to bear the load. The results are shown in figures 42 to 46 for 5 subjects.



(a) Dominant arm
10%MVC 30 sec
Conducting waves/sec: 22.1

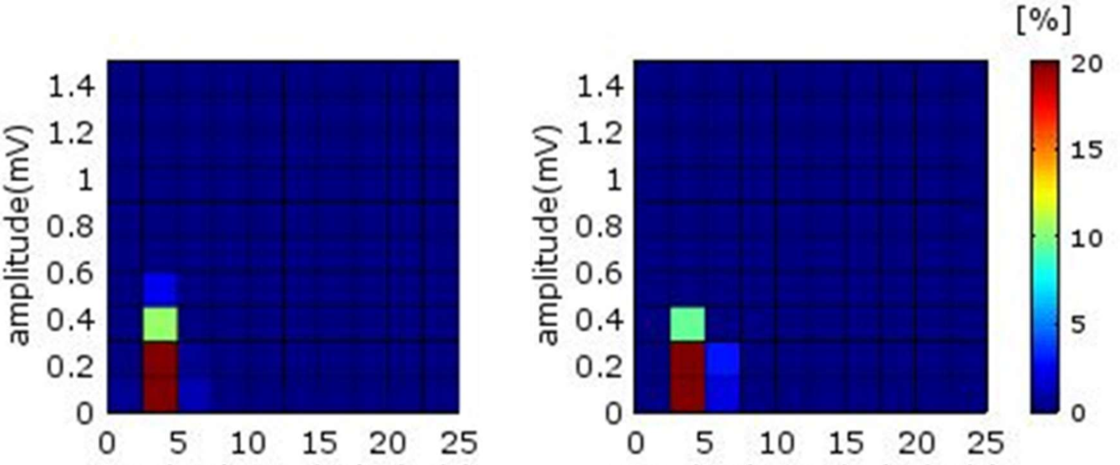
(b) Non-dominant arm
10%MVC 30 sec
Conducting waves/sec: 8.8



(c) Dominant arm
40%MVC 10 sec
Conducting waves/sec: 21.3

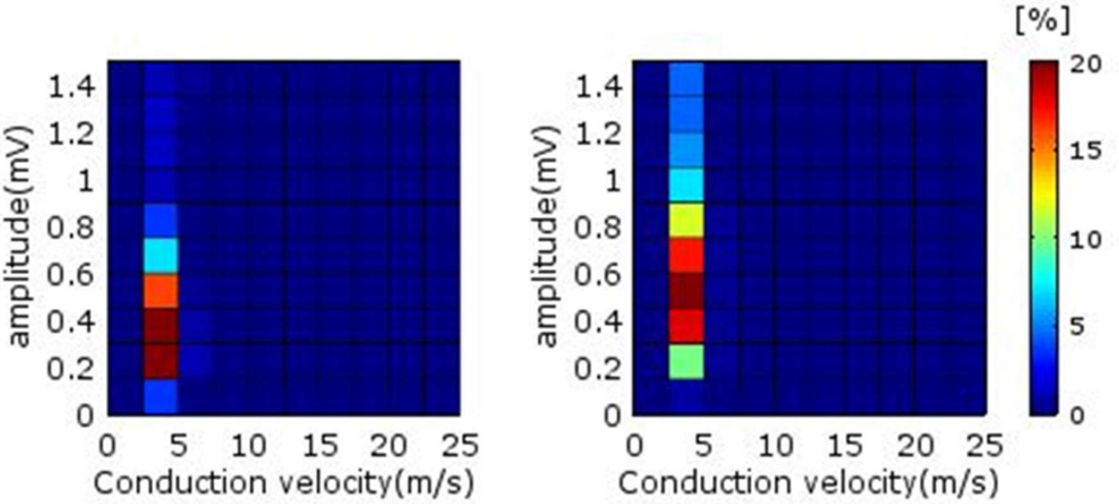
(d) Non-dominant arm
40%MVC 10 sec
Conducting waves/sec: 7

**Figure 42. The relation of Amplitude and CV in dominant and non-dominant arms (sub1)**



(a) Dominant arm
10%MVC 30 sec
Conducting waves/sec: 61.2

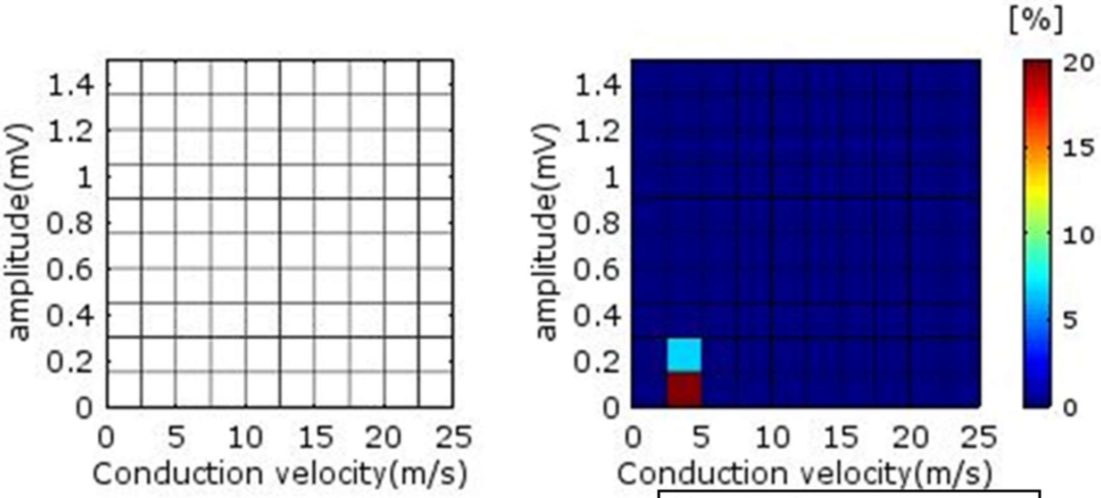
(b) Non-dominant arm
10%MVC 30 sec
Conducting waves/sec: 51.1



(c) Dominant arm
40%MVC 10 sec
Conducting waves/sec: 190.5

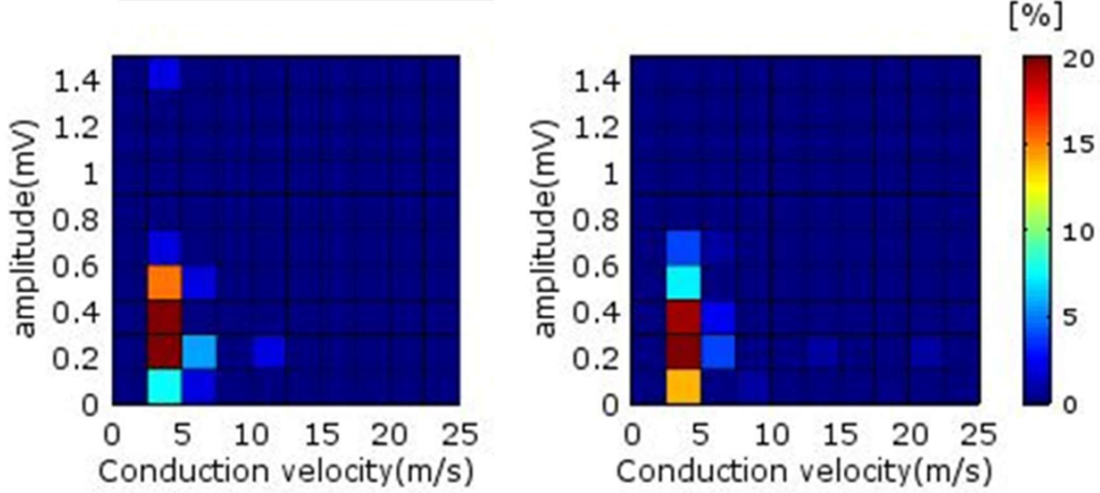
(d) Non-dominant arm
40%MVC 10 sec
Conducting waves/sec: 215.5

**Figure 43. The relation of Amplitude and CV in dominant and non-dominant arms (sub2)**



(a) Dominant arm
10%MVC 30 sec
Conducting waves/sec: 0

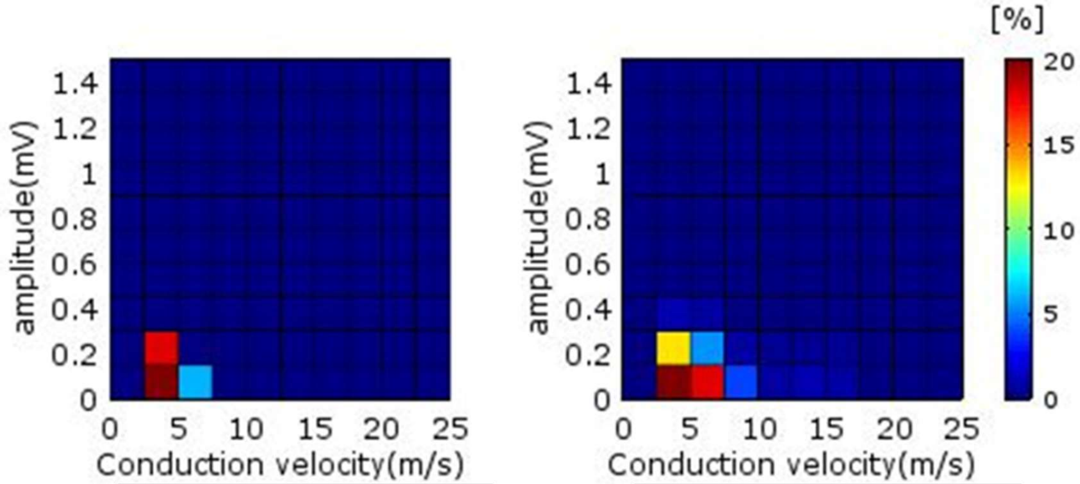
(b) Non-dominant arm
10%MVC 30 sec
Conducting waves/sec: 0.5



