The Development of a Wearable Device for Relieving the Lower Leg Muscles Fatigue

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การยืนเป็นท่าทางที่เหมาะสมที่สุดในการทำงานต่างๆ เนื่องจากแขนและขาสามารถขยับได้กว้างและสะดวกเมื่อเทียบกับท่าทางอื่น การยืนมีประโยชน์ทั้งต่อร่างกายและจิตใจแต่ในขณะเดียวกันการยืนเป็นเวลามากเกินไปก็อาจส่งผลเสียได้เช่นกัน งานวิจัยนี้มีวัตถุประสงค์เพื่อพัฒนาอุปกรณ์สำหรับบรรเทาความเมื่อยล้าของกล้ามเนื้อบริเวณปลายขาซึ่งเป็นผลมาจากการยืนเป็นเวลานาน รวมถึงทดสอบความสามารถในการทำงานของอุปกรณ์ดังกล่าว การออกแบบอุปกรณ์ใช้ความรู้พื้นฐานเรื่องความเมื่อยล้า ผลจากการยืนและเดินเป็นเวลานาน รวมไปถึงองค์ความรู้ที่ได้รับจากการค้นคว้าเกี่ยวกับแนวทางบรรเทาความเมื่อยล้า แนวคิดหลักของอุปกรณ์ที่พัฒนาในกรอบงานวิจัยนี้คือการเพิ่มอัตราการไหลเวียนโลหิตโดยใช้แนวทางการนวดด้วยลูกกลิ้งและการบีบรัด

การทดลองนี้มีผู้ร่วมทดลองทั้งหมดสี่คน โดยจะประเมินความเมื่อยล้าในทางกายภาพผ่านสัญญาณคลื่นไฟฟ้ากล้ามเนื้อและความสามารถในการทรงตัว ในขณะที่ความเมื่อยล้าทางจิตใจจะประเมินด้วยแบบสอบถาม ตัวแปรที่สื่อถึงความเมื่อยล้าประกอบด้วย เวลาเริ่มต้นที่เกิดความเมื่อยล้า ความถี่ของค่าพลังงานเฉลี่ย และความเร็วในการเปลี่ยนแปลงค่าจุดศูนย์กลางแรงดัน ผลลัพธ์ของงานวิจัยบ่งชี้ว่าการนวดและการบีบรัดสามารถลดความเมื่อยล้าได้จริง อุปกรณ์ที่พัฒนาขึ้นสามารถเพิ่มความสามารถในการยืนเป็นระยะเวลานานได้ อย่างไรก็ตามควรมีการปรับปรุงอุปกรณ์ให้มีขนาดและน้ำหนักที่ลดลงสำหรับงานวิจัยในอนาคต

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Standing is considered one of the most practical working postures since our limbs have the greatest range of motion. Standing yields plenty of benefits, however, prolonged standing could lead not only to discomfort but also to musculoskeletal disorders (MSDs). This study aims to design and develop a device that could help relieve muscle fatigue in the lower leg as the effects of prolonged standing as well as to evaluate the proposed device. The basics of fatigue, the consequences of prolonged standing and walking, and a review of the existing interventions to cope with muscle fatigue are used in designing the proposed wearable device. The main design concept is to increase blood circulation in the lower leg muscles using roller massage and compression methods.

An experiment is conducted on four subjects. The physical fatigue was evaluated through surface Electromyography (sEMG) and postural stability, whereas the psychological fatigue was assessed through a questionnaire survey. Indicators used in this assessment include the time-to-fatigue, the mean power frequency (MNF), and the speed of the center of pressure (CoP). The results of this study confirm the competence of the fatigue alleviating methods: massage and compression. The device can reduce discomfort and increase the capable amount of time in prolonged standing tasks. However, the device should be improved by reducing its weight and size in the future.

Field of Study: Mechanical Engineering		Student's Signature ....
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CHAPTER 1
INTRODUCTION

This chapter describes the background and significance of the study, the objectives, scope, outlines, as well as the expected benefits of this thesis.

1.1 BACKGROUND AND SIGNIFICANCE OF STUDY

Standing is one of the basic postures we act in when staying idle. In this position, our body remains in an upright position, supported by the feet. On the other hand, walking or gait is considerably one of the fundamental movements of humans. In everyday life, we might not notice that we are spending many hours standing and walking around. Additionally, standing and walking may be something that we are familiar with and be able to do without much effort, but actually, they are involved in the control of many muscles and the ability to maintain the body's stability [1].

Standing and walking result in both physical and emotional advantages, not only for the able-bodied but also for patients and elderlies [2, 3]. However, prolonged standing or walking may also cause disadvantages to our body either as short-term problems like discomfort and fatigue or as long-term problems like musculoskeletal diseases (MSDs) or chronic fatigue syndrome (CFS) [4, 5]. There is some research study on the suitable time for prolonged standing or walking [6, 7], though, for those who have to perform prolonged standing and walking in their everyday life or during their duty, this problem could be an inevitable major issue. As a result, over the past decades, there are many studies aimed to improve the understanding of the effect of prolonged standing and walking [1, 8-12]. Not surprisingly, the most concerned topic is muscle fatigue and its effects.

Muscle fatigue, well known as the decrease in the maximal capability to generate force [13], plays an important role in both our daily life and workplaces. Because muscle fatigue causes a loss in strength and in the ability of motor control, which could lead to chances of falling and accidents [5]. There are many solutions developed to deal with this problem, for example, a Walking Assist Exoskeleton (WAE), a sit-standing stool, an anti-fatigue mat, a fatigue monitoring device, and other muscle fatigue relief treatment methods.

Each solution has its strengths and limitations. However, the previous studies showed that the effects of prolonged walking and standing have some relevance. Thus, the design of a fatigue relief device could be optimized to specifically alleviate the fatigue that occurred in prolonged standing and walking. Thereby, this thesis yields two objectives. The first objective is to design and develop a fatigue relief device to alleviate fatigue in the lower leg. The second objective is to evaluate the use of the proposed device.

1.2 OBJECTIVES

The objective of this thesis is first to design and develop a device that could help relieve muscle fatigue in the lower leg as the effects of prolonged standing. The second objective is the evaluation of the proposed device.

1.3 SCOPE

The device and any prototypes developed within this research will be designed for and tested on healthy people. At least three male subjects with similar physical aspects are selected for the device's evaluation. The fatigue assessment of this study consists of a questionnaire survey on mental fatigue, as well as, the muscle fatigue assessment by the surface electromyography (sEMG) signal and postural stability.

1.4 THESIS OUTLINES

This thesis consists of six chapters. The first chapter is the introduction. The next chapter provides the related theories focusing on the anatomy of the human lower extremity and gait analysis. The third chapter describes the literature review of this thesis. The theme of this chapter is the understanding of fatigue, its effects, and the interventions against fatigue. The fourth chapter gives the methodology for the design and development of the device. The evaluation method of the proposed device and the experimental results are shown in the fifth chapter, while the discussion and conclusion are available in the final chapter.

1.5 EXPECTED BENEFITS

This thesis will provide a basic understanding of the human lower extremity anatomy, fatigue, as well as a review of the available interventions to alleviate fatigue, which could be beneficial for those who are interested and for further studies. Besides, the proposed device could be able to help in alleviating fatigue in the lower leg that occurred in prolonged standing, which is considered a significant problem involved by many people.

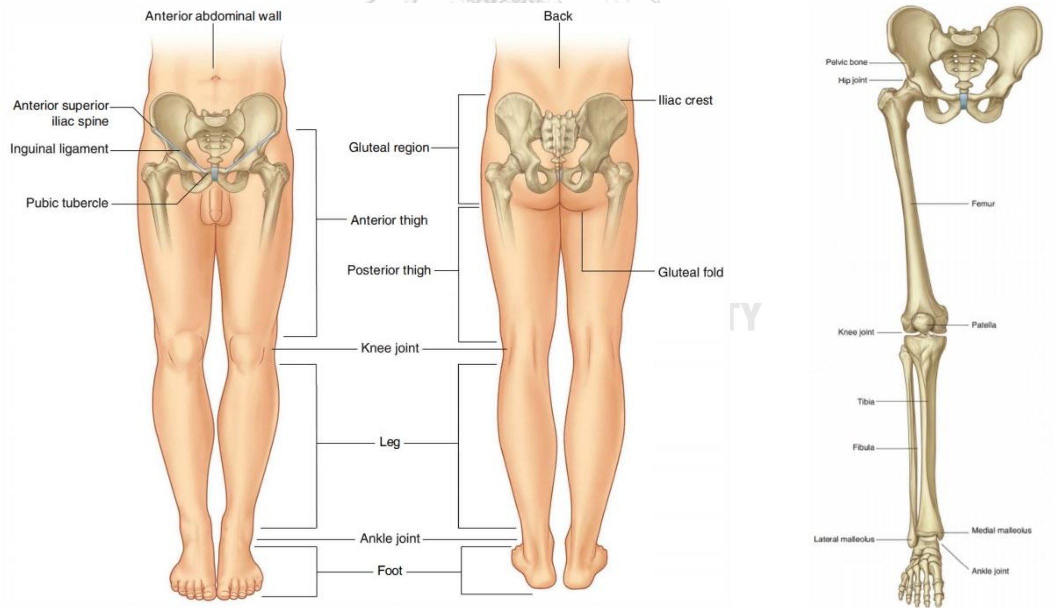
CHAPTER 2

RELATED THEORIES

This chapter presents the background knowledge of this thesis. The first part of the chapter is about the anatomy of the human lower limb. After that, the second part provides the basics of gait analysis. Finally, anthropometry which is essential information in designing the wearable device is also given.

2.1 STRUCTURE AND MOVEMENTS OF HUMAN LOWER EXTREMITY

The human lower extremity, or lower limb, consists of body parts lower than the sacroiliac joint between the sacrum and the ilium, which are the gluteal region, thigh, leg, and foot, as shown in figure 1 (a). The major joints of the lower limb are the hip joint, the knee joint, and the ankle joint. There illustrated in figure 1 (b) are the bones and joints of the lower limb. The hip joint is the joint between the ball head of the femur, the thigh bone, and the socket at the pelvis. Despite being considered one joint at the knee, there are four bones associated with the knee joint, which are the femur, the patella, the tibia, and the fibula. The principal link among them is the link between the femur and the tibia, which has to withstand the weight from the upper body. The fibula is attached to the lateral of the end of the femur. However, the fibula does not involve the movements of the knee joint but the ankle joint instead [14, 15].



(a) (b)

Fig 1 (a) Regions of the lower limb, (b) Bones and joints of the lower limb [14].

Being a ball and socket joint, the hip joint can perform several movements as presented in figure 2. In contrast, the knee joint is only capable of flexion and extension. Meanwhile, movements at the ankle joint, which are quite complex owing to the ankle joint's anatomy, can be defined in figure 3 [15].

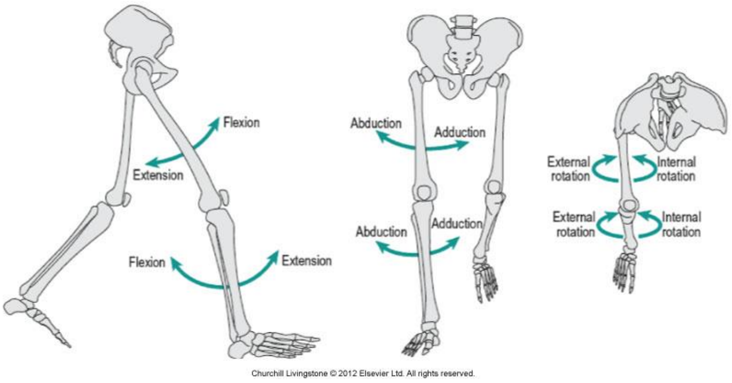


Fig 2 Movements of the hip and knee joint [15].

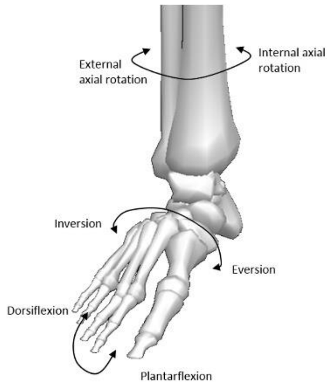


Fig 3 Movements of the ankle joint [16].

The lower limb has two main functions. The first is to support the bodyweight against gravity. Another function is to move the body from place to place. During standing, the vertical axis of the center of gravity will lie a little posterior to the hip joint, and anterior to the knee and ankle joints as demonstrated in figure 4. Besides, with the fully extended knee joint, there exists a locking mechanism that could help in weight-bearing, thus reducing muscular energy used to keep an upright position [14].

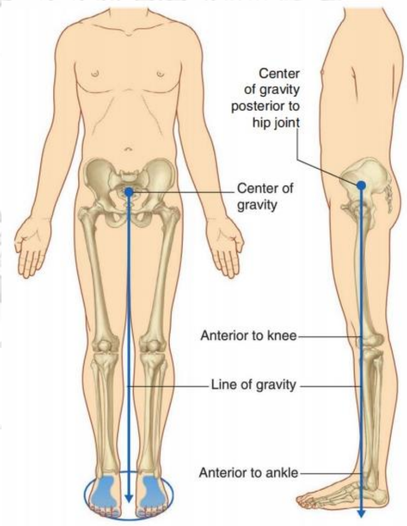


Fig 4 Center and line of gravity when standing [14].

2.2 ANATOMY OF LEG MUSCLES

Human legs consist of many muscles layered up, as illustrated in figure 5. Furthermore, most of them usually have more than one action. It might be easier to study the leg muscle anatomy through groups of muscles, which were categorized by the actions and location of the muscles in each group [14, 15].

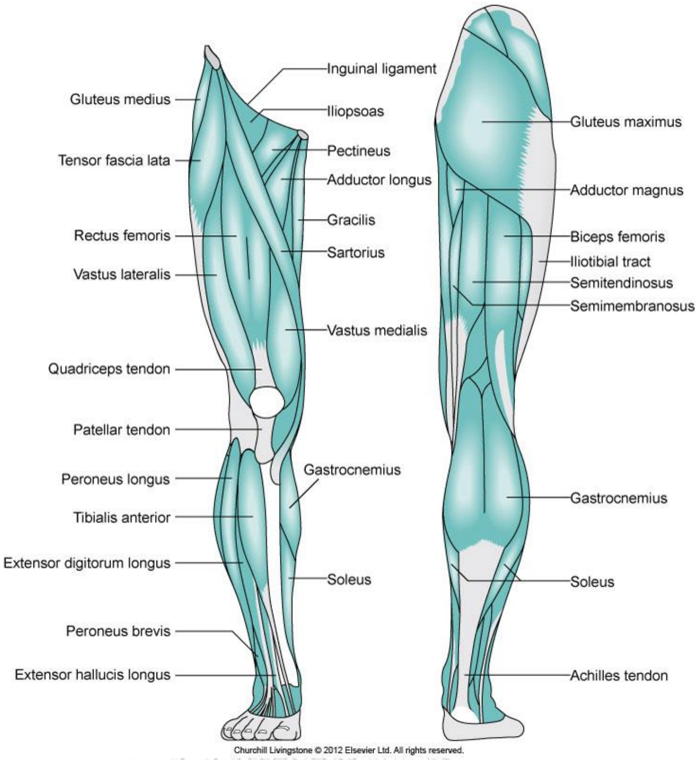


Fig 5 Muscles in the right leg [15].

