



A Study of Vibrotactile Stimulator for Quadriceps Muscle: Analysis of EMG Reaction Signal

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Abstract

For human daily motion, the ability to perform different fundamental movement skills is involved with motor ability in normal and consistent functions. However, in an elderly or injured person, this ability may decline. This study aimed to design vibrotactile stimulator for quadriceps muscles in order to improve mobility limitations and restore functions. The stimulator was designed by using Autodesk Tinkercad software and constructed with 3D printer. High-speed DC motor was selected to produce 300 Hz vibration frequency, maximum, in assembly with 8 mm. CAMS. Graphic User Interface, GUI, was designed using LabVIEW 2017 student edition with data acquisition model NI USB – 6009. EMG data was recorded by LabVIEW and then analyzed using MATLAB 2016b. Signal Envelope and Sample Entropy were applied for EMG signal analysis method in this study. The sample subjects included five undergraduates from Rangsit University. The results revealed that quadriceps stimulated at vibration frequency of 33 Hz with 3-minute stimulation time showing a better result when compared to the one stimulated at 22 Hz with 3-minute, at 22 Hz with 5-minute and at 33 Hz with 5-minute stimulation time, respectively. It may thus be concluded that the designed vibrotactile stimulator with suitable frequency and amplitude can help rehabilitate quadriceps muscle injuries or people with disabilities.

Keywords: *Vibrotactile Stimulator, Vibration Stimulation, Physical Therapy, Quadriceps Muscles, EMG*

1. Introduction

Physical Therapy (PT), a healthcare specialty, is the care treatment of injury or abnormal symptoms for a physically weak person such as elderly or injured person. Physical therapy will help improve mobility limitations and restore functions. With a variety of techniques, treatment with physical therapy includes exercise therapy, manual therapy, ice and heat therapy, light therapy, acupuncture and electrotherapy or electrical stimulation. In clinical practice, physical therapists (PTs) perform hands-on treatment with provision of selected suitable interventions or treatments under considerations, for example, the use of electrical stimulation for muscle contraction. It helps injured muscles restore and relearn their function.

Mechanical physical therapy like vibrotactile stimulation is one of classic stimulation for physical therapy. When a vibration stimulator generates vibration frequency on muscle, the muscle will contract without being controlled. Therefore, muscle spindles are stretch receptors, which initiate the muscle stretch reflex to detect changes in the length of the muscle. Muscle stretch reflex usually occurs when stimulation is applied directly to joint. For instance, Knee-jerk reflex also called Patellar reflex, is the movement of the lower leg suddenly active in response to a sharp tap on the patellar tendon.

Quadriceps muscles simply known as a large group of muscles are in action on the front part of thigh, and they are responsible for generating a bit of force to keep walking, running, jumping and squatting. The quads are in action when changes in leg posture and knee jerk reflex occur. The four quad muscles include rectus femoris muscle, vastus lateralis muscle, vastus medialis muscle and vastus intermedius muscle. Quadriceps muscles may be subjected to repetitive stresses and forces that can cause injury resulting in a condition of pain and limited function in walking ability. Due to damaged or fatigue quads, the stretching and flexibility of legs will be lost because the brain receives a pain signal from muscle receptors. If muscles are not in active for a long time, the size of the muscle will automatically decrease. For this reason, the way to prevent muscle loss and strength training is rehabilitation.

Vibrotactile stimulation is also one technique that physical therapists use to improve or maintain quadriceps muscle strength. The important parameters of vibration stimulation are vibration frequency and vibration amplitude. Tonic Vibration Reflex (TVR) has been presented in many research studies in terms of



muscle action when directly received stimulation by mechanical vibration frequency at tendon (McPheson, 2018). Regarding the vibration frequency and amplitude, muscle contraction occurs when inducing with a frequency range of 20 – 200 Hz with 0.5 – 4 mm. at tendons of hamstring muscles. Koki (2017) did the experiment with vibration frequency 80 - 100 Hz with the amplitude of 0.5 mm. added to tendon of Semitendinosus Muscle and Biceps Femoris Muscle. The results showed that the knee joint extension motion of semitendinosus muscle is more active than biceps femoris muscle (Koki, 2017). Derek et al. (2014) used vibration stimulator with 30 Hz 1.6 mm. and 60 Hz 0.4 mm. for quadriceps muscle stimulation and they found that 30 Hz is suitable for quadriceps muscles (Derek et al., 2014). ČAPIČÍKOVÁ et al. (2006) studied about human balance control. Their study focused on human stance control of lower leg by using vibration stimulator at the soleus muscles with 60 Hz and 1 mm. stimulation. They found that despite showing body lean and sway during vibratory stimulation, there was no significant difference between body sway amplitude and velocity pre and post stimulation for 10 - 20 second (ČAPIČÍKOVÁ et al., 2006). A study by Mike et al. (2013) employed vibration stimulator for post – stroke hand rehabilitation with 80 Hz of vibration frequency on five-finger flexor tendons. The results revealed that, together with virtual reality graphic game, the subjects were able to improve their hand movement more effectively (Mike et al., 2013).

