THE EFFECT OF ANKLE FOOT-ORTHOSES CONSTRAINED MOVEMENTS ON POWER OUTPUT DURING FUNCTIONAL ELECTRICAL STIMULATION CYCLING IN PARAPLEGICS

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Name of Candidate: Puteri Nur Farhana Hamdan

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Field of Study: Rehabilitation Engineering

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ABSTRACT

Previous research has investigated functional electrical stimulation (FES) cycle power output (PO) from the perspective of knee and hip joint biomechanics. However, ankle-foot biomechanics and, in particular, the effect of releasing the ankle joint on cycle pedal PO during FES cycling in individuals with spinal cord injury (SCI) has not been widely explored. Therefore, the purpose of this study is to determine whether releasing the ankle joint might influence the peak and average pedal PO during FES cycling in individuals with SCI. Seven individuals with motor complete SCI (C5-T11) participated in this study. All participants performed two sessions of FES cycling. For each session, the participants were required to cycle in fixed- and free-ankle setup, in randomized order. There were two stimulation modes of FES cycling for each session. In mode 1, the participants were required to perform FES cycling with the stimulation of the upper leg muscles [quadriceps (QUAD) and hamstrings (HAM)] (known as QH stimulation). In mode 2, the participants were required to perform FES cycling with the stimulation of both upper and lower leg muscles [QUAD, HAM, tibialis anterior (TA), and triceps surae (TS)] (known as QHT stimulation). The peak and average pedal PO of each condition were analyzed. Overall, there was no significant difference in the normalized peak and average pedal PO between fixed- and free-ankle FES cycling for both stimulation modes [F (3, 24) = 0.32, P = 0.81 and F (3, 24) = 1.19, P = 0.33, respectively]. However, the free-ankle FES cycling with QH stimulation contributed to the lowest normalized peak and average pedal POs compared to the other modes of FES cycling (0.66 ± 0.23 and 0.16 ± 0.07 W/W, respectively). The present study revealed that free-ankle FES cycling without the stimulation of shank muscles (TA and TS) caused loss of power during recovery phase of cycling. The power from the hip and knee was lost at the ankle joint, and thus produced low pedal PO. On the other hand, free-ankle FES cycling with QHT stimulation provided greater ankle ROM while

preventing power loss from the hip and knee at the ankle joint. The TS muscles stimulation is very important in free-ankle FES cycling to maximize the pedal PO. This finding might serve as a reference for future rehabilitative cycling protocols where both ankle muscle stretching and strength training are the simultaneous aim.

ABSTRAK

Kajian terdahulu telah dijalankan untuk menyiasat kuasa kayuhan dengan bantuan stimulasi elektrik berfungsi (FES) dari perspektif biomekanik sendi lutut dan pinggul. Walau bagaimanapun, bahagian biomekanik buku lali-kaki, khususnya kesan pembebasan pergerakan sendi buku lali terhadap kuasa kayuhan ketika berbasikal dengan bantuan FES dalam kalangan paraplegik tidak pernah diselidik secara meluas. Oleh itu, tujuan kajian ini dijalankan adalah untuk mengenal pasti kesan pembebasan pergerakan sendi buku lali paraplegik ketika berbasikal dengan bantuan FES terhadap kuasa kayuhan. Seramai tujuh peserta individu paraplegik menyeluruh (C5-T11) telah menyertai kajian ini. Kesemua peserta dikehendaki menjalani dua sesi berbasikal dengan bantuan FES. Bagi setiap sesi, setiap peserta dikehendaki berbasikal dengan bantuan FES dalam keadaan pergerakan sendi buku lali yang tetap dan bebas, dalam urutan rawak. Terdapat dua mod stimulasi bagi setiap sesi. Pada mod 1, kesemua peserta diminta untuk berbasikal dengan bantuan FES dengan otot bahagian atas kaki mereka distimulasi [peha depan (QUAD) dan peha belakang (HAM)] (dikenali sebagai stimulasi QH). Pada mod 2, kesemua peserta diminta untuk berbasikal dengan bantuan FES dengan kedua-dua otot bahagian atas dan bawah kaki mereka distimulasi [QUAD, HAM, betis depan (TA), dan betis belakang (TS)] (dikenali sebagai stimulasi QHT). Puncak dan purata kuasa kayuhan pedal untuk setiap kondisi dianalisis. Secara keseluruhannya, puncak dan purata kuasa kayuhan pedal ternormal tidak menunjukkan perbezaan yang ketara antara berbasikal dengan bantuan FES dalam keadaan pergerakan sendi buku lali yang tetap dan bebas bagi kedua-dua mod stimulasi [masing-masing F (3, 24) = 0.32, P = 0.81 dan F (3, 24) = 1.19, P = 0.33]. Walau bagaimanapun, berbasikal dengan bantuan FES dalam keadaan sendi buku lali yang tetap dengan QH stimulasi menghasilkan purata kuasa kayuhan pedal ternormal yang paling rendah berbanding dengan mod berbasikal yang lain (masing-masing 0.66 ± 0.23 dan 0.16 ±

0.07 W/W). Kajian ini mendapati bahawa berbasikal dengan bantuan FES dalam keadaan pergerakan sendi buku lali bebas tanpa stimulasi TA dan TS akan menyebabkan kehilangan kuasa kayuhan ketika fasa pemulihan. Kuasa kayuhan daripada sendi pinggul dan lutut hilang di sendi buku lali, dan menyebabkan penghasilan kuasa kayuhan pedal yang rendah. Sebaliknya, kajian terkini menunjukkan bahawa berbasikal dengan bantuan FES dalam keadaan pergerakan sendi buku lali yang bebas dengan stimulasi QHT membantu meningkatkan kadar pergerakan sendi buku lali di samping dapat mengelak daripada kehilangan kuasa kayuhan daripada sendi punggung dan lutut di sendi buku lali. Stimulasi otot TS adalah amat penting ketika berbasikal dengan bantuan FES dalam keadaan sendi buku lali bergerak bebas untuk mendapatkan kuasa kayuhan pedal maksimum. Hasil kajian ini mungkin boleh dijadikan sebagai panduan protokol berbasikal rehabilitasi pada masa akan datang di mana tujuan latihan berfokus kepada kedua-dua regangan dan kekuatan otot buku lali.

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LIST OF SYMBOLS AND ABBREVIATIONS

AB	:	Able-bodied
ACE	:	Arm crank ergometer
ADL	:	Activities in daily life
AFO	:	Ankle-foot orthosis
ASIA	:	American Spinal Cord Injury Association
BDC	:	Bottom dead center
BMD	:	Bone mineral density
DF AFO	:	AFO that allows the ankle to move from neutral position to dorsiflexion
DOF	:	Degree-of-freedom
DPF AFO	:	AFO that allows the ankle to move from neutral position to dorsi-plantarflexion
FES	:	Functional electrical stimulation
FES-LCE	:	Functional electrical stimulation-induced leg cycle ergometer
FP AFO	:	AFO that fix the ankle at neutral position (90°)
GLUT	:	Gluteus maximus
HAM	:	Hamstrings
Hz	:	Hertz
kJ	:	Kilojoules
mA	:	Miliampere
ms	:	Miliseconds
min	:	Minute
N	:	Newton

PF AFO	:	AFO that allows the ankle to move from neutral position to plantarflexion
PO	:	Power output
PW	:	Pulse width
QH	:	Stimulation of quadriceps and hamstrings
QHT	:	Stimulation of quadriceps, hamstrings, tibialis anterior, and triceps surae
QUAD	:	Quadriceps
ROM	:	Range of motion
rpm	:	Revolution per minute
SCI	:	Spinal cord injury
SNS	:	Sensory nervous system
T	:	Thoracic
TA	:	Tibialis anterior
TS	:	Triceps surae
VO_{2peak}	:	Peak oxygen consumption
W	:	Watt
W/W	:	Watt/watt
µs	:	Microseconds

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CHAPTER 1: INTRODUCTION

This chapter discusses the general idea of the study in brief. This chapter is divided into 8 sections. Section 1 describes the background of the study. Section 2 and 3 explains the motivation and problem statement for the study, respectively. Section 4 lists the objectives of the study. Section 5 and 6 highlight the hypothesis and aim of the study, respectively. Section 7 explains the scope of the study. The last section of this chapter describes the dissertation organization in brief.

1.1 Background of the Study

Cycling is a popular exercise modality for individuals with spinal cord injury (SCI). The general goal of cycling exercise is to produce the highest possible mechanical power to maximize the merit of health benefits (Ragnarsson et al., 1988). In SCI populations, such cycling exercise is artificially evoked by functional electrical stimulation (FES), whereby leg muscles are recruited by electrical pulses delivered on the skin surface overlying key muscles (Bakkum et al, 2012; Hunt et al, 2012). It has been proven to provide benefits including improved muscle strength, endurance, mechanical power output (PO), skin condition, cardiopulmonary fitness, reversal of muscle wasting, improved blood flow in the legs, reduced incidence of muscle spasms, better body composition, bone mass, quality of life, joint health and flexibility, and offsetting some of the secondary complication (Bakkum et al., 2012; Soest, Gföhler, & Casius, 2005). However, how the foot is affixed to the pedal has been of interest. A fixed ankle-foot orthosis (AFO) or fixed pedal boot is often deployed to affix the foot to the pedal and this has been widely used to also provide shank stability; thus restricting the leg movements in the sagittal plane during cycling (Abdulla et al., 2014; Berry et al., 2008; Perret et al., 2010; Trumbower & Faghri, 2005). In the standard setup for FES cycling, the ankle joint is immobilized using an orthosis, and stimulation is applied to quadriceps femoris (QUAD), gluteus maximus (GLUT), and hamstrings (HAM) using surface electrodes (Bakkum et al., 2012; Hunt et al., 2012).

Researchers have previously sought to elicit maximum PO during FES cycling in order to increase the benefits of cycling during rehabilitation. The magnitude of mechanical PO produced during FES cycling in individuals with SCI is very low compare to the PO produced during voluntary cycling in able-bodied (AB) (Berkelmans, 2008; Sinclair et al., 1996; Szecsi, Straube, & Fornusek, 2014; Duffell et al., 2008; Duffell, Donaldson, & Newham, 2010). The reasons of the low PO magnitude might be due to the inefficiency of artificial muscle activation, the crude control of muscle groups accomplished by stimulation, and muscle atrophy and transformation due to chronic paralysis and disuse (Duffell, Donaldson, & Newham, 2009). Consequently, several studies have investigated the origins of cycling PO during FES exercise (Gregor et al., 2002; Hunt et al., 2012).

Ankle positioning during cycling is one of the more important factors for effective pedaling (Pierson, Brown, & Dairaghi, 1997; Trumbower & Faghri, 2004), yet this has not received much previous research attention. Theoretically, the PO can be improved by releasing the ankle joint and adding triceps surae (TS) and tibialis anterior (TA) muscles evoked by neurostimulation (Soest et al., 2005). Stimulation of the TS and TA has been investigated before in fixed-ankle FES cycling and no remarkable effect on PO was noted, except that it only affected the cardiovascular and circulatory responses (Ferrante et al., 2005). The stimulation of the TA and TS in a free-ankle setup produced 14% greater PO than the fixed-ankle FES cycling only with the tuning of contact point between the foot and pedal to the relative strength of the ankle plantar flexors (Soest et al., 2005). However, the calf muscle generates limited knee flexion action due to the presence of orthosis that fixed the ankle angle, which may reduce the maximum PO

(Ferrante et al., 2005). In another study, it is reported that the free-ankle FES cycling with the stimulation of the shank muscles (TS and TA) was found safe and increased the ankle excursions that might have improved joint mobility and prevent contractures in persons with paralysis (Fornusek, Davis, & Baek, 2012). Taken together, these studies have further shown the importance of investigating maximum PO as a function of ankle movements during FES cycling in individuals with SCI.

1.2 Motivation for the Study

Maximizing PO during FES cycling has been a great concern in the rehabilitation systems to maximize the health benefit of FES cycling. Based on previous studies, a limited number of studies have investigated the origin of cycle PO from the perspective of ankle-foot biomechanics. The using of fixed AFO or fixed pedal boot were highly favored by many researchers. However, the effect of different ankle movements on the pedal power PO during FES cycling in individuals with SCI has not been carried out in experimentally. Therefore, it is important for the body of knowledge to investigate the effect of different ankle movements on the pedal PO during FES cycling, which was subsequently carried out in this study.

1.3 Problem Statement

The pedal PO generated during FES cycling in individuals with SCI is very low compared to the voluntary cycling in AB individuals. This problem has become a great concern among researchers, as the primary goal of FES cycling is to produce highest PO to maximize the merit of health benefit. Therefore, important parameter such as types of ankle joint movements during cycling has been taken into consideration in order to maximize the pedal PO during FES cycling in individuals with SCI. To our knowledge, no experiments have been done to quantify the effect of fixed- and free-ankle joint movements during FES cycling in individuals with SCI.

Fixing the ankle joint using a fixed AFO or fixed pedal boot has been highly favored among researchers during FES cycling in individuals with SCI, due to its safety and kinematical reasons. However, fixed AFO or fixed pedal boot restricts the ankle joint movement throughout the cycling, and thus limits the natural ankle joint movement as produced during voluntary cycling in AB individuals. The limitation of the natural ankle joint movement might limit the pedal PO during FES cycling in individuals with SCI. Therefore, releasing the ankle joint to move in natural movement might help to maximize the pedal PO during FES cycling in individuals with SCI. The effect of fixing and releasing the ankle joint movement during FES cycling on the pedal PO has been investigated before using the model simulation methods. Theoretically, the stimulation of the TA and TS in a free-ankle setup produced 14% greater PO than the fixed-ankle FES cycling only with the tuning of contact point between the foot and pedal to the relative strength of the ankle plantar flexors. However, it was expected that there is no difference in PO generated between fixed- and free-ankle FES cycling if it is uphold reality. Therefore, it is important for us to quantify and clarify the effect of fixed- and free-ankle FES cycling on pedal POs experimentally.

Due to the limited previous studies, it is important for us to identify the types ankle joint movements that will maximize the pedal PO during cycling in AB individuals beforehand. Previous studies have used fixed AFO/pedal boot and free pedal boot in voluntary recumbent cycling. Fixed AFO/pedal boot locks the ankle joint at neutral position (90°) throughout the cycling, while free pedal boot allows the ankle to move in natural movement (from neutral to dorsi-plantarflexion). In this study, AFOs constrained ankle movements will be used to investigate the effect of ankle-constrained movements during voluntary cycling in AB individuals. These AFOs constrained ankle movements will assist specific types of ankle movements (FP AFO locks the ankle at 90° throughout the cycling, DPF AFO allows the ankle to move from neutral to dorsi-plantarflexion movement, DF AFO allows the ankle to move from neutral to dorsiflexion movement, and PF AFO allows the ankle to move from neutral to plantarflexion movement) during voluntary cycling in AB individuals. This is a very important step in order to determine which types of ankle joint movements that will maximize the pedal PO during voluntary cycling. Consequently, it will help us to understand the natural behavior of ankle joint movement during cycling that will be implemented later in FES cycling in individuals with SCI. To our knowledge, no studies have been done to investigate the effect of different ankle constrained movements during voluntary cycling in AB individuals.

Taken these together, the ankle-foot biomechanics during FES cycling have received less attention from the researchers as a parameter in maximizing the pedal PO in FES cycling. Therefore, this study is important to quantify the effect of ankle-foot biomechanics on the pedal PO during FES cycling in individuals with SCI.

1.4 Objectives of the Study

In general, the objective of the study is to determine whether a fixed- and free-ankle movements might influence cycle pedal PO during FES cycling in individuals with SCI. Therefore, the specific objectives of this study are:

i. To quantify if AFOs of a fixed position (FP), in dorsi-plantarflexion (DPF), in dorsiflexion (DF), and in plantarflexion (PF)-constrained movements might influence the peak and average pedal POs during voluntary cycling exercise (without FES-evoked) in AB.

ii. To quantify the effect of fixed- and free-ankle movements on the peak and average pedal POs during FES cycling in individuals with SCI.

The best two types of ankle constrained movements found during voluntary recumbent cycling in AB were further carried over to the second experiment, which was to quantify in FES cycling in individuals with SCI.

1.5 Hypothesis of the Study

We hypothesize that releasing the ankle joint during voluntary and FES cycling might alter the production of peak and average pedal POs, as the biomechanics are affected by the ankle movements.

1.6 Aim of the Study

The aim of the study is to find out whether the fixed- and free-ankle movement will alter the peak and average pedal POs during FES cycling in individuals with SCI, experimentally. Previous studies have only investigated the effect of fixed- and free-ankle movements on the PO during FES cycling through model simulation method. To our knowledge, no experiments have been carried out to investigate the effect of fixed- and free-ankle movement on PO during FES cycling in individuals with SCI. Therefore, this study is important to achieve the ultimate goal of FES cycling, which is to gain maximum PO to maximize the merit of health benefit in individuals with SCI. Higher pedal PO generated from FES cycling will help individuals with SCI to do FES cycling outdoor and probably might help the SCI athletes in a race competition. Consequently, this study might help individuals with SCI to enjoy their rehabilitation exercises and improve their quality of life.

1.7 Significance of the Study

The significance of the study:

i. The study provided within the framework of power output assessment to critically appraisal of the current evidence on the effectiveness of constrained ankle movements to alter power output during FES cycling into clinical practices.

ii. This study would serve as a reference for future rehabilitative cycling protocols.

iii. This study highlighted the evidence supporting constrained ankle movements as the mechanical counterpart of power output in recumbent cycling exercise.

1.8 Scope of the Study

The scope of the study was divided into two parts. The first scope was to compare the effect of different AFOs constrained movements on the pedal PO during voluntary cycling in AB participants. The aim of this scope is to obtain the initial hypothesis of the effect of ankle-constrained movements on the pedal PO and the cycling biomechanics. The second scope was to compare the effect of fixed- and free-ankle movements during FES cycling on the pedal PO and the cycling biomechanics between the AB and SCI participants, in relation to current literature.

1.9 Dissertation Organization

This dissertation consists of six chapters, which are Introduction, Literature Review, Methodology, Results, Discussion, and Conclusion.

Chapter 1 is the Introduction. It explains the general idea of the study in brief. This chapter also contains the motivation of the study, research objective, research significance, research scope, and dissertation organization.

Chapter 2 is the Literature Review. It mainly addresses the critical analysis of previous relevant studies in relation to the present study.

Chapter 3 is the Methodology. This chapter describes the protocols and materials that have been used in the study.

Chapter 4 is the Results. It contains all the findings of the current study. This chapter identifies which ankle setup contributes to higher production of the peak and average pedal PO during FES cycling.

Chapter 5 is the Discussion. This chapter discusses the findings of the current study. This chapter clarifies the findings of the current research with the previous studies.

Chapter 6 is the Conclusion. This chapter summarizes the findings of the current study. In addition, a few suggestions and recommendations were made to develop a better approach to achieve the goals of FES cycling in individuals with SCI.

CHAPTER 2: LITERATURE REVIEW

This chapter contains a critical study of currently available literature related to the study. This chapter is divided into 9 sections. The first section explains the introduction to spinal cord injury (SCI). The second section describes the types of exercises that are suitable for individuals with spinal cord injury (SCI). The third and fourth sections introduce functional electrical stimulation (FES) in general and the use of functional electrical stimulation (FES) in cycling exercises for individuals with spinal cord injury (SCI), respectively. The fifth section describes the standard set up for functional electrical stimulation (FES). The sixth section compares the standard set up of functional electrical stimulation (FES) cycling within previous studies. The seventh and eighth sections explain the power output (PO) production from functional electrical stimulation (FES) cycling and the reasons of the low power output (PO) in functional electrical stimulation (FES) cycling, respectively. The last section summarizes currently available literature related to the study.