The first group is the muscles in the gluteal region, whose action is mostly at the hip joint. The Gluteus maximus is the largest superficial muscle in this area. It is responsible for extending the hip. Lying under the gluteus maximus is gluteus medius and gluteus minimus, respectively. Their function is to abduct the hip. Another superficial muscle in this region is tensor fascia lata. This muscle involves hip abduction and internal rotation. Other movements of the hip joint are done by deep muscles around the pelvis, as shown in figure 6 and figure 7 [14, 15].

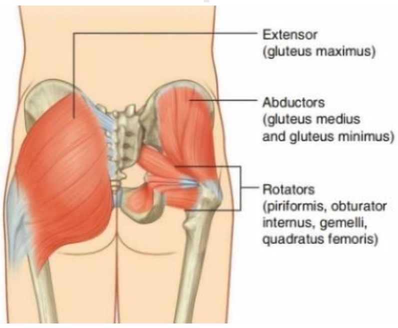


Fig 6 Muscles in the gluteal region [14].

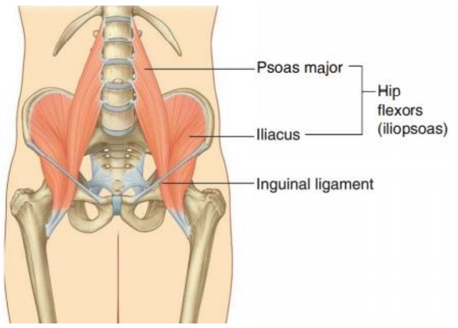


Fig 7 Major hip flexors [14].

There are two muscle groups in the thigh area. The anterior group is the quadriceps muscle, which consists of the vastus medialis, vastus lateralis, and rectus femoris. The function of this muscle group is to extend the knee. The posterior group is the hamstrings muscle. This group includes des biceps femoris, semitendinosus, and semimembranosus. Besides, it is one of the hip extensors and knee flexors [14, 15].

Finally, in the lower leg, there exist two groups of muscles. Firstly, the anterior tibial group. This group contains extensor hallucis longus, extensor digitorum longus, tibial anterior, and peroneus tertius. The action of this group is the dorsiflexion of the ankle with the main effect from the tibialis anterior. The second group is called the triceps surae. It is the group of gastrocnemius and soleus which are capable of plantar flexor the ankle. Moreover, the gastrocnemius is also involved in knee flexion [14, 15].

Table 1 Summary of leg muscles typically selected for muscle activity evaluation.

Muscle	Abbreviation	Location	Actions
Gluteus maximus	GM	The gluteal region	Hip: extension, lateral rotation, abduction
Vastus medialis	VM	Anterior thigh	Knee: extension
Rectus femoris	RF	Anterior thigh	Knee: extension Hip: flexion
Biceps femoris	BF	Posterior thigh	Knee: flexion Hip: extension, lateral rotation
Semitendinosus	ST	Posterior thigh	Knee: flexion Hip: extension, medial rotation
Tibialis anterior	TA	Anterior leg	Ankle: dorsiflexion, inversion
Gastrocnemius	GS, GC	Posterior leg	Ankle: plantarflexion Knee: flexion
Soleus	SOL	Posterior leg	Ankle: plantarflexion

As stated above, there are numerous muscles in the leg. However, for the evaluation of muscle activity, a repetitive cluster of muscles was typically selected, as shown in Table 1 [1, 9, 11]. These muscles are superficial and have the main effect on the movements of the leg, as described in the rightmost column [14].

2.3 GAIT ANALYSIS

Gait analysis is the study focusing on the way we walk. The significant tool of gait analysis is the Gait Cycle (GC). Walking is a repetitive yet symmetric job for each leg. As a result, we may define the gait cycle as the time interval between the movements of one leg that happens in one stride. As shown in figure 8, there are seven events of the leg that occurred cyclically. The initial contact of the right foot is usually picked as the starting point of the gait cycle [15].

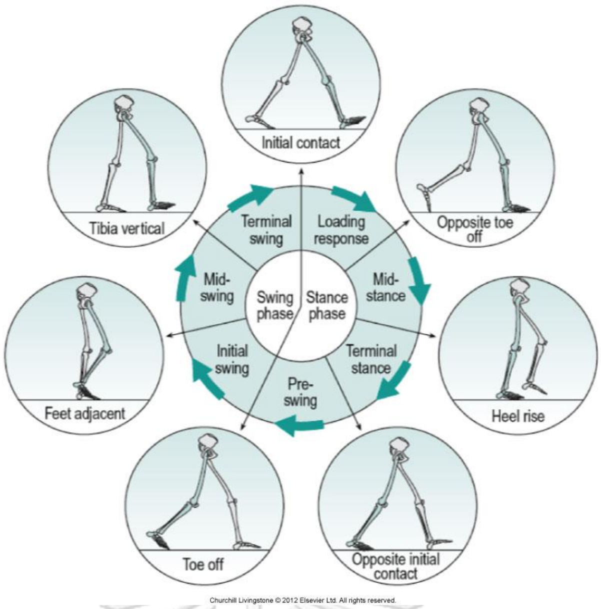


Fig 8 Positions of the legs during one gait cycle [15].

Owing to the seven events, the gait cycle is now divided into seven periods. The four periods between the initial contact and the toe-off will be counted as the stance phase. In this phase, there will be at least one foot that stays in contact with the ground. As a result, this phase is also known as the support phase or contact phase. Thus, the last three periods will be clustered in the swing phase. In the swing phase, the focused leg will be lifted in the air letting the other leg alone support the whole bodyweight. This occasion is known as the single support or the single stance [15].

Table 2 Timing of periods and status of leg support during one gait cycle [17].

Phase	Period	Support	% of GC	Ending Event
Stance Phase	Initial contact	Double	0-2	-
	Loading response		2-12	Opposite toe-off
	Mid-stance	Single	12-31	Heel rise
	Terminal stance	Single	31-50	Opposite initial contact
	Pre-swing	Double	50-62	Toe off
Swing Phase	Initial swing	Single	62-75	Feet adjacent
	Mid-swing	Single	75-87	Tibia vertical
	Terminal swing	Single	87-100	Opposite initial contact

The single support not only occurs in the swing phase but also some parts of the stance phase. During the stance phase, there are two moments that both of the feet touch the floor which creates the double support, or double stance. That moments occur during loading response and the pre-swing period, where one foot is in the initial contact position while the other foot is in the toe-off position. Table 2 presents the timing of each period in the gait cycle and the status of the leg support. The data is obtained from Perry and Burnfield (2014) [17]. Referring to their textbook, they subdivide the stance phase into five periods in order to specifically describe the objective of the leg movements.

2.4 ANTHROPOMETRY

Anthropometry is the study that measures the physical properties of the human body. This information could lead to the proper design of the things we use in everyday life. As a result, improve ergonomics and help to prevent work-related injuries. Moreover, the statistical data of anthropometry could also be useful in designing the wearable device since it represents the mean body dimensions of the focused group of people. In 2008, Klamklay et al. [18] gathered the anthropometric data of Thai university students aged between 18 and 25. They divided the students into two groups. The first group is 100 males and 100 females who live in the south of Thailand. The second group is 50 males and 50 females inhabiting in lower-southern of Thailand. Figure 9 illustrates the measurement of the anthropometric data.

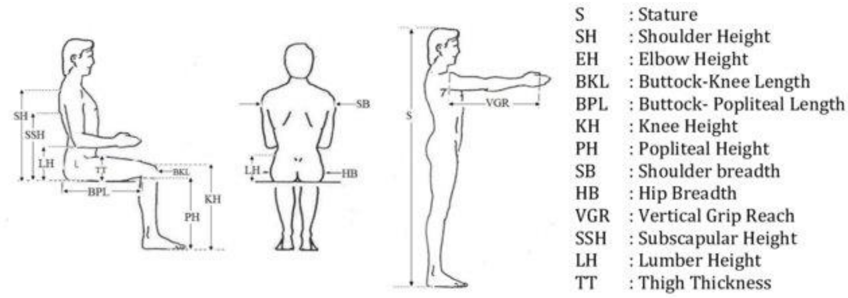


Fig 9 Anthropometric measurement guide [19].

Table 3 Summary of mean values for southern and lower-southern Thai male adults.

Dimension	South (n = 100)	Lower-south (n = 50)	Mean Value weight 2:1 (south:lower-south)
Weight (kg)	61.85	59.65	61.12
Stature (cm)	171.94	169.17	171.02
Buttock-knee length (cm)	58.52	59.08	58.71
Buttock-popliteal length (cm)	48.23	48.59	48.35
Calf circumference (cm)	NA	31.72	31.72
Hip breadth (cm)	34.34	32.68	31.72
Hip height (cm)	84.96	NA	84.96
Knee height (cm)	52.81	NA	52.81
Popliteal height (cm)	43.04	41.77	42.62
Thigh thickness	14.21	NA	14.21

*Data are partly selected from Klamklay et al. (2008) [18].

Table 3 reveals the selected statistics that were related to the design of the lower limb device. However, this study used two independent surveys to compare the data of each group with another two previous experiments. As a result, some dimensions may be unmatched and available only to one group of students. The last column of Table 3 shows the mean value of the data from two student groups. The calculation was done by weighting the data with the number of participants.

CHAPTER 3
LITERATURE REVIEW

This chapter provides the related literature review of this thesis. The first part talks about the background and measurement of fatigue. The second and third parts give a summary of the experiments about prolonged standing and walking. Finally, the last part exposes the review of the existing fatigue-reducing interventions.

3.1 BACKGROUND OF FATIGUE

Fatigue, for humans, may be described as the state that we are tired and cannot do something the way we usually can. It is believed to be one of the body mechanisms preventing us from the excessive loss of metabolic or muscle fibers [5]. Anyway, fatigue is a common problem for every living. Fatigue can be divided into two main categories, which are muscle or physical fatigue and mental or psychological fatigue. Muscle fatigue is well-defined by Vøllestad (1997) as “any exercise-induced reduction in the maximum capacity to generate force or power output” [13]. On the other hand, mental fatigue is usually recognized as a lack of concentration, tiredness, or sleepiness [5]. Fatigue could affect both short-term problems such as discomfort, decrease in strength and the ability to motor control, and long-term problems like musculoskeletal disorders (MSDs) and chronic fatigue syndrome (CFS) [5].

To understand the underlying of muscle fatigue, adequate biochemistry knowledge is required. Displayed in figure 10 is the mechanism of muscle contraction, the cross-bridge cycle, which is explained by the sliding filament theory. From the figure, the biochemistry of calcium ions and ATP play a vital role in muscle contraction and relaxation.

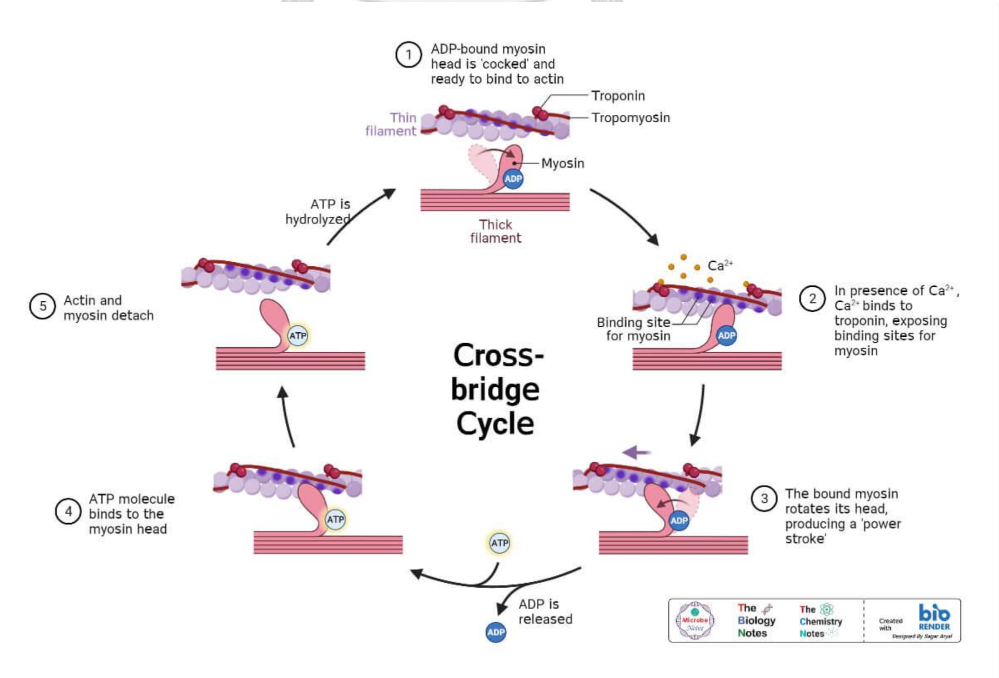


Fig 10 The mechanism of muscle contraction [20].

Muscle fatigue is defined as the inability to maintain a desired power output which results from muscle contraction against a load with a decline in both force and velocity of shortening. A decline in maximal force production with fatigue results from a reduction in the number of active cross-bridges as well as in the force produced per cross-bridge. As fatigue develops, the production of force usually declines earlier and to a greater extent than shortening velocity. Other characteristics of fatigued are lower rates of both force production and relaxation, owing to impaired release and reuptake of Ca^{2+} from the sarcoplasmic reticulum (SR). Therefore, fast movements become difficult or impossible, and athletic performance suffers accordingly. Nevertheless, fatigue may serve an important protective role in allowing contractions at reduced rates and lower forces while preventing extreme changes in cell composition that could cause damage [21].

The cause of muscle fatigue can be classified into central and peripheral components. Central fatigue occurs at the central nervous system (CNS), which decreases the neural drive to the muscle and decreases maximal voluntary activation level. Central fatigue reflects changes in the CNS and may involve altered input from muscle sensory nerve fibers, reduced excitatory input to motor control centers of the brain and spinal cord, and altered excitability of motor neurons. The contributions of these factors vary with the individual and with the nature of the activity. Peripheral fatigue corresponds to all changes at or distal to the neuromuscular junction [22].