2. Objectives

1. To design vibrotactile stimulator for quadriceps muscles.
2. To determine the suitable frequency and amplitude for vibrotactile stimulator.

3. Materials and Methods

3.1 Vibrotactile stimulator design

The stimulator was designed by using Autodesk Tinkercad software and constructed with 3D printer. High-speed DC motor was selected to produce 300 Hz vibration frequency, maximum, in assembly with 8 mm. CAMS. Since the natural frequency of whole-body muscle is 20–200 Hz, the designed vibration frequency, therefore, covers all ranges of whole-body muscle frequency. The prototype design of vibrotactile stimulator is shown in Figure 1.

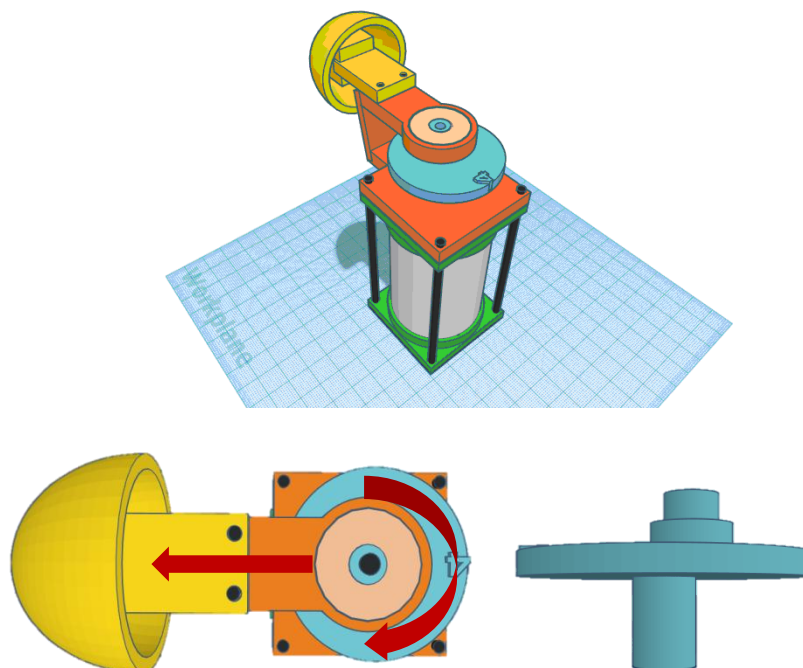


Figure 1 Prototype of Vibrotactile Stimulator



3.2 Software design

Graphic User Interface, GUI, comprises two functions: First, to control stimulator frequency with pulse-width modulation technique. Second, to record and display the EMG data of quadriceps muscle from bio amplifier. GUI was designed using LabVIEW 2017 student edition with data acquisition model NI USB – 6009. Block Diagram of LabVIEW GUI is shown in Figure 2.