2.1 Introduction to Spinal Cord Injury (SCI)

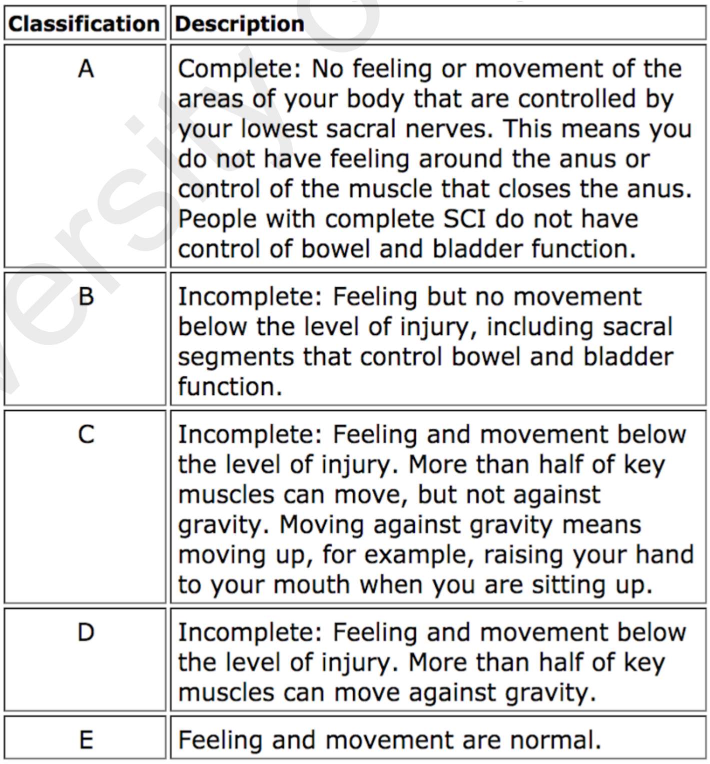
This section will help the researcher to understand the causes of SCI and the classifications of SCI. Besides that, this section will also help the researcher to understand the effect after SCI corresponding to the classification of SCI in individual with SCI.

SCI is an impairment to the spinal cord that causes the blockage of pulse signals transmission from the brain to the body system (Ahmad et al., 2012). SCI is often caused either by traffic accidents, falls, or sports activities (Rasmussen et al., 2004). Due to SCI, the affected individuals usually sustain loss of function, and reduced mobility due to paralysis (Rasmussen et al., 2004).

2.1.1 Neurological Classification for Individuals with SCI

Each individual with SCI is different from each other, depending on their impairment level and remaining function. In terms of their remaining function, the *International Standards for Classification of Spinal Cord Injury* has set a benchmark system to classify individuals with SCI according to the American Spinal Cord Injury Association (ASIA) (Maynard et al., 1997). This standard system is very important to help clinicians classify individuals with SCI accurately and consistently (Jacobs & Nash, 2004).

Generally, ASIA A is classified for individuals with SCI who loss both motor and sensory function below the level of injury, while ASIA B is classified for individuals with SCI who loss motor function but conserve sensory function below the injury level. For individuals with SCI with ASIA C and D, both motor and sensory functions are less impaired (**Figure 2.1**).



Classification	Description
A	Complete: No feeling or movement of the areas of your body that are controlled by your lowest sacral nerves. This means you do not have feeling around the anus or control of the muscle that closes the anus. People with complete SCI do not have control of bowel and bladder function.
B	Incomplete: Feeling but no movement below the level of injury, including sacral segments that control bowel and bladder function.
C	Incomplete: Feeling and movement below the level of injury. More than half of key muscles can move, but not against gravity. Moving against gravity means moving up, for example, raising your hand to your mouth when you are sitting up.
D	Incomplete: Feeling and movement below the level of injury. More than half of key muscles can move against gravity.
E	Feeling and movement are normal.

Figure 2.1: ASIA classification based on the remaining function in individulas with SCI.
Retrieved from
https://myhealth.alberta.ca/Health/pages/conditions.aspx?hwid=ug2627#ug2627-sec

2.1.1.1 Tetraplegia and paraplegia

As mentioned in **2.1.1**, individuals with SCI are classified based on the remaining functional systems and the impairment level. The second type of classification refers to their level of lesion, thus injury, either tetraplegia or paraplegia. Based on **Figure 2.2**, the level of injury in individuals with SCI can be classified into four regions; cervical, thoracic, lumbar, and sacral.

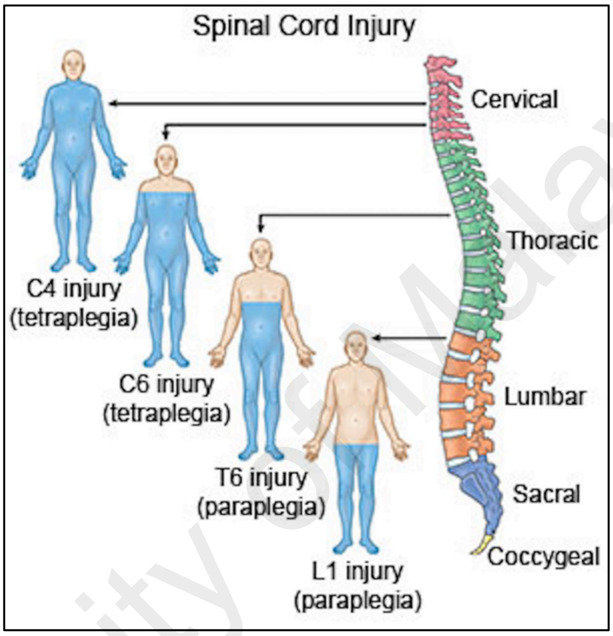


Figure 2.2: Classification of SCI based on the level of injury.
Retrieved from http://grierstrong.com/sci-information/

According to the ASIA, tetraplegia and paraplegia are defined as below (Jacobs & Nash, 2004):

Tetraplegia is defined as: "A term referring to impairment or loss of motor and/or sensory function in the cervical segments of the spinal cord due to damage of neural elements within the spinal canal. Tetraplegia results in impairment of function in the arms as well as the trunk, legs, and pelvic organs."

Paraplegia is defined as: "A term referring to impairment or loss of motor and/or sensory function in the thoracic, lumbar or sacral (but not cervical) segments of the spinal cord, secondary to damage of neural elements within the spinal canal. With paraplegia, arm functioning is spared, but depending on the level of injury. The trunk, legs, and pelvic organs may be involved."

2.1.1.2 Complete and incomplete SCI

Apart from the tetra- and paraplegia, individuals with SCI are also classified based on the remaining functional system. This type of classification is categorized into two; complete and incomplete SCI. According to the ASIA, complete and incomplete lesions are defined as below (Marino et al., 1999) :

Complete injury: "A term describing absence of sensory and motor function in the lowest sacral segment."

Incomplete injury: "A term describing partial preservation of sensory and/or motor functions below the neurological level and including the lowest sacral segment. Sacral sensation includes sensation at the anal mucocutaneous junction as well as deep anal sensation."

2.1.2 Effect After SCI

Due to SCI, individuals with prolonged SCI show an inactive lifestyle and rapid degenerative changes due to paralysis (Vrencken et al., 2007; Bremner et al., 1992; Dolbow et al., 2014). The most outstanding effects after SCI are the decrease of fitness levels and development of health complications (Davis, Hamzaid, & Fornusek, 2008; Jacobs & Nash, 2004).

Many researchers have highlighted the after effects associated with individuals with SCI. For example, individuals with SCI show rapid decline in muscle mass below the level of injury due to paralysis (Berkelmans, 2008; Carraro et al., 2005; Gerrits et al., 2000; Griffin et al., 2009; Hamzaid et al., 2012). Besides that, individuals with SCI also experience decrease in bone mineral density (BMD) (Berkelmans, 2008), baseline and peak blood flow (Cash et al., 1997; Hopman et al., 2002), muscle venous pump (Hamann et al., 2003), cardiac output (Hooker et al., 1992), and cardiorespiratory fitness (Davis et al., 2008). Consequence to the above matters, individuals with SCI frequently develop secondary complications (Chilibeck et al., 1999; Griffin et al., 2009). The risk to get osteoporosis, pressure sores, obesity, diabetes mellitus, and rapid muscles fatigue are high. Therefore, suitable exercises are very important for individuals with SCI to improve their fitness and promote health (Nash, 2005).

The next section (**2.2**) will describe in details the types of exercises that are suitable for individuals with SCI based on their remaining functions. Next section will help the researcher to select a suitable exercise mode for individuals with SCI, based on the goal of the exercise.

2.2 Exercises for Individuals with Spinal Cord Injury (SCI)

This section describes the types of exercise that are suitable for individuals with SCI. It is well-known that exercise is important to stay fit and healthy (Bakkum et al., 2012), either in able-bodied (AB) or in individuals with SCI (Bakkum et al., 2015; Davis et al., 2008). Due to its role as a preventative and therapeutic role, exercise training promises the greatest improvements in health (Berry et al., 2008).

There are various types of exercise training that are suitable for individuals with SCI. Such exercises include exercise for upper body, lower body, or combine both upper and lower body (hybrid mode). FES-evoked exercise is also suitable for individuals with SCI to improve the muscle strength and endurance of the paralyzed limbs (Hartkopp et al., 2003; Petrofsky, Stacy, & Laymon, 2000). The use of FES in cycling in individuals with SCI will be further described in sections **2.3** and **2.4**.

2.2.1 Upper Body Exercises

Individuals with SCI are highly dependent on a wheelchair for mobility due to paralysis of the lower body (Bakkum et al., 2015). Therefore, upper body exercises such as wheelchair propulsion and arm crank ergometer (ACE) (**Figure 2.3** and **Figure 2.4**) are commonly prescribed for individuals with SCI (Valent et al., 2008, 2009).


[redacted]

Figure 2.3: An example of wheelchair propulsion exercise.
Retrieved from http://www.bath.ac.uk/research/news/2014/08/04/spinal-cord-injury-study

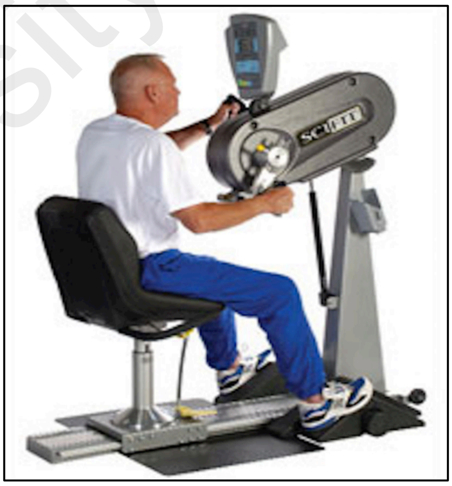


Figure 2.4: An example of ACE exercise.
Retrieved from http://responsive.ptproductsonline.com/2008/03/upper-body-ergometers/

However, the benefits gained from the upper body exercises alone are not sufficient for individuals with SCI. It is reported that the upper body exercises rise the risk of shoulder pain and damage from overuse (Burnham et al., 1993; Perkins et al., 2002).

Apart from that, the health outcomes from the upper body exercises alone are limited compared to the lower body exercises. This might be due to the small muscle mass available, inactivity of the venous muscle pump of the legs, and deficient cardiovascular reflex responses (Brurok et al., 2012). Hence, the upper body exercises alone may not be able to prevent the secondary complications associated with SCI (Brurok et al., 2012). Therefore, lower body exercises are frequently prescribe to maximize the health benefits in individuals with SCI.

2.2.2 Lower Body Exercises

Due to the limited health outcomes from the upper body exercises, lower body exercises are frequently prescribed for individuals with SCI (Hunt et al., 2004). Lower body exercise such as cycling involves the leg muscles that are larger than the upper body muscles (Perkins et al., 2002). However, individuals with SCI are always restricted to the lower body exercises due to paralysis (Hasnan et al., 2013). Therefore, FES is necessary to accomplish the lower body exercises in individuals with SCI (Bakkum et al., 2015; Hunt et al., 2004; Thijssen et al., 2006). FES helps to activate the leg muscles and allow the leg to temporary restore function during cycling exercise training (Berry et al., 2008). **Figure 2.5** shows the leg cycling exercise with FES in individual with SCI.

Figure 2.5: An example of leg cycling exercise with FES.
Retrieved from http://www.cybathlon.ethz.ch/en/

The advantages of the leg cycling exercise with FES are it augments the venous muscle pump of the legs (Perkins et al., 2002), elicit cardiovascular fitness (Bakkum et al., 2015; Perkins et al., 2002), and prevent secondary complications (Bremner et al., 1992). Therefore, the lower body exercises promises a larger health benefit compared to the upper body exercises alone (Bakkum et al., 2015).

However, the maximum submaximal oxygen uptake from the leg cycling exercise is not high as in ACE exercise (Barstow et al., 2000). Therefore, hybrid exercise is favorable as it maximizes the health benefits in individuals with SCI as it combines both upper and lower body exercises (Bakkum et al., 2015; Brurok et al., 2011).

2.2.3 Hybrid Mode Exercise

Hybrid mode exercise or also known as hybrid cycling exercise (Brurok et al., 2011) consisting of FES-induced leg cycling exercise and voluntary arm exercise (Bakkum et al., 2015). **Figure 2.6** shows the hybrid mode exercise in individual with SCI.

Figure 2.6: An example of hybrid mode exercise.
Retrieved from http://www.cybathlon.ethz.ch/en/

It activates more muscle mass and provide greater exercise responses to promote greater health outcome (Bakkum et al., 2015; Brurok et al., 2011; Hettinga & Andrews, 2008; Mutton et al., 1997) than the upper or lower body exercises alone. Researchers have studied the outcomes of hybrid cycling exercise (Brurok et al., 2011; Hooker et al., 1992; Mutton et al., 1997; Raymond et al., 1997; Valent et al., 2009). Hybrid cycling exercise has showed greater peak oxygen consumption (VO_2), work rates, and stroke volumes in individuals with SCI. In overall, a better cardiovascular training would be possibly achieved through hybrid exercise (Berkelmans, 2008).

Next section will describe briefly the use of FES in cycling and its purposes. The next section will also help the researcher to understand the application of FES in other rehabilitation exercises. Thus, it will help the researcher to understand the goal of FES-evoked exercises to maximize the health benefits in individuals with SCI.

2.3 Functional Electrical Stimulation (FES)

As mentioned in section **2.2.2**, FES has been used to assist the lower body exercises in individuals with SCI. Generally, FES is a technique where electrical stimulus is applied to the paralyzed muscles to artificially activate the paralyzed muscles (Bajd et al., 1999). The main objective of FES is to provide muscle contraction and functional movement (Davis et al., 2008; Hasnan et al., 2013). The electrical stimulus is applied to the paralyzed muscles through surface electrodes (Pilissy et al., 2008).

The purpose of FES are to strengthen the muscles, restore the function of paralyzed muscles (Abdulla, Sayidmarie, & Tokhi, 2014; Ambrosini et al., 2014; Askari et al., 2013; Berry et al., 2008; Duffell et al., 2010), regain mobility and health benefits (Berkelmans, 2008; Hamzaid et al., 2012), correct drop-foot (Chen et al., 2004), and as a rehabilitation therapy or an exercise regimen (Davis et al., 2008). FES has been widely used in rehabilitation field for different approaches depending on the individual's needs. The following section will describe the application of FES in rehabilitation field.

2.3.1 FES Application

FES application is very important in rehabilitation practices to maximize health benefits following SCI (Griffin et al., 2009). The first application of FES was designed to restore lower limb functions in individuals with stroke and SCI (Ahmad et al., 2012). FES has been used in individuals with SCI to produce functional movements such as cycling, rowing, knee extension, standing, stepping, walking, and grasping (Bijak et al., 2005; Davis et al., 2008; Popovic et al., 2001). FES cycling is relatively easier than FES walking due to the absence of balancing problem (Perkins et al., 2002; Ragnarsson et al., 1988), thus enhancing safety during exercise (Berkelmans, 2008). Therefore, FES cycling has been widely practiced by individuals with SCI for ongoing rehabilitation (Fornusek & Davis, 2004; Perret et al., 2010).

2.4 Functional Electrical Stimulation (FES) Cycling

This section describes the use FES in cycling and the types of FES cycling being used in individuals with SCI. Besides that, this section also explains the advantages and disadvantages of using FES cycling in individuals with SCI. This section will help the research to select a suitable type FES cycling for individuals with SCI in maximizing the advantages gained from FES cycling exercise.

FES cycling is an exercise that uses FES signals to stimulate paralyzed leg muscles in a specific sequence to perform pedaling motion (Abdulla et al., 2014). FES cycling is a popular exercise training for rehabilitation population because it is safe, familiar to the individuals with SCI, and recruits a large lower limb muscle mass (Bremner et al., 1992).

2.4.1 Types of FES Cycling

There are many types of FES cycling have been used in the previous studies for research and commercial purposes. The first commercialized FES-leg cycle ergometer

(FES-LCE) is ERGYS® (Therapeutic Technologies Incorporated) (Trumbower & Faghri, 2004). ERGYS® was used by individuals with upper motor neuron lesions SCI for fitness and exercise purposes. Then, other FES-LCE such as Monark and Regys were commercially available (Gföhler & Lugner, 2004; Trumbower & Faghri, 2004). FES-LCE is available in either stationary cycling and mobile cycling (Hunt et al., 2006).

2.4.1.1 Stationary FES cycling

Stationary cycling is a task that required coordination of the lower limb to cycle through a constrained path (Fregly & Zajac, 1996). The goals of stationary FES cycling are for muscle strength training and cardiopulmonary function enhancement (Chen et al., 2004). One of the examples of stationary FES cycling is Hasomed GmbH (**Figure 2.7**). Hasomed GmbH is used in individuals with SCI for indoor activities.


[redacted]

Figure 2.7: An example of stationary FES bike.

Typically, the stationary FES bike is assisted with electric motor (Hunt et al., 2004). Therefore, overall PO can be increased as it can help to reduce muscles fatigue during cycling (Hunt et al., 2004). Hence, individuals with SCI can benefit maximum performance of cycling. The POs reported for stationary FES cycle in individuals with SCI ranged from 26 Watt (W) to 55 W for 30 minutes of cycling (Eser et al., 2003; Hunt et al., 2004; Petrofsky & Stacy, 1992).

2.4.1.2 Mobile FES cycling

Unlike the stationary FES cycling, mobile FES cycling is used by individuals with SCI for mobility, recreation, or fitness purposes (Eser et al., 2003). The aim of mobile FES cycling is to make FES cycling more attractive. **Figure 2.8** shows the example of mobile FES bike.

Figure 2.8: An example of mobile FES bike.
Retrieved from http://www.cybathlon.ethz.ch/en/

Mobile FES bike can be used in individuals with SCI for outdoor activities. However, low PO production (Duffell et al., 2008) and difficulty to overcome disturbances such as slope and wind (Hunt et al., 2004) prevents FES mobile cycling from being used outdoors more extensively. Individuals with SCI are required to produce at least 30 W for mobile outdoor cycling (Duffell et al., 2010; Eser et al., 2003). Therefore, stationary FES cycling has been more commonly used in individuals with SCI compared to the mobile FES bike (Eser et al., 2003).