(c) Dominant arm
40%MVC 10 sec
Conducting waves/sec: 5.4

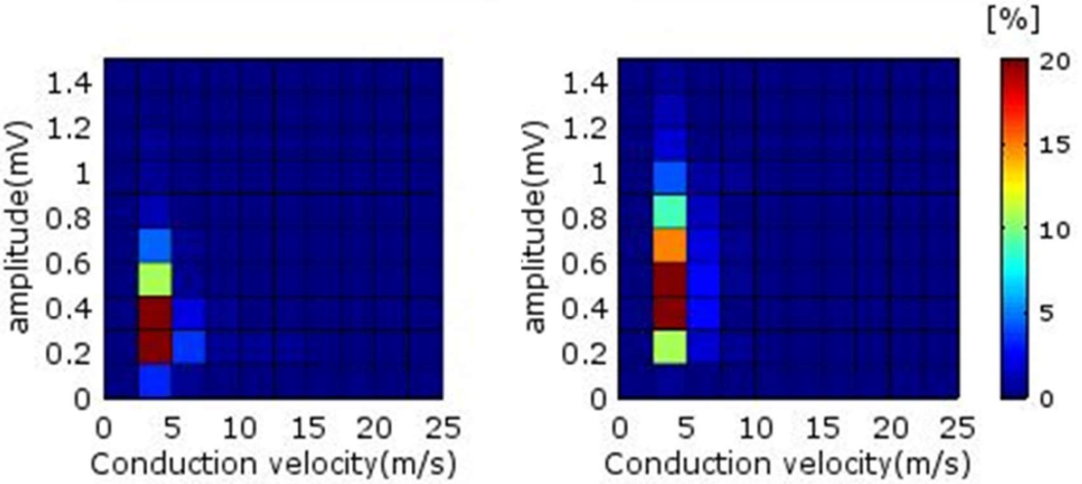
(d) Non-dominant arm
40%MVC 10 sec
Conducting waves/sec: 13.5

**Figure 44. The relation of Amplitude and CV in dominant and non-dominant arms (sub3)**



(a) Dominant arm
10%MVC 30 sec
Conducting waves/sec: 1.1

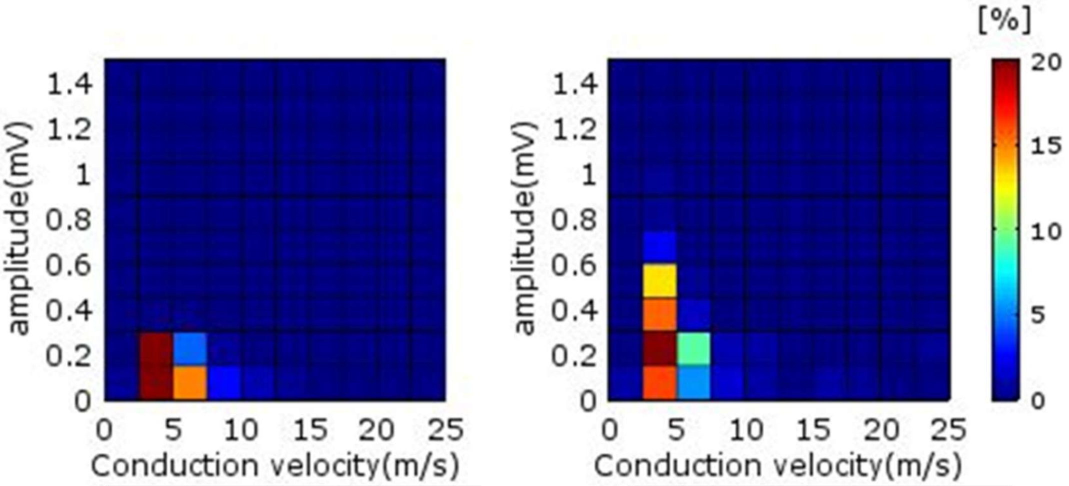
(b) Non-dominant arm
10%MVC 30 sec
Conducting waves/sec: 18.1



(c) Dominant arm
40%MVC 10 sec
Conducting waves/sec: 47.8

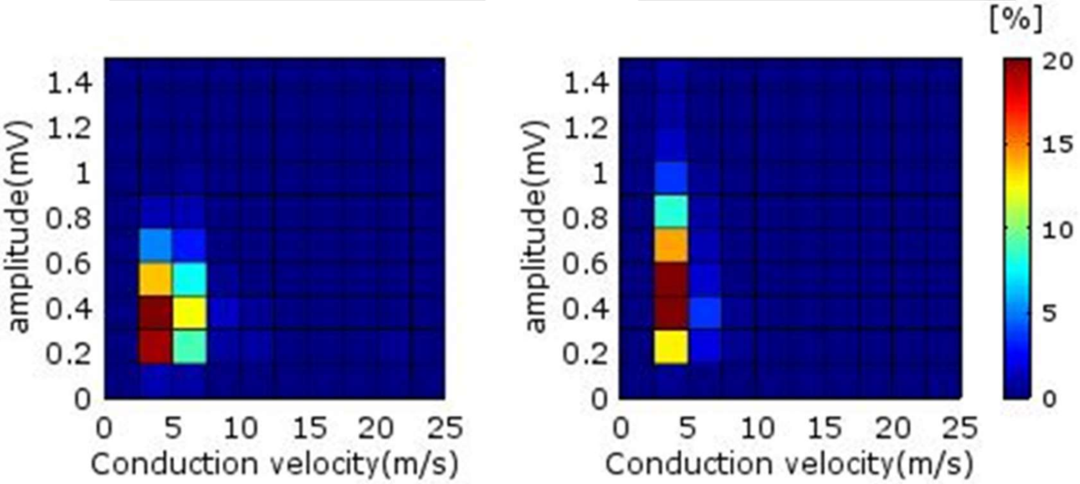
(d) Non-dominant arm
40%MVC 10 sec
Conducting waves/sec: 94.2

**Figure 45. The relation of Amplitude and CV in dominant and non-dominant arms (sub4)**



(a) Dominant arm
10%MVC 30 sec
Conducting waves/sec: 25.2

(b) Non-dominant arm
10%MVC 30 sec
Conducting waves/sec: 19.6



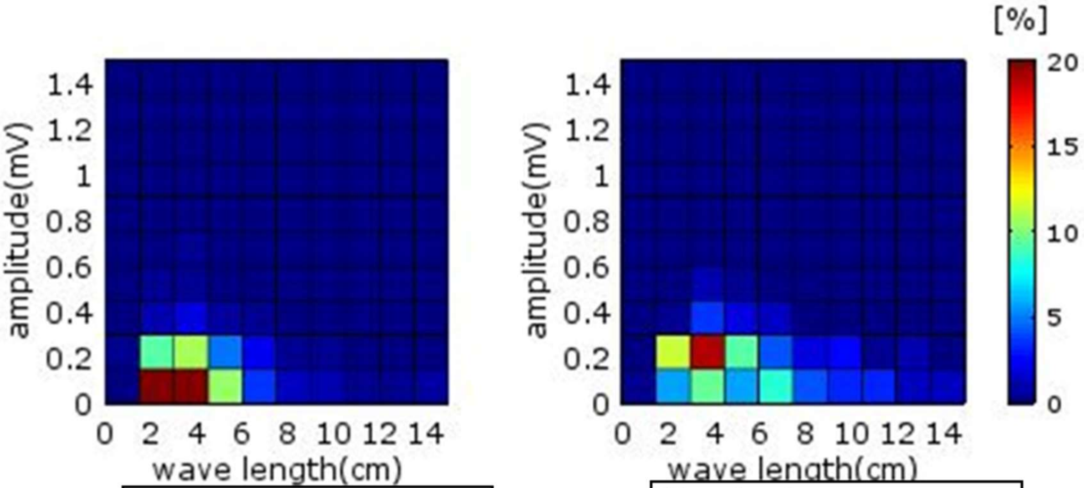
(c) Dominant arm
40%MVC 10 sec
Conducting waves/sec: 103