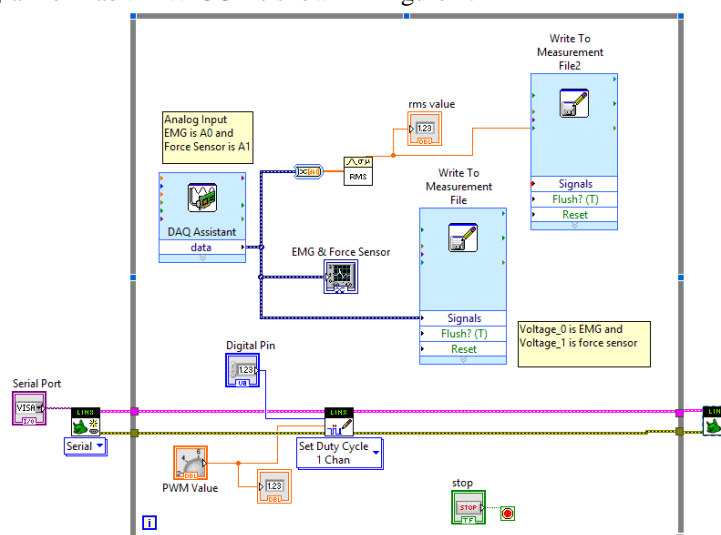


Figure 2 Block Diagram of LabVIEW GUI

3.3 Experimental protocol

The aim of this study is to design vibrotactile stimulator for quadriceps muscles. The key parameters of experiment are amplitude, frequency and the period of stimuli. As for the experimental design, two protocols are constructed as follows:

3.3.1 Measuring and recording EMG data before and after stimulation. EMG data acquisition system was set on quadriceps muscle and tendon as shown in Figure 3. The subjects participating in the experiment sat on the chair with legs fully extended downward. EMG from quadriceps muscles of right leg was continually recorded while the subjects needed to swing their right leg to fixed-point position and immediately swung back to induce EMG potential from leg extension posture. The resting time between leg extension was 10 second. The timing daigram of this process was designed as shown in Figure 4.

3.3.2 Stimulation experiment. Vibrotactile stimulator was set on the right knee at tendon of quadriceps position as shown in Figure 5. The subjects still needed to sit on the chair with legs fully extended downward in the same way as in EMG measurement before the stimulation process. EMG was not measured in this process since vibration frequency from vibrotactile stimulator would produce noise in EMG signal. While the subjects were stimulated with constant frequency at quadriceps tendon with 3- and 5-minute stimulation, the right leg automatically extended due to tonic vibration reflex. The vibration frequencies used in this experiment were 22 Hz and 33 Hz with 8 mm in amplitude, respectively. Timing diagram of stimulation experiment is shown in Figure 6.

3.4 Signals processing

EMG data was measured twice, before and after stimulation with the vibrotactile stimulator. Data was recorded by LabVIEW and then analyzed using MATLAB 2016b. Signal Envelope and Sample Entropy were applied for EMG signal analysis method in this study.

3.4.1 Signal Envelope is a conventional technique used for complex and non – linear signal analysis to determine a boundary of signal in the time domain. The boundary can be defined by RMS or a peak of each signal cycle. The envelope signal is more linear and easy to visualize. Example of signal envelope is shown in Figure 7. (MATLAB, 2016)

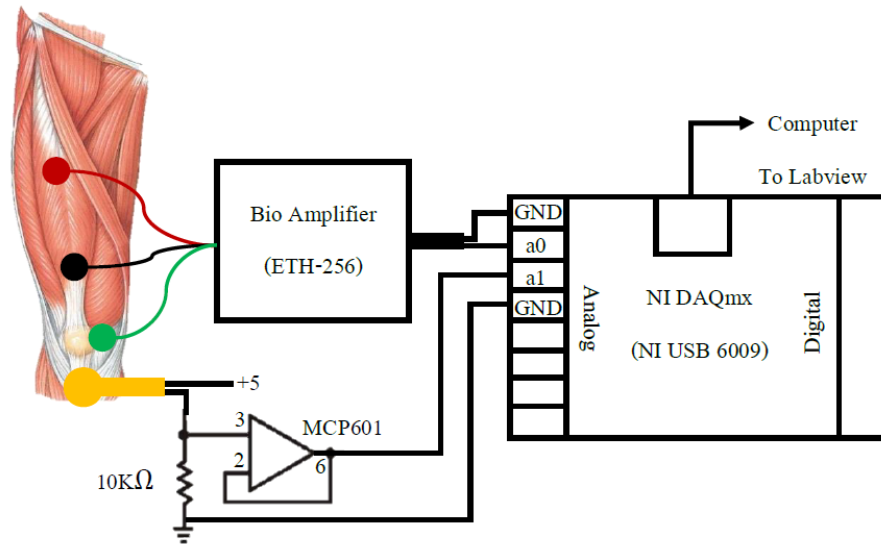
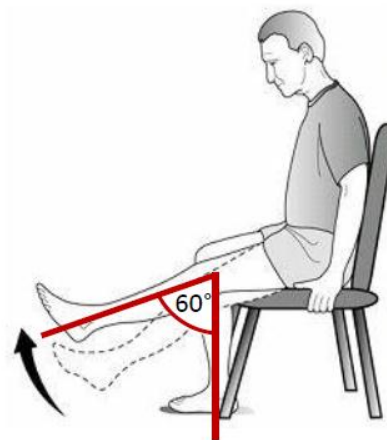
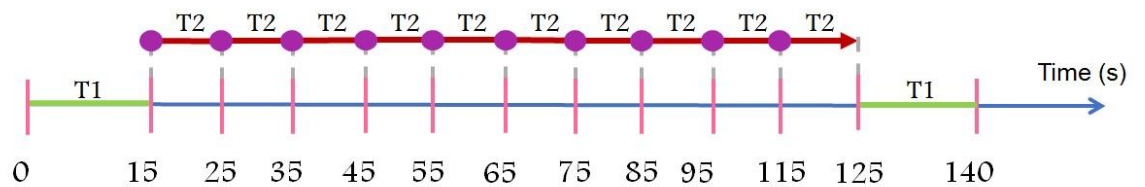