2.4.2 Advantages of FES Cycling

FES cycling offers a highly attractive exercise modality for individuals with SCI (Hunt et al., 2002). Continuous FES cycling in individuals with SCI shows improvements in:

i. Cardiac output (Petrofsky & Stacy, 1992; Raymond et al., 1997).

ii. Cardiovascular and cardiorespiratory fitness (Berkelmans, 2008; Gföhler et al., 2001; Gfohler & Lugner, 2000; Griffin et al., 2009).

iii. Blood circulation in lower limbs (Berkelmans, 2008; Davis et al., 2008; Griffin et al., 2009).

iv. Self-image of disabled (Berkelmans, 2008; Davis et al., 2008; Griffin et al., 2009).

v. Muscle strength (Ragnarsson et al., 1988).

vi. Peak pedaling power or mechanical PO (Petrofsky & Stacy, 1992) which reflected the fitness and health.

vii. Locomotion performance (Ragnarsson et al., 1988).

viii. Muscle endurance (Crameri et al., 2002; Petrofsky & Stacy, 1992; Raymond et al., 1997).

ix. Range of motion (ROM) which is useful to transfer or perform activities in daily life (ADL) (Bremner et al., 1992).

In addition, FES cycling also contributes to the reversal of muscle atrophy (Berkelmans, 2008; Davis et al., 2008), prevention of bone loss (Griffin et al., 2009), reduction of BMD loss (Gföhler et al., 2001; Gfohler & Lugner, 2000), and pressure ulcers (Berkelmans, 2008). The most outstanding advantage of FES-induced cycling is it can relieve and prolong the onset of the secondary complications (Hunt et al., 2004).

2.4.3 Disadvantages of FES Cycling

Despite of health benefits gain from FES cycling in individuals with SCI, it is less acceptable by the clinicians (Braz, Russold, & Davis, 2009). This might be due to the difficulty to manually set up and operate the cycling training exercise program for individuals with SCI (Braz et al., 2009). The procedures were repeatable for each individual with SCI and time consuming (Ambrosini et al., 2014).

Besides that, the expensive FES cycling technology restricts the low income individual with SCI or low income country from benefits the health outcome of FES cycling (Fornusek et al., 2012).

Other than that, individuals with SCI often experience plateau performance after a few months of training, which limit their fitness gains (Fornusek et al., 2012). This behavior might be due to the onset of premature muscle fatigue in individuals with SCI (Eser et al., 2003; Fornusek, Sinclair, & Davis, 2007; Gregory, Dixon, & Bickel, 2007). Fatigue can limit the exercise performance (Martin & Brown, 2009). It leads to the production of low efficiency and power during FES cycling (Hunt et al., 2013). The FES cycling efficiency was found to be as half of the volitional cycling efficiency (Hunt et al., 2013). Therefore, many researchers have sought solutions to overcome fatigue in individuals with SCI in order to gain maximum health benefits (Haapala, Faghri, & Adams, 2008).

2.5 Standard Set Up of Functional Electrical Stimulation (FES) Cycling

This section explains the standard set up that is commonly used in individuals with SCI during FES cycling. Standard set up in FES cycling is necessary to guide the clinicians to make sure that the patients receive maximum benefit from the exercise training. The standard set up such as the muscle stimulation, the use of leg's support such as fixed AFO or pedal boot, stimulation parameters, and pedaling cadences are further described in the following sub-sections. The standard set up of FES cycling for individuals with SCI will affect the overall performance of cycling, such as power production, and thus reflecting the health benefits from the FES cycling exercise.

2.5.1 Muscle Stimulation

In FES cycling, stimulation is typically applied to the quadriceps femoris (QUAD), gluteus maximus (GLUT), and hamstrings (HAM) muscles groups through the surface electrodes (Ahmad et al., 2012; Berkelmans, 2008; Soest et al., 2005; Haapala et al., 2008) (**Figure 2.9**). Stimulation of these muscles provides benefits such as elevated cardiorespiratory activity (Mohr et al., 1997), improved circulation (Gerrits et al., 2001; Hooker et al., 1992), and reduced muscle atrophy (Bremner et al., 1992) in individuals with SCI.

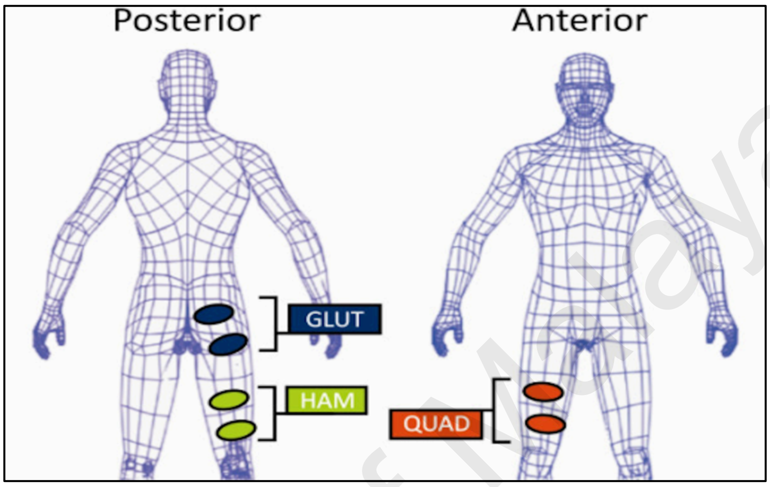


Figure 2.9: Standard muscles stimulation during FES cycling (Haapala et al., 2008).

The most important muscle for completing cycling task is QUAD (Bini et al., 2008; Trumbower & Faghri, 2004; Trumbower, Rajasekaran, & Faghri, 2006). QUAD muscles are stimulated to extend the knees during propulsion phase (also known as power phase) of cycling and contributes to the highest PO than the other group muscles regardless of the resistance (Ericson et al., 1986). The HAM muscles are stimulated during the cycling recovery phase to flex the knees, while GLUT muscles are stimulated to extend the hip as part of early propulsion phase, prior to knee extension.

Sometimes, the calf muscles are also stimulated in FES cycling (Berkelmans, 2008) to plantarflex the ankle (TS) and dorsiflex the ankle (TA) at late propulsion phase and early recovery phase, respectively. Calf muscles stimulation promote blood circulation in the lower legs even though it contributes almost zero power during FES cycling (Berkelmans, 2008). Besides that, calf stimulation may also improve muscle-pumping action of the lower leg muscles and thus increasing the venous blood return to the heart (Trumbower & Faghri, 2005).

2.5.2 Fixed Ankle-Foot Orthoses (AFO) or Pedal Boot

Researchers from previous studies (Bakkum et al., 2015; Berkelmans, 2008; Berry et al., 2008; Duffell et al., 2008; Ferrante et al., 2005; Haapala et al., 2008; Hasnan et al., 2013; Hunt et al., 2002, 2004; Perkins et al., 2002; Szecsi et al., 2014; Trumbower & Faghri, 2005) had commonly used fixed ankle support in individuals with SCI during FES cycling (**Figure 2.10**). In the standard FES cycling set up, the ankle is always locked or fixed in neutral position (90°) (Hakansson & Hull, 2009). The ankle joint is immobilized by either fixed AFO or pedal boot (Trumbower & Faghri, 2005; Soest et al., 2005).


[redacted]

Figure 2.10: An example of fixed AFO or pedal boot used in FES cycling.
Retrieved from http://www.cybathlon.ethz.ch/en/

The purpose of fixing the ankle joint is to enhance safety and allowing the ankle to move in one degree-of-freedom (DOF) only (Abdulla et al., 2014; Berry et al., 2008; Perret et al., 2010; Trumbower & Faghri, 2005), since there is no stimulation to the lower leg muscles. The fixed AFO or pedal boot also helps in preventing the hip abduct- and adduction, and ankle inversion and plantarflexion that might be cause by the weight of the upper legs or due to the FES stimulation (Perkins et al., 2002). In some cases, it helps to control the ankle joint movement of individuals with ankle muscle spasticity or paresis (Petrofsky & Phillips, 1984; Szecsi et al., 2009). However, the main purpose of fixing the ankle joint is to transmit the torque from the whole leg to the pedal (Abdulla et al., 2014) thus to produce work (Trumbower & Faghri, 2005).

2.5.3 Stimulation Parameters

Optimizing stimulation parameters for each individual with SCI are important to maximize FES cycling performance such as power production and fatigue resistance (Berkelmans, 2008; Chou & Macleod, 2007; Gorgey et al., 2009; Gorgey & Dudley, 2008; Gregory et al., 2007; Kesar, Chou, & Macleod, 2008). Stimulation parameters such as stimulation intensity, frequency, pulse width (PW), and training duration of FES cycling affects the overall strength of the resultant muscles contraction (Gorgey et al., 2006; Mesin et al., 2010; Sheffler & Chae, 2007).

Generally, increasing the stimulation intensity produced stronger muscle contraction (Mesin et al., 2010). The stimulation intensity will be decreased if the muscles contraction is too intense or if the legs are moving too fiercely (Bakkum et al., 2012). Normally, stimulation intensity is manually adjusted specific to individuals with SCI within their comfort to optimize the FES cycling performance (Kroon et al., 2005).

On the other hand, the stimulation frequency and PW are usually fixed at a range between 20-50 Hertz (Hz) and 200-500 microseconds (μs), respectively (Hankey et al., 2006). Shorter PW (50-400 μs) recruits active motor axons, whereas longer PW (500-1000 μs) recruits more sensory axons (Bergquist et al., 2011). Higher stimulation frequency and PW during FES cycling exposes individuals with SCI to rapid fatigue muscle (Eser et al., 2003).

However, it is very difficult to achieve optimized stimulation parameter since each individual with SCI has his/her own optimize parameter combination (Berkelmans, 2008). **Table 2.1** shows the standard FES parameter for FES cycling.

Table 2.1: Standard FES cycling parameter (Berkelmans, 2008).

Parameter	Range	Common
Frequency	20-60 Hz	30 Hz
Maximum current	120-300 miliampere (mA)	150 mA
Pulse duration	0.1-1 miliseconds (ms)	0.4 ms
Pulse form	Block, sinus, triangle	Block
Polarity	Mono-biphasic	Biphasic
Pulse train	Ramp up, ramp down, initial doublet	Ramp up

2.5.4 Pedaling Cadence

Traditional pedaling cadence for FES cycling is 50 revolutions per minute (rpm) (Fornusek & Davis, 2004). This cadence is normally assisted by a motorized system to help individuals with SCI to perform cycling due to paralysis. However, 50 rpm imposes rapid muscle fatigue rate compared to slower pedaling cadences during FES cycling (Fornusek & Davis, 2004). Therefore, 50 rpm causes low torque and muscle force production over 35 min of FES cycling (Fornusek & Davis, 2004).

2.6 Comparison of Functional Electrical Stimulation (FES) Cycling Set Up Used in Previous Studies

Section **2.5** has described the standard set up of FES cycling that have been commonly used in individuals with SCI. However, previous researchers have used different set up of FES cycling in individuals with SCI, to maximize the objectives of the exercise training. Therefore, this section presents the comparison between the differences of FES cycling set up used for individuals with SCI in previous studies. **Table 2.2** shows the differences of muscles stimulation, use of fixed AFO or pedal boot, stimulation parameters, and pedaling cadence used during FES cycling among all studies. The aim of this section is to investigate the most favored FES cycling set up used by the researchers for individuals with SCI during FES cycling exercise training.

Table 2.2: FES cycling set up used in previous studies.

No.	FES cycling	Participants	Training (weeks)	Motorized	Arm cranking	Fixed AFO/pedal boot	Intensity (mA)	PW (µs)	Frequency (Hz)	Cadence (rpm)	Muscles stimulated
1	Hybrid cycle (BerkelBike Pro, BerkelBike BV, St Michielsgestel, the Netherlands) and handcycle (Speedy-Bike, Reha-Technik GmbH, Delbruck, Germany) (Bakkum et al., 2015)	18 chronic SCI	16 [2x/week for 18-32 minutes (min)]	No	Yes	Yes	0-150	NM	NM	NM	QUAD, HAM, GLUT
2	BerkelBike (Berkelmans, 2008)	NM	NM	No	Yes	Yes	150	300	NM	NM	QUAD, HAM, GLUT

No.	**FES cycling**	**Participants**	**Training (weeks)**	**Motorized**	**Arm cranking**	**Fixed AFO/pedal boot**	**Intensity (mA)**	**PW (µs)**	**Frequency (Hz)**	**Cadence (rpm)**	**Muscles stimulated**
3	Mobile recumbent tricycle (Inspired Cycle Engineering Ltd., Falmouth, Cornwall, UK) (Berry et al., 2008)	12 SCI - ASIA A (T3-T12)	52 (60 min)	No	Yes	Yes	80-150	300-400	20-50	50	QUAD, HAM, GLUT, TS
4	Stationary computer-controlled FES ergometer (hybrid FES cycling exercise that included stimulated asynchronous leg cycling and voluntary arm cranking) (Thijssen et al., 2006)	9 SCI	6 (30 min)	NM	Yes	NM	50-150	NM	NM	50	QUAD, HAM, GLUT

No.	**FES cycling**	**Participants**	**Training (weeks)**	**Motorized**	**Arm cranking**	**Fixed AFO/pedal boot**	**Intensity (mA)**	**PW (µs)**	**Frequency (Hz)**	**Cadence (rpm)**	**Muscles stimulated**
5	ERGYS 2 Rehabilitation System (Therapeutic Alliances Inc., Fairborn, OH, USA – hybrid cycle (Brurok et al., 2012)	15 SCI (8 SCI-high, 7 SCI-low)	NM	No	Yes	No	NM	NM	NM	40	QUAD, HAM, GLUT, calf
6	Recumbent cycle ergometer (ERGYS 1 System, TTI, Dayton, USA) (Crameri et al., 2002)	6 SCI (T4-T12)	10 (3x/week for 30 min)	NM	NM	NM	300	300	35	35	NM
7	Computer-controlled FES-leg cycle ergometer (ERGYS 2; Therapeutic Alliance, Fairborn, OH) (Chilibeck et al., 1999)	5 SCI - 4M, 1F (C5-T8)	8 (3x/week for 30 min)	Yes	No	NM	10-140	NM	NM	50	QUAD, HAM, GLUT

No.	FES cycling	Participants	Training (weeks)	Motorized	Arm cranking	Fixed AFO/pedal boot	Intensity (mA)	PW (µs)	Frequency (Hz)	Cadence (rpm)	Muscles stimulated
8	FES-LCE (Trumbower & Faghri, 2005)	6 (3 AB, 3 SCI)	AB-untrained, SCI-12	NM	NM	Yes	NM	450	30	50	QUAD, HAM, GLUT
9	Custom-designed isokinetic FES cycle ergometer (Fornusek et al., 2004)	7 SCI (5 SCI: T4-T11, 2 SCI: C5 and C7)	Minimum 12 (2-3x/week)	Yes	No	Moveable pedal boot	NM	300	30	15	QUAD, HAM, GLUT, calf
10	iFES-LCE and a motorized cycle ergometer module (MOTOmed Viva, Reck, Germany) (Fornusek & Davis, 2004)	9 SCI - ASIA A	Minimum 24	Yes	No	NM	70-140	250	35	20, 50	QUAD, HAM, GLUT

No.	**FES cycling**	**Participants**	**Training (weeks)**	**Motorized**	**Arm cranking**	**Fixed AFO/pedal boot**	**Intensity (mA)**	**PW (µs)**	**Frequency (Hz)**	**Cadence (rpm)**	**Muscles stimulated**
11	Home-based FES-LCE [RT300 FES cycle (Restorative Therapies, Baltimore, MD, USA)] (Dolbow et al., 2014)	1 SCI - ASIA A (T6)	48	Yes	No	NM	140	250-300	33.3-50	36-43	QUAD, HAM, GLUT
12	Commercial tricycle with 18 gears (Trice; Inspired Cycle Engineering, Ltd., UK) (Duffell et al., 2008)	11 complete SCI and 10 untrained AB	52	Yes	No	Yes	NM	NM	50	45-55	QUAD, HAM, GLUT, calf
13	Tricycle ergometer (Duffell et al., 2010)	5 SCI and 5 AB	48 (5x/week)	Yes	No	NM	The maximal used during training	NM	50	50	QUAD, HAM, GLUT, calf

No.	FES cycling	Participants	Training (weeks)	Motorized	Arm cranking	Fixed AFO/pedal boot	Intensity (mA)	PW (µs)	Frequency (Hz)	Cadence (rpm)	Muscles stimulated
14	StimMaster (ELA, Dayton, Ohio) cycle ergometers (Eser et al., 2003)	19 SCI	3x/week	Yes	No	NM	140	300-400	30, 50, 60	40-50	QUAD, HAM, GLUT
15	Motorised recumbent tricycle modified for FES cycling (Ferrante et al., 2005)	2 complete SCI (T10, T9)	NM	Yes	No	Yes	NM	300, 500	20	10, 30, 50	QUAD, HAM, GLUT, calf
16	Custom-designed semirecumbent motorized isokinetic FES cycle ergometer (Fornusek et al., 2004)	10 SCI - ASIA A (T4 and T9)	Minimum 12 (3x/week)	Yes	No	NM	0-140	250	35	50	NM

No.	**FES cycling**	**Participants**	**Training (weeks)**	**Motorized**	**Arm cranking**	**Fixed AFO/pedal boot**	**Intensity (mA)**	**PW (µs)**	**Frequency (Hz)**	**Cadence (rpm)**	**Muscles stimulated**
17	RT300 FES bike (Restorative Therapies Ins; Baltimore, Maryland) (Gorgey et al., 2014)	10 SCI – ASIA A and B (C5-T10)	3x/week for 2-3 hours (h)	Yes	No	NM	140 (QUAD, HAM) and 100 (GLUT)	200, 350, 500	33.3	40-45	QUAD, HAM, GLUT
18	ERGYS I™ (Therapeutic Alliances®, Inc., Fairborn, OH) semi-reclined cycle ergometer (Haapala et al., 2008)	6 SCI - 4 complete and 2 incomplete SCI (C4 or below)	NM	Yes	No	Yes	140	500	50	50	QUAD, HAM, GLUT
19	iFES-LST (Hamzaid et al., 2012) and iFES-LCE (Fornusek et al., 2004)	5 SCI – ASIA A and B (T4-T10)	Minimum 8	Yes	No	Moveable AFO	110-140	400	35	10, 20, 30	QUAD, HAM, GLUT

No.	**FES cycling**	**Participants**	**Training (weeks)**	**Motorized**	**Arm cranking**	**Fixed AFO/pedal boot**	**Intensity (mA)**	**PW (µs)**	**Frequency (Hz)**	**Cadence (rpm)**	**Muscles stimulated**
20	ACE, FES-LCE, a combined ACE and FES-LCE system (ACE+FES-LCE), and a commercially available arm and leg tricycle (HYBRID; BerkelBike BV, ś-Hertogenbosch, the Netherlands), which incorporated an FES system to recruit the leg musculature (Hasnan et al., 2013)	9 M SCI – ASIA A, B and C	Minimum 8	NM	NM	Yes	140	300	35	50	QUAD, HAM, GLUT

No.	FES cycling	Participants	Training (weeks)	Motorized	Arm cranking	Fixed AFO/pedal boot	Intensity (mA)	PW (µs)	Frequency (Hz)	Cadence (rpm)	Muscles stimulated
21	Standard recumbent tricycle, which has been adapted to FES cycling (Hunt et al., 2002)	3 complete SCI (T7-T10)	6-8 (1x/week)	Yes	No	Yes	Maximum 120	0-800	20	NM	QUAD, HAM, GLUT
22	Standard recumbent tricycle (Hunt et al., 2004)	1 paraplegic (T8/9)	72	Yes	No	Yes	Maximum 120	0-800	20	NM	QUAD, HAM, GLUT
23	Recumbent tricycle (Crystal Engineering Trice) (Perkins et al., 2002)	1 SCI (T9)	NM	NM	No	Yes	3.2	2-990	20	25-85	Nerve root
24	Recumbent cycle ergometer (Ergys-1 Home Rehabilitation System, Therapeutic Alliance Inc, Dayton, USA) (Sinclair et al., 1996)	6 SCI (T4-T10) and 6 AB	SCI-8, AB-untrained	Yes	No	Yes	0-132	NM	30	50	QUAD, HAM, GLUT

No.	**FES cycling**	**Participants**	**Training (weeks)**	**Motorized**	**Arm cranking**	**Fixed AFO/pedal boot**	**Intensity (mA)**	**PW (µs)**	**Frequency (Hz)**	**Cadence (rpm)**	**Muscles stimulated**
25	MOTOmed Viva cycle ergometer (Reck Medizintechnik, Betzenweiler, Germany) (Sinclair et al., 2004)	7 SCI – ASIA A and B (T4-T9)	NM	Yes	No	NM	NM	NM	NM	NM	QUAD
26	Stationary tricycle (AC-servo MR 7434, ESR Pollmeier Ltd, Ober-Ramstadt, Germany) (Szecsi et al., 2014)	16 SCI - ASIA A (C5-T12)	24-192 (1-3x/week)	Yes	No	Yes	127	500	30	57-63	QUAD, HAM

*Noted that NM in the **Table 2.2** is information was not mentioned in the literature.