(d) Non-dominant arm
40%MVC 10 sec
Conducting waves/sec: 185.2

**Figure 46. The relation of Amplitude and CV in dominant and non-dominant arms (sub5)**

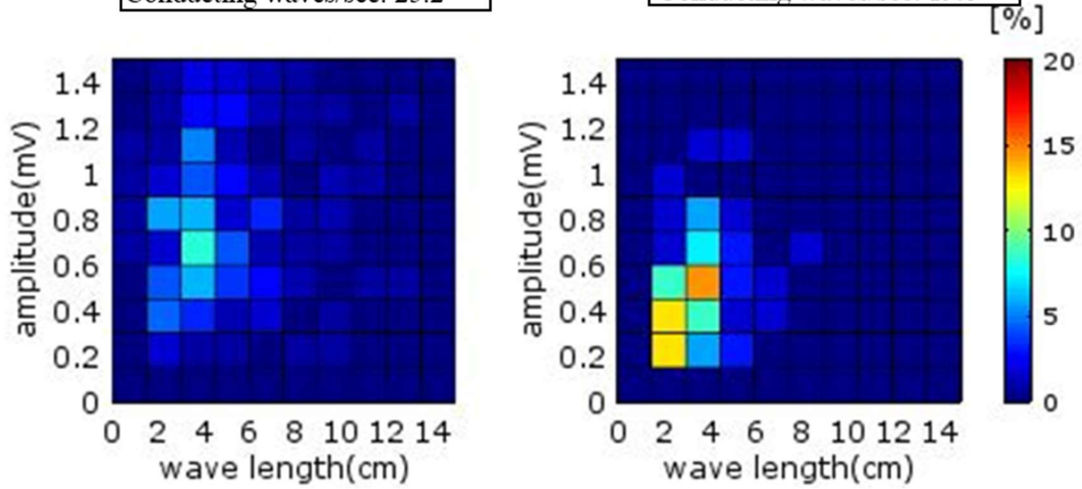
### 6.2.2. Changes of Amplitude and Wavelength in dominant an dnon-dominant arms

For 10% MVC load, it was confirmed that the distribution spreads relatively similar in the dominant arm among multiple subjects. In the case of a small load (10% MVC) that can be felt in daily life, the motor units of the dominant arm participates in the activity, so a certain distribution may appear. On the other hand, it was possible that if a large load (40% MVC) was used that could not be felt in daily life, a large number of motor units which participate in muscle contraction might be seen on the dominant and non-dominant arms to be able to carry the excessive load. For 40% MVC load, the motor unit needs to perform contraction activity in a large block, so the distribution is considered to be large. The results are shown in Figures 47 to 51 from a to b and from c to d for 5 subjects.



(a) Dominant arm
10%MVC 30 sec
Conducting waves/sec: 25.2

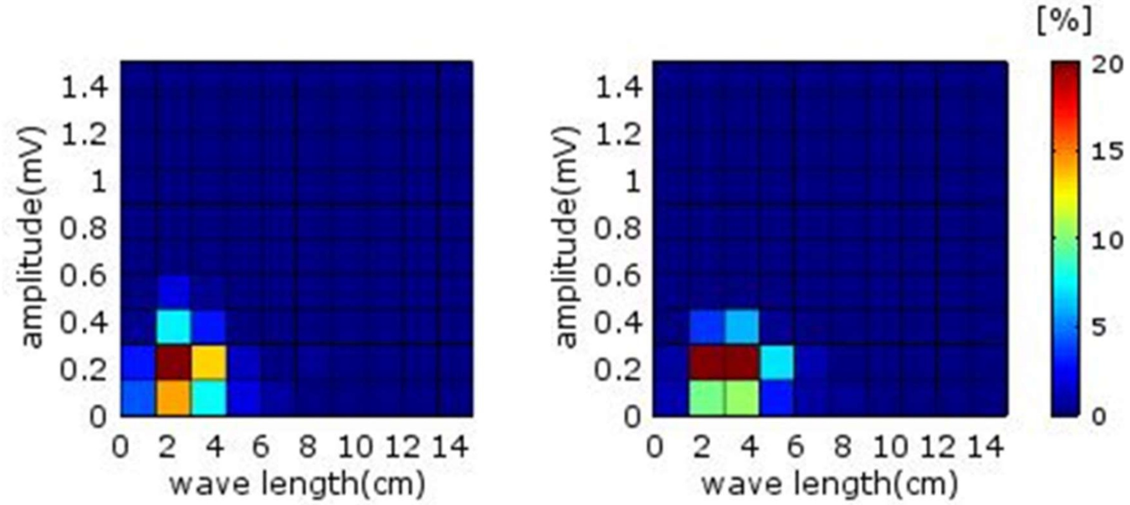
(b) Non-dominant arm
10%MVC 30 sec
Conducting waves/sec: 19.6



(c) Dominant arm
40%MVC 10 sec
Conducting waves/sec: 103

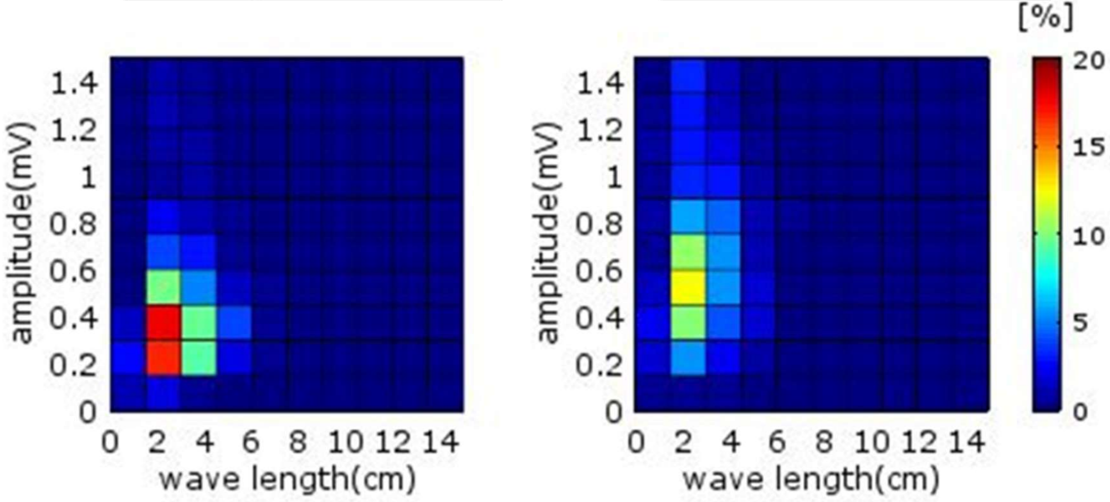
(d) Non-dominant arm
40%MVC 10 sec
Conducting waves/sec: 185.2

**Figure 47. The relation of Amplitude and Wavelength in dominant and non-dominant arms (sub1)**



(a) Dominant arm
10%MVC 30 sec
Conducting waves/sec: 25.2

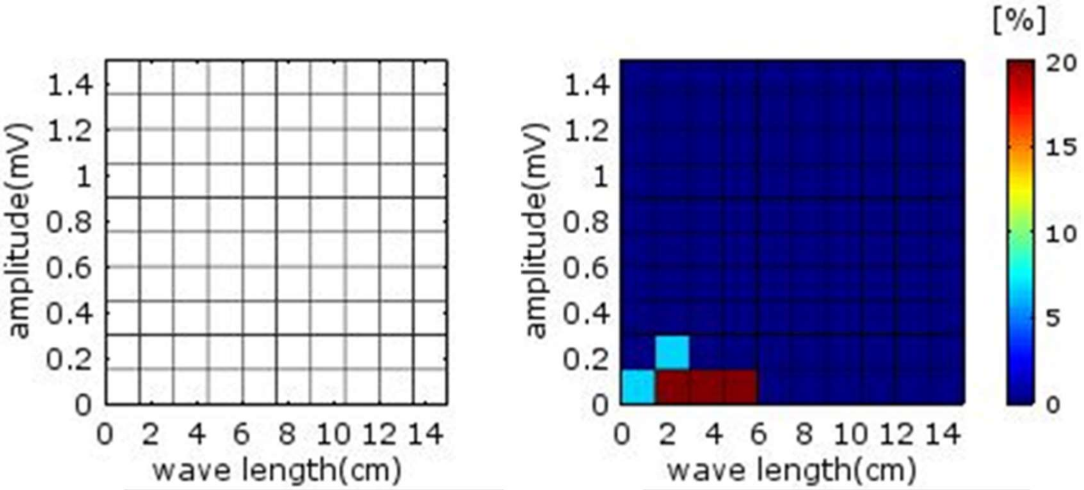
(b) Non-dominant arm
10%MVC 30 sec
Conducting waves/sec: 19.6



