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 people, this ability may decline. The aim of this study was to design mechanical vibrotactile stimulator applied along the vertical direction for quadriceps muscles in order to improve mobility limitations and restore functions. The stimulator was designed by using Autodesk Tinkercad software and constructed with a 3D printer. High-speed DC motor, in assembly with 8–mm cam, was employed. 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 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 a 3–minute stimulation time showed better results when compared to the one stimulated at 22 Hz with a 3–minute, at 22 Hz with a 5–minute and at 33 Hz with a 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, Tonic Vibration Reflex (TVR), 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 an 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 provisions of selected suitable interventions or treatments under considerations, for example, the use of electrical stimulation for muscle contraction. It helps injured muscles to restore and relearn their function (Fong et al., 2009).

Mechanical physical therapy like vibrotactile stimulation is one of the classic stimulations for physical therapy. When a vibration stimulator generates vibration frequency on muscle, the muscle will contract without being controlled (Humphries, Warman, Purton, Doyle, & Dugan, 2004). 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 a 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 the 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. Hindle, Whitcomb, Briggs and Hong (2012) further described that, due to tight 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 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 physical therapy such as vibrotactile stimulation.

Vibrotactile stimulation is also one technique that physical therapists use to improve or maintain quadriceps muscle strength. Fallon and Macefield (2007) indicated that 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. For example, Ivanenko, Grasso and Lacquaniti (2000) explained that 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. Kavounoudias, Roll & Roll (2001) stated that, in order to assess the relative contribution and muscle proprioceptive feedback in controlling human erect posture, combined vibratory stimuli were applied to the forefoot areas and to the tendons of the tibialis anterior muscles using various vibration frequency patterns (ranging from 20 to 80 Hz).

A variety of stimulators have been used, including mechanical (Kavounoudias et al., 2001) and pneumatic vibrotactile stimulation devices (Brigg et al., 2004). As for mechanical devices applied along the horizontal direction, Honda & Kiguchi (2017) did the experiment at frequency 80–100 Hz with the amplitude of 0.5 mm horizontal stimulation applied 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 the biceps femoris muscle. Rinderknecht, Kim, Santos-Carreras, Bleuler & Gassert (2013) employed mechanical vibrotactile stimulator for post–stroke hand rehabilitation with 80 Hz of horizontal 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.

Regarding pneumatic devices applied along the vertical direction, Derek, Ryan & Blackburn (2014) used pneumatic vibrotactile stimulator with 30 Hz 1.6 mm and 60 Hz 0.4 mm vertical stimulation and they found that 30 Hz is suitable for quadriceps muscles. Moreover, Čapičikova, Rocchi, Hlavačka, Chiari & Capello (2006) studied about human balance control. Their study focused on human stance control of the lower leg by using pneumatic vibrotactile stimulator at the soleus muscles with 60 Hz and 1 mm vertical stimulation. They found that despite showing a lean body and sway during vibratory stimulation, there was no significant difference between body sway amplitude and velocity pre– and post– stimulation for 10–20 seconds.

Each of these devices has advantages and drawbacks (Brigg et al., 2004). Manual devices are difficult to control, but flexible to use. Pneumatic systems offer simplicity, compatibility with the magnetic environment. However, those are expensive and sensitive to placement. Thus, the development of simple, efficient and cost-effective vibrotactile stimulator is warranted. In this study, we propose a prototype of mechanical vibrotactile stimulator applied along the vertical direction for quadriceps muscles together with software design to control stimulator frequency and to record and display EMG data. It aims to offer simplicity, effectiveness and flexibility in actual clinical practice.

2. Objectives

1. To design a mechanical vibrotactile stimulator applied along the vertical direction for quadricep muscles
2. To determine the suitable frequency and amplitude for a vibrotactile stimulator

3. Materials and Methods

3.1 Vibrotactile stimulator design

The stimulator was designed by using Autodesk Tinkercad software and constructed with a 3D printer. A high-speed DC motor was used in assembly with an 8-mm cam. A range of stimulus frequency with a DC motor was between 10–300 Hz (Nawarathna et al., 2006). Since the natural frequency of whole-body muscle is 20–200 Hz, the design of vibrotactile stimulator, therefore, covers all ranges of whole-body muscle frequency. The prototype vibrotactile stimulator is shown in Figure 1.

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 EMG data of quadriceps muscle from a 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.