Based on **Table 2.2**, 23 studies have used stationary FES bike compared to mobile FES bike. This might be due to the low PO production in individuals with SCI, which is not enough to cycle mobile FES cycling (Duffell et al., 2008). Typically, the stationary FES bike is assisted with electric motor (Hunt et al., 2004). Therefore, overall PO can be increased as it can help to reduce muscles fatigue during cycling (Hunt et al., 2004). Hence, individuals with SCI can benefit maximum performance of cycling. Unlike the stationary FES cycling, mobile FES bike has difficulty to overcome disturbances such as slope and wind (Hunt et al., 2004), and thus prevents it from being used outdoors more extensively. Therefore, stationary FES cycling has been more commonly used in individuals with SCI compared to the mobile FES bike (Eser et al., 2003).

Besides that, the most common muscles stimulated in individuals with SCI are QUAD, HAM, and GLUT (15 studies). These muscles are the biggest group of muscles and the most important muscles in producing power for cycling task. Stimulation of these muscles will help to elevate cardiorespiratory activity (Mohr et al., 1997), improve circulation (Gerrits et al., 2001; Hooker et al., 1992), and reduce muscle atrophy (Bremner et al., 1992) in individuals with SCI.

Table 2.2 also shows that the fixed AFO or pedal boot has been commonly used in previous studies (13 studies). The fixed AFO or pedal boot was highly favored among researchers due to its safety reason by allowing the ankle to move in one degree-of-freedom (DOF) only (Abdulla et al., 2014; Berry et al., 2008; Perret et al., 2010; Trumbower & Faghri, 2005), since there is no stimulation to the lower leg muscles. By fixing the ankle joint, work can be produced (Trumbower & Faghri, 2005) by transmitting the torque from the whole leg to the pedal (Abdulla et al., 2014).

In addition, the stimulation parameters used are almost similar in most of the studies that are within the range of the standard FES stimulation parameters shown in **Table**

2.1. Stimulation intensity, stimulation frequency and PW that were commonly used in individuals with SCI are 140 mA, 50 Hz, and 300 µs, respectively. While the most common cadence selected in the previous studies was 50 rpm (14 studies).

This section helps the researcher to select the suitable stimulation parameters for individuals with SCI to maximize the overall performance of FES cycling exercise training. In the end of the FES cycling exercise training, high PO becomes the primary goal in individuals with SCI. Therefore, it is important for the researcher to find suitable stimulation parameters to achieve high PO from FES cycling in individuals with SCI. The next section will explain the PO generated from FES cycling. The next section will help the researcher to understand the importance of maximizing PO in FES cycling.

2.7 Power Output (PO)

This section will explain how PO generated during FES cycling and the importance of maximizing PO in FES cycling. In FES cycling, PO is the outcome of the stimulation intensity that produces muscles contraction force and the velocity (Berry et al., 2008; Duffell et al., 2010; Schutte et al., 1993). Power produced during cycling is delivered from the upper part of the body to the crank and pedal through the hip, knee, and ankle joints (Martin & Brown, 2009). PO produced by individuals with SCI during FES cycling reflects the exercise performance and health benefits (Duffell et al., 2008, 2009, 2010, 2010 (1)). Therefore, higher PO during FES cycling is crucial in order to maximize the health benefits of FES cycling (Duffell et al., 2008, 2009, 2010, 2010 (1)).

During cycling, the positive force is mainly produced in the power phase (downstroke) (when the crank is at the top dead center (TDC) of the rotation (0°), to when the crank is at the bottom dead center (BDC) of the rotation (180°)) (Hug et al., 2008; Zameziati et al., 2006). While resistive force is produced in the upstroke (from 180° at BDC to 0° at TDC).

2.7.1 Types of PO

The PO was categorized into 2 types; joint PO (internal PO) and mechanical PO (external PO). These POs are closely related to each other in order to complete FES cycling task.

2.7.1.1 Joint / internal PO

Joint PO is the PO resulted from muscles force generation (Haapala et al., 2008) multiplying by joints angular velocity. In cycling, the joint power is transferred from the upper body to the lower body through the hip joint, and to the pedal through the ankle joint (Martin & Brown, 2009). Joint PO is determined with standard inverse dynamic analysis. Generally, low joint PO is produced when the muscles are exposed to fatigue (Martin & Brown, 2009). This low joint PO affects the magnitude of the external PO as well.

In FES cycling, the QUAD muscles contribute to the largest force (Haapala et al., 2008; Martin & Brown, 2009; Szecsi et al., 2007; Trumbower & Faghri, 2004). QUAD muscles are responsible for knee extension, which is very important during the power propulsion phase of cycling (Szecsi et al., 2014). Knee joint is the major joint that is free to move during cycling. Therefore, changes of the knee movement affect the changes in PO (Haapala et al., 2008).

Other than QUAD, GLUT muscles also contribute larger force during cycling (Franco et al., 1999; Haapala et al., 2008). However, GLUT produces less power when the hip joint is hyper-flexed (at TDC) and hyper-extended (at BDC) (Perkins et al., 2002).

The ankle produces least power compared to the hip and knee during cycling (Martin & Brown, 2009). This is because of the small volume of the ankle muscles. The hind ankle muscles (plantarflexor); i.e. gastrocnemius and soleus complex, work to transmit the force from the hip and knee to the crank and pedal during cycling (Zajac, Neptune, & Kautz, 2002).

In overall, the knee and hip extensors contribute most of forces to propel the crank. Power phase (power production phase) of FES cycling occurs during early-middle knee-extension, middle-late hip-extension, early-middle knee-flexor phase, and middle-late hip-flexion (Szecsi et al., 2014).

2.7.1.2 Mechanical / external PO

Mechanical PO is the PO that is exerted externally to the crank and pedal to do cycling. Mechanical PO is developed from the internal PO of the muscles multiplied by the angular velocity. Typically, mechanical PO generated during FES cycling in individuals with SCI is very low (Gföhler et al., 2001). It ranged within 8 to 35 Watt (W) (Duffell et al., 2010).

Unlike joint PO, instrumented pedals or pedal sensors are frequently used to measure the mechanical PO during FES cycling (Blake, Champoux, & Wakeling, 2012; Hunt et al., 2012). **Table 2.3** shows the various types of sensors and methods used in the previous studies to measure the mechanical PO in individuals with SCI during FES cycling.

Table 2.3: Types of instrumented pedal/pedal sensor used to measure external PO during FES cycling in individuals with SCI.

Ergometer types	**Types of instrumented pedal/pedal sensor used**
Mobile recumbent tricycle (Inspired Cycle Engineering Ltd., Falmouth, Cornwall, UK) (Berry et al., 2008)	A motor and a crankshaft-mounted power sensor (SRM Powermeter; Schoberer Rad Messtechnik GmbH, Julick, Germany)
iFES-LCE (Fornusek & Davis, 2004)	Calculated from the motor current (derived torque) and crank velocity data.
Commercial tricycle (Trice; Inspired Cycle Engineering, Ltd., UK) (Duffell et al., 2008)	Calculated from the trainer setting and cycling cadence
Tricycle ergometer (Duffell et al., 2010)	Torque measurement sensor
StimMaster (ELA, Dayton, Ohio) cycle ergometers (Eser et al., 2003)	Calculated from the force applied to the flywheel and cadence
Custom-designed semirecumbent motorized isokinetic FES cycle ergometer (Fornusek et al., 2004)	Calculated from the instantaneous motor current and angular velocity
iFES-LST (Hamzaid et al., 2012) [developed based on the Biodex BioStep (Biodex Medical Sytem Inc., NY, USA) and iFES-LCE [developed based on the Motomed Viva system (Fornusek et al., 2004) (Motomed Viva 1, Reck Medizintechnik GmβH, Betzenweiler, Germany]	A set of 3 piezoelectric force transducers attached to and arranged along each foot pedal
ACE, FES-LCE, a combined ACE and FES-LCE system (ACE + FES-LCE), and a commercially available arm and leg tricycle (HYBRID; BerkelBike BV, ś-Hertogenbosch, the Netherlands), which incorporated an FES system to recruit the leg musculature (Hasnan et al., 2013)	Calculated by HYBRID, which is mounted on a stationary cycle resistance trainer (Tacx i-Magic; Tacx BV, Wassenaar, the Netherlands)
Recumbent cycle ergometer (Ergys-1 Home Rehabilitation System, Therapeutic Alliance Inc, Dayton, USA) (Sinclair et al., 1996)	An instrumented pedal

2.8 Low Power Output (PO) in Individuals with Spinal Cord Injury (SCI) during Functional Electrical Stimulation (FES) Cycling

The most outstanding problem in FES cycling in individuals with FES is the lower PO compared to the voluntary cycling in AB (Berry et al., 2012; Duffell et al., 2010; Eser et al., 2003; Fornusek et al., 2012; Gföhler et al., 2001; Sinclair et al., 2004; Szecsi et al., 2014). Low PO constrains the health benefits from FES cycling (Theisen et al., 2002; Soest et al., 2005). Maximize PO from FES cycling is very important as it reflects fitness (Soest et al., 2005).

Table 2.4 shows the POs generated during FES cycling in individuals with SCI reported from previous studies. This section is very important to this study as it provides a standard range of POs associated to the parameters that have been used in the previous studies that affect the PO during FES cycling in individuals with SCI. The PO reported in previous studies were ranged from 10 to 25 W (Mutton et al., 1997) and 5 to 10 W (Theisen et al., 2002). Gföhler *et al*. (Gföhler et al., 2001) reported the peak and average PO of 15 W and 8 W, respectively. On the other hands, Berry *et al*. reported increase in peak PO from 0.77 to 20.82 W between 0 to 6 months (Berry et al., 2008). Berry *et al*. also reported the highest SCI individual peak PO value of 35.6 W after 12 months of training (Berry et al., 2008).

There are many causes that contribute to the limited power production in individuals with SCI during FES cycling. One of the factors is the lower efficiency in converting metabolic energy into mechanical work compared to AB cyclists (Crameri et al., 2000; Duffell et al., 2009; Hunt et al., 2007). The other factors are insufficiency of artificial muscle activation, the crude control of muscle groups accomplished by stimulation, and muscle atrophy (Hunt et al., 2012; Szecsi et al., 2014). These factors lead to rapid fatigue rate, and hence further limiting the PO and health benefits from FES cycling (Rasmussen et al., 2004).

Low PO is not a significant problem for stationary FES cycling compared to mobile FES cycling (Hunt et al., 2013; Newham & Donaldson, 2007). Hence, it is important to investigate the factors that maximize the PO during FES cycling in order to maximize the health benefits outcome in individuals with SCI (Duffell et al., 2008; Eser et al., 2003).

Table 2.4: POs reported in the previous studies.

Study	SCI participants	Factor affecting PO	Reported PO
Physiologic responses during functional electrical stimulation leg cycling and hybrid exercise in spinal cord injured subjects (Mutton et al., 1997)	11 (C5-6 to T12-L1)	Types of exercise (hybrid exercise vs FES leg cycle training alone)	10-25 W
External power output changes during prolonged cycling with electrical stimulation (Theisen et al., 2002)	5 (4 males and 1 female) ASIA A (T4-T9)	Duration of cycling	5 to 10 W
Test bed with force-measuring crank for static and dynamic investigations on cycling by means of functional electrical stimulation (Gföhler et al., 2001)	4 paraplegics	Geometry for FES cycling	Peak PO: 15 W, average PO: 8W
Cardiorespiratory and power adaptations to stimulated cycle training in paraplegia (Berry et al., 2008)	12 (10 males and 2 females) ASIA A (T3-T12)	Duration and frequency of training exercises per week	Peak PO: increased from 0.77 to 20.82 W between 0 to 6 months of training. Highest SCI individual peak PO value: 35.6 W after 12 months of training
Consequences of ankle joint fixation on FES cycling power output: A simulation study (Soest et al., 2005)	None	Ankle joint movement	Releasing the ankle joint may elevate the PO by 14% with the tuning of contact point between the foot and pedal to the relative strength of the ankle plantar flexors, and with the addition of TS and TA muscles

Study	**SCI participants**	**Factor affecting PO**	**Reported PO**
Leg joint power output during progressive resistance FES-LCE cycling in SCI subjects: Developing an index of fatigue (Haapala et al., 2008)	6 SCI	Resistance	Ankle PO: 24.5 to 38.8 W Knee PO: 26.2 to 120.0 W Hip PO: -88.5 to 27.1 W Resultant pedal force: 22.6 to 25.0 Newton (N)
Maximizing muscle force via low-cadence functional electrical stimulation cycling (Fornusek & Davis, 2004)	9 ASIA A (T4-T9)	Cadence	Knee PO for 15 rpm: 2.7 to 1.1 W Knee PO for 50 rpm: 3.0 to 1.7 W
Influence of different stimulation frequencies on power output and fatigue during FES-cycling in recently injured SCI people (Eser et al., 2003)	19 recently injured SCI ASIA A (above T12)	Stimulation parameter (frequency)	30 Hz: 7 to 21 W 50 or 60 Hz: 9 to 30 W
Effects of electrical stimulation-induced leg training on skeletal muscle adaptability in spinal cord injury (Crameri et al., 2002)	5 complete SCI (T4 or below)	Training duration	11-112 kilojoules (kJ)

2.8.1 Factors Affecting the PO during FES Cycling

In order to understand the factors that can increase the PO of FES cycling, a vast parameters; either mechanically or physiologically, need to be considered. Such parameters are the movement of ankle joint, muscles stimulation, pedaling cadence, resistance or workload, stimulation parameters, and training duration.

2.8.1.1 Fixing and releasing ankle joint

Ankle positioning during cycling is one of the more important factors for effective pedaling (Pierson et al., 1997; Trumbower & Faghri, 2004), yet this has not received much research attention. It is reported that the calf muscle generates limited knee flexion movement due to the presence of orthosis that fixed the ankle angle, which may reduce the maximum PO (Ferrante et al., 2005; Haapala et al., 2008). The use of fixed AFO or pedal boot strongly affects the knee PO (Haapala et al., 2008), and thus affects the PO of FES cycling in individuals with SCI. On the other hand, the PO of fixed-ankle FES cycling can only be increased with the increasing of pedaling cadence (Soest et al., 2005).

In addition, fixing the ankle joint during cycling can increase the cardiorespiratory demand (Hakansson & Hull, 2009), reduce the energy demand on the upper leg muscles, and minimize the power loss at the ankle joint (Martin & Brown, 2009). Plantar flexor muscles at the ankle joint are important to transfer power generated in the whole limb to the pedal (Zajac et al., 2002). Therefore, fixing the ankle joint might minimize the power loss across this joint in the fatigued condition (Martin & Brown, 2009).

In contrast to the fixed-ankle FES cycling, only very few studies investigated the effect of free ankle joint in individuals with SCI during FES cycling, especially the effect on PO. Theoretically, releasing the ankle joint may elevate the PO by 14% with the tuning of contact point between the foot and pedal to the relative strength of the ankle plantar flexors, and with the addition of TS and TA muscles stimulation (Soest et al., 2005). Stimulation of the TS and TA in fixed-ankle FES cycling does not elevate the PO, except that it affected the cardiovascular and circulatory responses (Ferrante et al., 2005). However, it is expected that there is no difference in PO production between fixed- and free-ankle FES cycling if it is tested experimentally (Soest et al., 2005).

On the other hand, releasing the ankle joint would produce greater ankle DOF that negatively effect the kinematic relation between the crank and joint angles (Soest et al., 2005). However, previous study had suggested to allow the ankle joint to move in sagittal plane to resemble the pedal force and orientations of AB semireclined leg cycling (Trumbower & Faghri, 2005). Therefore, the pedaling effectiveness of free-ankle FES cycling can be improved (Faghri et al., 2001).

Besides that, freeing the ankle joint during cycling may cause hyperextension of the knee. However, it was found that freeing the ankle joint during FES cycling is not harmful if the knee is position in less extension at the BDC (Fornusek et al., 2012). The free-ankle FES cycling with the stimulation of the shank muscles (TS and TA) is found safe (Fornusek et al., 2012). In addition, free-ankle FES cycling increases the ankle excursions, which helps to improve joint mobility and prevent contractures in individuals with SCI (Fornusek et al., 2012).

Surprisingly, no studies have investigated the effect of free-ankle FES cycling on PO in reality. Therefore, it is important to quantify the effect of fixed- and free-ankle FES cycling on the PO generated during FES cycling in individuals with SCI, experimentally in this study.

2.8.1.2 Muscles stimulation

It is better to stimulate all five groups of muscle (QUAD, HAM, GLUT, TA and TS) during FES cycling in individuals with SCI. Stimulation of more muscles groups can contribute to a larger PO production (Fornusek et al., 2012). On the other hand, it was reported that shank muscles stimulation of TA and TS during FES cycling contribute to almost zero PO (Berkelmans, 2008) and did not affect the peak PO (Berry et al., 2008).

However, shank muscles stimulation of TA and TS could increase the ankle excursion (Fornusek et al., 2012) compared to the traditional muscles stimulation alone (QUAD, HAM, and GLUT). Therefore, it may help to treat ankle contractures, which are common complications for individuals with SCI. Contractures are likely unfavorable as this condition can hinder the performance of motor tasks (McDonald, Garrison, & Schmit, 2005). Besides that, shank muscles stimulation can also enhance blood flow to the lower legs, while delivering greater strength and endurance (Berkelmans, 2008; Fornusek et al., 2012) that may reduce the highly fatigable muscles of individuals with SCI. Low fatigable leg muscles could perhaps lead to the increase in PO.

However, to accomplish the shank muscles stimulation in individuals with SCI, the fixed AFO or pedal boot must be eliminated first. In other words, free-ankle FES cycling with all leg's muscles stimulation could contribute to greater PO production.

2.8.1.3 Pedaling cadence

PO in FES cycling is changing with the pedaling cadence (Schutte et al., 1993). Lower cadence produces higher muscle forces (Fornusek & Davis, 2004), thus produces lower PO. Therefore, higher pedaling cadence is needed in order to maximize the PO production of FES cycling in individuals with SCI.