There are several factors contributing to fatigue. For example, impaired calcium release from the SR has been identified as a contributor to fatigue in muscle fibers. Decreased oxygen availability to exercising muscle has profound consequences on muscle fatigue. In addition, fatigue can result from the depletion of ATP (adenosine triphosphate). Since muscle fibers require ATP for contraction and relaxation, therefore, the cells must maintain ATP to avoid fatigue. However, recent studies indicate that muscle fatigue is not related to lactate accumulation. Lactate released from muscle enters exclusively oxidative tissues in which lactate is low such as heart and diaphragm; then it is converted back to pyruvate and oxidized. Retained lactate is oxidized to generate the ATP needed to replenish phosphocreatine stores following exercise and to restore normal distribution of Ca^{2+}, Na^{1+}, and K^{1+} [21-23].

Blood flow plays an important role in the maintenance of force output by bringing oxygen necessary for ATP production and remove by-products of metabolic processes in working muscles. Decreased oxygen availability to exercising muscle has profound impacts on muscle fatigue. Enhanced O2 delivery to the exercising muscles directly reduces muscle fatigue and increases muscle efficiency. Thus, O2 is one of the important factors on relieving muscle fatigue while blood flow provides O2 to the working muscles [24].

Understanding the factors affecting muscle fatigue can contribute to development of fatigue relieving equipment. For example, a device which apply pressure and massaging to the target muscle may increase blood flow to provide O_2 to the working muscles. Researchers also suggest that treatment methods such as heat therapy, massage, and nutritional supplements can help with muscle fatigue alleviation [24-28].

3.2 MEASUREMENT OF FATIGUE

For the next step, common measurements of fatigue are presented. Mental fatigue cannot be measured physically. Therefore, most of the studies utilize questionnaire surveys to examine subjective mental fatigue [9, 10, 28]. Besides, some may utilize the body part symptom survey form, or the visual analog scale in their surveys so that it will be clearer. The competence of using questionnaire surveys to investigate mental fatigue can be assured by the research of Ramalingam et al. (2019). Their results show that there is statistically significant accordance among the discomfort rating of 100 respondents during a 2-hr standing test [28].

The previous studies show that there are many methods and indicators for muscle fatigue assessment. The most elementary method is to use the maximum voluntary contraction force (MVC). The MVC is the greatest force that one can perform [13]. This parameter is easy to measure yet directly reflects the definition of muscle fatigue given by Vøllestad (1997) [13]. As a result, the MVC is like the gold standard of fatigue-related experiments and is also used for normalizing the data among experimental participants [29].

The electromyography (EMG) signal is also one of the popular tools for muscle fatigue evaluation. The parameters that point to the amplitude and the value of the signal in the frequency domain can be extracted from the raw EMG signal. We can tell that the muscle is fatigued if the amplitude of the EMG signal increases while the frequency domain parameter decreases [9, 30]. Another muscle fatigue indicator that can be obtained from the EMG signal is called the time-to-fatigue. It is observed by the time when the amplitude of the EMG signal is significantly changed [9, 31]. Examples of the studies that use this parameter are the studies of Halim et al. (2012) and Toro et al. (2019).

Stability is another remarkable index of muscle fatigue assessment, as fatigue reduces the ability of muscle control, subjects tend to change their behavior either to regain their stability or to relieve the occurred muscle fatigue. In standing test, postural stability is usually observed by the recorded center of pressure (CoP) data of the experimental participants [8, 32]. On the other hand, the walking test typically uses parameters such as the coefficient of variation (CV) of the gait cycle and the amplitude of the acceleration for the assessment. The coefficient of variation (CV) of the gait cycle time is the fraction of the standard deviation to the mean of the gait cycle time. This value implies the distribution of the results among the samples. It is found in the previous research that the amplitude of the shock wave from the heel strike is increasing along the time of prolonged treadmill running. Though, the research of Yoshino (2004) shows that the mean amplitude of the acceleration in the vertical direction of the experimenters is decreasing. It could be because the participants were assigned to walk at their preferred speed, so they decided to lessen their pace and avoid intense heel strike. Thereby, the amplitude of the acceleration in the vertical direction may be useful for the experiment with the fixed speed goal. However, the amplitude of acceleration in the other axes is also beneficial in the evaluation of stability [11].

Autonomous nerve activity is another sign indicating muscle fatigue. It can be examined implicitly from heart rate variability (HRV) analysis, in which two main parameters are heart rate (HR) and the ratio of low-frequency power to high-frequency power (LF/HF ratio) [11]. The autonomic nervous system (ANS) is responsible for the involuntary actions of organs. It consists of two nervous systems, which are the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS). The actions of the parasympathetic nervous system lead us to a relaxed state, while the sympathetic nervous system increases alertness and prepares our body for a dangerous situation [14].

LF/HF ratio is the proportion between the nerve activity of the sympathetic nervous system to the nerve activity of the parasympathetic nervous system. Thus, the higher the value of the LF/HF ratio is, the greater muscle fatigue could be implied.

Heart rate (HR) is one of the basic fatigue indicators, which appears in many activity trackers [33]. Heart rate usually increases with exercise intensity. However, a prolonged low intensity can result in a rise in heart rate as well [11].

Tetanic force or muscle twitch force (MTF) is also used to point out muscle fatigue in much research [13, 34]. In addition, there is a suggestion of using the zero-crossing rate (ZCR) and amplitude of muscle tension (AMT) as the criterion for knee rehabilitation monitoring systems as well [35].

3.3 EFFECTS OF PROLONGED STANDING

The effects of prolonged standing can be explored via the research of Halim et al. (2012) [9]. This experiment is run on twenty production workers from a metal stamping company. The objective of this experiment is to examine the psychological fatigue and evaluate the muscle activity of the workers who are prolonged performing the tasks in the standing posture. The experiment lasts for seven hours and 30 minutes a day with a 15-minute break between the morning shift and a 90-minute lunch break, three days in repeat. As a result, the measurement time is a continuous five hours and 45 minutes in total.

The surface electromyography (sEMG) is applied to three muscles, which are the erector spinae (ES), the tibialis anterior (TA), and the gastrocnemius (GS), for both the right and left sides of the body. The participants will answer a questionnaire as shown in figure 11 which is adapted from the body part symptoms survey form and a 0 to 4 Likert scale.

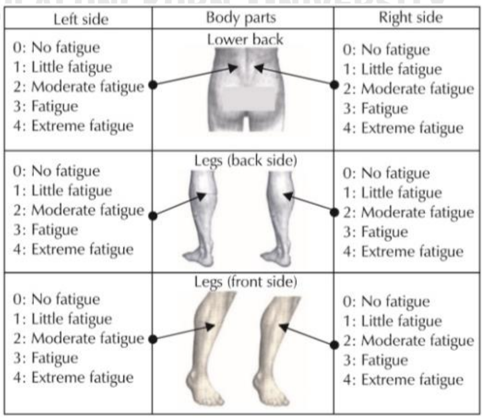


Fig 11 Questionnaire used in the experiment of Halim et al. (2012) [9].

The results show that most of the participants reported fatigue in the gastrocnemius and the tibialis anterior, respectively. However, the erector spinae are stated to be moderate and very fatigued by some workers, but no severe level of fatigue was reported. In addition, figure 12 presents that the trend of the mean power frequency (MPF) average of all muscles is decreasing throughout the experiment except for those of the erector spinae at the beginning of the workday, which can imply an increase level of muscle fatigue through the experiment. However, there is no significant relationship between the results of the psychological fatigue and on muscle fatigue. Another finding of this research is that the time-to-fatigue of the muscle on the right side tends to be shorter than on the left side, as shown in figure 13. Moreover, the quickest time-to-fatigue is found at the right gastrocnemius, with a time around 20 minutes. This research did not mention which the dominant hand of the workers is. However, we may assume that they are right-handed.

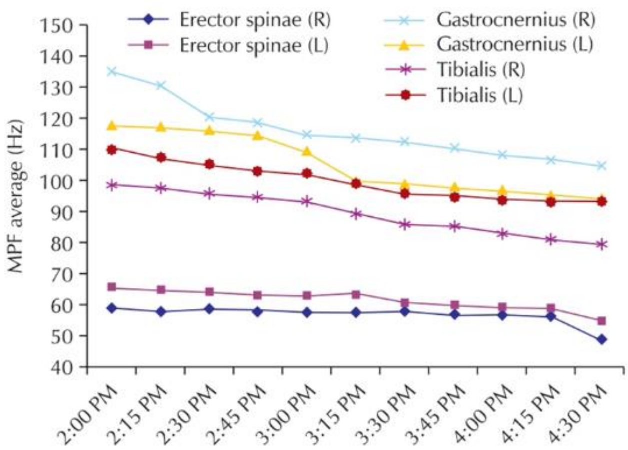


Fig 12 Trend of the MNF average from the study of Halim et al. (2012) [9].

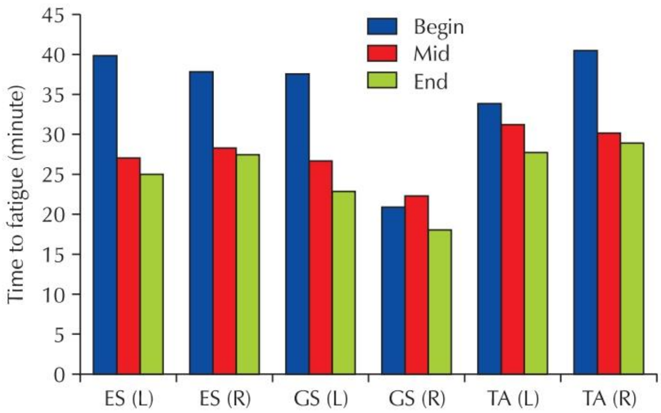


Fig 13 The results of time-to-fatigue from the study of Halim et al. (2012) [9]

3.4 EFFECTS OF PROLONGED WALKING

In 2004, Yoshino et al. [11] conduct an experiment aimed to study the underlying changed gait patterns and physiological rhythms, as the effects of prolonged free walking. Participants of this study include 12 normal men aged between 19 and 26 years old. They are asked to walk on the treadmill at their preferred speed for three hours and report their fatigue level on the 10-point linear scale at every 30 minutes. There is a 15-minute break before and after walking.

In this research, the EMG signal from the tibialis anterior (TA) and the biceps femoris (BF) is collected, as well as the acceleration of the subject's body in three axials. Moreover, the electrocardiogram (ECG) is applied throughout the experiment. The subjects are divided into two groups in the evaluation process. The first group, group A, consists of eight subjects whose mean gait cycle time in the last 90 minutes is longer than those of the first 90 minutes, as shown in figure 14.

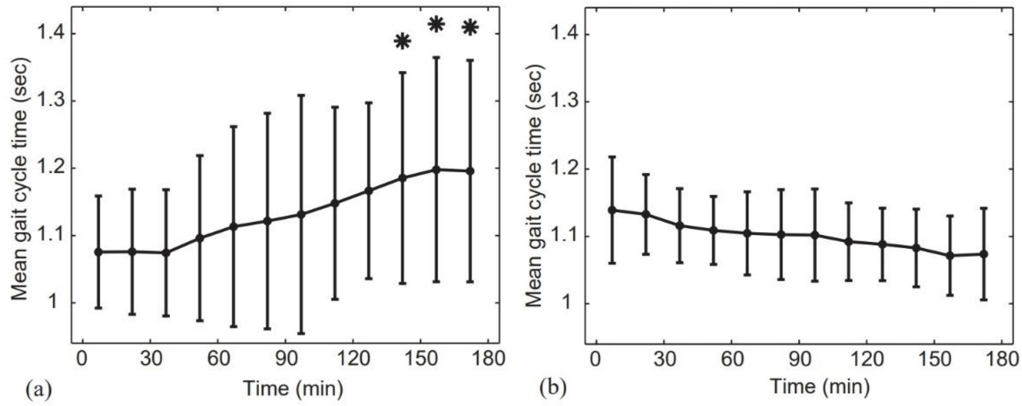


Fig 14 Plots of mean gait cycle time from the study of Yoshino et al. (2004) [11].

It is found that the age of the subject in group A (age 23.12±1.55) is considerably higher than the subjects in the other group (age 20.75±1.25). Group A shows a significant decrease in the MPF of the EMG signal from the TA (as shown tin figure 15), an increase in variations in gait rhythm, and a decline in walking stability, over time. However, group B does not reveal much sign of muscle fatigue. Besides, they tended to walk faster without losing their local dynamic stability.

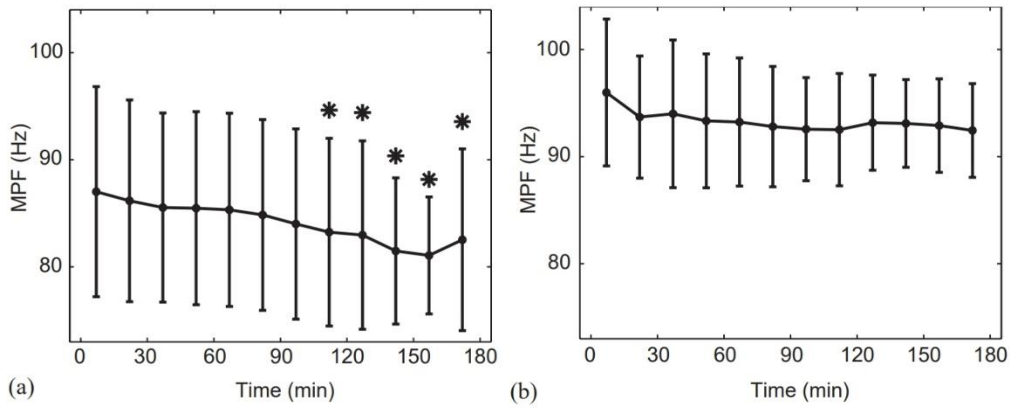


Fig 15 Plots of the MPF of EMG signal from the study of Yoshino et al. (2004) [11].

The results of this experiment indicate that, in prolonged walking, the muscles associated with the movements of the ankle joint tend to be more fatigued compared to the muscles that move the knee joint. Furthermore, tired people do decline their gait speed to enhance their stability.

3.5 INTERVENTIONS TO ALLEVIATE MUSCLE FATIGUE

Fatigue happens to everyone and yields a large effect on its life. As a result, there are many devices created to alleviate problems caused by fatigue. According to the review, we may categorize the devices associated with fatigue into five categories.