(c) Dominant arm
40%MVC 10 sec
Conducting waves/sec: 103

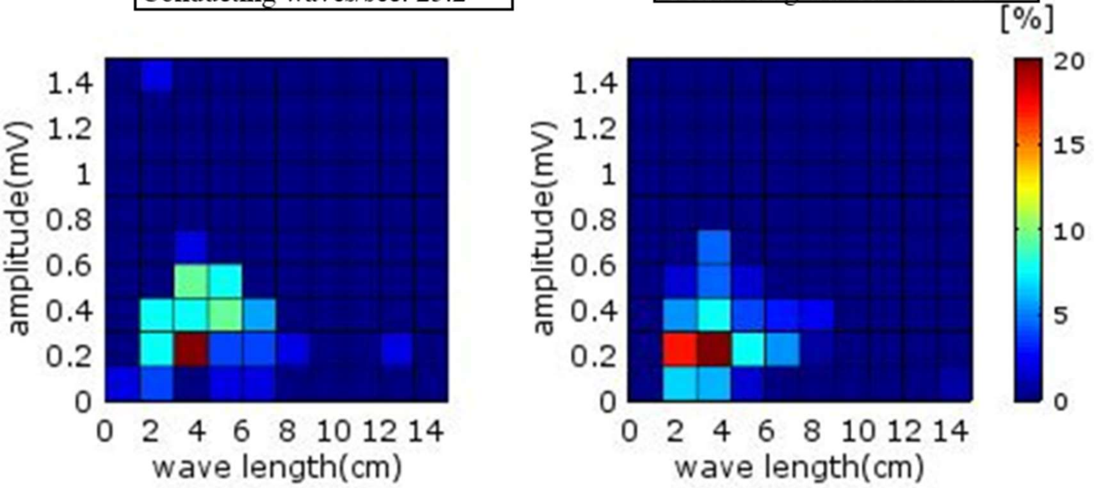
(d) Non-dominant arm
40%MVC 10 sec
Conducting waves/sec: 185.2

**Figure 48. The relation of Amplitude and Wavelength in dominant and non-dominant arms (sub2)**



(a) Dominant arm
10%MVC 30 sec
Conducting waves/sec: 25.2

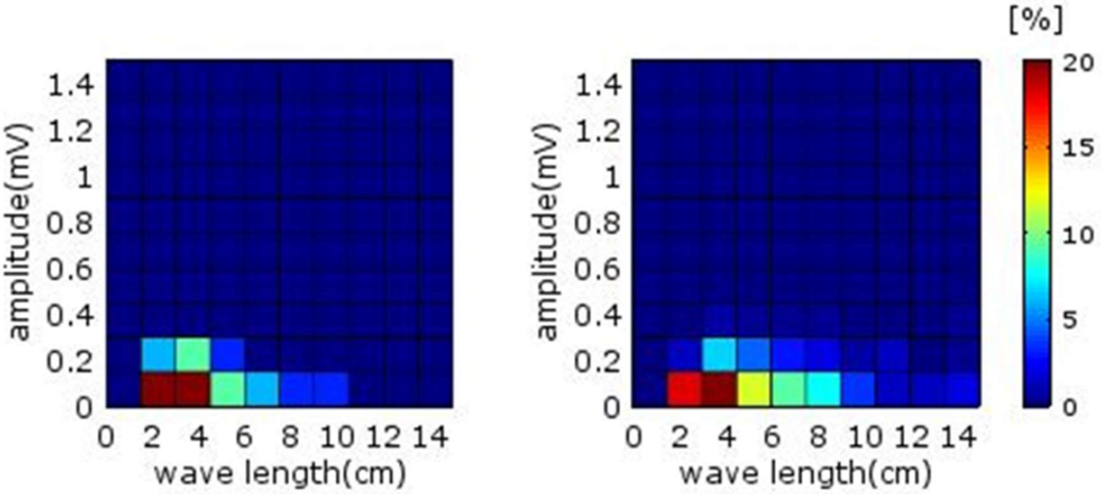
(b) Non-dominant arm
10%MVC 30 sec
Conducting waves/sec: 19.6



(c) Dominant arm
40%MVC 10 sec
Conducting waves/sec: 103

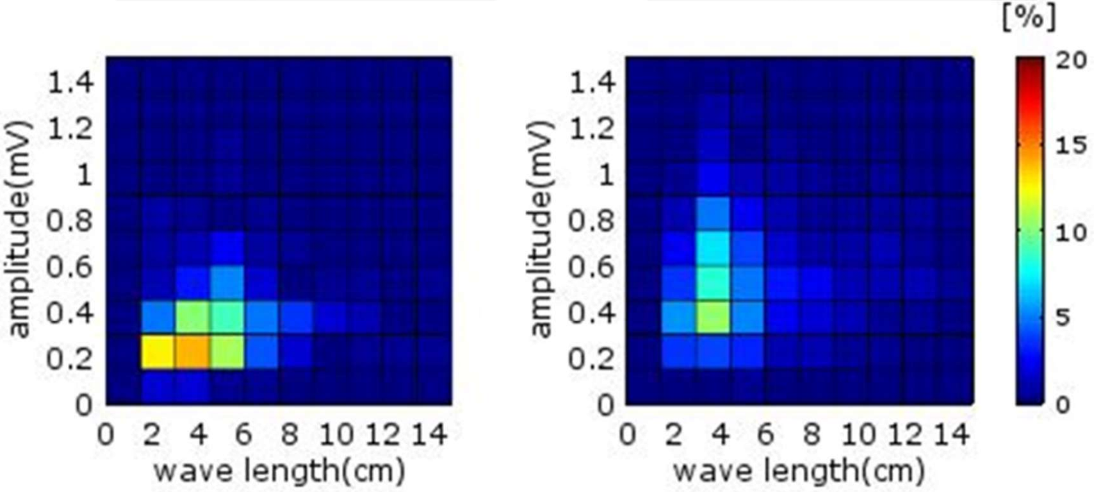
(d) Non-dominant arm
40%MVC 10 sec
Conducting waves/sec: 185.2

**Figure 49. The relation of Amplitude and Wavelength in dominant and non-dominant arms (sub3)**



(a) Dominant arm
10%MVC 30 sec
Conducting waves/sec: 25.2

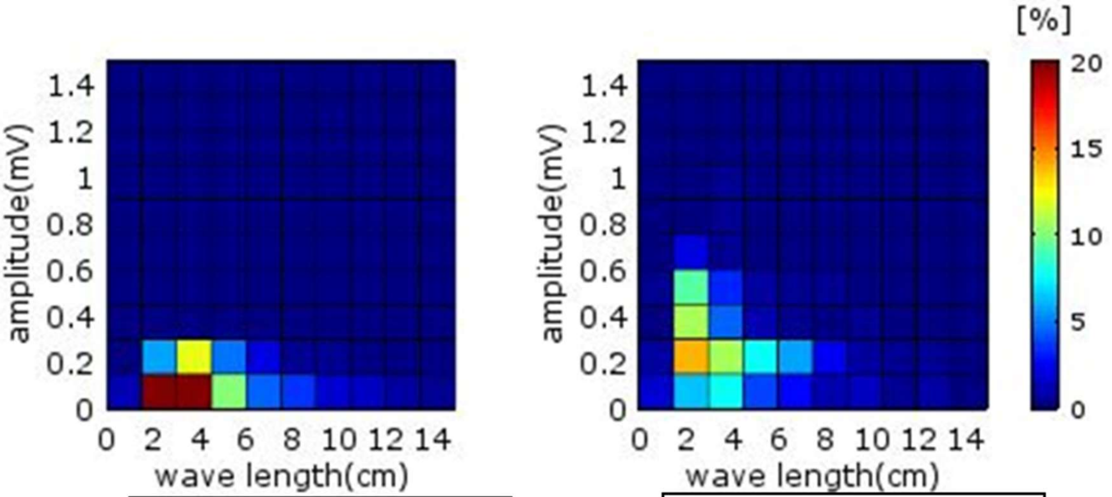
(b) Non-dominant arm
10%MVC 30 sec
Conducting waves/sec: 19.6



(c) Dominant arm
40%MVC 10 sec
Conducting waves/sec: 103

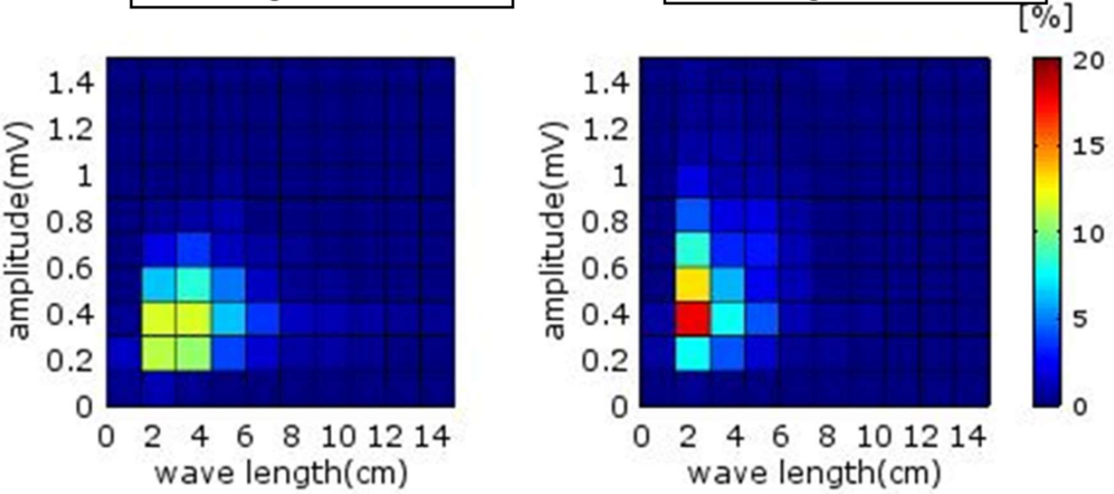
(d) Non-dominant arm
40%MVC 10 sec
Conducting waves/sec: 185.2

**Figure 50. The relation of Amplitude and Wavelength in dominant and non-dominant arms (sub4)**



(a) Dominant arm
10%MVC 30 sec
Conducting waves/sec: 25.2

(b) Non-dominant arm
10%MVC 30 sec
Conducting waves/sec: 19.6



(c) Dominant arm
40%MVC 10 sec
Conducting waves/sec: 103

(d) Non-dominant arm
40%MVC 10 sec
Conducting waves/sec: 185.2

**Figure 51. The relation of Amplitude and Wavelength in dominant and non-dominant arms (sub5)**

### 6.2.3. The changes of Amplitude, CV and wavelength over time

About the time-dependent change of the conducting wave parameter extracted by 3ch conduction judgment of multi-channel method, it investigated the waveform feature in the measurement of load 10% MVC for 30 seconds. The amplitude value, CV and wavelength on the vertical axis and time on the horizontal axis are shown in Figures 50 to 59. It should be mention that all the participates of this study were right handed. Furthermore, right hand is dominant arm and left hand is non-dominant arm in this study.