2.8.1.4 Resistance or workload

Apart from the pedaling cadence, the PO is also affected by the changing of resistance or workload (Schutte et al., 1993). The activity of the muscle is highly associated with workload (Blake et al., 2012). Higher resistance contributes to higher PO production (Haapala et al., 2008). Therefore, greater resistance or workload is required to maximize PO of FES cycling in individuals with SCI. Furthermore, resistance or workload is important to improve and maintain muscle strength, muscle hypertrophy, and bone during FES cycling training.

2.8.1.5 Stimulation parameters

Stimulation parameters adjustment during FES cycling for each individual with SCI is very important to optimize PO. Researchers or clinicians have to avoid the use of too intense stimulation parameters that can cause rapid fatigue to individuals with SCI (Eser et al., 2003). Prolonged exposure to higher stimulation parameters such as stimulation frequency and PW can reduce the PO production.

2.8.1.6 Training duration

Studies have showed that prolonged FES cycling exercise training promotes increased PO in individuals with SCI (Berry et al., 2008; Kakebeeke et al., 2008). Significant increase in power has been reported (Berry et al., 2008) during early stage of training when both training resistance and volume are progressive.

It was reported that the peak PO increases from 0.77 to 20.82 W after 6 months of training and 35.6 W (mechanical plus joint PO) after 12 months of training (Berry et al., 2008). However, the PO was not further increased after 12 months of training (Berry et al., 2008). The training reaches plateau state, which might be due to the low of motivation levels and lower muscle endurance (Berry et al., 2008). Five well-trained SCI cyclists reach plateau as the PO dropped from 35 to 8 W (Duffell et al., 2010).

Besides that, PO of FES cycling was still low (less than 50 W) after one year of training (Mohr et al., 1997).

On the other hand, low level of FES cycling training (30 min, three times per week) was also able to improve PO after 10 to 12 weeks of training (Crameri et al., 2002). Another study however reported that one year of intensive FES cycling training (four one-hour sessions per week) showed a significant increase in PO in individuals with SCI (Berry et al., 2012).

2.9 Summary

As mentioned in section **2.4.2**, FES cycling exercise has been reported to provide health advantages to individual with SCI. The sole goal of FES cycling exercise is to get maximum PO as it reflects the fitness and performance capabilities of individuals with SCI. However, the PO generated during FES cycling in individuals with SCI is very low compared to the voluntary cycling in AB individuals. Therefore, researchers have sought for potential parameters to maximize the PO of FES cycling. One of the parameters is the ankle-foot biomechanics. Based on section **2.8.1.1**, a limited numbers of studies have investigated the relationship between the biomechanics of ankle-foot and the pedal PO (mechanical PO) during FES cycling in individuals with SCI. None of the studies have investigated the effect of fixed- and free-ankle joint movements on PO production during FES cycling in individuals with SCI in reality. The effect of fixed- and free- ankle joint movement during FES cycling on the pedal PO has been investigated before using the model simulation methods.

Fixed-ankle FES cycling has been highly favored among researchers due to its safety and kinematical reasons. However, fixed-ankle FES cycling restricts the ankle joint movement, and thus limits the natural movement of the ankle joint. The limitation of the natural movement at the ankle joint might limit the pedal PO during FES cycling in individuals with SCI. Therefore, free-ankle joint movement that allows the ankle to move in natural movement might help to maximize the pedal PO during FES cycling in individuals with SCI. Theoretically, releasing the ankle joint may elevate the PO by 14% with the tuning of contact point between the foot and pedal to the relative strength of the ankle plantar flexors, and with the addition of TS and TA muscles stimulation (Soest et al., 2005). In addition, the free-ankle FES cycling with the stimulation of the shank muscles (TS and TA) is found safe (Fornusek et al., 2012). In addition, free-ankle FES cycling increases the ankle excursions, which helps to improve joint mobility and prevent contractures in individuals with SCI (Fornusek et al., 2012). Stimulation of the TS and TA in fixed-ankle FES cycling does not elevate the PO, except that it affected the cardiovascular and circulatory responses (Ferrante et al., 2005). However, it is expected that there is no difference in PO production between fixed- and free-ankle FES cycling if it is tested experimentally (Soest et al., 2005).

Overall, we can conclude that, free-ankle FES cycling might give more advantages in terms of kinetics and kinematics to the individuals with spinal cord injury compared to the fixed-ankle FES cycling. Therefore, it is important to quantify the effect of fixed- and free-ankle joint movements on pedal PO during FES cycling in individuals with SCI. Due to the limited research from the previous studies, it is important to investigate the effect of the ankle-constrained movements on the pedal PO in AB first. AB has more power to perform cycling at any conditions compared to the individuals with SCI. Therefore; we can understand the “natural behavior” of the pedal PO and biomechanics of the leg joints during cycling with ankle-constrained movements in AB. This is important as we can set a standard where the effect of ankle-constrained movements on pedal PO and leg biomechanics during FES cycling in individuals with SCI could be compared.

Pertaining to the parameter of interest, 4 types of AFOs constrained movements (FP, DFP, DF, and PF AFO) will be used in this study to quantify which types of ankle movement will maximize the pedal PO during voluntary cycling in AB individuals. Each AFO will assist different types of ankle movements throughout cycling. FP AFP fixed the ankle at neutral position (90°) throughout cycling. DPF AFO allows the ankle to move from neutral to dorsi-plantarflexion position (provides natural ankle joint movement). DF AFO allows the ankle to move from neutral to dorsiflexion positon, while PF AFO allows the ankle to move from neutral to plantarflexion position. To our knowledge, none of the previous studies have investigated the specific types of ankle movement on the PO during cycling. Through these AFOs constrained movements, we can identify which ankle movement will be helpful to maximize the pedal PO during voluntary cycling in AB individuals.

The best two types of ankle-constrained movements found during voluntary recumbent cycling in AB individuals were further carried over to the second experiment, which was to quantify in FES cycling in individuals with SCI. In this study, complete individuals with SCI were chosen due to their inability to move without FES stimulation during cycling. Hence, any changes of PO production will solely be associated to the FES activity only and from the voluntary muscles activities.

CHAPTER 3: METHODOLOGY

This chapter describes the protocols and materials used in the study. It explains the participants' information, medical ethics, study design, experimental setup, data collection protocol, and data processing and analysis during voluntary and FES cycling in AB and SCI participants, respectively.

Pertaining to the first objective of the study, the effects of AFOs constrained movements on the peak and average pedal POs during voluntary cycling will be investigated. Then, the best two types of AFOs constrained movements found during voluntary cycling in AB participants were selected and further investigated in the second of the study in FES cycling in individuals with complete SCI. Therefore, there are 2 sub-sections for each section in this chapter; able-bodied (AB) and spinal cord injury (SCI) participants. The first sub-section reflects the first objective of the study, while the second sub-section reflects the second objective of the study.

3.1 Participants

3.1.1 Able-Bodied (AB) Participants

25 healthy participants (six males: 22.7 ± 1.9 y, 71.2 ± 14.1 kg and nineteen females: 21.6 ± 0.9 y, 58.7 ± 13.8 kg) participated in this study. All participants performed recumbent cycling with DF AFO, but only data of twenty participants who used FP AFO, and seventeen used DPF AFO and PF AFO, were retained and analyzed, because not all were able to maintain their cadences within the set cycling cadence. Individuals without previous or ongoing record of neurological, musculoskeletal, rheumatological, cardiovascular disorders or orthopaedic lower limb injuries were included. All the participants were untrained and unfamiliar with the recumbent cycling.

3.1.2 Spinal Cord Injury (SCI) Participants

7 individuals with complete SCI participants (ASIA-A and ASIA-B, lesion level between T11 to C5), six males (47.2 ± 12.4 y and 71.7 ± 8.5 kg) and one female (49 y and 82 kg) participated in this study (**Table 3.1**). The data was tested by bias in terms of age, gender, lesion level, and AIS. The results showed that the variances were equal for age below and above 50 [F (1, 26) = 0.26, *P* = 0.62)], males and female [F (1, 26) = 3.80, *P* = 0.06)], lesion level below and above C6 [F (1, 26) = 0.37, *P* = 0.55)], and ASIA A and B [F (1, 26) = 0.84, *P* = 0.37)]. Participants with no previous or ongoing record of neuromuscular, musculoskeletal, rheumatological, cardiovascular disorder or orthopaedic lower limb injuries were included. To meet the inclusion criteria of the SCI participants, clinicians had performed an ASIA assessment on the SCI participants. All the participants were trained with FES cycling for at least 12 weeks (Hamzaid et al., 2012; Sinclair et al., 1996).

Table 3.1: Physical characteristics of the SCI participants.

Participants	Age (y)	Gender	Lesion level	AIS	Height (m)	Weight (kg)
YU	49	F	T4	B	1.74	82
TS	51	M	C8	A	1.62	79.6
RI	30	M	C7	B	1.71	62.4
BO	36	M	C6	A	1.70	75.9
LC	59	M	C5-C7	B	1.73	80
MA	46	M	C6-C7	B	1.79	71.6
FO	61	M	T10-T11	A	1.72	60.5

3.2 Medical Ethics

All participants provided their written informed consent before taking part in the study (Appendix A). This study was approved by the local Medical Ethics Committee, University of Malaya Medical Centre, University Malaya, Kuala Lumpur, Malaysia due to involving human participants (Ref No.: 1003.14(1)) (Appendix C).

3.3 Experimental Setup

3.3.1 Able-Bodied (AB) Participants

A recumbent cycle ergometer (BerkelBike Pro, BerkelBike B.V., St. Michielsgestel, Netherlands) with its front wheel fixed to rollers during cycling was utilised in this study (**Figure 3.1**). Four AFOs (FP, DPF, DF, and PF AFO) with different ankle movements (**Figure 3.2**) were fabricated by the researcher herself using the same measurement of original AFO provided with the BerkelBike, where all participants' leg could fit into it. The AFOs were fabricated using 5 mm polypropylene and the types of ankle joints used were Tamarack (DPF AFO) and Oklahoma (DF and PF AFOs) joints. The lower legs of each participant were placed in the AFO that was affixed to a force sensing pedal (Garmin-Vector, Garmin Ltd. Kansas City, USA) through custom made footplate. The footplate, which was fixed onto the bottom of the AFO, was connected to the pedal (**Figure 3.3**). It allowed the AFOs to be unscrewed from the pedal to change to another AFO. During cycling, FP AFO was used to fix the ankle angle at neutral position (90°); DPF AFO allowed the ankle to move from the neutral position to both dorsiflexion and plantarflexion; DF AFO allowed the ankle to move from the neutral position to dorsiflexion; and PF AFO allowed the ankle to move from neutral position to plantarflexion. The distance between seat position and the crank axle was adjusted for each participant according to their height and leg length. The distance was adjusted until the knee joint angle of each participant reached 160° at the BDC (180° was where the knee joint is fully extended). The backrest was standardized to 45° as this angular posture was reported to provide maximum PO during recumbent cycling (Schutte et al., 1993). The backrest angle was measured using an analogue goniometer. To measure the joint angles, a two-dimensional approach using a single video camera was used to capture the markers placed at the right shoulder, hip, knee, ankle and fifth metatarsophalangeal joint. The marker placements for the ankle and fifth metatarsophalangeal joints were on the AFO. The upper limb positions were standardized between participants as shown in **Figure 3.1**.

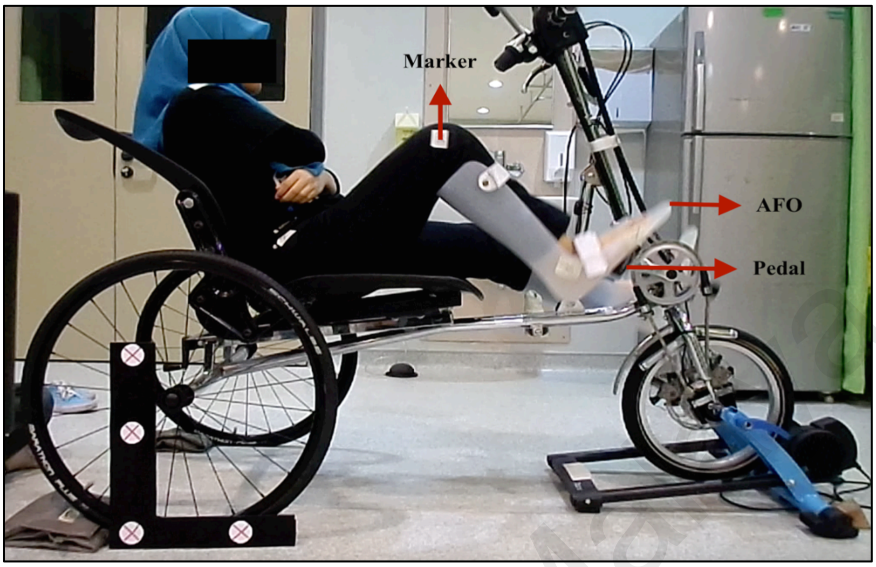


Figure 3.1: Set up for recumbent cycling with FP AFO-constrained ankle movement. Shown is the standardized seat back angle and markers on key anatomical locations.


a) FP AFO
b) DPF AFO
c) DF AFO
d) PF AFO

Figure 3.2: The AFOs constrained movements used in the study; a) FP AFO, b) DPF AFO, c) DF AFO, and d) PF AFO. The arrow indicates the movement allowed by the orthoses at the ankle joint.

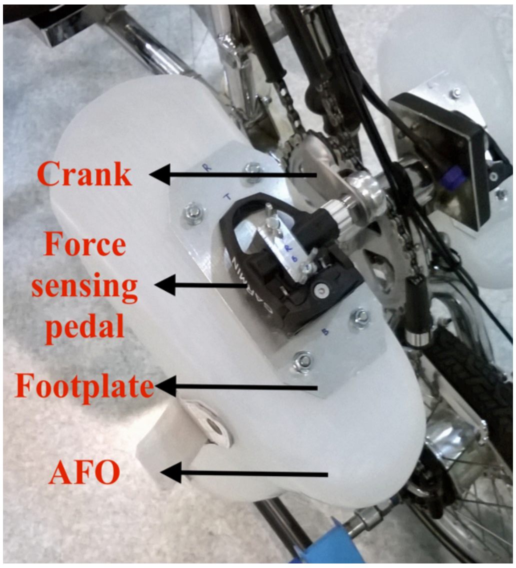


Figure 3.3: Customized footplate used in the study. The footplate was fixed onto the bottom of the AFO, and connected to the pedal. It allowed the AFOs to be unscrewed from the pedal to change to another AFO.

3.3.2 Spinal Cord Injury (SCI) Participants

A FES cycle ergometer (MOTOmed viva 2) was utilized in this study (**Figure 3.4**). Self-adhesive gel electrodes were placed over the belly of the leg muscles that were stimulated (QUAD, HAM, TA and TS). For QUAD, the proximal electrode was placed 1/3 of the distance from the inguinal line to the superior patellar border and the distal electrode placed 6–8cm proximally to the patellar border (Szecsi et al., 2014). For HAM, the proximal electrode placed 2–4 cm below the gluteal crease and the distal electrode placed above 4–5 cm above the popliteal space (Szecsi et al., 2014). Electrode placement measurement was kept consistent between trials. An in-shoe F-Scan system (Tekscan Incorporated, Boston, Massachusetts) was placed under the participants' foot and connected to a cuff unit that linked the foot sensors to a computer via a 10-m cable (Kearney, Lamb, Achten, Parsons, & Costa, 2011). For the fixed-ankle FES cycling, the lower legs of each participant were placed on FP AFO that was fixed to the pedal to restrict the ankle joint movement (**Figure 3.5**). During cycling, FP AFO was used to fix the ankle angle at neutral position (90°). Free-ankle cycling allowed the ankle to move from the neutral position to dorsi-plantarflexion (**Figure 3.5**). The seat position from the crank axle was adjusted and recorded for each participant so that the knee extension did not exceed 150-160° at the bottom dead center (BDC) (Szecsi et al., 2014). The knee extension angles were measured using analogue goniometer. Motion capture systems (Qualisys and Vicon) were used to capture the marker placed at the hip, knee, ankle, fifth metatarsophalangeal joints, crank axle and pedal. The markers placement for the ankle and fifth metatarsophalangeal joints were on the AFO.

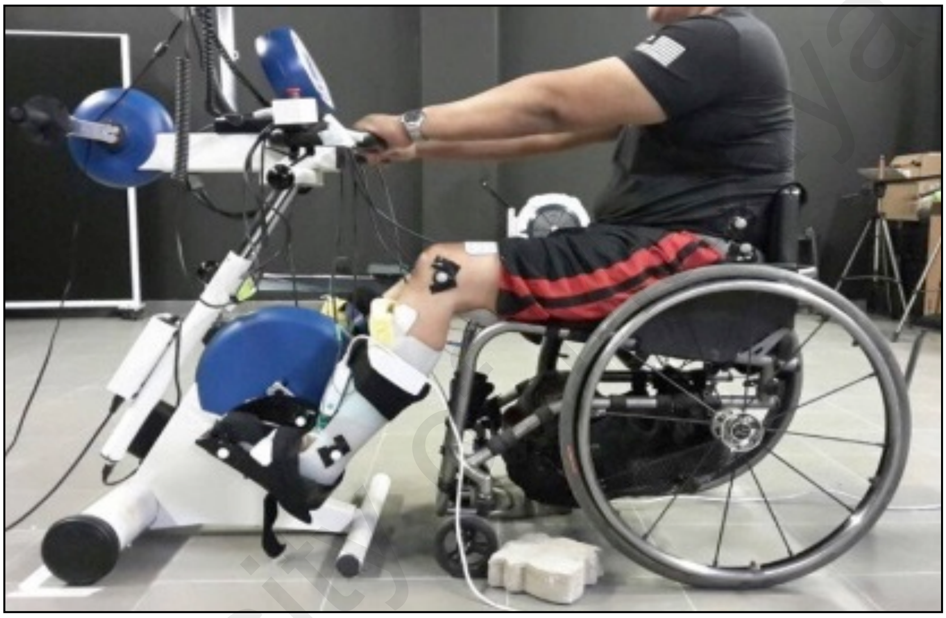


Figure 3.4: Experimental set up for FES cycling in the SCI participants.

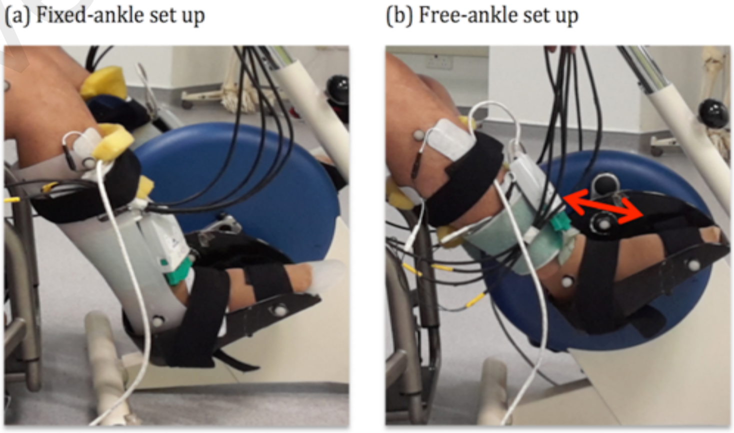


Figure 3.5: Ankle set up used in this study during FES cycling in SCI participants; a) fixed-ankle FES cycling, b) free-ankle FES cycling. The arrow indicates the movement allowed by the orthosis at the ankle joint.

3.4 Experimental Design and Data Collection Protocol

The participants were instructed to rest a day before the day of the experiment to prevent fatigue during the experiment. Before the collection of the data began, the AB participants were instructed to cycle with AFOs constrained ankle movements within the cadence ranging of 60 – 80 rpm, while the SCI participants were instructed to cycle in fixed- and free-ankle set up during FES cycling. The participants were required to wear sport shoes and tight pant during the experiment.