3.5.1 WALKING ASSIST EXOSKELETONS

Walking Assist Exoskeleton (WAE) is a wearable device created to enhance people’s walking ability. Until now, the walking assist exoskeleton has been developed in various designs. Some cover up the whole leg, while some focus on assisting one specific part of the leg. However, we can simply classify exoskeletons by their operating system, which consists of an active and passive/quasi-passive system. Shown in figures 16 and 17 are the examples of active and passive WAEs, the HEXAR [36], and the XPED2[37], respectively.

Fig 16 The active assistive exoskeleton HEXAR [36].

Fig 17 The passive walking assist exoskeleton XPED2 [37].

Even though the usual objective of the WAE is to aid the user in walking, some models could help in standing as well. Figures 18 and 19 show examples of the active and passive WAE that could perform the bodyweight support during standing.

Fig 18 The walking assist device with a bodyweight support system [38].

Fig 19 Design of the lower-extremity exoskeleton (LEE) [39].

3.5.2 ANTI-FATIGUE MATS

Standing is considered one of the most practical working positions since our arms have the largest range of motion, and some jobs require frequent moves between the nearby workstations [9]. However, as prolonged standing could lead to many hardships, anti-fatigue mats and cushioned shoe insoles are widely used. They are usually used together with a standing desk to improve ergonomics and encourage movement change. The previous study claims that the underlying purpose of these devices is to promote bodyweight distribution which can decrease strain in the musculoskeletal system and enhance blood flow in the feet [40]. Examples of the famous commercial anti-fatigue mats are shown in figures 20 and 21.

Fig *20 The ergonomic mat Topo [41].*

Fig 21 The ergonomic mat by Imprint Mats [42].

3.5.3 SIT-STANDING STOOLS

Sit-standing stools may also be helpful for those who have to perform tasks in the static standing position. The use of the sit-standing stool is to lessen the load on the user's legs by transferring some of the bodyweight to the ground. Their other functions are to encourage the postural change of the user and postural improvement. Figure 22 illustrates one of the experiments on the sit-standing stools. According to the experiment, sit-standing posture is reported able to reduce discomfort in the lower leg and improve blood circulation in the foot compared to standing posture [43]. Similar to the experiment of Antle et al. (2015), the passive lower-limb exoskeleton in figure 23 is evaluated in the research of Luger et al. (2019) [44]. The result of this study shows that the exoskeleton can decrease muscle activity in the calf muscle compared to the standing case. However, the activity of the thigh muscle is found to be a bit higher. Moreover, most of the participants also frequently stated discomfort in their buttock, the upper back/shoulder, and lower back, respectively.

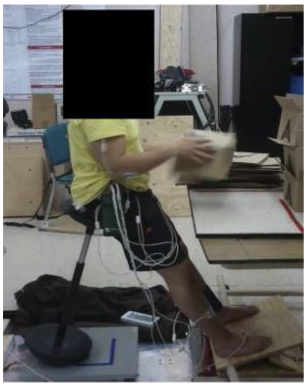


Fig 22 The experiment of Antle et al. (2015) [43].

Fig 23 The Chairless Chair used in the experiment of Luger et al. (2019) [44].

As seen in figure 19, most of the sit-standing stools are not fully portable since they are designed to be used in a specific place like an office or a factory. However, some commercial products are developed so that we can use them in everyday life. Shown in figures 24 and 25 are the LEX [45] and the SITPACK [46]. The LEX [45] is a wearable chair developed by Astride Bionix. It works similarly to the Chairless Chair [44], but it has a folding mechanism that makes it possible to be worn and carried around. The SITPACK [46] is a portable chair that utilizes the telescoping mechanism in its design. As a result, when it was folded, the size of the product was as small as a 50cl can.

Fig 24 The wearable chair LEX. [45].

Fig 25 The foldable chair SITPACK [46].

To sum it up, sit-standing stools seem to succeed in reducing muscle fatigue in the lower limb in prolonged standing. Nevertheless, this device also has limitations since it requires sufficient space and the ability to stabilize the device. Furthermore, cause discomfort to the other parts of the body due to compression at the contact between the user's body and the device.

3.5.4 FATIGUE MONITORING DEVICES

Another promising fatigue-related device is a fatigue monitoring device. It was developed mostly for drivers; whose work requires long-time concentration [47]. In an alternative field, fatigue monitoring devices were used to evaluate the worker’s conditions, both before and during work, to avoid injuries or accidents that might happen due to overuse of the fatigued muscles [33, 48]. To monitor fatigue, sEMG was usually embedded onto the elastic component type of garment. For example, the shirt and the leggings shown in figures 26 and 27, correspondingly.

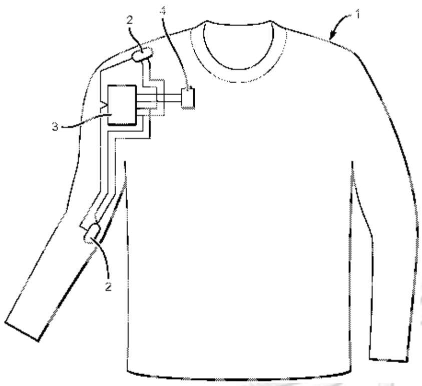


Fig 26 The patented embroidered garment for fatigue monitoring [49].

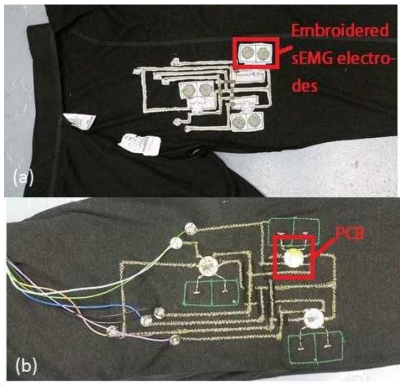


Fig 27 The (a) interior and (b) exterior of the sensor-embroidered leggings [50].

3.5.5 TREATMENT METHODS

Four methods are found to reduce muscle fatigue. The first method is to apply the electricity directly to the user’s body. Two types of electrical treatments yield each different objective. Electrical Muscle Stimulation (EMS) is a treatment used to build muscle and increase muscle strength [21, 51]. The other treatment, electrotherapy, is used to attenuate muscle pain, especially for patients who suffer from chronic pain conditions.

The second method is to use vibration or massage on the fatigued muscles. Massagers are divided into electrical and non-electrical types. A non-electrical massager is usually a tool used together with a manual hand massage [27, 52]. On the other hand, an electrical massager mostly utilizes low-frequency vibration, which is proved to help in reducing muscle fatigue [28, 53]. Some electrical massagers also come up with a mechanism that provides the user with a similar experience as the manual hand massage [54].

The third method is to apply heat to the muscles. This method typically appears with another approach, for example, vibration [55, 56]. Heat therapy is reported to help in increasing blood flow, as well as decreasing discomfort and muscle fatigue [25]. It also promotes the recovery of the muscle [26]. However, Pereira et al. (2011) also state that heat also has a significant effect on lowering muscle strength. Therefore, applying heat therapy to those who are working may not be feasible due to safety reasons.

The last method is to use the compression sleeve or stocking. This technique is often used in sports and medication. The research of Miyamoto et al. (2011) [57] and Wang, Xia, and Fu (2016) [58] reveal that compression has benefits in relieving muscle fatigue and enhancing muscle endurance in long-term exercise without decreasing the MVC torque.

CHAPTER 4
METHODOLOGY OF DESIGN AND DEVELOPMENT

This chapter explains the details of the design and development of the proposed device. The first part is the conceptual design of the device. After that, the development of the device then written in the second part of this chapter.

4.1 CONCEPTUAL DESIGN

Each of the fatigue-reducing interventions and treatment methods has its strengths and limitations. Among them, walking assist exoskeletons and sit-standing tools have the same principle, which is to reduce the bodyweight of the user by partly transferring it to the ground. To achieve this goal, the devices have to own the structural components that link the center of gravity of the user's body to the ground. As a result, most of them have to provide the user with a seat. However, reducing the bodyweight of the user is just one approach to alleviate muscle fatigue in the legs. Additionally, the previous studies show that, in prolonged walking or standing, muscle fatigue mostly and easily occurred in the lower leg [9, 11]. Thus, it could be more reasonable to create a device focusing on the lower leg region.

Anti-fatigue mats contribute to bodyweight support, which promotes blood circulation in the feet and reduces musculoskeletal strain [40]. But, according to the abundant possibility of material choices and shape designs, it could be better to conduct systematic research focusing on the mat's specification on the next occasion.

Monitoring devices are developed to enhance the user's awareness so that they can avoid the overuse of the muscles, which could lead to accidents. The idea of the monitoring devices could be useful for safety purposes or to use as a trigger for a device's mechanism.

Fatigue relief treatment methods are various in designs and approaches. We may classify them into four categories. First are the electrical treatments, which are delicate and require specialized knowledge and care. As a result, it might not be appropriate to utilize electrical treatment in the design. The second approach is to use vibration or massage. This method is widely used since ancient times and is reported to help in both fatigue relief and muscle recovery [27, 28]. The third approach is to apply heat to the fatigued muscles. This method works well in relieving muscle fatigue and recovering, but it is also reported to decrease muscular strength [25]. Thus, it may not be suitable to apply heat to those who are working. The last approach is to implement the external compression onto the muscle. This tool has been used broadly both in sport and medication [57, 58].

Therefore, the device developed in this thesis will focus on using either compression or massage treatment method to alleviate fatigue. In addition, the target area is the lower leg according to the relevance between the effects of prolonged standing and prolonged walking, which reveals that the easiest muscle to feel fatigued is located in the lower leg.

4.2 DESIGN DEVELOPMENT

The prototype for preliminarily test is designed to apply compression onto the calf using an elastic bandage. The idea of this prototype is to create a device similar to a compression sleeve, however, the pressure of the sleeve could be adjusted to match the wearer’s preference or massage patterns. As displayed in figure 28, a spool mechanism is attached to a shin guard (deep blue part) and is connected to a flexible shaft, and a DC motor, respectively. The flexible shaft is utilized in order to transfer rotation and torque from the DC motor to the spool, and so that the motor and power supply unit can be placed away from the wearer’s leg. The yellow, red, and green colored parts are made of PLA plastic by a 3D printer. After a few trials, it turns out that the flexible shaft cannot successfully transfer torque to the spool. The flexible shaft is tangled up and its end cannot maintain its shape, as shown in figure 29.

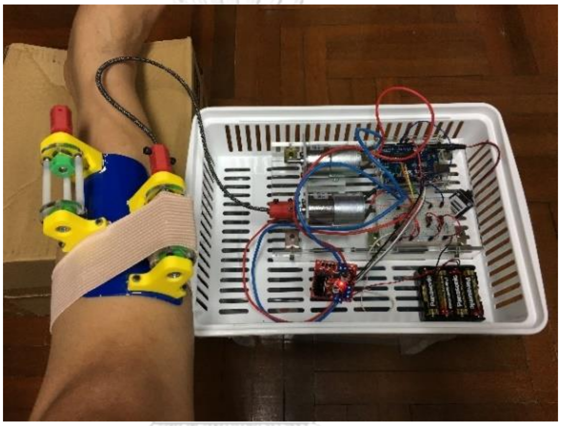


Fig 28 The prototype for preliminarily test.

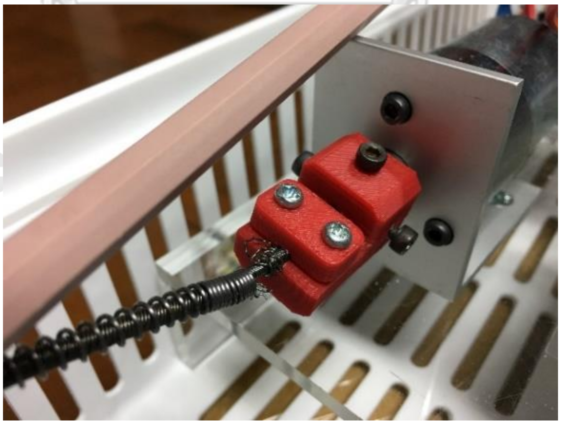


Fig 29 The connection between the flexible shaft and the DC motor shaft.

It is learned from this prototype that the structure of the device should be more stable. Consequently, a new method providing compression is searched for the subsequent design. A pressure cuff from a blood pressure monitor is selected because it requires less component to drive and is easier to create a system to retain the compression pressure. Moreover, a roller massage system is also added in the design. This system is similar to a roller massager frequently used in sports.

The device, therefore, consists of two working systems. The first system is to offer massage treatment, and the second system is to provide compression around the target area. As presented in figure 30, the main components of this system are the set of massage rollers (light blue parts), massage unit shafts, and leadscrews. Attached between two massage unit shafts are four tension springs that keep the massage rollers pressing on the calf of the wearer. The specification of the tension spring is available in Appendix A. According to the design calculation, the roller set could produce up to 17.45 N of the pressing force at the middle of each roller when the rollers reach the maximum angle. The pressing force can be adjusted to meet the wearer's satisfaction by changing, adding, or removing the tension springs. The translation in the vertical axis is provided by leadscrews, which are driven by a timing belt, pulleys, and a DC motor. The yellow arrow demonstrates the motion of the roller massage unit. The roller set can go up and down within 10 cm in length. According to the present DC motor's specification, the roller massage unit can move at a speed of 0.1 meters per minute. Moreover, a limit switch is installed to control the vertical position of the massage roller unit.

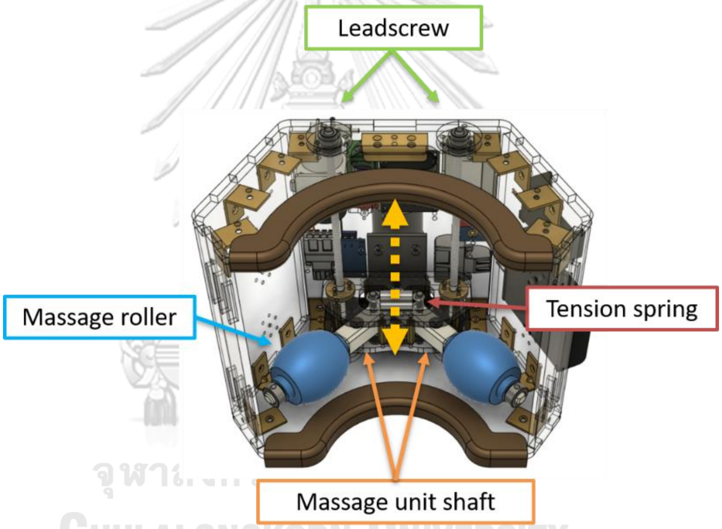


Fig 30 CAD model of the proposed device.