There was no tendency for the amplitude value to change with time (Figures 52 to 56).

It can be seen from Figures 57 to 61 that the non-dominant arm tends to extract the conducting waves with a little faster conduction velocity than the dominant arm, concerning the temporal changes of CV.

In the non-dominant arm, it is considered that not only the slow motor units but also the fast motor units temporarily participated in the muscle contraction for a load of 10% MVC. Since the fast motor unit is the muscle fiber that is more easily fatigued than slow motor unit, the number of motor units participate in muscle contraction decreased after 20 seconds from the start of measurement. In the non-dominant arm which less frequently used as compared to the dominant arm, the motor units of muscle tends to participate in the activity over time for the load of 10% MVC.

As shown in Figures 62 to 66, the wavelength in the non-dominant arm tended to be higher than the dominant arm. It has been thought that for a daily load of 10% MVC, the number of igniting motor units of the non-dominant arm is higher than the dominant arm. Besides, since the wavelength of the non-dominant arm tends to increase in 10 to 20 seconds, the effect of muscle fatigue can be seen. It is assumed that in the non-dominant arm, which is used less frequently on a daily basis, the effect of fatigue tends to be more visible than the dominant arm, even with a 10% MVC load.

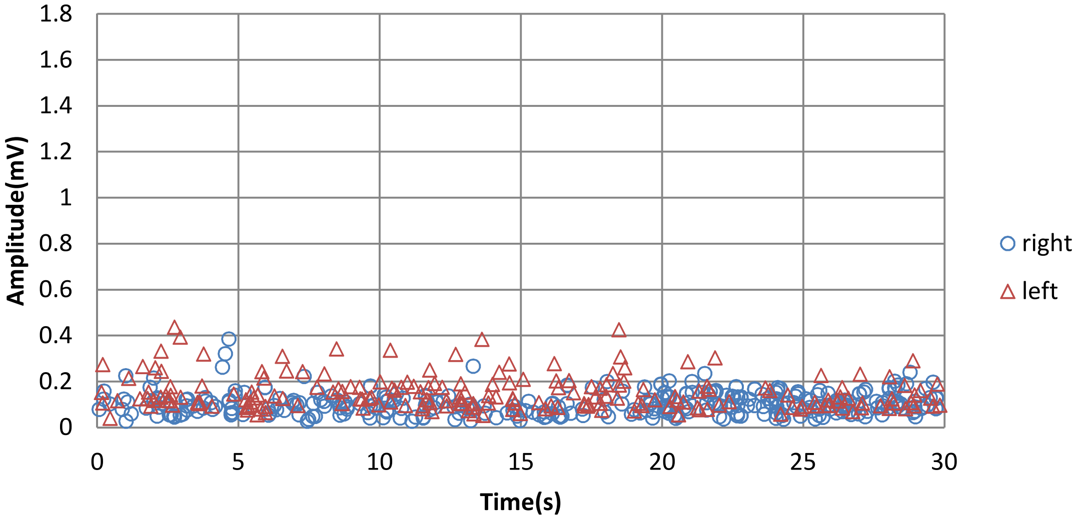


Figure 52. The changes of Amplitude over Time (sub1)

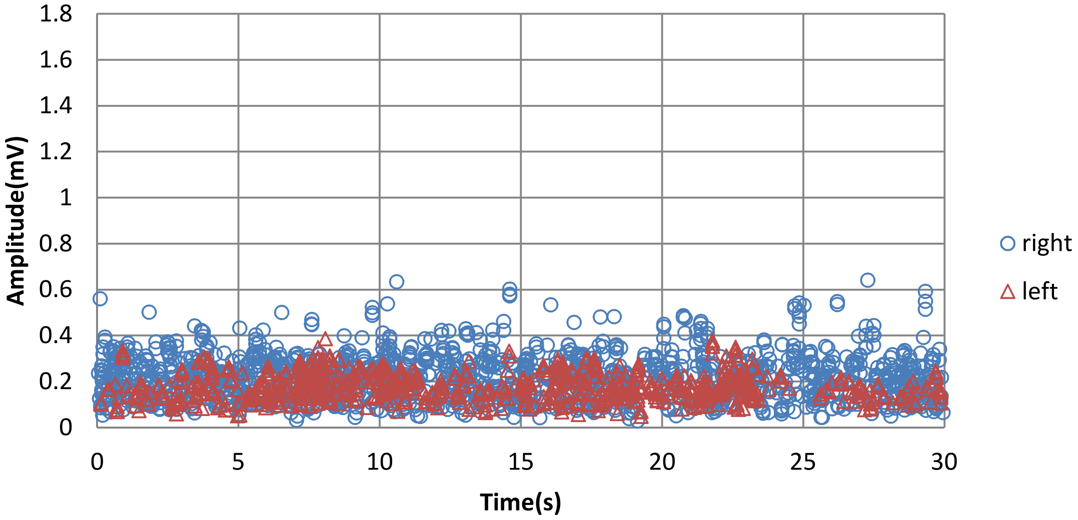


Figure 53.The changes of Amplitude over Time (sub2)

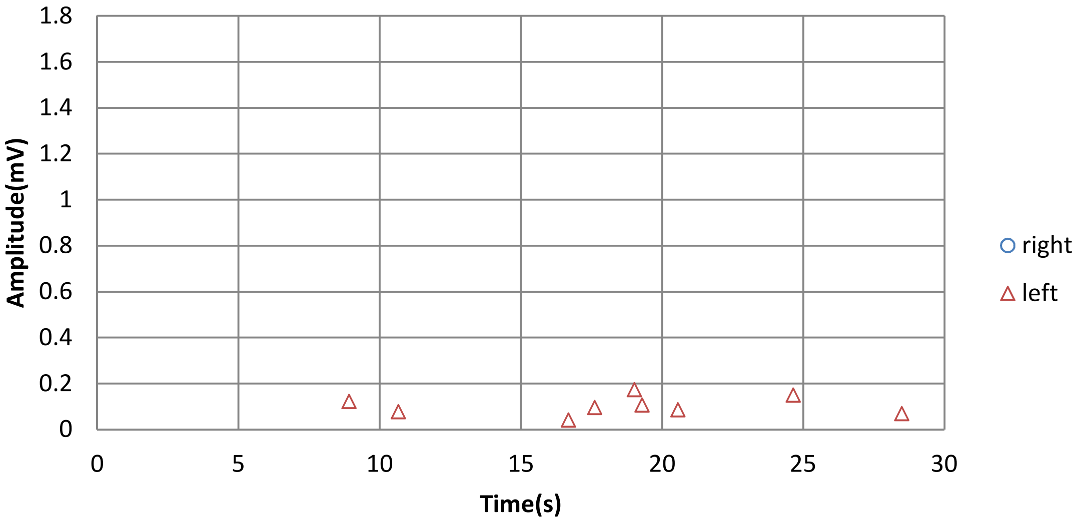


Figure 54.The changes of Amplitude over Time (sub3)

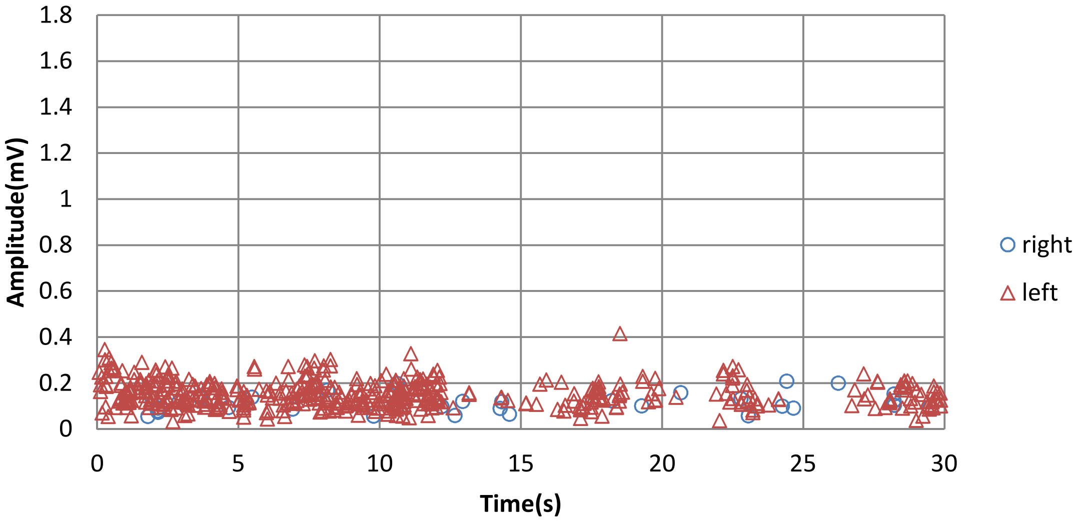


Figure 55.The changes of Amplitude over Time (sub4)