3.4.1 Able-Bodied (AB) Participants

Each AB participant in this cross-sectional study underwent the measurement of the peak and average pedal POs for 4 types of AFOs constrained ankle movement during voluntary cycling in one experimental session. The participants performed minimum loaded cycling within the set cadence range using visual feedback. The cadence range was measured using the Garmin Edge 510 placed on the front part of the cycle. Each participant was required to perform cycling with the FP, DPF, DF and PF AFOs in randomized order for one-minute followed by 5-minutes recovery periods. A one-minute cycling with instructed speed ranging of 60 to 80 rpm was set for each constrained ankle movements to extract maximum PO during cycling. Power phase was defined from TDC to whereas recovery phase was defined from BDC to TDC.

3.4.2 Spinal Cord Injury (SCI) Participants

Each SCI participants in this cross-sectional study underwent the measurement of the peak and average pedal POs for the fixed- and free-ankle set up during FES cycling. Testing was conducted in two sessions. The first session required the participants to perform fixed-ankle FES with FP AFO. The second session required the participants to perform free-ankle FES cycling. Two stimulation modes of cycling were performed for each session. In mode 1, the participants were required to perform FES cycling with

QUAD and HAM stimulation (known as QH stimulation). While in mode 2, the participants were required to perform FES cycling with QUAD, HAM, TA, and TS stimulation (known as QHT stimulation). **Figure 3.6** shows the protocol involved in the study. For each session, the participants were required to perform 1 min of passive cycling (warm up), 2 min of FES cycling (with different modes), 1 min of passive cycling (cool down), and 10 min of resting phase. The order of each session was randomized for each participant. The participants performed two sets of trials sets for each session to extract PO. Each trial was separated by at least 48 hours of recovery periods to prevent fatigue. The participants performed cycling at 50 rpm. Fixed stimulation PW and frequency, and the highest possible stimulation intensity that the participants can withstand were applied by an 8-channel stimulator (RehaStim ScienceMode, HASOMED GmbH, German) (**Table 3.2**). Power phase was defined during downstroke from TDC (270°) to BDC (90°), whereas recovery phase was defined during upstroke from BDC (90°) back to TDC (270°). The stimulation angle of each muscle was fixed between the participants and within the cycling modes. **Figure 3.7** shows the stimulation angle that was used in this study. The QUAD was stimulated from 197° to 337°, HAM was stimulated from 17° to 157°, TA was stimulated from 127° to 247°, and TS was stimulated from 337° to 77°. Note that the stimulation angle was determined based on the crank position during cycling.

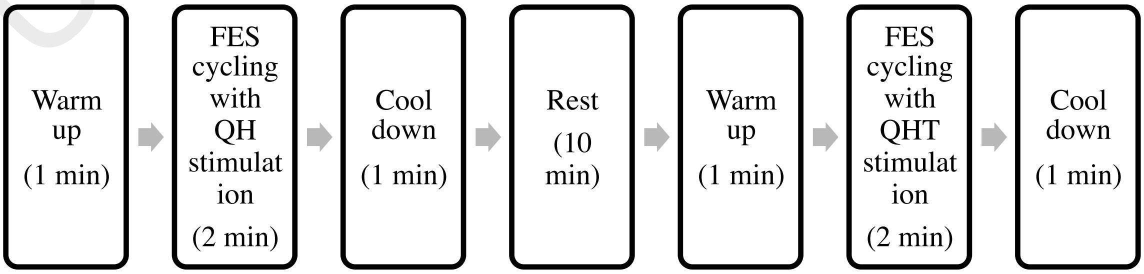


Figure 3.6: The test protocol of the study for the SCI participants.

Table 3.2: Stimulation parameters used in the study.

Participants	PW (μs)	Frequency (Hz)	Stimulation intensity (mA)
YU	300	30	100
TS	300	30	60
RI	300	30	100
BO	300	30	100
LC	300	30	100
MA	300	30	100
FO	300	30	60

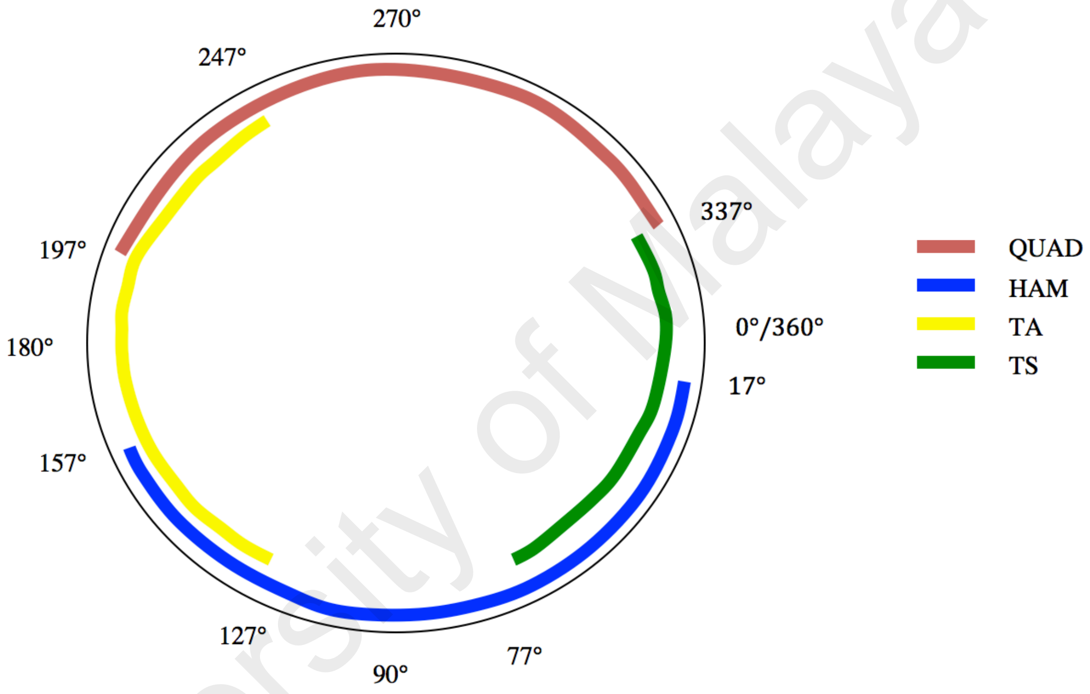


Figure 3.7: The stimulation angle used in the study.

3.5 Data Processing and Analysis

3.5.1 Able-Bodied (AB) Participants

The cycle PO and cadence of each 1-minute cycling session was recorded wirelessly (ANT+ module, Garmin Ltd. Kansas City, USA) using a commercial data acquisition unit (Garmin Edge 510, Garmin Ltd. Kansas City, USA) and software (Golden Cheetah, version 3.1, Golden Cheetah open project) to store the data into a PC for offline analysis. The PO was obtained directly from the force sensing pedal (Garmin-Vector, Garmin Ltd. Kansas City, USA). The outcome measurement is in Watts (W) unit. Static and dynamic calibration of the force sensing pedal were done beforehand to maximize the accuracy of the sensor. The angles of the hips, knees and ankles were recorded at 120 Hz. The last one minute of the event was synchronized, extracted and further analyzed using Kinovea software (0.8.15, Kinovea open project). The video was synchronized with the sensing pedal since the beginning of the experiment using a timer. The peak and average PO of each constrained ankle movement during the entire cycling period for each participant was used for further analysis.

3.5.2 Spinal Cord Injury (SCI) Participants

The kinetic data for each trial was recorded and analyzed in real time at 120 Hz by the software (Tekscan Incorporated, Boston, Massachusetts) to store the data into a PC for offline analysis. The kinematic data were also recorded simultaneously by the motion capture systems (Qualisys and Vicon) at 120Hz. Only the last 20 s kinetic and kinematic data of each cycling mode for each session were recorded and analyzed (**Appendices E** and **F**, respectively).

3.6 Statistical Analysis

Levene's test was performed to analyze the equality of the variances in different group of participants. One-Way Repeated Measures Analysis of Variance (ANOVA) between group factor analysis was performed to analyze the effect of PO generated by the ankle movement. K-S test was also performed to analyze the normality of data distribution. All statistical analysis was performed at a significance level of $\alpha = 0.05$. Therefore, a $P \leq 0.05$ was considered statistically significant. All data were statistically analyzed using SPSS software (IBM SPSS Statistics, version 20, New York, USA)

CHAPTER 4: RESULTS

This chapter presents all the findings of the study. All parameters of interest associated with the study were compared statistically among the participants, AFOs constrained ankle movements, and FES cycling modes. The results are presented in graph and table. This chapter is divided into 2 main sections associated with the parameters of interest of the study; pedal power output (PO) and kinematics of the leg joints for able-bodied (AB) and spinal cord injury (SCI) participants.

4.1 Pedal Power Output (PO)

4.1.1 Able-Bodied (AB) Participants

There was no significant difference between PO generated from pedal forces at cadence ranging between 60 to 80 rpm. **Figures 4.1** and **4.2** portray the peak and mean PO values generated by the FP, DPF, DF, and PF constrained ankle movements. The peak and average POs in all constrained ankle movements was (min – max) [27.2 ± 12.0 W (range 6 – 60)] and [17.2 ± 9.0 W (range 2 – 36)], respectively, with only 14.6 % variance between mean data among AFOs. The present study observed that there was no significant difference in the peak [F (3, 75) = 2.31, P = 0.083, η^2 = 0.085] and average pedal POs [F (3, 75) = 2.54, P = 0.063, η^2 = 0.0992] between AFO-constrained ankle movements during recumbent cycling. However, DPF AFO contributed to the highest normalized peak and average pedal POs compared to the other AFO-constrained ankle movements. On the other hand, DF AFO produced lowest normalized peak and average pedal POs. Therefore, FP AFO (fixed-ankle) and free-ankle constrained movements have been chosen to be further investigated in FES cycling in individuals with SCI. DPF AFO used during recumbent cycling in AB participants works exactly like free-ankle FES cycling in SCI participants.

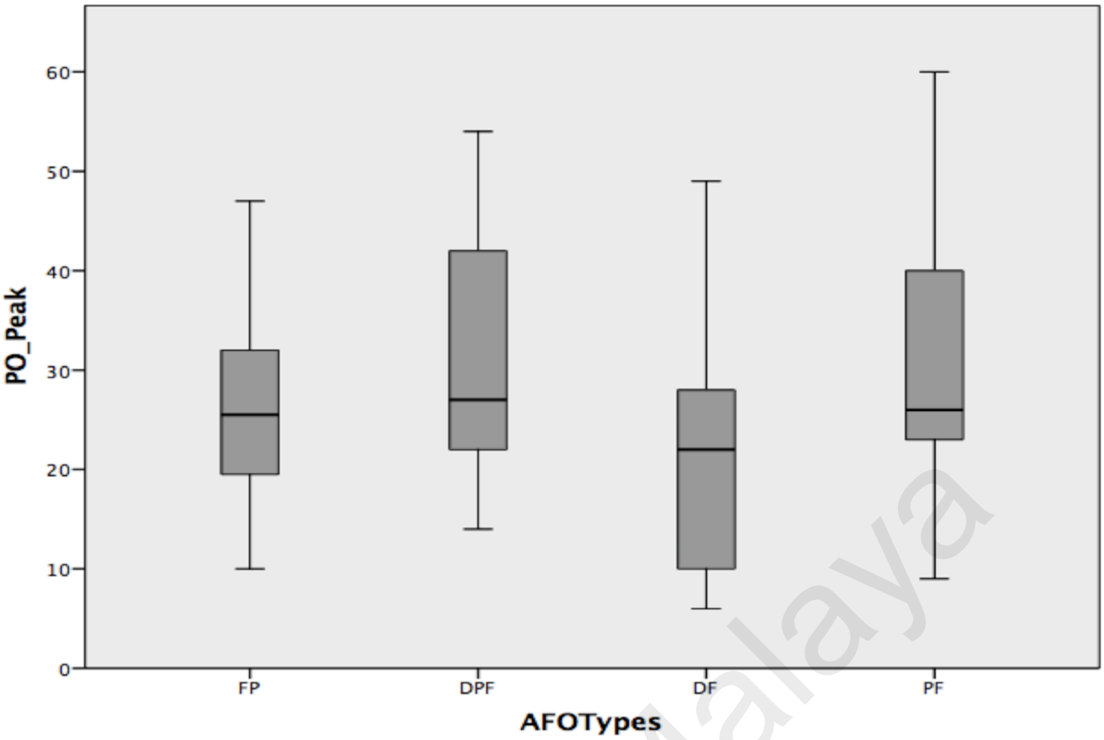


Figure 4.1: Peak PO values generated by the ankle movements during cycling.

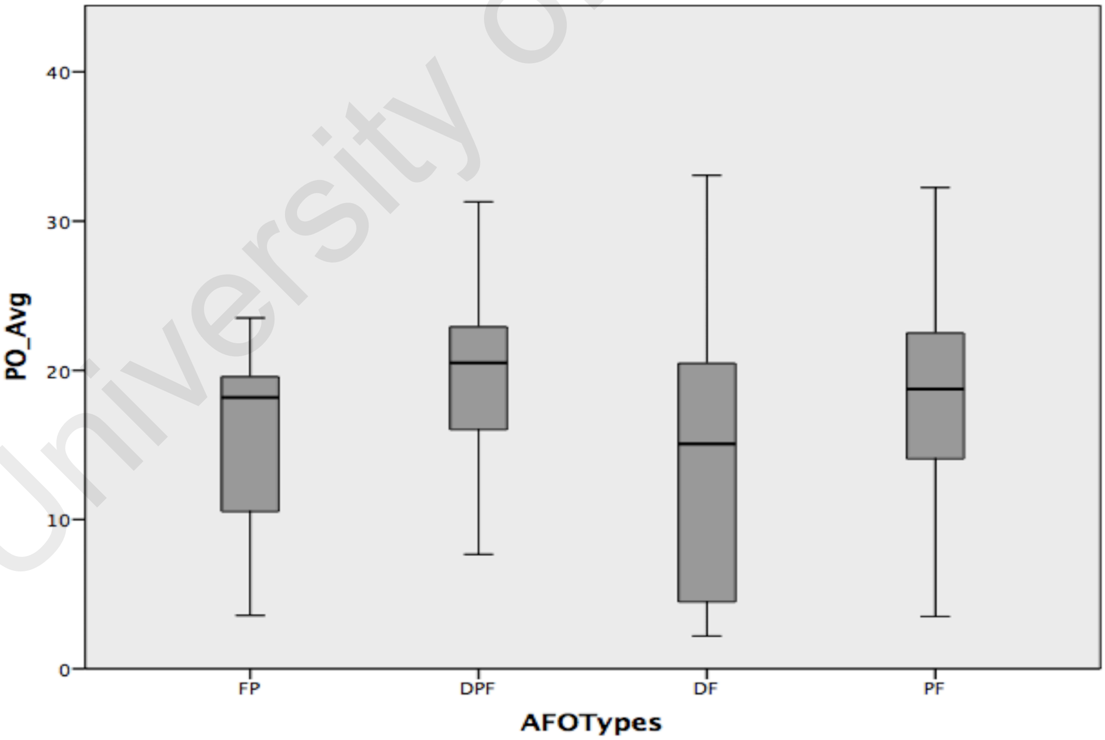


Figure 4.2: Average PO values generated by the ankle movements during cycling.

4.1.2 Spinal Cord Injury (SCI) Participants

The present study observed that there was no significant difference in the normalized peak [F (3, 24) = 0.32, *P* = 0.81] and average pedal POs [F (3, 24) = 1.19, *P* = 0.33] during fixed- and free-ankle FES cycling with QH and QHT stimulation modes. The present study also observed that the normalized peak and average pedal POs did not deviate significantly from normal [D (28) = 0.12, *P* = 0.20 and D (28) = 0.14, *P* = 0.14, respectively]. **Figures 4.3** and **4.4** portray the normalized peak and average pedal POs generated during fixed- and free-ankle FES cycling with QH and QHT stimulation modes. Based on **Figures 4.3** and **4.4**, free-ankle FES cycling with QH stimulation produced the lowest normalized peak and average pedal POs compared to other modes of FES cycling. Fixed-ankle FES cycling with QH stimulation contributed to the highest normalized peak pedal PO. While, free-ankle FES cycling with QHT stimulation produced highest normalized average pedal PO. **Table 4.1** further illustrates the normalized peak and average pedal POs between FES cycling modes.

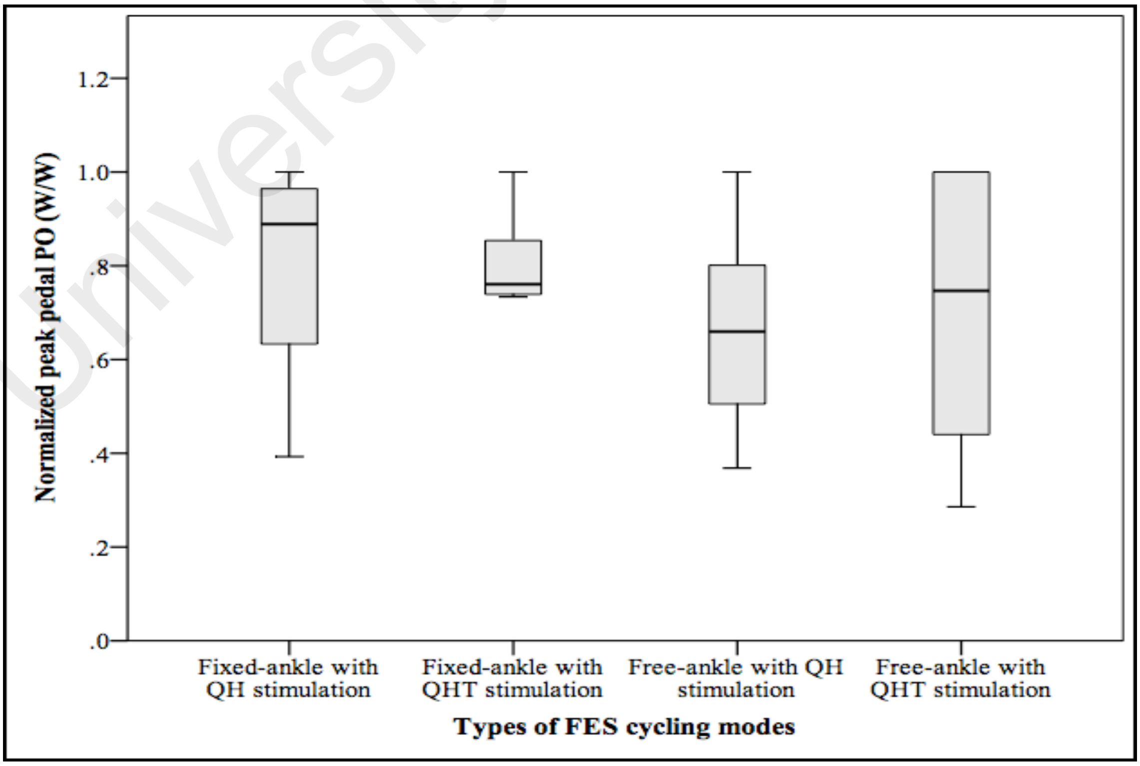


Figure 4.3: Normalized peak pedal PO produced between FES cycling modes.