The components of the compression system are adapted from a blood pressure monitor. As shown in figures 31 and 32, the pressure cuff is controlled by a pressure sensor to provide 25 mmHg pressure around the target area. This value comes from the specification of the compression stocking used in the experiment of Miyamoto et al. (2011) [57]. The actuators used in this system are an air pump and a solenoid valve, which are both connected to a 2-channel relay.

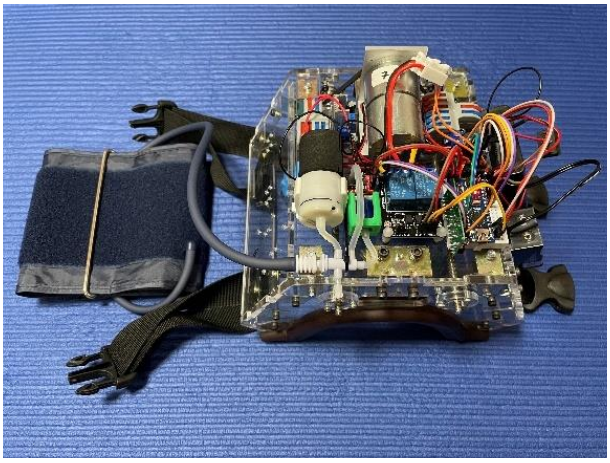


Fig 31 The proposed device.

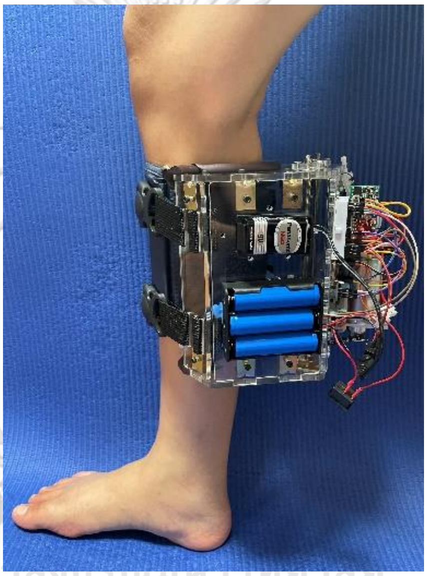


Fig 32 The device attached to the right leg (side view).

The body of the prototype is made of a 5-mm acrylic sheet to provide strength and is designed to be closed-shape to refrain the user from any unsafe interaction with the mechanical parts. Furthermore, the device is installed with adjustable straps and cushioning foam at the contacts between the device and the user's leg to offer comfort and prevent slip. Batteries and electronic parts, as well as actuators are mounted on the acrylic case. As a result, the device does not require any external power supply. The electronic parts are controlled by a microcontroller board, Arduino Nano. A radio frequency (RF) remote controller is used to start the massage and compression function. The wiring diagram of the electronic parts is displayed in figure 33, while the programming code is accessible in Appendix B.

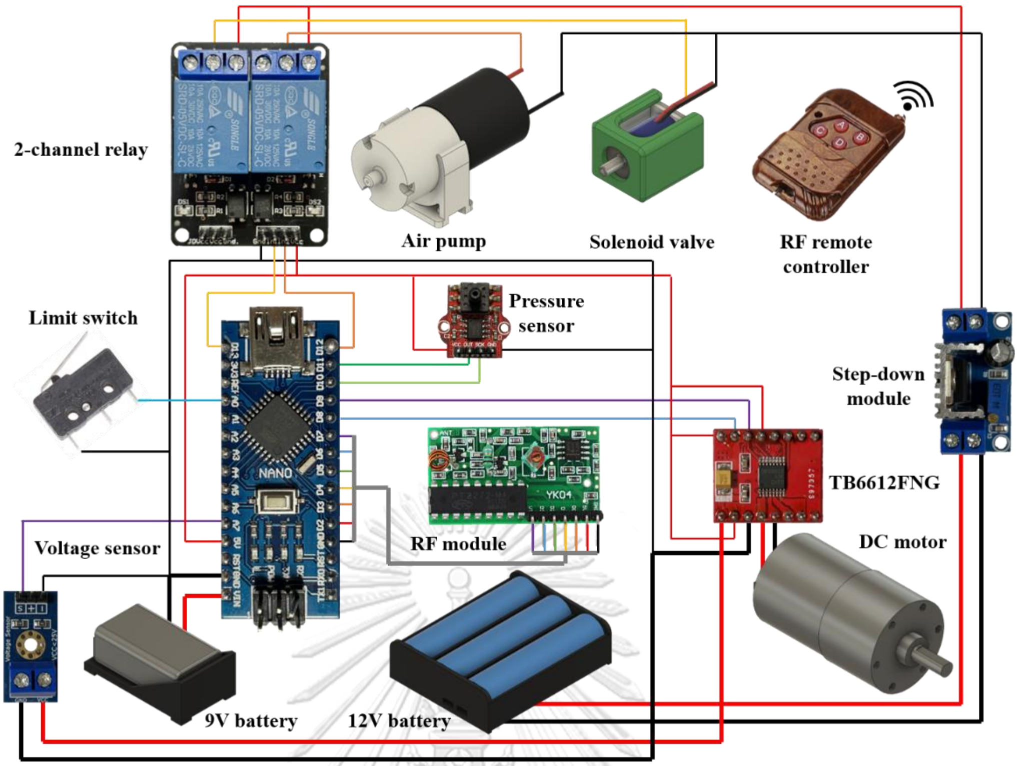


Fig 33 Wiring diagram of the device.
*Photo source: limit switch [59], RF module and RF remote controller [60].

Table 4 The weight of each component group of the second prototype.

Component group	Weight (g)	Weight percentage
Acrylic	600	30.0%
Actuator	327	16.4%
Battery	174	8.7%
Electronic parts	89	4.5%
Mechanical parts	808	40.4%
Total weight	1998	

The device succeeds in providing massage and compression as designed. The total weight of the device is around two kilograms. The weight proportion of each component group is presented in table 4. In addition, the weight and quantity of every component can be found in Appendix A. For this design, the heaviest component group is the mechanical parts. Among them, the massage unit shafts weigh about 30.7% (124 g per piece), which is quite heavy. This results from the usage of stainless steel as material due to an excessive allowance of design strength. The drawing of the massage unit shaft is shown in Appendix A as well.

CHAPTER 5
EXPERIMENTAL RESULTS

This chapter describes the experiment conducted to evaluate the device and its results. This chapter contains three parts. The first part is the details of the participants and the scenario of the experiment. Providing in the second part is the equipment used in this study. The third part of this chapter explains the analysis process of the data. Finally, written in the last part are the experimental results.

5.1 EXPERIMENT SETUP

According to the device's objective, to alleviate muscle fatigue in the lower leg caused by prolonged standing, an experiment to evaluate the device is conducted. The experiment is designed to imitate an actual prolonged standing task. As a result, a 2-hr standing trial with a light typing task is selected. Four healthy men participate in the experiment. All of them are right-handed. Their characteristics are listed in table 5, including age, weight, height, BMI value, and duration of active activity per week. The experiment begins in the morning, before their work and workout routine. The participant does not show any MSD symptoms before the test trial. Moreover, there is a 20-min sitting break before the experiment.

Table 5 Characteristics of the experimental participants.

Characteristics	Average value (n=4)	Standard deviation
Age (years old)	23.50	1.73
Weight (kg)	60.75	9.95
Height (cm)	167.00	1.83
BMI	21.75	3.26
Active activity (min/week)	197.50	272.08

Displayed in figure 34 is the scene of the experiment. The workstation setting comprises an adjustable height standing desk and a laptop. The participants have to perform a static standing task and complete light typing work while standing barefoot on a force platform. The EMG sensors are attached to the participant's both legs in order to collect the EMG signal from the gastrocnemius (GS) muscle. They are asked to maintain equal weight on both feet as much as possible throughout the experiment. However, some minor movements are still allowed to prevent excessive pain.

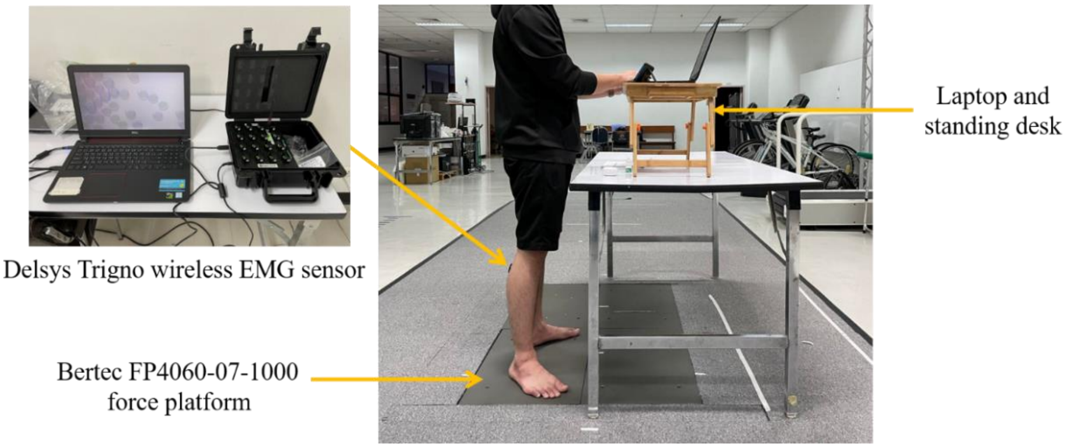


Fig 34 The experiment scenario (side view).

Table 6 Experimental timeline.

Experiment time	Left leg	Right leg
0-50 min	Standing without intervention	Standing without intervention
50-52 min		*Device installation (2 min)
52-68 min		*Treatment session (16 min)
68-70 min		*Device removal (2 min)
70-120 min		Standing without intervention

*Periods when data is collected from the force platform only (without EMG data)

Table 6 shows the timeline of the experiment. The participants have to perform a 120-min standing task. The device will be attached to the participant's right leg after the experiment has been started for 50 min. The treatment session includes 2 sets of 4-min roller massage and 4-min compression. After the intervention, the device is then removed from the participant's leg. The center of pressure (CoP) data from the force platform is collected through the experiment. However, the EMG sensor cannot be recorded as the device is installed. As a result, the EMG data of the right leg during the experiment time 50 to 70 min is not available. Figure 35 illustrates the experiment scene during that period.

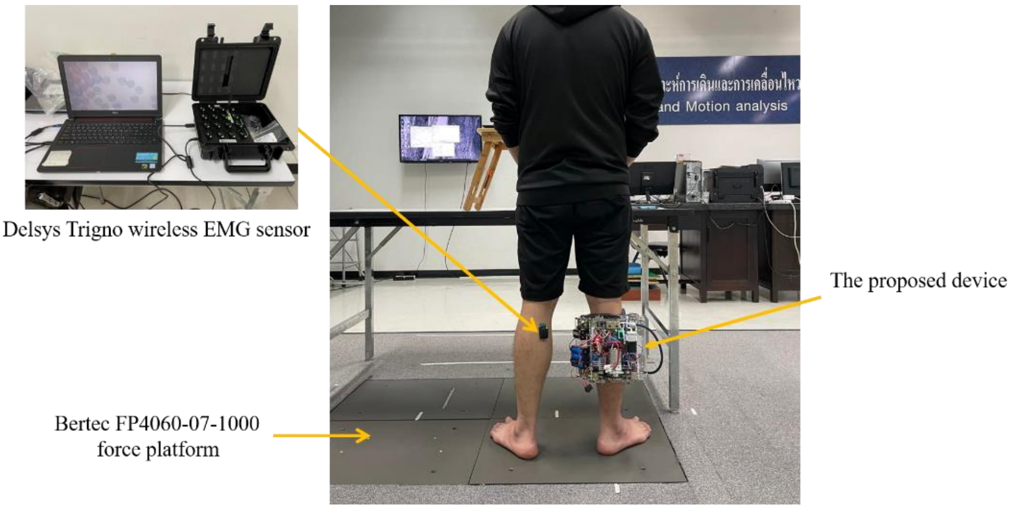


Fig 35 The experiment scene when the device is installed.

5.2 EQUIPMENT

In this study, both mental and muscle fatigue are observed. To examine subjective mental fatigue, all participants are asked to rate their perceived discomfort on both legs in the questionnaire every 10 minutes throughout a 2-hr standing test. The questionnaire survey consists of a rating scale for 8 body parts, namely left and right thigh, knee, calf, and foot, to help the subjects to easier identify the level of discomfort in each region. The discomfort score ranges from 0 (*nothing*) to 10 (*extremely strong*) according to Borg's CR-10 scale. Figure 36 demonstrates the questionnaire survey used during the test trial.

Left		Nothing at all		Extremely weak		Very weak		Weak		Moderate		Strong		Very strong			Extremely strong
(thigh/knee/calf/foot)		0	0.3	0.5	0.7	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10
	10																
	20																
	30																
	40																
	50																
Time (min)	60																
	70																
	80																
	90																
	100																
	110																
	120																

Fig 36 The questionnaire survey on mental fatigue (left leg).

EMG data and CoP data are used in the muscle fatigue assessment. The tools used in data collection consist of the Delsys Trigno wireless EMG sensor and the Bertec FP4060-07-1000 force platform. Their specification is shown in table 7 and 8, respectively. These sensors are available at the Excellent Center for Gait and Motion, faculty of medication, Chulalongkorn University. In this experiment, both data are recorded at a 1000 Hz sampling rate.

Table 7 Technical specification of the Delsys Trigno wireless EMG sensor.

Specification	Value
Dimension	27*37*13 mm
Weight	14 g
Inter-electrode spacing	10 mm
EMG bandwidth	10-850 or 20-450 Hz
Contact material	99.9% silver
Sensor resolution	16 bits
EMG baseline noise	50 nV
Operating range	40 m in RF mode
Wireless protocol	2.400-2.483 GHz ISM Band, Proprietary RF Protocol or BLE V4.2

*Data from the Delsys Incorporated website [61].

Table 8 Technical specification of the Bertec FP4060-07-1000 force platform.

Specification	Value
Dimension	400*600*75 mm
Mass	38 kg
Sampling frequency	1000 Hz
Max load (Fx, Fy, Fz)	5000, 5000, 2500 N
Natural frequency (Fx, Fy, Fz)	300, 300, 450 Hz
Static resolution (Fz)	±0.4 N
Resolution (Fz)	0.2 N per least significant bit
Linearity	0.2 % full scale output

*Data from the product datasheet [62].

5.3 ANALYSIS METHOD

Muscle fatigue is assessed based on the EMG signal and postural stability. Indicators used in this assessment include the time-to-fatigue, the mean power frequency (MNF), and the CoP speed. The data are processed using MATLAB software. The raw EMG data have to go through the following procedure.