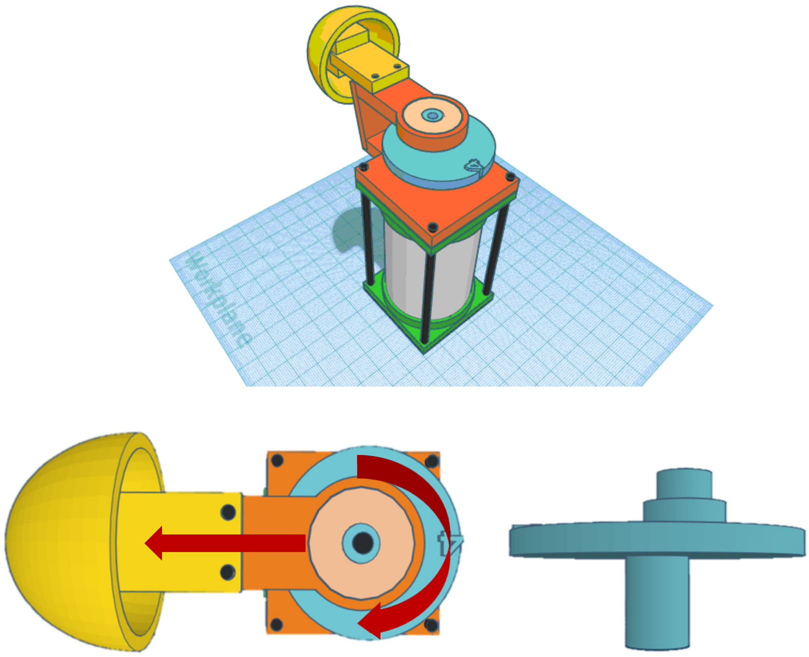


Figure 1 Prototype of Vibrotactile Stimulator

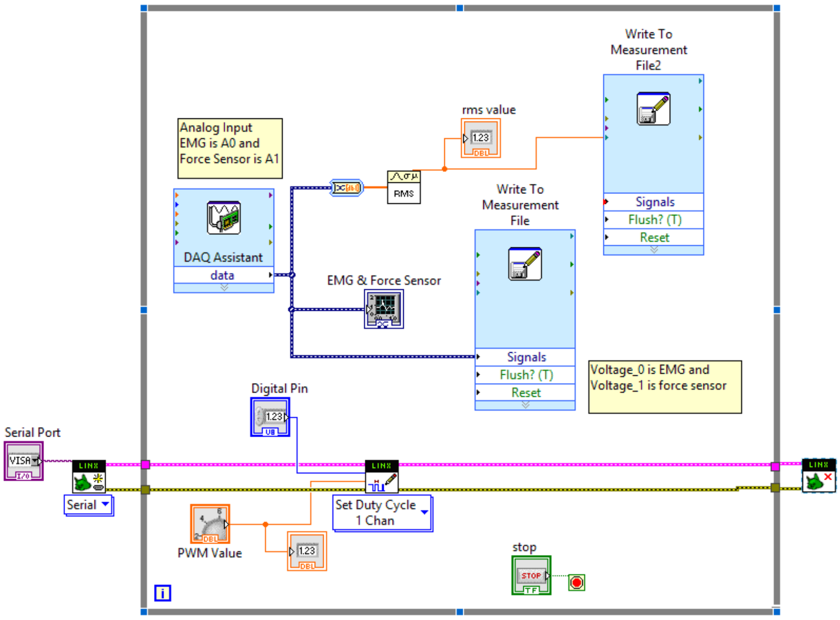


Figure 2 Block Diagram of LabVIEW GUI

3.3 Experimental protocol

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

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

3.3.2 Stimulation experiment. As aforementioned, the whole-body muscle vibration frequency extended from 20 to 200 Hz. Like the frequency, the amplitude and the direction of the vibration may vary. In this study, we designed a vibrotactile stimulator for quadricep muscles in order to improve mobility limitations and restore functions. Using bouncing stimuli, the input of vibrotactile stimulator is manually controlled to induce tonic vibration reflex (TVR). In this regard, our study considered 8 mm since it is the lowest amplitude to trigger the TVR in active muscles. Lower amplitudes such as 2 mm and 4 mm are not applicable as they are not able to induce the vibration reflex at tendon while higher amplitudes are not considered to avoid an acute injury at tendon. In terms of the direction of vibration, we used vertical-vibration stimuli. Vertical-vibration is preferred due to dynamic movements such as gait improved the balance ability through activation of the trunk stabilizer muscles (Gu & Hwangbo, 2016). Vibrotactile stimulator was set on the right knee at tendon of quadriceps position as shown in Figure 5. In this study, the period of the resting stage between pre- and post-stimulation was 15 minutes (Pierce, 1995). A stimulation experiment was performed in 5 subjects stimulated consecutively, one session of 3–minute and one session of 5–minute stimulation with 15–minute rest. During the resting stage, 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–minute and 5–minute stimulation, the right leg automatically extended due to tonic vibration reflex. The findings of this study may be applied to the design of hand-held power tools, since their vibration triggers the TVR in active muscles. In order to check the constant amplitude applied to tendon, since the vibrotactile stimulator is mainly for manual tasks, we employed force sensors to check the voltage to induce tonic vibration.