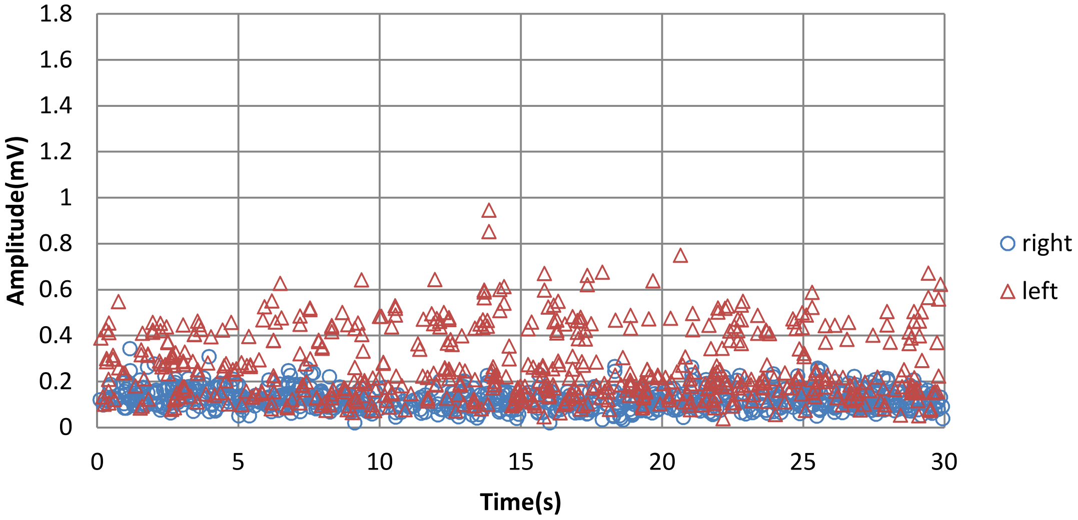


Figure 56.The changes of Amplitude over Time (sub5)

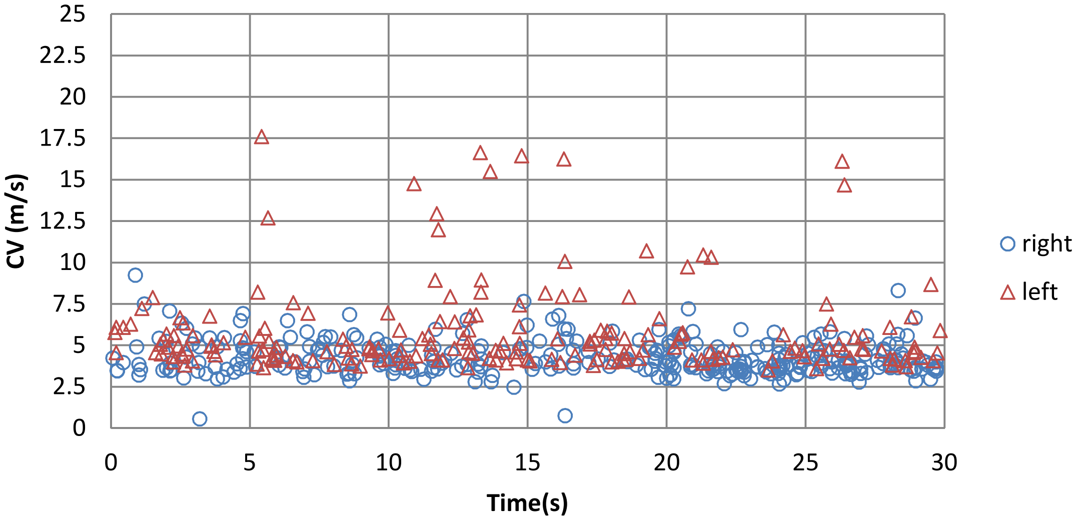


Figure 57.The changes of CV over Time (sub1)

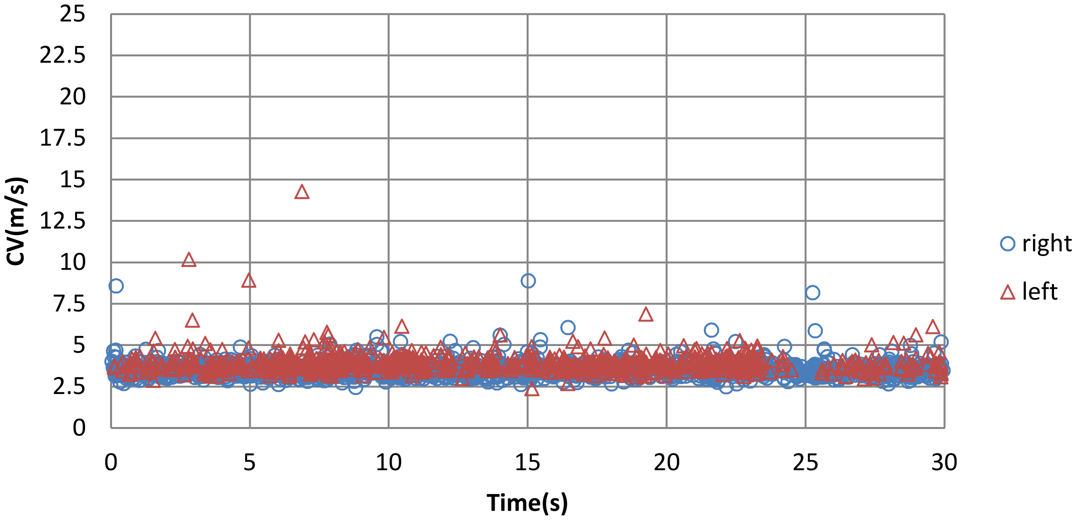


Figure 58.The changes of CV over Time (sub2)

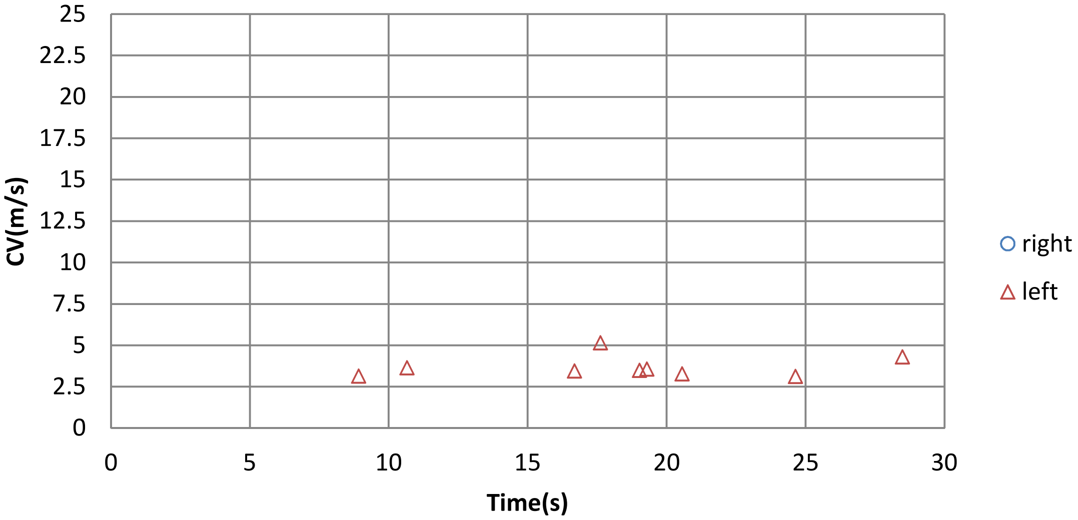


Figure 59.The changes of CV over Time (sub3)