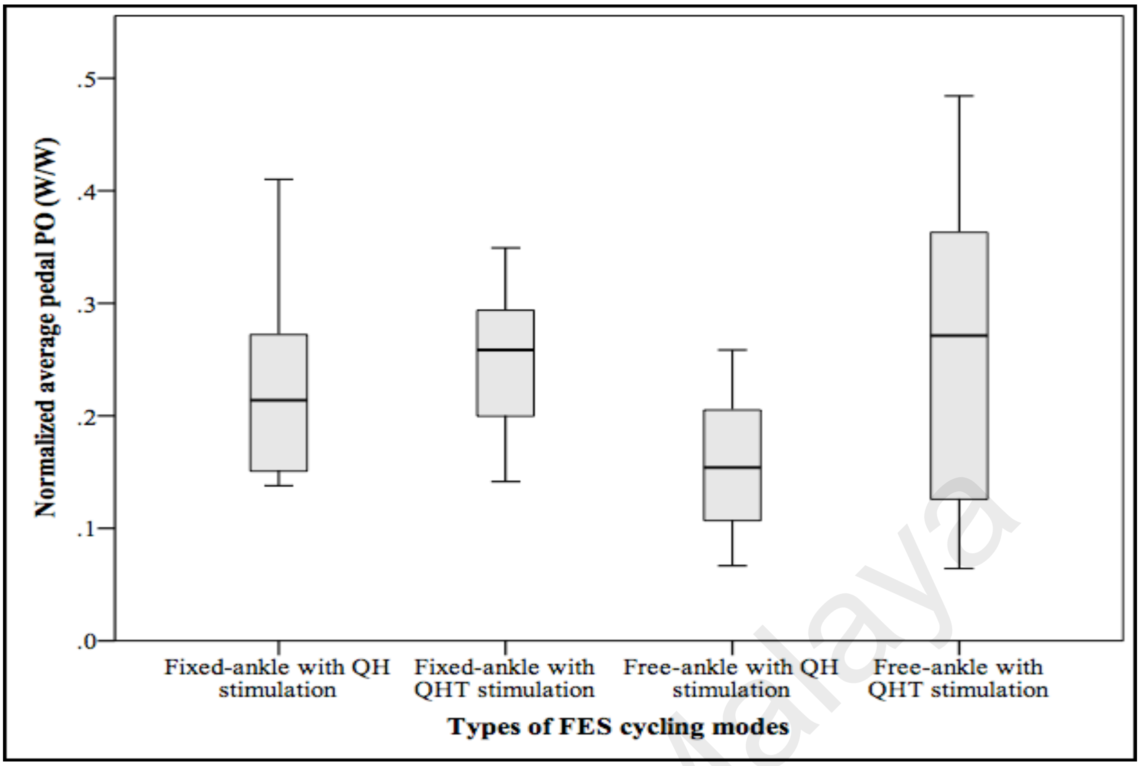


Figure 4.4: Normalized average pedal PO produced between FES cycling modes.

Table 4.1: The normalized peak and average pedal POs between FES cycling modes.

FES cycling modes	Normalized peak pedal PO (W/W)	Normalized average pedal PO (W/W)
Fixed-ankle with QH stimulation	0.78 ± 0.23	0.23 ± 0.10
Fixed-ankle with QHT stimulation	0.75 ± 0.21	0.25 ± 0.07
Free-ankle with QH stimulation	0.66 ± 0.23	0.16 ± 0.07
Free-ankle with QHT stimulation	0.70 ± 0.31	0.26 ± 0.16

The present study also observed that there was significant difference in the normalized pedal PO between FES cycling modes at every 20° of crank angle (**Figure 4.5**). Different groups of muscle were being stimulated at the same time at different crank angle during cycling. Therefore, the normalized PO for every 20° of crank angle throughout the cycling was analyzed. **Figure 4.5** shows that the significant difference in the normalized pedal PO between FES cycling modes occurred during the power phase of cycling, at the crank angle of 20° and 100°. Overall, the present study showed that

QUAD and HAM muscles produced higher normalized pedal PO than TA and TS muscles in all FES cycling modes (**Figure 4.5**). **Tables 4.2** and **4.3** further illustrate the relationship between the normalized pedal PO and FES cycling modes at every 20° of crank angle. There was significant difference in the normalized pedal PO between the fixed-ankle FES cycling with QHT stimulation and free-ankle FES cycling with QH stimulation at the crank angle of 20° and 80°. There was also significant difference in the normalized pedal PO observed between the fixed- and free-ankle FES cycling with QH stimulation at the crank angle of 60° and 80°. Besides that, the normalized pedal PO shows significant difference between free-ankle FES cycling with QH stimulation and free-ankle FES cycling with QHT stimulation at the crank angle of 80° and 100°.

The present study also revealed the magnitude of the peak and average pedal POs in all FES cycling modes of (min – max) (22.4 ± 17.9 – 48.6 ± 44.3 W) and (6.7 ± 7.4 – 13.0 ± 11.2 W), respectively.

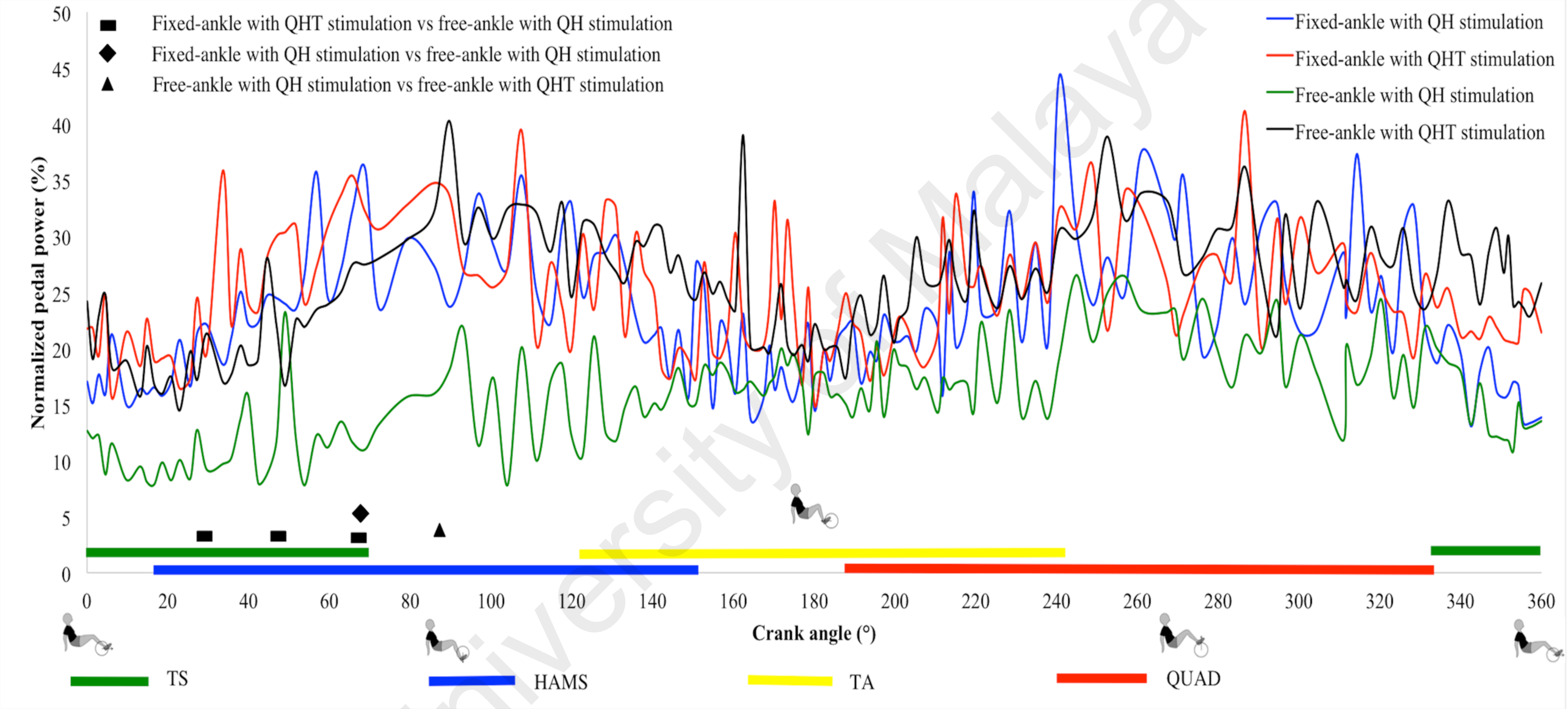


Figure 4.5: The significant difference in the normalized pedal PO between FES cycling modes at every 20° of crank angle.

Table 4.2: Symbols used in Figure 4.5 to identify the types of FES cycling mode.

FES cycling modes	Symbol
Fixed-ankle with QHT stimulation and free-ankle with QH stimulation	■
Fixed-ankle with QH stimulation and free-ankle with QH stimulation	◆
Free-ankle with QH stimulation and free-ankle with QHT stimulation	▲

Table 4.3: Significant difference in the normalized pedal PO between FES cycling modes.

Crank angle (°)	FES cycling modes	Normalized pedal PO (W/W)	Significant difference
20 - 40	■	23.0 ± 7.7 and 10.3 ± 4.3	F (3, 24) = 2.0, P = 0.03
40 – 60	■	27.2 ± 11.5 and 12.5 ± 4.4	F (3, 24) = 2.1, P = 0.03
60 – 80	■	32.5 ± 16.8 and 12.1 ± 5.0	F (3, 24) = 3.07, P = 0.01
60 – 80	◆	28.7 ± 14.7 and 12.1 ± 5.0	F (3, 24) = 3.07, P = 0.03
80 - 100	▲	16.6 ± 3.6 and 32.8 ± 21.6	F (3, 24) = 1.91, P = 0.04

4.1.3 Summary

To conclude, there was no significant difference in the peak and average pedal POs between all constrained ankle movements and stimulation modes in both AB and SCI participants. However, there was significant difference in the normalized pedal PO between FES cycling modes at every 20° of crank angle during the power phase of cycling in SCI participants.

4.2 Kinematics of the Leg Joints

4.2.1 Able-Bodied (AB) Participants

There were also no significant differences in the changes of the hip and knee joints angles with different AFOs (P = 0.974 and P = 1.00, respectively). However, there was significant difference in the changes of the ankle joint angle ($P < 0.01$). The hip, knee, and ankle joint excursions are presented in **Figures 4.6**, **4.7**, and **4.8**. It can be clearly seen that only ankle joint excursions are different among AFOs (min – max) (FP: 90.0 – 90.0°, DPF: 84.8 ± 8.1 – 95.1 ± 5.5°, DF: 82.7 ± 7.8 – 91.8 ± 10.7°, PF: 95.0 ± 7.3 – 102.9 ± 9.7°).

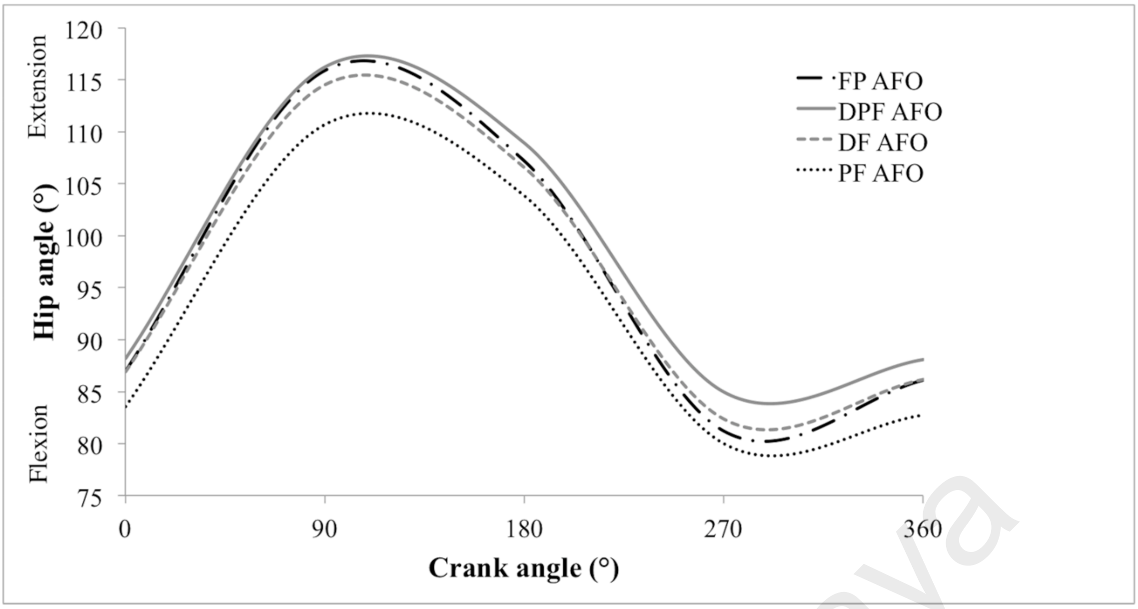


Figure 4.6: Changes in the hip joint excursions as a function of crank angle during cycling.

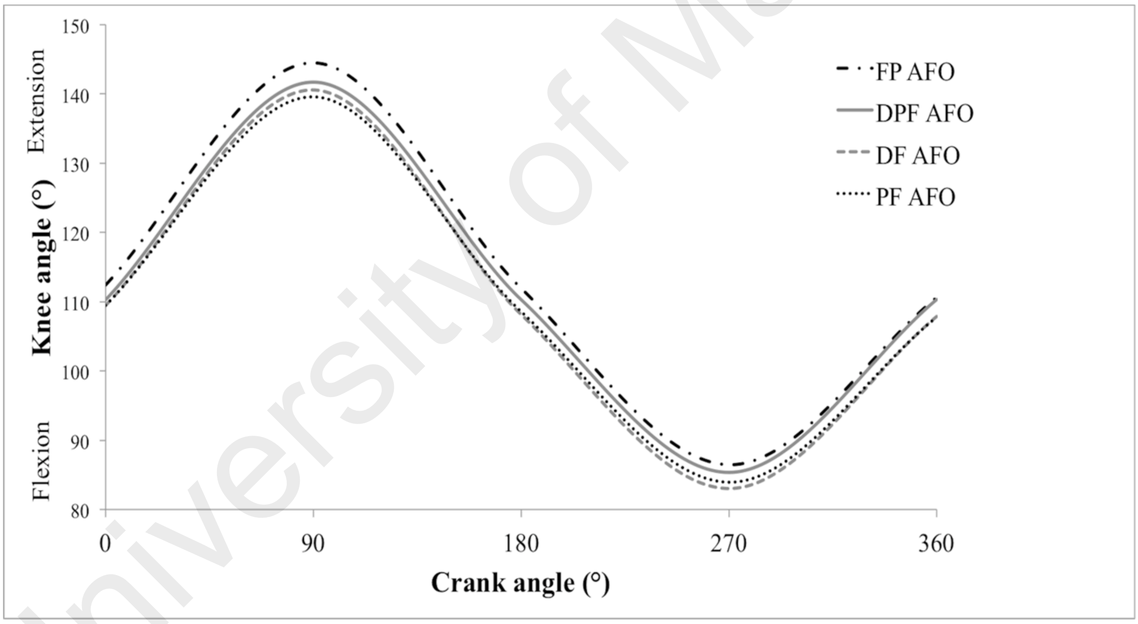


Figure 4.7: Changes in the knee joint excursions as a function of crank angle during cycling.

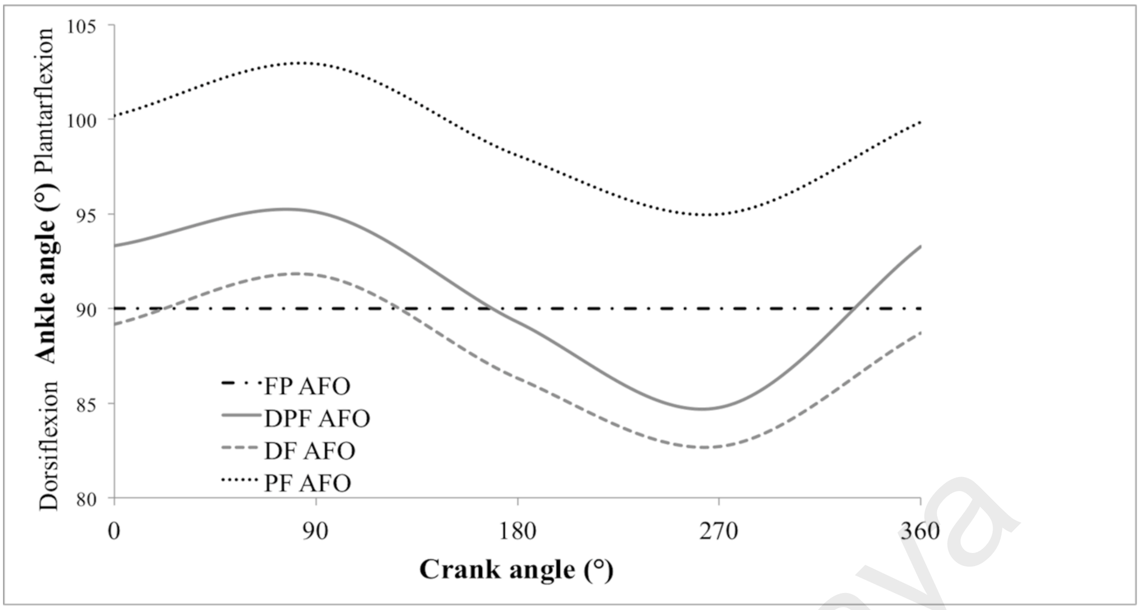


Figure 4.8: Changes in the ankle joint excursions as a function of crank angle during cycling.

4.2.2 Spinal Cord Injury (SCI) Participants

The hip, knee, and ankle joint ROMs are presented in **Figures 4.9**, **4.10**, and **4.11**, respectively. The hip and knee joint ROMs did not show any significant differences between the FES cycling modes [F (3, 24) = 0.43, *P* = 0.73; and F (3, 24) = 0.2, *P* = 0.9, respectively]. On the other hand, there was signicant difference in the ankle joint ROM between the FES cycling modes [F (3, 24) = 3.35, *P* = 0.04]. The present study also observed that the ankle ROM [D (28) = 0.23, *P* = 0.001] significantly non-normal; however, the knee [D (28) = 0.16, *P* = 0.07] and hip ROMs [D (28) = 0.12, *P* = 0.20], were both did not deviate significantly from normal.

Based on **Figure 4.11**, free-ankle FES cycling with QHT stimulation contributed to the largest ankle joint ROM (18.6 ± 9.9°), while fixed-ankle FES cycling with QH stimulation produced the lowest ankle joint ROM (4.2 ± 4.5°). The ankle joint ROMs produced by fixed-ankle FES cycling with QHT stimulation and free-ankle FES cycling with QH stimulation contributed were 9.3 ± 11.1° and 12.6 ± 7.9°, respectively.