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. An example of signal envelope is shown in Figure 7.

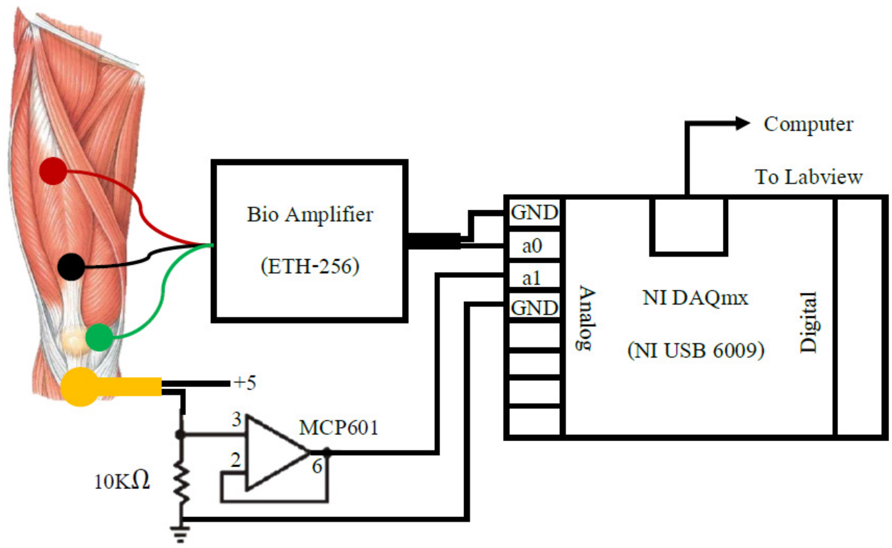
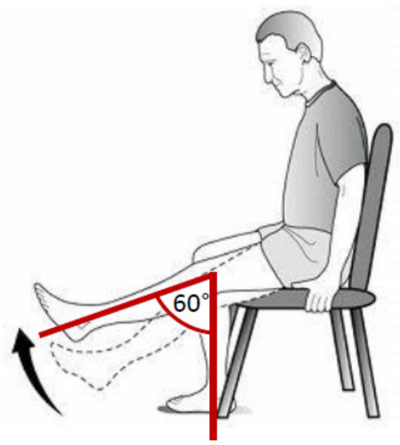
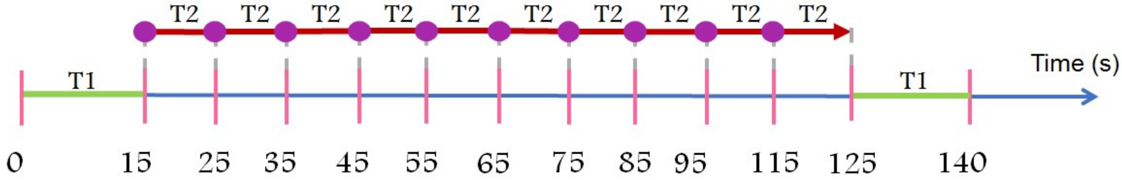


Figure 3 EMG Data Acquisition System



4a)



4b)