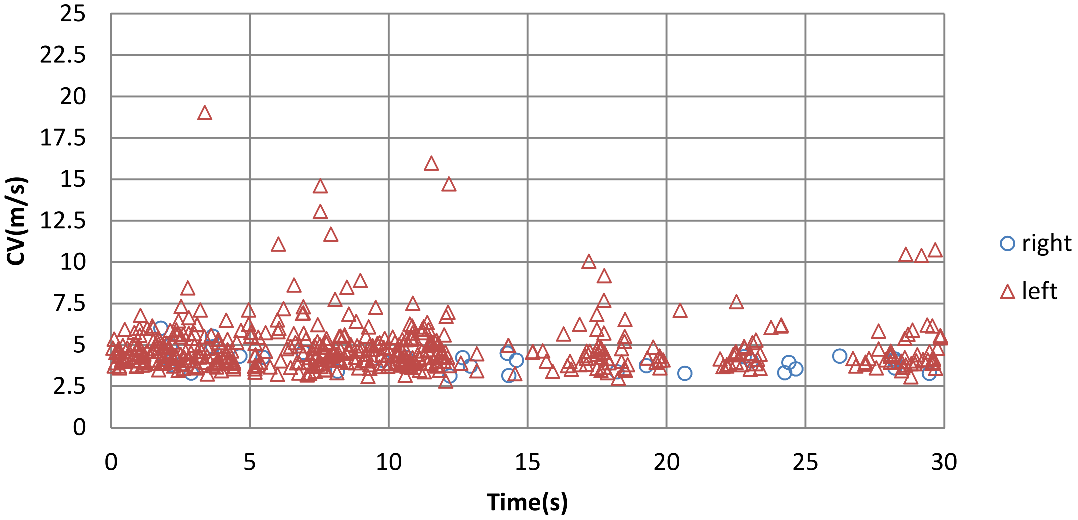


Figure 60.The changes of CV over Time (sub4)

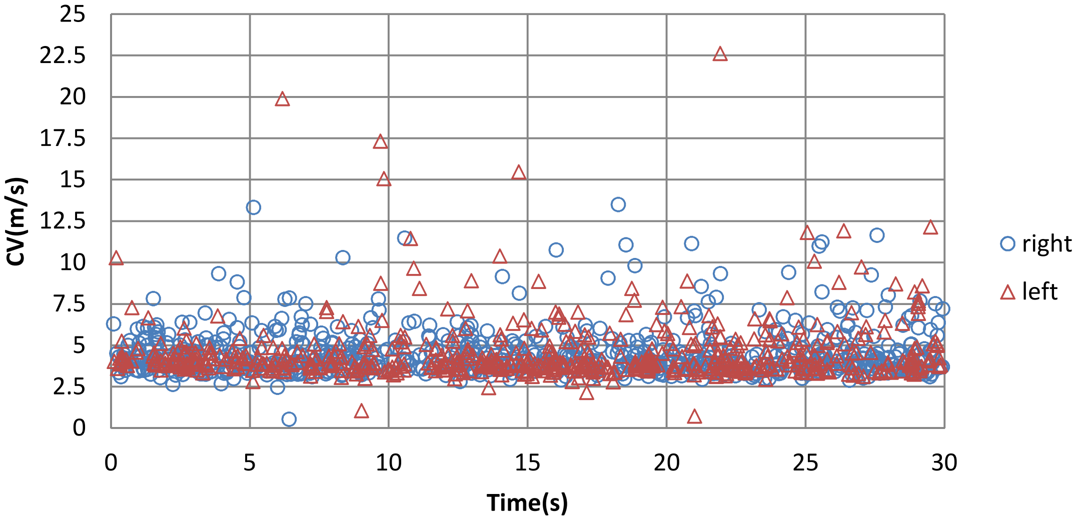


Figure 61.The changes of CV over Time (sub5)

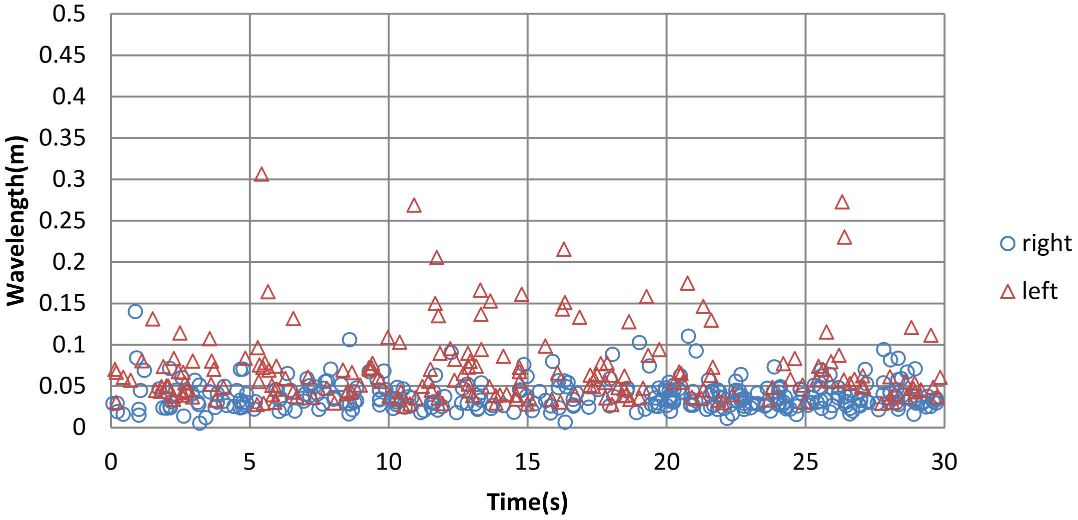


Figure 62.The changes of Wavelength over Time (sub1)

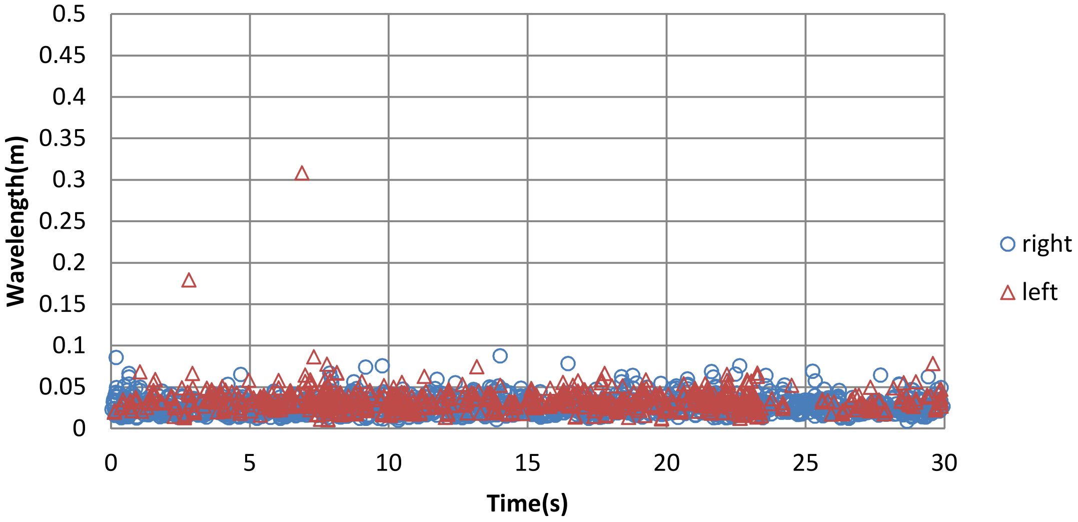


Figure 63.The changes of Wavelength over Time (sub2)

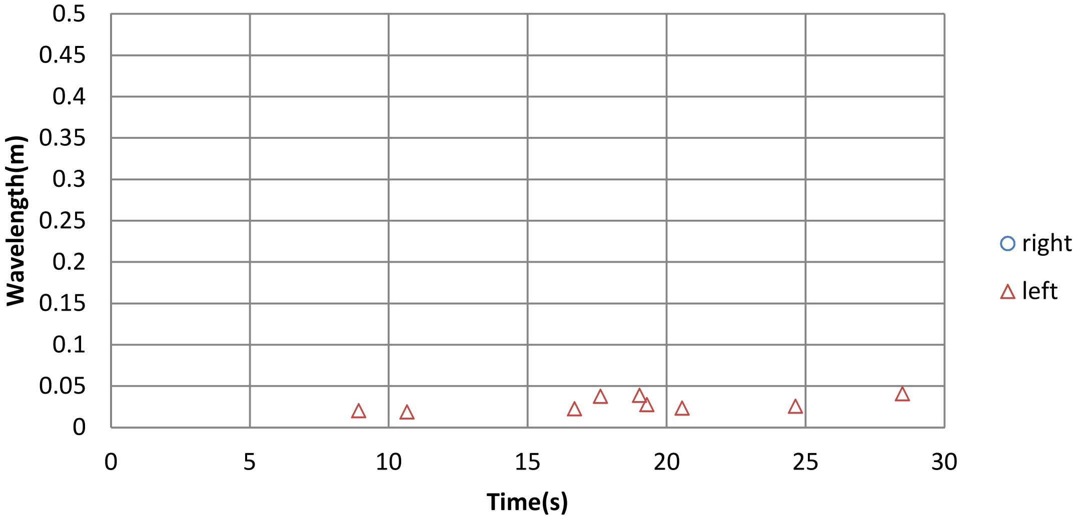


Figure 64.The changes of Wavelength over Time (sub3)