Figure 3 EMG Data Acquisition System



4a)



4b)

Figure 4 a) Leg Extension Posture
 b) Timing Diagram of Pre – Post Stimulation Experiment

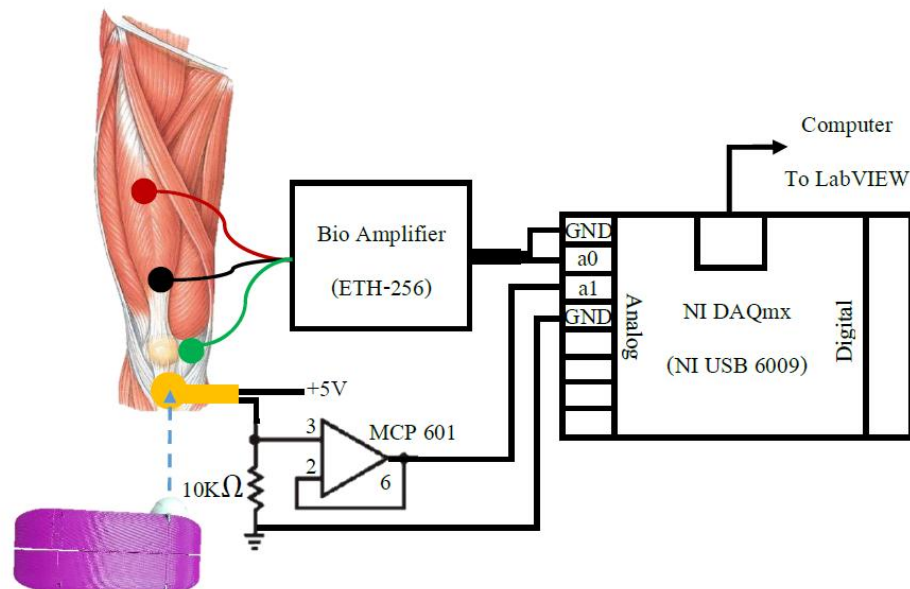


Figure 5 Vibration Stimulation Experiment

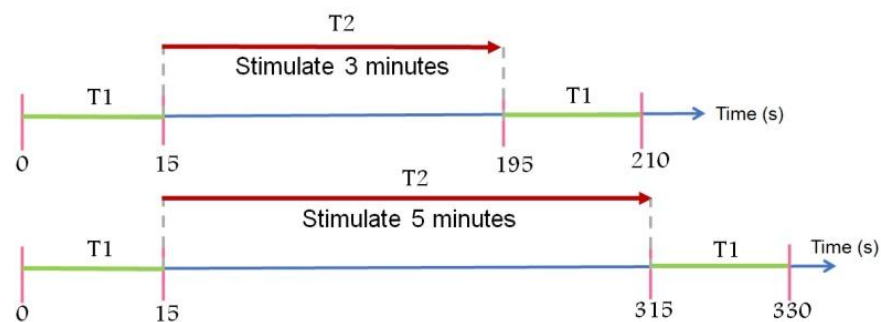


Figure 6 Timing Diagram of Vibration Stimulation Experiment

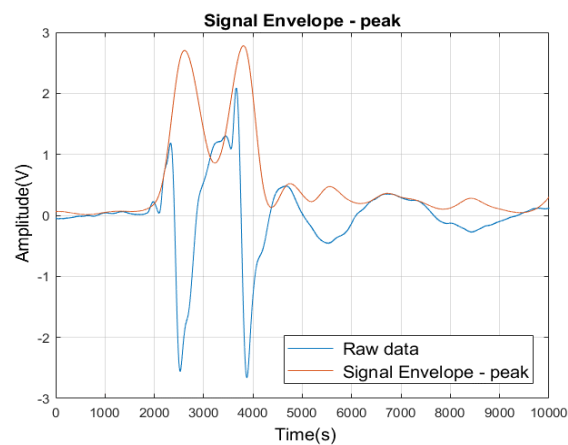


Figure 7 Signal Envelope of EMG with Knee Jerk Reflex



3.4.2. Sample Entropy known as one of information entropies that could be used to analyze biological data. Information entropy was originally proposed by Claude E. Shannon for change of information data analysis. (Don S. Lemons, 2013) Sample entropy divides the data into sequences and then determines the sample entropy according to the function.

$$SampEn(m, r, N) = -\log \left(\frac{\sum A_i}{\sum B_i} \right) = -\log \frac{A}{B}$$

where m is the template length, r is the tolerance for accepting matches, N is the number of data points, A_i is the number of matches of length $m+1$, and B_i is number of matches of length m .

4. Results and Discussion

It is necessary to mention that there was a displacement of 8 mm instead of using 0.4 mm or 1.6 mm amplitude as cited by a study of Derek et al. (2014). As for the stimulation process, this study employed bouncing stimuli. Therefore, 8 mm. is the lowest amplitude to induce tonic vibration reflex. The results from five subjects were analyzed and discussed. We compared EMG results obtained from before and after stimulation with vibrotactile stimulator using the same amplitude of 8 mm, but with different stimulation time (3 minutes and 5 minutes) and different vibration frequency (22 Hz and 33 Hz).