1. Applying a filter to remove signal offset and noises. A second order 40-400 Hz bandpass Butterworth filter is selected referring to the previous study [29].
2. Compute the root mean square (RMS) of the signal to rectify and make the signal smoother. The formula of the RMS is

$$RMS = \sqrt{\frac{1}{n}\sum_i x_i^2} \tag{1}$$

when N is the number of samples and x_i is the value of the signal in the i sample.

3. Calculate the root mean square error (RMSE) of the signal in order to indicate significant changes in the signal. The value of the RMSE is

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \hat{x}_i)^2}{N}} \tag{2}$$

when N is the number of samples, x_i is the value of the signal in the i sample, and $\hat{x}_i$ is the average value of the overall signal.

Figure 37 displays the process to find the time-to-fatigue. The RMS of the EMG signal is plotted with the blue line, while the red line is the RMSE value. The earliest point when the RMS of the EMG signal surpasses the RMSE value indicates the time-to-fatigue of that subject in that time section.

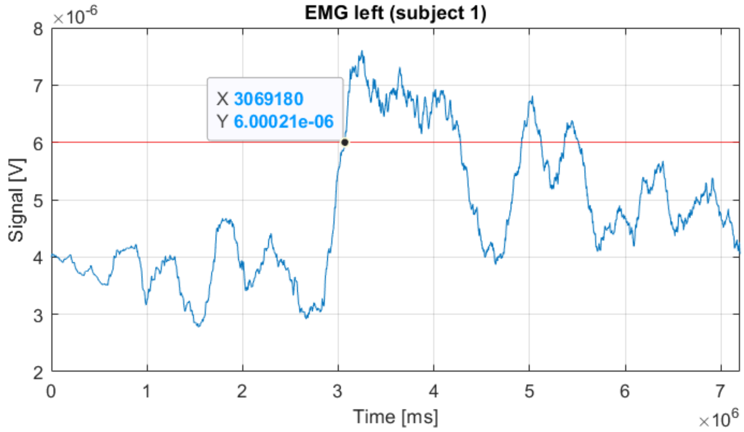


Fig 37 Process to find the value of the time-to-fatigue.

4. Cut the filtered signal into sectioned data and transfer them into the frequency domain by using the fast Fourier transform (FFT).
5. Compute the MNF in each section. The formula of the MNF is

$$MNF = \frac{\sum_{j=1}^{M} f_j P_j}{\sum_{j=1}^{M} P_j} \tag{3}$$

when f is the frequency value of the EMG power spectrum in frequency interval j, P_j is the EMG power spectrum in frequency interval j, and M is the length of the frequency interval.

A force platform is used to record the CoP trajectory of the subjects. The previous research suggest that subjects tend to change their behavior as they feel tired [1] and the CoP speed of the fatigued subject group is significantly higher than the non-fatigue subject group [8]. As a result, the CoP speed in the anterior-posterior (A/P) and the medial-lateral (M/L) direction are chosen as the indicators for changes in postural stability.

5.4 RESULTS

The experimental results consist of three parts. Firstly, the results on mental fatigue obtained by the questionnaire survey are presented. The second part provides the results on muscle fatigue assessed by the EMG signal data. Finally, the muscle fatigue results based on the postural stability are described.

The trends of average discomfort scores among participants are shown in figure 38. The vertical axis is the discomfort score rating scale between zero to 10. The horizontal axis is the experiment time in minutes. The trend of the score of the right leg before the intervention, the right leg after the intervention, and the left leg is presented in the blue, orange, and gray colored lines, respectively.

The score in every region on both legs is reported similarly in the first half of the experiment. In the second half of the experiment (after an intervention on the right leg), the trend of the right leg's discomfort score is notably lower than those of the left leg in every region, except for the foot region. Moreover, the maximum rating score is found in the feet area at a score of around nine out of 10, while the other region's maximum score is around six out of 10. There is also a one scale decrease in discomfort level after the treatment session in the right calf which cannot be found in the other regions.

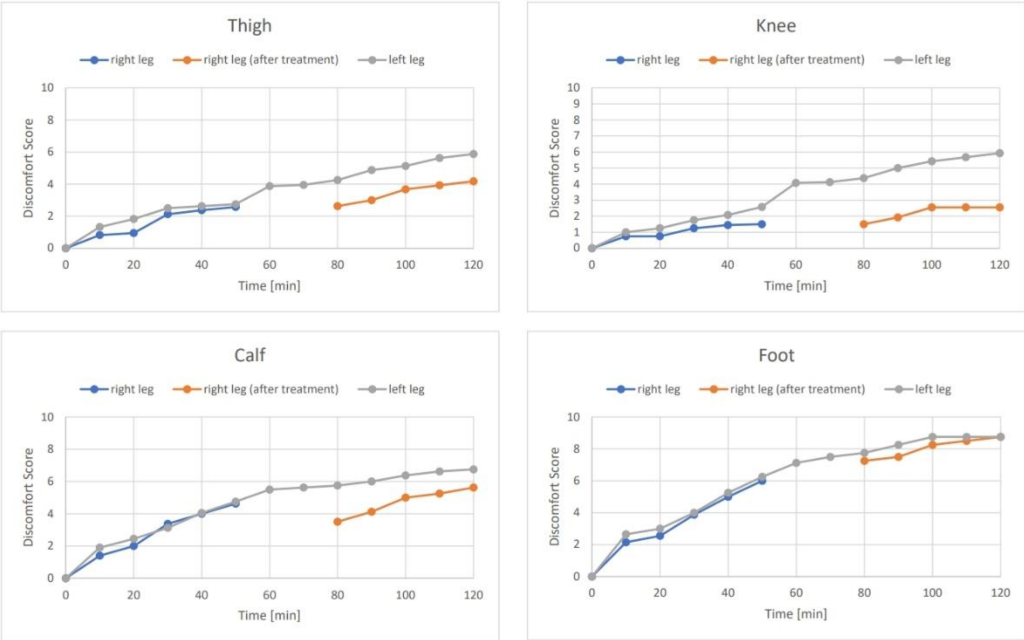


Fig 38 Average discomfort score of each leg region.

The results from the EMG signal compose of time-to-fatigue and the trend of the MNF. Time-to-fatigue, which is the earliest time that the EMG signal changes significantly, can be recognized by the RMSE value of the signal. Shown in table 9 is the time-to-fatigue of each participant and the average value, as well as the standard deviation of the time-to-fatigue. According to the table, the fastest average time-to-fatigue is 17.42 min and is found in the right leg before the intervention. After the treatment, the average time-to-fatigue in the right leg is increased to 29.17 min. The longest average time-to-fatigue is found in the left leg.

It can be noticed that the pattern of the time-to-fatigue of subjects 2 and 4 are quite similar, as the time-to-fatigue in the left leg is comparable to in the right leg before the treatment session. However, their time-to-fatigue in the right leg is increased after the intervention.

Table 9 Average time-to-fatigue among participants.

Subject	Left leg [min]	Right leg (before treatment) [min]	Right leg (after treatment) [min]
1	51.15	N/A	32.86
2	31.21	29.61	40.72
3	31.83	11.88	11.12
4	10.69	10.76	31.97
Average	31.22	17.42	29.17
SD	16.52	10.57	12.66

Figure 39 displays the plot of the average MNF of all experimental participants. The trend of the MNF of the right leg before the intervention, the right leg after the intervention, and the left leg is presented in the blue, orange, and gray colored lines, respectively. The trend of the average MNF increase until the middle of the experiment. After that, the trend of the MNF begin to decrease slightly.

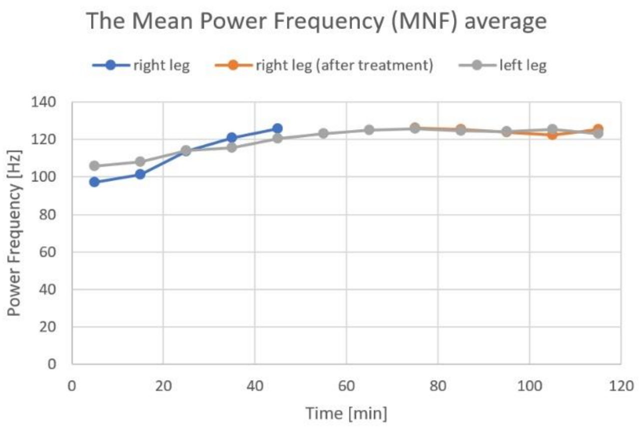


Fig 39 The trend of the MNF of the experimental participants.

Changes in postural stability can be examined from the results of the CoP data. The trajectory of each experimental participant is divided and plotted into five experiment time sections, in order to study the growth in the CoP trajectory area over time. The CoP trajectory of each experimental subject in five time-section is plotted in Figures 40 to 43, respectively from subject 1 to subject 4.

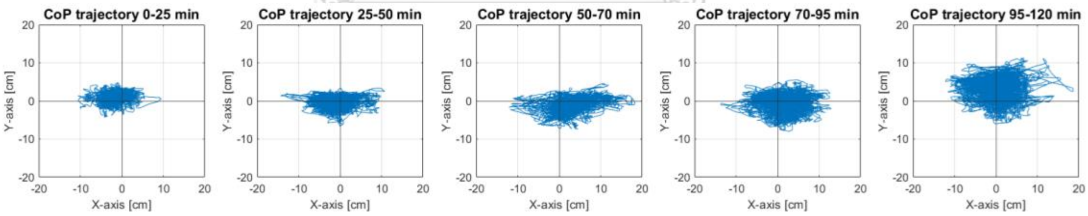


Fig 40 The CoP trajectory in each time section of the first participant.

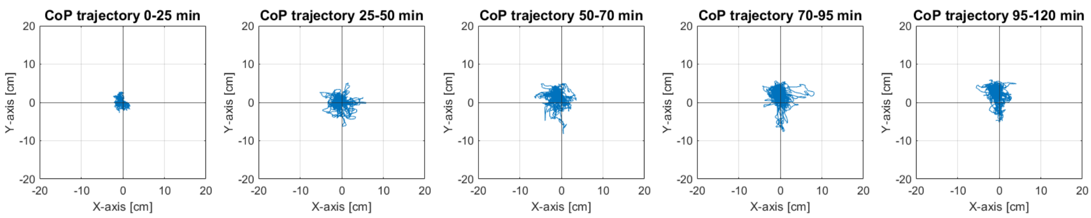


Fig 41 The CoP trajectory in each time section of the second participant.

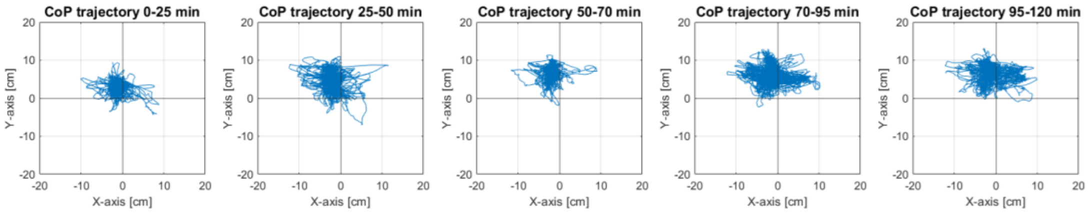


Fig 42 The CoP trajectory in each time section of the third participant.

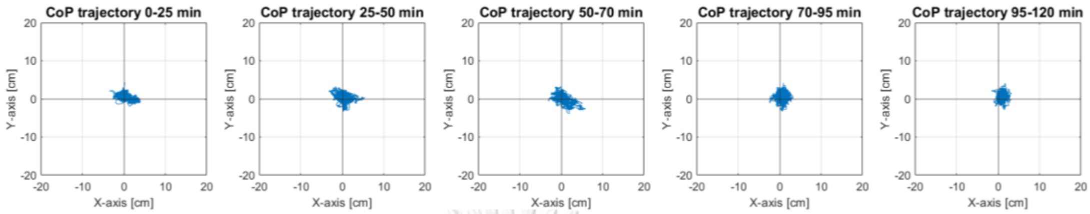


Fig 43 The CoP trajectory in each time section of the fourth participant.

The plots indicate that subjects tend to move their CoP to a larger area as the experiment time increases. Remarkable changes in the CoP area growth can be found in subjects 1 and 2 between the first and the second time section and in subject 1 between the fourth and the last time section. The area of the CoP trajectory decreases in the results of subject three between the second and the third time section.

Among the participants, subject 1 has the largest area of the CoP trajectory, which means that he tends to sway in the broader magnitude compared to others. On the other hand, subject 4 does not show much change in the CoP trajectory area. Another finding is that the participants have a tendency to lean forward compared to their starting point, especially subjects 2 and 3.

Another result that can be obtained from the CoP data is the speed of the CoP. The previous studies usually divided the speed of the CoP movement into two directions, including the anterior-posterior (A/P) direction and the medial-lateral (M/L) direction. The definition of both directions can be studied in figure 44. The average CoP speed, in the A/P and the M/L directions, among experimental participants is plotted in figure 45. The exact value of the CoP speed and acceleration is available in Appendix C.

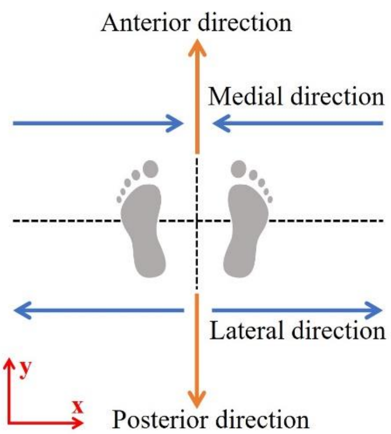


Fig 44 The anterior-posterior (A/P) and medial-lateral (M/L) directions.

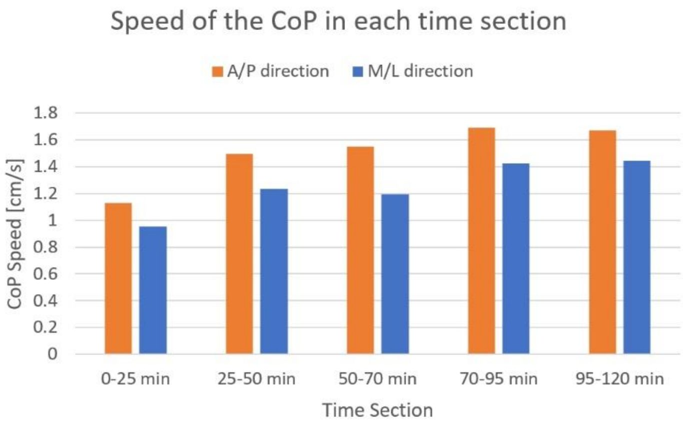


Fig 45 The average CoP speed among the participants.