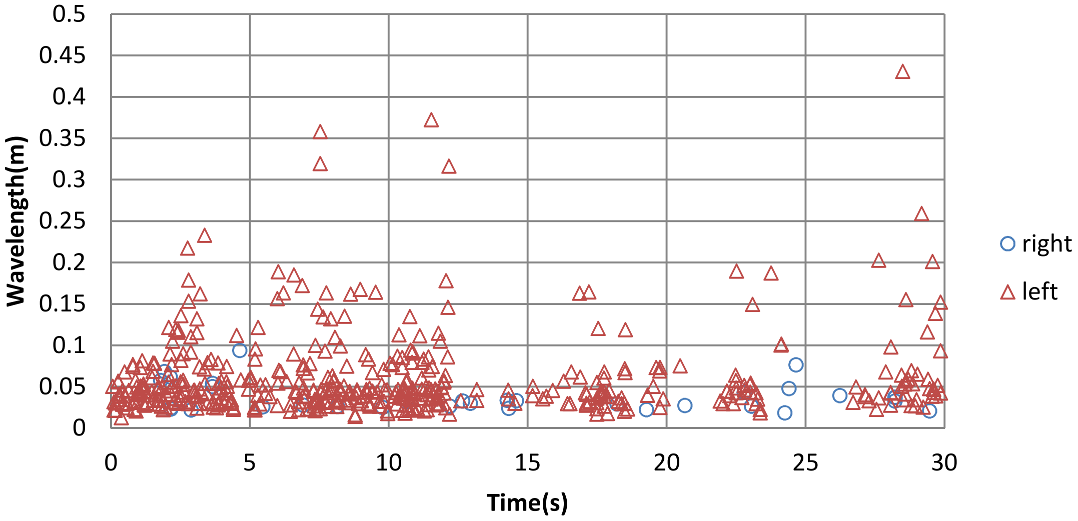


Figure 65.The changes of Wavelength over Time (sub4)

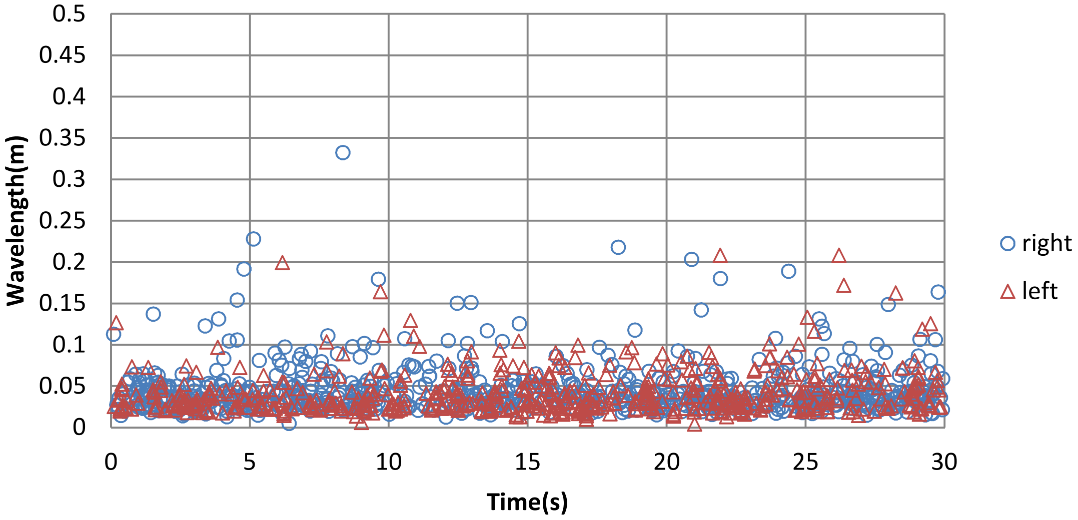


**Figure 66.The changes of Wavelength over Time (sub5)**

# 7. CONCLUSION

As it was mentioned in chapter 2, there are 2 ways to measure the electronical signal of the action potential: surface EMG and intramuscular EMG. There are different researches about motion control mechanism of the muscles according to data achieved from intramuscular EMG between1960 to.1980. But using the intramuscular EMG fallen out of favor, because it hurts the patient and puts a lot of stress on them. Therefore, in this study, multi-channel surface EMG had been used, because contact with the muscle is indirect and does not cause any pain. In rehabilitation, EMG is important to achieve some information about the recovery process of the muscle. In this research, multi-channel surface EMG had been used to achieve the data of muscle and multi-channel method could newly analyze the waveforms conduct from end-plate to the both directions of tendon. The test muscle was biceps brachii muscle and the distribution of end-plate and control of muscle contraction had been considered. The present study mainly aimed to use multi-channel surface electromyography (EMG) to characterize pairs of symmetric conducting waves and analyze the characteristics of waveforms traced from the pairs of symmetric conducting waves to the end-plate.

The **first purpose** of this study is to clarify the characteristics of pairs of symmetric conducting waves that conduct symmetrically in opposite directions to the tendon, elucidate the characteristics of waveforms conducted near the end-plate and clarify the effect of the end-plate on conducting waves.

Accordingly, experiment 1 was designed. In this experiment, all the participants were asked to keep the elbow of their right hand at a 90 degree angle for 60 sec while carrying a load with 40% of their MVC. Accordingly, we decided to examine the pairs of symmetric conducting waves and also, check the characteristics of them. By using the data achieved in the experiment, the relationship between amplitude, CV and spatial wavelength of waves and their changes over the time have been examined and results had been shown in colored maps to be able to discuss about the mechanism of muscles. The waves with higher CV were found in the distal direction and had a different start compared to waves in the proximal direction. It is known that conducting waves start to move when muscle activity starts, but in the case of pairs of symmetric conducting waves, there was a delay, which means the waves started to move slightly after muscle activity started. The pairs of symmetric conducting waves are considered to be a phenomenon that occurs when muscle contraction is continued for a certain period of time. It was confirmed that the waveforms generated from the end-plate had monotonous change of amplitude.

Additionally, in the case of pairs of symmetric conducting waves, the wave in the distal direction was affected more by the end-plate than the other waves.

The time that this experiment had been done was 60 sec and short. It was expected that all the muscle fibers join the contraction during 60 sec but the delay happened and it was common in all the cases. Accordingly, we doubt about the way that muscle fibers are controlled and join the muscle contraction. Therefore, experiment 2 had been designed.

The **second purpose** of this study is, analyzed the difference of muscle fibers composition and influence of cortex and spinal cord in dominant and non-dominant arms by applying different loads and using multi-channel surface EMG. In addition, by comparing the conducting waves of the biceps brachii in the dominant arm and non-dominant arm, the differences in muscle fiber composition and control of muscle of both arms had been considered. As a result, it was found that the end-plate is widely distributed on the distal side. Also, according to results of muscle contraction of both arms, dominant arm has the same type of motor units that cause the conduction than the non-dominant arm. Since there is a phenomenon that the conducting waves become uniform by the training of muscle, the possibility that the recovery process of the muscle can be judged by the uniformity of the type of the motor units that cause the conduction was shown.

In Experiment 2, same as experiment1, all the participants were asked to keep their elbow at a 90 degree angle but this time, same experiment had been done for dominant and non-dominant hands of participants. Motor unit recruitment defines as the successive activation of the motor units with increasing strength of voluntary muscle contraction. Since, full motor unit recruitment happens when all the motor units join the contraction and usually the MVC is about 20% to 30%, in this experiment, the behavior of motor units before and after full motor unit recruitment had been examined. Therefore, loads with10% MVC and 40% MVC had been used. First, the experiment with 10% MVC had been done for 30 sec and after that, the load changed to 40% MVC for 10 sec. The relationship between amplitude, CV and spatial wavelength of waves and their changes over the time have been examined.

For 10% MVC, which is likely similar to a load that will be used even in daily life, it is speculated that there are many motor units of the dominant arm that participate in the contraction activities compare to the non-dominant arm. For 40% MVC, which is an extraordinary load, in the non-dominant arm, it is considered that more motor units ignite than the dominant arm to bear the load.

In the conventional methods, only the size of the integrated electromyogram was compared, but according to the multi-channel method, the type of motor units active in the dominant arm and the non-dominant arm, and the tendency of motor units to participate in the contractile activity of each arm were clarified.

From the results achieved in this experiment, it was quantified that the dominant and non-dominant arms contracted differently by changing the applied load. In addition, the difference in muscle contraction activity between the dominant arm and non-dominant arm with respect to the applied load suggests that it may serve as an index for determining whether it is the motion control of dominant arm (controlled by spinal) or non-dominant arm (controlled by cortex). In particular, one indicator is that the number of extracted conducting waves changes for both dominant and non-dominant arms by changing the applied load. For small loads, more waves were extracted from dominant arm than non-dominant arms, but when a large load was applied, more waves were extracted from non-dominant arms than dominant arms. This suggests that, when an excessive load is applied, the motion control of non-dominant arm (controlled by cortex) may temporarily show a function similar to the motion control of dominant arm (controlled by spinal). It means that when a heavy load is applied, first, the brain gets the control of the body to estimate how heavy the load is and after that, the muscle contraction happens.

The results of this research will be a new indicator for strengthening muscles during rehabilitation and training by using multi-channel surface EMG. By using multi-channel surface EMG, it will be possible not only to achieve detailed information about the composition of the muscles but also be able to estimate how muscles are controlled in different activities.

# 8. FUTURE WORK

In the future, in order to clarify the reasons that the results of this research achieved, it is necessary to check appear of pairs of symmetric conducting waves while doing training or muscle fatigue to be able to compare the results. It is needed to clarify the effect of end-plate on dominant and non-dominant arms to be able to compare with the data achieved in this research. It is also important to clarify the characteristics of pairs of symmetric conducting waves in dominant and non-dominant arms.

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