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

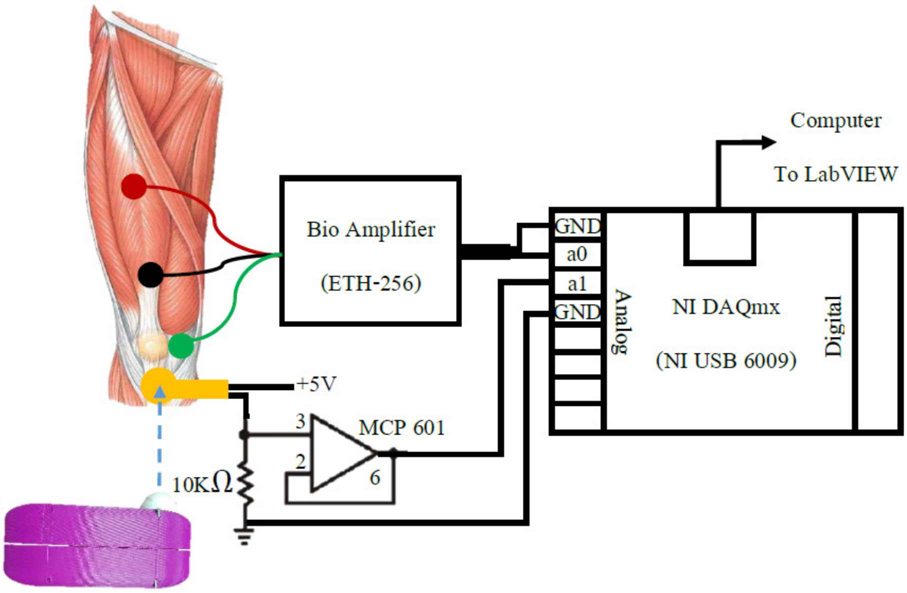


Figure 5 Vibration Stimulation Experiment

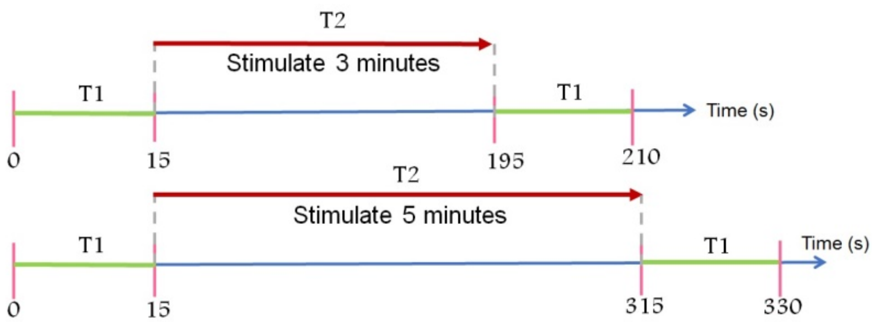


Figure 6 Timing Diagram of Vibration Stimulation Experiment

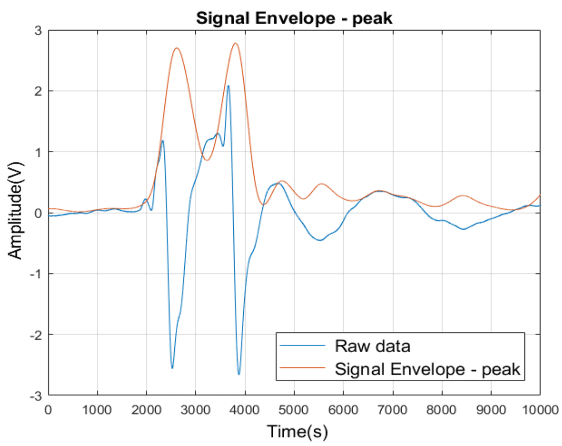


Figure 7 Signal Envelope of EMG with Knee Jerk Reflex

3.4.2. Sample Entropy is known as one of the 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 (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). Unlike Derek's pneumatic vibrotactile stimulator, this prototype is a mechanical device with vertical 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 2016b. 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 are presented in Table 1 and Table 2.

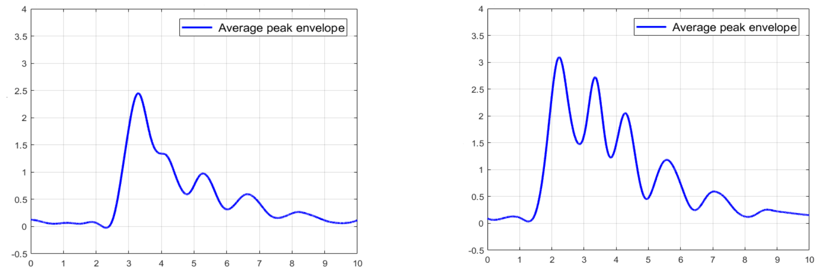
Table 1 The differential signal envelope with 3 - minute stimulation time

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.



a) Pre - Stimulation b) Post - Stimulation

Figure 8 Envelope Signal Pre – Post Stimulation

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.

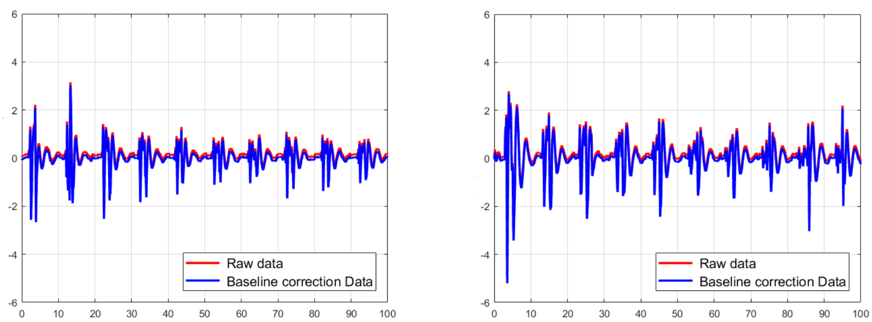
Table 3 The differential sample entropy with 3 - minute stimulation time

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.



a) Pre – Stimulation b) Post – Stimulation

Figure 9 EMG data Pre – 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 a 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.

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

6. Acknowledgements

The authors would like to show our gratitude to Dr. Samit Chakrabarty, School of Biomedical Science, University of Leeds, who suggested this topic as well as provided insight and expertise that greatly assisted the research. The authors are also grateful to Dr. Thapanee Khemanuwong, King Mongkut's Institute of Technology Ladkrabang, for assistance with English language editing and proofreading.

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