The trend of the average CoP speed in both directions increases throughout the entire experiment. Moreover, the CoP speed in the A/P direction seems to be higher than the speed in the M/L direction, which means that the participants tend to move their CoP forward or backward more than sideward.

Table 10 Changes in the CoP speed between time sections.

The CoP speed between time section …	Changes in CoP speed in the A/P direction [cm/s]	Changes in CoP speed in the M/L direction [cm/s]
1 and 2	0.36	0.28
2 and 3	0.06	-0.04
3 and 4	0.14	0.23
4 and 5	-0.02	0.02

Table 10 shows the change in the CoP speed between time sections. It can be seen that the CoP speed is barely changed between the second to the third time section, as well as between the fourth and the fifth time section.

CHAPTER 6
DISCUSSION AND CONCLUSION

This chapter provides the discussion and conclusion of the study concerning the evaluation of the proposed device from the experiment conducted. For the design and development of the device, the suggestion for possible design development of the device is provided.

6.1 DISCUSSION AND CONCLUSION OF THE STUDY

At the beginning of this research, the background knowledge about fatigue and interventions to alleviate fatigue is searched. Both the results from the study on the effects of prolonged standing and the study on the effects of prolonged walking suggest that muscle fatigue often occurs in the lower leg region. Accordingly, the device is developed aimed to relieve muscle fatigue in the lower leg caused by prolonged standing. The principle of a roller massager and a compression sleeve frequently used in sports and medications is utilized. Despite being quite large and weighty, the device can effortlessly achieve both design functions: massage and compression. Therefore, an experiment is conducted in the next step to study the effects of the massage and compression interventions against fatigue caused by prolonged standing, as well as to evaluate the device.

The experiment is designed to imitate an actual prolonged standing task using a 2-hr standing trial with a light typing task. Four healthy men participate in the experiment. They are asked to wear the device on their right leg after the test trial has been started for 50 min. The treatment session includes two sets of 4-min roller massage and 4-min compression. After the intervention, the device is then removed from the participant’s leg. The center of pressure (CoP) data from a force platform is collected through the experiment. However, the EMG sensor cannot be recorded as the device is installed. As a result, the EMG data of the right leg during the experiment time of 50 to 70 min is not available. The results are analyzed based on discomfort scores in four regions on both legs. Muscle fatigue is then assessed based on the EMG signal and postural stability. Indicators used in this assessment include the time-to-fatigue, the mean power frequency (MNF), and the CoP speed.

In this study, both mental and muscle fatigue are observed. To examine subjective mental fatigue, all participants are asked to rate their perceived discomfort on both legs in the questionnaire every 10 minutes. The questionnaire survey consists of a rating scale for eight body parts, which are the left and right thigh, knee, calf, and foot, to help the subjects to easier identify the level of discomfort in each region. The discomfort score ranges from 0 (*nothing*) to 10 (*extremely strong*) according to Borg’s CR-10 scale. The questionnaire results show that the trends of the average score of both legs are comparable in the first half of the experiment. However, after the intervention on the right leg, the trends of the discomfort score of the right leg tend to incline at a lower rate compared to the score of the left leg. Moreover, after the intervention on the right leg, the score of the right calf decreases by 24%, while the score of the right thigh and knee is not increased compared to the score rated before the treatment session. At the end of the experiment, the score of the right calf is

16.7% lower than the score of the left leg. Thus, the results from the questionnaire survey suggest that the proposed device can reduce fatigue in the lower leg caused by prolonged standing.

Time-to-fatigue is the earliest time that the EMG signal is significantly changed. Results from the study of Halim and others (2012) [9] confirm that the time-to-fatigue tends to decrease over time while the worker is working on a prolonged task. The results of this study found that the time-to-fatigue of the left leg is greater than that of the right leg which suggests that the fatigue in the right leg occurs at an earlier time as compared to the left leg. The findings are in accordance with the results of Halim et al. (2012) [9]. Moreover, the results indicate that time-to-fatigue after massaging is extended by 67% which suggests that the massage roller can be used effectively for fatigue alleviating devices.

According to previous studies, the reduction in the mean power frequency (MNF) indicates that muscle fatigue has occurred. In the study of Halim and others (2012) [9], the trend of the MNF tends to constantly decrease throughout the actual working hours in standing posture. Nevertheless, the results from the present study show that the trend of the MNF starts to decline in the second half of the standing test trial. These contrary findings can be caused by the differences between static standing and working in a standing posture, which still enables some postural changes when the legs feel tired.

Postural stability is another indicator for muscle fatigue assessment in this study. As fatigue reduces muscle performance and the ability to control muscles, the increase in the speed of the center of pressure (CoP) can imply muscle fatigue as well. The experimental results show that the area of the CoP grows over time. In addition, the area of the CoP of each experimental participant tends to shift forward which means that the subjects have a tendency to lean forward as their leg are fatigued. This may answer why the calf is the easiest muscle to feel fatigued in prolonged standing tasks. As the gastrocnemius, the main muscle of the calf, is mainly responsible for the ankle plantar flexion movement. Moreover, the change in the CoP speed before the intervention is notably higher than the change after the treatment. The results obtained from the CoP data are in accordance with the previous studies [8, 32].

The questionnaire results indicate that muscle discomfort of both left and right legs is equal in the first half of the experiment. The results of the questionnaire indicate that muscle discomfort of both left and right legs is equal in the first half of the experiment. However, time-to-fatigue is found to differ for both left and right legs. The findings suggest that human perception regarding the level of discomfort may vary from the physical fatigue measured directly from the muscle.

In conclusion, muscle fatigue assessment in this study is based on the EMG signals, postural stability, and the questionnaire using various indicators, including time-to-fatigue, mean power frequency (MNF), and CoP speed. The findings suggest that there are different contributions and limitations of various methods for testing muscle fatigue. The utilization of the EMG sensor provides detailed accuracy data but is rather expensive for its requirement of special laboratory equipment. The use of questionnaires may seem to be rather subjective but the results indicate that the questionnaire can provide an effective assessment of muscle fatigue. Finally, the use of the CoP data for the postural stability evaluation does not provide results distinguishing between the left and right legs but may be a convenient and economical method for muscle fatigue assessment.

In order to compare subjects with different protocols and to eliminate experimental bias, further experiments may conduct in different settings such as using a control group under no intervention for comparison to subjects who use the device. On the other hand, the device may be installed at the beginning of the experiment instead of divided into the first half and treatment session. Alternatively, the experiment may also extend the intervention to both the left and right legs. Moreover, future studies may investigate the effect of adjusting the spring stiffness and velocity of the roller massage unit.

6.2 SUGGESTION FOR DESIGN IMPROVEMENT

For design improvement, the weight and size of the device are the most concerning matters. Table 11 and figure 46 show lists and details of suggestions to simply remove the excess weight of the device, respectively.

Table 11 Suggestion for reducing weight of the device.

No.	Group	Plans	Approximate weight reduction	
1	Acrylic	Decrease thickness from 5 to 3 mm	40% of the total acrylic component weight	240 g
2	Acrylic	Remove excessive area in the acrylic part “Case-SW”	40% of the part “Case-SW”	43 g
3	Acrylic	Remove excessive area in acrylic parts “Lid-upper” and “Lid-lower”	25% of the part “Lid-upper” and “Lid-lower”	30 g
4	Battery	Remove 9V battery (use 12V battery instead)	28% of the total battery component weight	49 g
5	Electronic	Replace a relay with a motor driver TB6612FNG	28% of the total electronic parts weight	25 g
6	Mechanical	Redesign or change material of the massage unit shafts	30% of the massage unit shafts	74 g
7	Mechanical	Remove redundant brackets	9% of the total mechanical parts weight	75 g
		Total weight reduction	26.8% of total weight	536 g

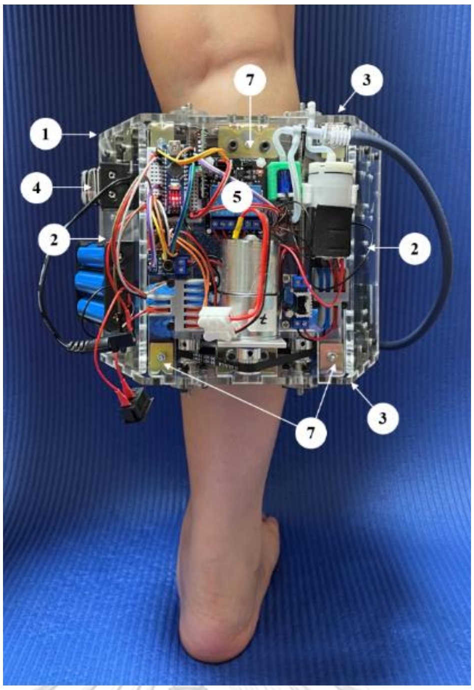


Fig 46 Illustration of suggestion for weight reduce.

After following these suggestions, the device's weight should be decreased to 1.46 kg. Furthermore, the device can be improved by relocating some of the massive components to be in a close position to the leg, in order to lessen the moment felt by the wearer. According to the above suggestions, most of the weight reduction is owing to changes in the case part of the device. As a result, methods such as using carbon fiber to create the case of the device are also recommended.

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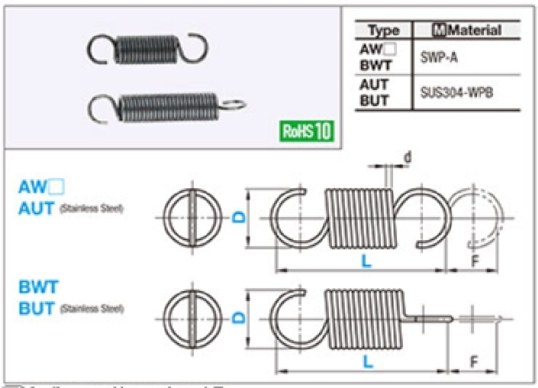
APPENDIX A
Additional Details for Device Design



Medium to Heavy Load Type

Part Number Type	Part Number D-L	Wire Dia. dmm	Dynamic Load Max. Deflection Fmax. mm	Dynamic Load Max. Load N	(Initial Tension) N	(Springs Constant) N/mm	Unit Price
AWF	3-10	0.45	2.2	6.47	1.57	2.26	
	15		4.5			1.08	
	20		6.7			0.74	
	25		9.1			0.54	
	30		11.4			0.43	
AWF	4-15	0.55	4.5	8.43	1.86	1.47	
	20		7.1			0.93	
	25		10.0			0.66	
	30		12.6			0.52	
	35		15.2			0.43	
	40		18.1			0.36	Quotation
AWF	5-15	0.7	3.9	14.71	2.45	3.14	
	20		6.9			1.77	
	25		9.6			1.28	
	30		12.5			0.98	
	35		15.6			0.78	
	40		19.2			0.64	
	45		21.9			0.56	
	50		25.0			0.49	
AWF	6-20	0.9	3.9	23.54	5.88	4.51	
	25		6.0			2.94	
	30		7.8			2.26	
	35		10.0			1.77	
	40		12.0			1.47	
	45		13.8			1.28	
	50		16.4			1.08	
	55		18.0			0.98	
	60		20.0			0.88	
AWF	8-25	1.1	5.8	31.38	6.86	4.23	
	30		8.3			2.94	
	35		10.9			2.26	
	40		13.2			1.86	
	45		15.6			1.57	
	50		18.5			1.32	
	55		21.7			1.13	
	60		23.8			1.03	
	65		26.3			0.93	
	70		27.8			0.88	
AWF	10-30	1.4	6.5	49.03	12.75	5.58	
	35		8.7			4.17	
	40		10.7			3.39	
	45		12.9			2.81	
	50		15.2			2.39	
	55		17.2			2.11	
	60		19.5			1.86	
	70		23.1			1.57	
	80		27.4			1.32	
	90		32.1			1.13	
	100		46.2			0.79	
AWF	12-35	1.8	5.0	83.36	23.54	12.0	
	40		7.0			8.55	
	45		9.0			6.65	
	50		11.0			5.44	
	55		13.0			4.60	
	60		14.5			4.13	
	70		17.8			3.36	
	80		21.3			2.81	
	90		24.5			2.44	
	100		27.5			2.18	

Heavy Load * marked dimensions are for AWT / AUT only.

Part Number Type	Part Number D-L	Wire Dia. dmm	Dynamic Load Max. Deflection Fmax. mm	Dynamic Load Max. Load N	(Initial Tension) N	(Springs Constant) N/mm	Unit Price AWT BWT	Unit Price AUT BUT
AWT AUT BWT BUT	3-10	0.5	2.0	8.8	2.16	3.24		
	15		3.7			1.77		
	20		5.2			1.27		
	25		6.8			0.98		
	*30		8.5			0.78		
AWT AUT BWT BUT	4-15	0.6	4.0	11.1	2.55	2.16		
	20		6.4			1.37		
	25		8.4			0.98		
	30		10.9			0.78		
	*35		12.4			0.69		
	*40		15.0			0.57		
AWT AUT BWT BUT	5-15	0.8	2.9	20.79	5.1	5.39		
	20		4.6			3.43		
	25		6.4			2.45		
	30		8.4			1.86		
	35		10.0			1.57		
	*40		11.4			1.38		
	*45		13.3			1.18		
	*50		15.2			1.03		
AWT BWT AUT BUT	6-20	1.0	3.7	33.15	8.6	6.57		
	25		5.3			4.61		
	30		6.9			3.53		
	35		8.3			2.94		
	40		10.0			2.45		
	*45		10.8			2.27		
	*50		12.5			1.96		
	*55		14.3			1.71		
	*60		15.6			1.57		
AWT BWT AUT BUT	8-25	1.2	5.3	41.19	9.81	5.88		
	30		7.3			4.31		
	35		9.1			3.43		
	40		11.9			2.65		
	45		13.6			2.35		
	50		15.5			2.06		
	*55		16.8			1.87		
	*60		18.8			1.67		
	*65		20.6			1.52		
	*70		22.8			1.38		
AWT BWT AUT BUT	10-30	1.6	5.2	77.47	20.59	10.89	Quotation	
	35		6.8			8.34		
	40		8.4			6.77		
	45		10.0			5.69		
	50		11.6			4.9		
	55		13.2			4.31		
	60		15.2			3.73		
	*65		17.0			3.35		
	*70		19.3			2.95		
	*75		20.7			2.75		
	*80		24.1			2.36		
	*90		26.3			2.16		
	*100		29.0			1.96		
AWT BWT AUT BUT	12-40	2.0	6.6	120.62	34.3	13.04		
	45		7.7			11.18		
	50		9.4			9.22		
	55		10.5			8.24		
	60		12.1			7.16		
	65		13.1			6.57		
	70		14.9			5.79		
	75		16.0			5.39		
	80		17.6			4.9		
	*90		19.1			4.52		
	*100		22.0			3.92		
AWT	14-40	2.3	5.8	154.95	45.11	19.02		-
	45		7.0			15.59		
	50		8.4			13.14		
	55		9.6			11.47		
	60		10.9			10.1		
	65		12.9			8.53		
	70		14.2			7.75		
	75		15.3			7.16		
	80		16.7			6.57		
	90		18.6			5.91		
	100		21.1			5.21		
	125		28.0			3.92		
AWT	16-50	2.6	7.5	195.15	55.9	18.63		-
	55		9.0			15.49		
	60		10.4			13.34		
	65		11.9			11.67		
	70		13.4			10.4		
	75		15.0			9.32		
	80		16.5			8.43		
	90		19.4			7.16		
	100		22.4			6.18		
	125		28.4			4.90		
	150		35.5			3.92		
AWT	18-55	2.9	8.3	236.34	68.65	20.1		-
	60		10.0			16.67		
	65		11.6			14.71		
	70		12.5			13.44		
	75		14.1			11.77		
	80		15.8			10.79		
	90		18.4			9.12		
	100		21.6			7.75		
	125		27.1			6.19		
	150		34.2			4.90		
AWT	20-60	3.2	9.2	281.45	82.38	21.57		-
	70		11.9			16.67		
	80		14.7			13.53		
	90		17.5			11.38		
	100		20.1			9.9		
	125		27.8			7.16		
	150		33.8			5.89		
	175		40.6			4.90		
AWT	24-80	4.0	11.7	430.51	123.6	26.48		-
	90		13.7			22.46		
	100		16.6			18.63		
	125		22.5			13.63		
	150		28.5			10.79		
	175		34.4			8.92		
	200		41.2			7.45		

Initial tension and spring constant are for reference only. Load (kgf) = Load Nx0.101972

Fig 47 Catalogue of the tension spring used in the device.
*Data from: https://th.misumi-ec.com/th/vona2/detail/110302288510

Table 12 Lists of quantity and weight of the device's components.