In each epoch, a peak envelope of EMG signal was gathered from 10 epoch data on average and noise reduction was also required. After that, a peak signal envelope was analyzed using MATLAB. At that point, we found the different signal envelope between before and after stimulation by subtraction "After" stimulation signal envelope with "Before" stimulation signal envelope. The results from differential signal envelope were presented in Table 1 and 2.

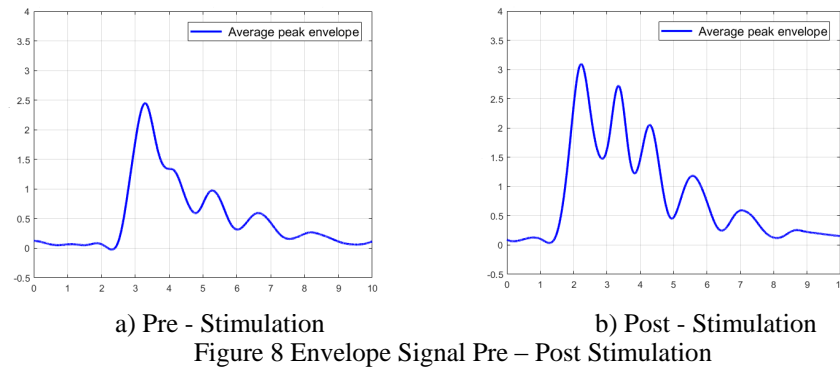
Table 1 The differential signal envelope with 3 - minute stimulation time

Subject	22 Hz	33 Hz
RSU01	0.1552	0.2325
RSU02	0.0062	-0.0296
RSU03	-0.0332	0.1080
RSU04	-0.0275	0.0897
RSU05	0.0299	0.3206

Table 2 The differential signal envelope with 5 - minute stimulation time

Subject	22 Hz	33 Hz
RSU01	-0.0032	-0.0056
RSU02	-0.0027	0.0118
RSU03	0.0770	0.1145
RSU04	-0.0998	-0.1168
RSU05	-0.1526	-0.0525

As shown above, the results from five subjects presented both positive and negative values. The positive value means EMG signal after stimulation was greater than before stimulation. In contrast, the negative value means EMG signal after stimulation was less than before stimulation. This study revealed that the signal envelope with 3-minute stimulation time showed better results as compared to the one with 5-minute stimulation time. When compared between different vibration frequencies, the signal envelope stimulated at 33 Hz showed better results than the one stimulated at 22 Hz vibration frequency. Figure 8 shows a comparison between envelope signal pre and post 3-minute stimulation with 33 Hz vibration frequency.