Group	Part Name	Weight (g)	Quantity	Sum/part (g)
Acrylic	Case-SW	90.0	2	180.0
Acrylic	Case-mid	115	1	115.0
Acrylic	Lid-lower	109.0	1	109.0
Acrylic	Lid-upper	91.0	1	91.0
Acrylic	Case-NW	30.0	2	60.0
Acrylic	Base	18.5	2	37.0
Acrylic	Bearing cap	2.0	4	8.0
Actuator	DC motor and motor bracket	237.0	1	237.0
Actuator	Air pump and clamp	67.0	1	67.0
Actuator	Solenoid valve	23.0	1	23.0
Battery	Battery 12V and case	125.0	1	125.0
Battery	Battery 9V and case	49.0	1	49.0
Electronic	Relay 2 channel	27.0	1	27.0
Electronic	Terminal 2 to 6	13.0	1	13.0
Electronic	Mini breadboard	13.0	1	13.0
Electronic	Terminal 2 to 4	11.0	1	11.0
Electronic	Step down module	10.0	1	10.0
Electronic	Arduino Nano	6.0	1	6.0
Electronic	Voltage sensor	3.0	1	3.0
Electronic	Limit switch	3.0	1	3.0
Electronic	TB6612FNG	2.0	1	2.0
Electronic	Pressure sensor	1.0	1	1.0
Mechanical	Massage unit shaft	124.0	2	248.0
Mechanical	Mini bracket and 2*M3*1.5	10.0	16	160.0
Mechanical	Pressure cuff	80.0	1	80.0
Mechanical	Leadscrew M5 20 cm and nut	28.7	2	57.4
Mechanical	M3*15 bolt and nut	1.5	28	42.0
Mechanical	40mm bracket	15.0	2	30.0
Mechanical	Massage roller	14.0	2	28.0
Mechanical	Adjustable strap	6.0	4	24.0
Mechanical	M4*10 bolt and nut	2.5	8	20.0
Mechanical	Tension spring AWT8-35	4.0	4	16.0
Mechanical	Collar ID8	7.0	2	14.0
Mechanical	Collar ID5	3.0	4	12.0
Mechanical	Pillar	2.0	6	12.0
Mechanical	Spring shaft (stud and pin)	3.0	4	12.0
Mechanical	Cushioning foam	12.0	1	12.0
Mechanical	Bearing C-FL695ZZ	2.9	4	11.6
Mechanical	Pulley gear 20 teeth ID5	4.0	2	8.0
Mechanical	M5 shoulder bolt GMSB5-30	5.0	1	5.0
Mechanical	Ball roller BCHJJ7	1.0	4	4.0
Mechanical	Pulley gear 20 teeth ID6	4.0	1	4.0

Group	Part Name	Weight (g)	Quantity	Sum/part (g)
Mechanical	Joint valve	3.0	1	3.0
Mechanical	Solenoid case	3.0	1	3.0
Mechanical	Pulley belt	2.0	1	2.0

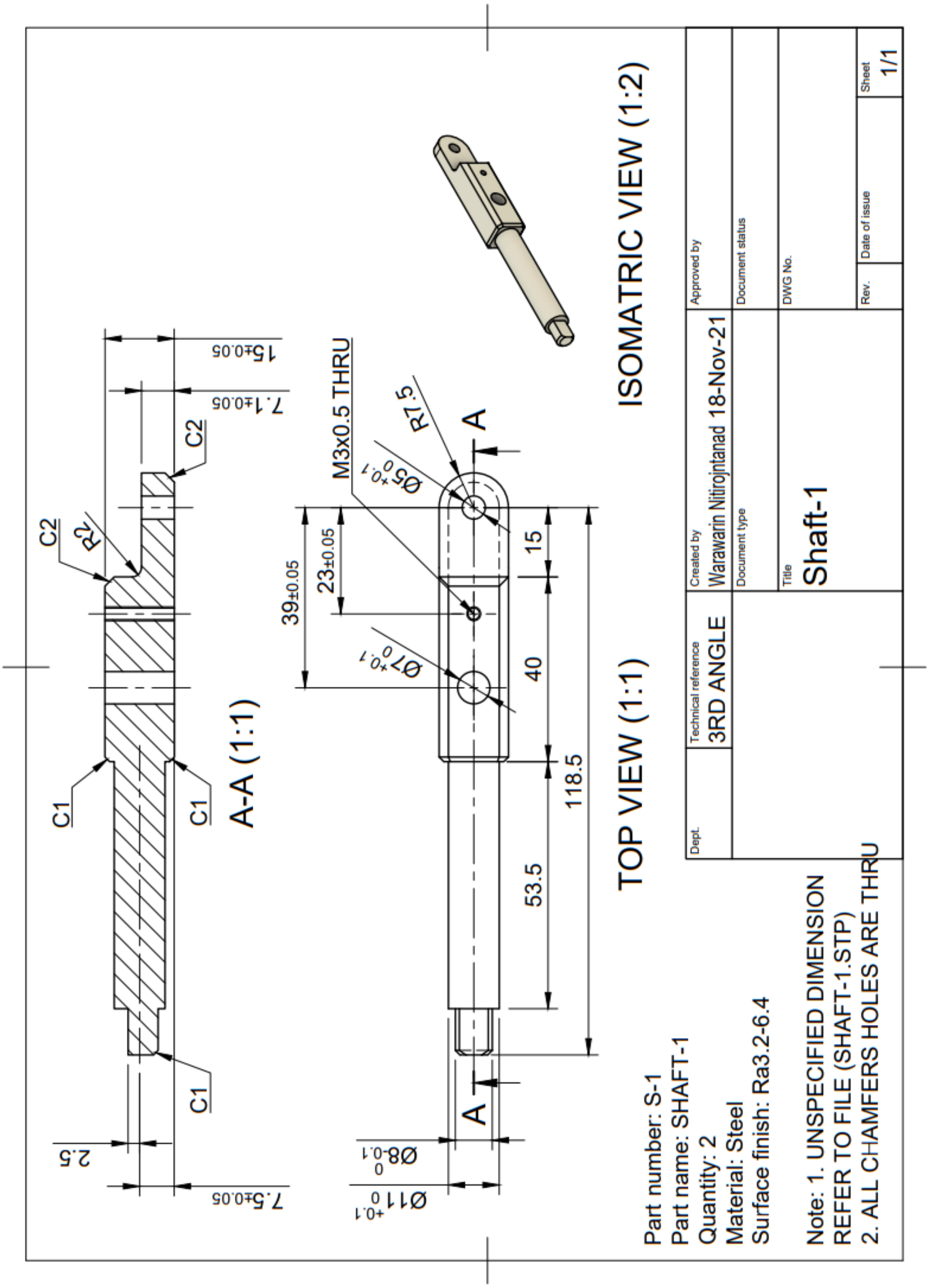


Fig 48 Drawing of the massage unit shaft.

APPENDIX B
Program Code for Controlling the Device

```
// Pressure Measurements with the MPS20N0040D Breakout Board with the
HX710B/HX711 ADC
#include <Q2HX711.h>
// Read RF remote button codes using the RM4 library and send them over serial.
#include <rm4.h>

// Arduino pin connected to the receiver VCC in. Set this high to enable the reciever.
static const int kEnablePin = 2;
// Arduino pins connected to the data pins on the receiver.
static const int kData0PinB = 3; // button B
static const int kData1PinD = 4; // button D
static const int kData2PinA = 5; // button A
static const int kData3PinC = 6; // button C

const int AIN1 = 8;
const int AIN2 = 9;
const int relay1valve = 13;
const int relay2pump = 12;
char limitSW = A0;
char voltageSensor = A6;

const float calibrate1 = 32.735/50;                 // for pressure sensor A
const float calibrate2 = 25.11;                     // for pressure sensor A

// Create an RM4 object to read the button codes from the remote.
RM4 remote(kData0PinB, kData1PinD, kData2PinA, kData3PinC);
const byte MPS_SCK_pin = 10; // clock data pin
const byte MPS_OUT_pin = 11; // OUT data pin
Q2HX711 MPS20N0040D(MPS_OUT_pin, MPS_SCK_pin);   // start comm with the
HX710B

void setup() {
  Serial.begin(9600);                               // start the serial port

  pinMode(kEnablePin, OUTPUT);
  digitalWrite(kEnablePin, HIGH);

  pinMode(kData0PinB, INPUT);
  pinMode(kData1PinD, INPUT);
  pinMode(kData2PinA, INPUT);
  pinMode(kData3PinC, INPUT);

  pinMode(AIN1, OUTPUT);
  pinMode(AIN2, OUTPUT);
  pinMode(relay1valve, OUTPUT);
  pinMode(relay2pump, OUTPUT);
```

```
  // clear button status
  digitalWrite(AIN1, LOW);
  digitalWrite(AIN2, LOW);
  digitalWrite(relay1valve, HIGH);
  digitalWrite(relay2pump, HIGH);
}

void loop() {
    //read battery voltage
  int rawVoltage = analogRead(voltageSensor);
  float batteryVoltage = 4.2*5.0*rawVoltage/1023.0;
//    if (batteryVoltage<=10) {
//      analogWrite(A1,255);
//      delay(500);
//      analogWrite(A1,0);
//}

    if (digitalRead(kData1PinD) == HIGH) {
      digitalWrite(AIN1, LOW);      // roller up
      digitalWrite(AIN2, HIGH);     // roller up
    } else{
      digitalWrite(AIN1, LOW);      // stop motor
      digitalWrite(AIN2, LOW);      // stop motor
    }

  if (digitalRead(kData2PinA) == HIGH) {              // 2 min roller massage
    while (true){
      int limitval = analogRead(limitSW);
      Serial.println(limitval);
      if (limitval > 125){
      digitalWrite(AIN1, LOW);      // roller up
      digitalWrite(AIN2, HIGH);     // roller up
      } else {
        break;
      }
    }

    for(int counterA = 1; counterA <= 60; counterA++){
      digitalWrite(AIN1, HIGH);     // roller down
      digitalWrite(AIN2, LOW);      // roller down
      delay(1000);
    }

    while (true){
      int limitval = analogRead(limitSW);
      Serial.println(limitval);
      if (limitval > 125){
```

```
      digitalWrite(AIN1, LOW);     // roller up
      digitalWrite(AIN2, HIGH);    // roller up
      } else {
        break;
      }
    }

    for(int counterA = 1; counterA <= 60; counterA++){
      digitalWrite(AIN1, HIGH);    // roller down
      digitalWrite(AIN2, LOW);    // roller down
      delay(1000);
    }

    digitalWrite(AIN1, LOW);      // stop motor
    digitalWrite(AIN2, LOW);      // stop motor
  }

  if (digitalRead(kData0PinB) == HIGH) {            // Press B for compression
    float calibrate1 = 32.735/50;            // for pressure sensor
    float calibrate2 = 25.11;                // for pressure sensor

//  for(int counterA = 1; counterA <= 100; counterA++){
    while (true){
      float rawPressure = MPS20N0040D.read();
      float pressurekPa = calibrate1*((5000*rawPressure/(128*16777215)) -
calibrate2);  // pressure value in [kPa] unit
      float pressuremmHg = pressurekPa*7.5;

      if (pressuremmHg < 25){
        Serial.println(pressuremmHg);
        digitalWrite(relay1valve, HIGH);
        digitalWrite(relay2pump, LOW);              // remove 5v from pin to turn relay on
      } else{
        digitalWrite(relay2pump, HIGH);             // add 5v to pin to turn relay off
      }
      delay(1);
      if (digitalRead(kData3PinC) == HIGH){
        digitalWrite(relay1valve, LOW);
        break;
      }
    }

  }
}
```

APPENDIX C
Additional Results

Table 13 The average CoP speed in detail.

Experiment time	CoP speed in the A/P direction [cm/s]	CoP speed in the M/L direction [cm/s]	CoP speed of the overall trajectory [cm/s]
0-25 min	1.129	0.9533	1.645
25-50 min	1.492	1.232	2.159
50-70 min	1.550	1.196	2.182
70-95 min	1.687	1.422	2.465
95-120 min	1.668	1.445	2.468

Table 14 The average CoP acceleration in detail.

Duration	Acceleration in the A/P direction [cm/s^2]	Acceleration in the M/L direction [cm/s^2]	Acceleration of the overall trajectory [cm/s^2]
Section 1 to 2	2.421E-06	1.858E-06	3.430E-06
Section 2 to 3	3.827E-07	-2.432E-07	1.491E-07
Section 3 to 4	9.137E-07	1.510E-06	1.887E-06
Section 4 to 5	-1.263E-07	1.505E-07	1.818E-08

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