Sample Entropy was also calculated to determine the differential sample entropy. In line with the differential signal envelope, the differential sample entropy was the subtraction between pre and post stimulation. The results of sample entropy were presented in Table 3 and Table 4.

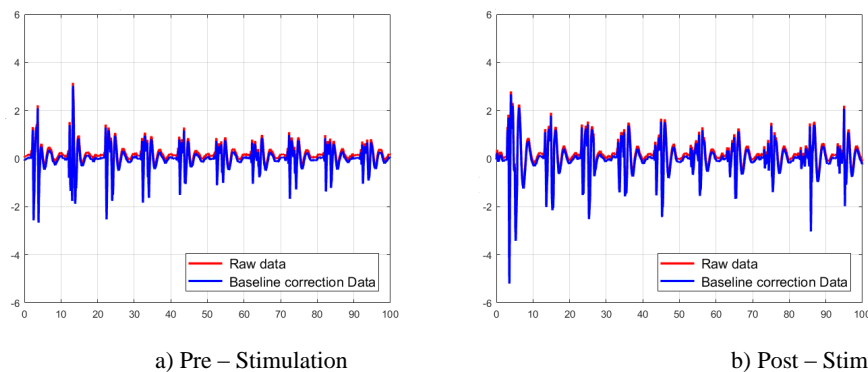
Table 3 The differential sample entropy with 3 - minute stimulation time

Subject	22 Hz	33 Hz
RSU01	-0.0111	-0.0133
RSU02	-0.2496	0.2059
RSU03	0.0015	-0.0209
RSU04	-0.0018	-0.0190
RSU05	-0.0080	-0.0001

Table 4 The differential sample entropy with 5 - minute stimulation time

Subject	22 Hz	33 Hz
RSU01	0.0031	0.0261
RSU02	-0.0459	-0.0011
RSU03	-0.0269	-0.0199
RSU04	0.0170	0.2793
RSU05	0.0117	0.0039

As shown in Table 3, the differential sample entropy revealed that the sample entropy “After” stimulation was less than “Before” stimulation. Despite showing the opposite results compared with the differential signal envelope in Table 1, it can be accepted because the sample entropy was used for analyzing the complexity of data. EMG pre and post stimulation data were considered, as shown in Figure 9, EMG before stimulation was at low amplitude but with high frequency. However, EMG after stimulation was at high amplitude but with low frequency. Accordingly, the sample entropy of pre – stimulation was a little higher than post – stimulation.





5. Conclusion

In this study, we designed vibrotactile stimulator for quadriceps muscles and determined the suitable frequency and amplitude for vibrotactile stimulator using EMG reaction signal analysis. Vibrotactile stimulator was designed based on mechanical vibration with dc motor and cam. The vibration frequency can control in a range of 20 – 200 Hz with constant amplitude 8 mm. The results from EMG analysis revealed that 33 Hz is the suitable frequency for stimulation and 3-minute stimulation time per trial can increase muscle reaction.

Regardless of determining the suitable vibration frequency and stimulation time, we still have some concerns about two parameters: First, vibration amplitude because the prototype stimulator cannot adjust the amplitude. Second, a period of stimulation either per day or per week since stimulation time will help us to design protocol for training quadriceps muscle injuries or people with disabilities so that they can move their legs by themselves.

For further study, we will increase the sample size for more reliable results and look forward to applying this system to clinical practice.

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7. References

- ČAPIČÍKOVÁ et al. (2006). Human Postural Response to Lower Leg Muscle Vibration of Different Duration. *Physiological Research*, S129 – S134, Vol.55.
- Derek et al. (2014). The acute effects of local muscle vibration frequency on peak torque, rate of torque development, and EMG activity. *Journal of Electromyography and Kinesiology*. 888 – 894.
- Don, L.(2013). *A Student's Guide to Entropy*, Cambridge.
- Koki, H. (2017). A Study of Motion Change during Lower-limb Knee Joint Extension Motion Induced by Vibration Stimulation for Perception-Assist. *IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*, 957-962.
- Mike et al. (2013). Combined Tendon Vibration and Virtual Reality for Post – Stroke Hand Rehabilitation. *IEEE World Haptics Conference 2013.*, 277 – 282.
- Tomas, M. & Tomas, A. (1991). *Element of Information Theory*, John Wiley & Sons.