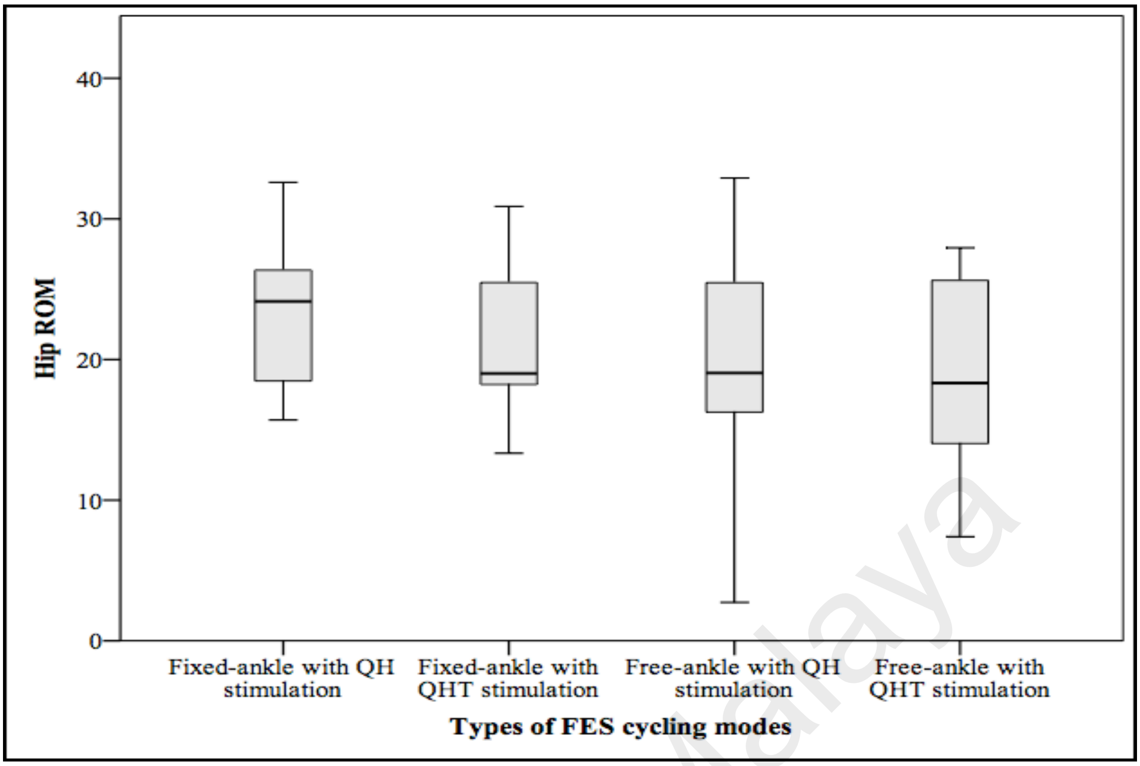


Figure 4.9: Changes in the hip joint ROM between FES cycling modes.

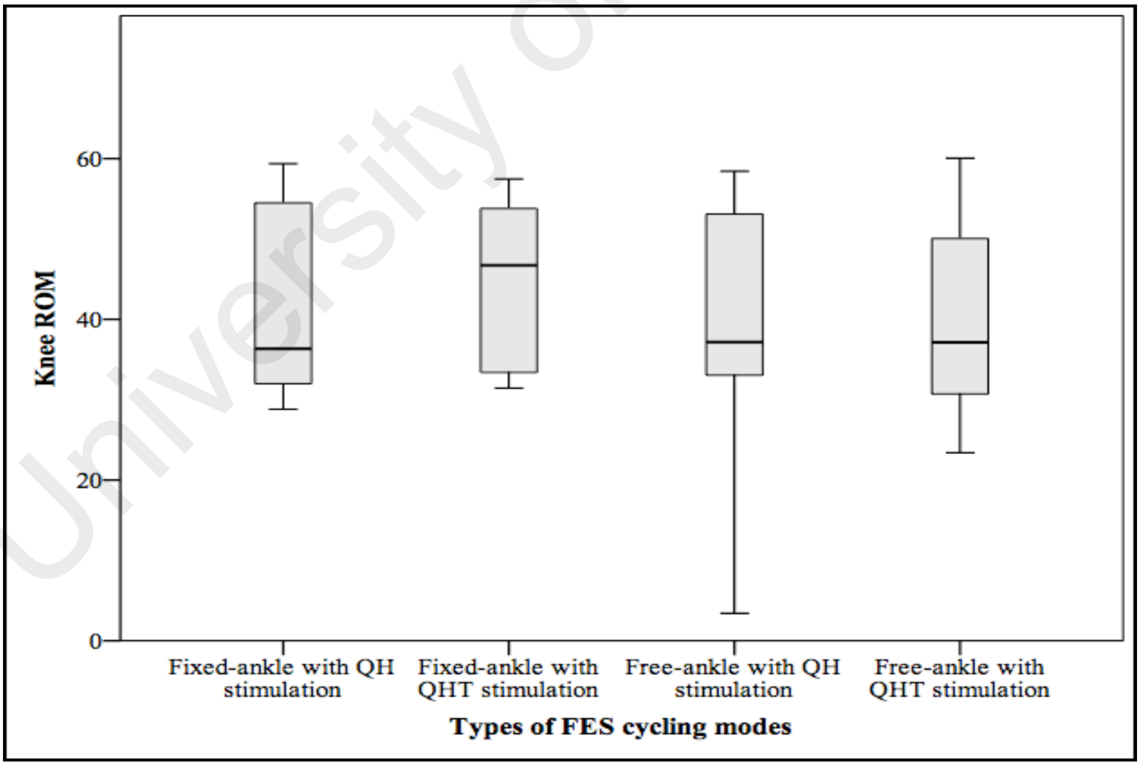


Figure 4.10: Changes in the knee joint ROM between FES cycling modes.

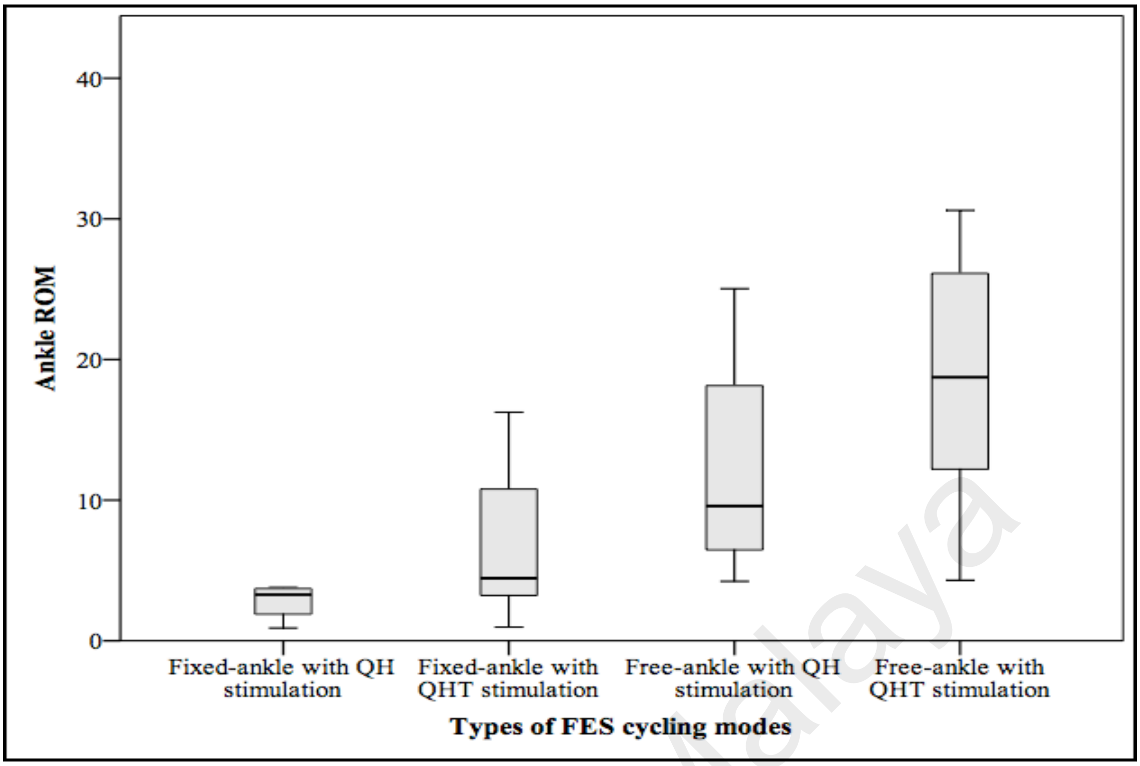


Figure 4.11: Changes in the ankle joint ROM between FES cycling modes.

Figures 4.12, **4.13**, and **4.14** potray the changes in the hip, knee, and ankle joint excursions between FES cycling modes, respectively. Based on **Figure 4.14**, it can be clearly seen that only ankle joint excursions were differed between FES cycling modes. **Table 4.4** illustrates the changes in the hip, knee, and ankle joint excursions (min – max) between FES cycling modes. On the other hand, **Figure 4.14**, showed significant difference in the ankle ROM between FES cycling modes at every 20° of crank angle. The significant change in the ankle ROM occured mostly in the power phase of cycling. **Table 4.5** further illustrates the significant difference in the ankle joint ROM between FES cycling modes at every 20° of crank angle.

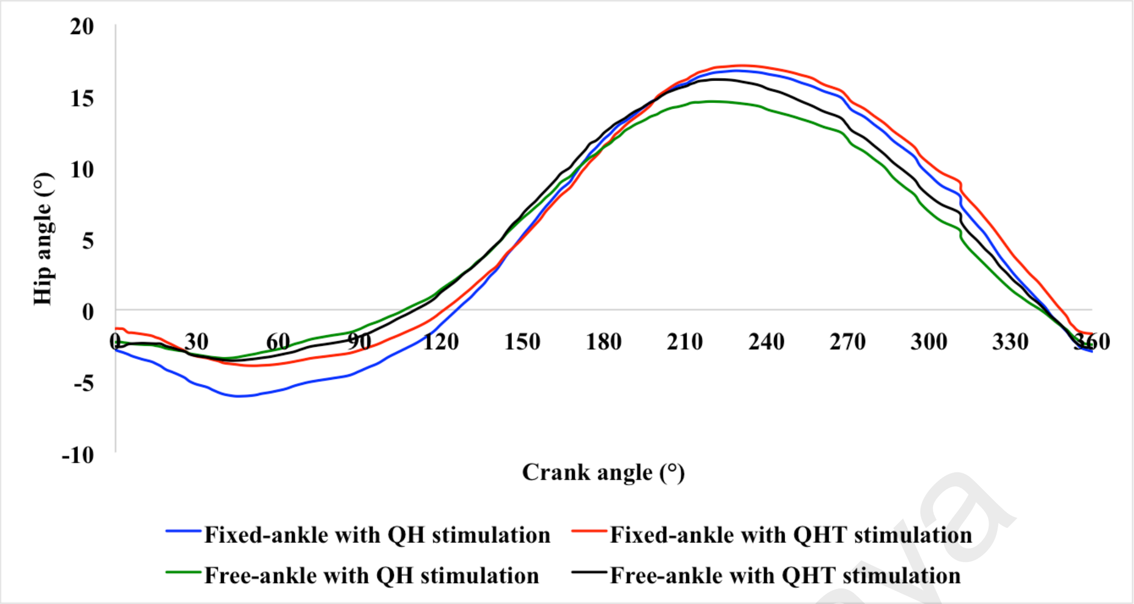


Figure 4.12: Changes in the hip joint excursions between FES cycling modes.

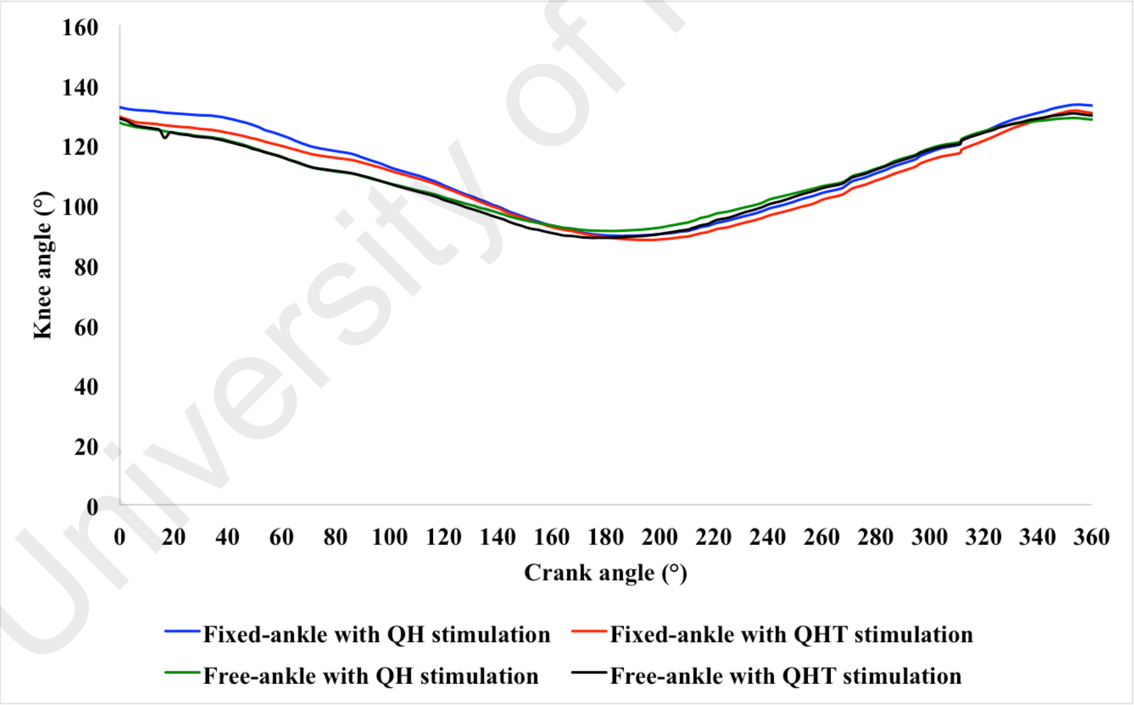


Figure 4.13: Changes in the knee joint excursions between FES cycling modes.

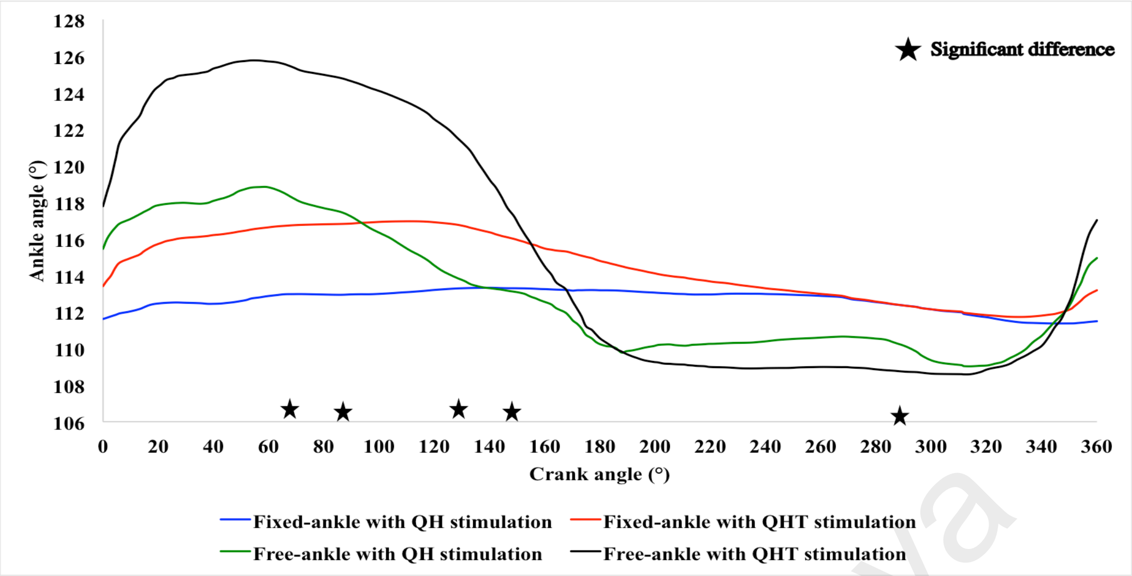


Figure 4.14: Changes in the ankle joint excursions between FES cycling modes.

Table 4.4: Changes in the hip, knee, and ankle joint excursions between FES cycling modes.

FES cycling modes	Hip joint excursions	Knee joint excursions	Ankle joint excursions
Fixed-ankle with QH stimulation	-6.1 ± 2.2 to 16.7 ± 5.7°	89.6 ± 10.4 to 133.4 ± 9.5°	111.4 ± 3.8 to 113.3 ± 3.9°
Fixed-ankle with QHT stimulation	-3.4 ± 5.1 to 14.6 ± 7.2°	91.3 ± 12.7 to 129.0 ± 14.5°	109.0 ± 8.9 to 118.8 ± 11.0°
Free-ankle with QH stimulation	-3.9 ± 2.7 to 17.1 ± 4.9°	88.3 ± 9.9 to 131.4 ± 9.9°	111.7 ± 4.2 to 117.0 ± 7.3°
Free-ankle with QHT stimulation	-3.6 ± 1.8 to 16.1 ± 5.4°	89.0 ± 10.1 to 130.5 ± 9.4°	108.6 ± 7.0 to 125.7 ± 10.2°

Table 4.5: Changes in the ankle joint ROM between FES cycling modes at every 20° of crank angle.

Crank angle (°)	Ankle ROM (°)				Significant difference value
	Fixed-ankle with QH stimulation	Fixed-ankle with QHT stimulation	Free-ankle with QH stimulation	Free-ankle with QHT stimulation	
60 – 80	0.18 ± 0.14	0.21 ± 0.18	0.82 ± 0.66	0.49 ± 0.53	F (3, 24) = 3.24, *P* = 0.04
80 – 100	0.24 ± 0.23	0.15 ± 0.12	0.99 ± 0.78	0.64 ± 0.65	F (3, 24) = 3.77, *P* = 0.24
120 -140	0.36 ± 0.44	0.59 ± 0.54	1.19 ± 1.25	2.60 ± 1.74	F (3, 24) = 5.64, *P* = 0.05
140 – 160	0.55 ± 0.64	0.73 ± 0.73	1.09 ± 1.23	3.97 ± 2.06	F (3, 24) = 10.8, *P* = 0.00
280 - 300	0.41 ± 0.34	0.35 ± 0.43	1.06 ± 0.71	1.19 ± 0.71	F (3, 24) = 3.33, *P* = 0.36

4.2.3 Summary

In summary, there were no significant changes in the hip and knee joint excursions between all constrained ankle movements and stimulation modes in AB and SCI participants. There was also no significant difference in the hip and knee joint ROMs between the ankle constrained movements and stimulation modes in SCI participants.

However, only the ankle joint excursions were varied with different ankle constrained movements and stimulation modes in both AB and SCI participants. Besides that, there was significant difference in the ankle ROM between FES cycling modes at every 20° of crank angle in SCI participants especially during the power phase of FES cycling.

CHAPTER 5: DISCUSSION

This chapter discusses all the findings that reflect the objectives of the study. The findings of the study are divided into two sections associated to the parameters of interest; pedal PO and kinematics of leg joints. Based on the objectives of the study, the present study sought to quantify:

i. The possible differences in the peak and average pedal POs generated by the FP, DPF, DF, and PF AFOs that constrained ankle movements during voluntary recumbent cycling in AB individuals.
ii. The effects of fixed- and free-ankle movements on the peak and average pedal POs during FES cycling in individuals with SCI.

The best two types of AFOs constrained movements found in voluntary cycling in AB participants were further investigated and compared in FES cycling in individuals with SCI.

The first section of this chapter highlights the significant changes in the peak and average pedal POs generated during; 1) voluntary cycling with AFOs constrained ankle movements in AB participants, and 2) FES cycling with fixed- and free-ankle set up in SCI participants. The second section of this chapter highlights the significant changes in the biomechanics of the hip, knee, and ankle joints during; 1) voluntary cycling with AFOs constrained ankle movements in AB participants, 2) FES cycling with fixed- and free-ankle set up in SCI participants.

5.1 Pedal PO

The peak and average pedal POs during voluntary cycling revealed in the current study were 27.2 ± 12.0 W and 17.2 ± 9.0 W, respectively. While, the peak and average pedal POs in all FES cycling modes revealed in the present study were ranged (min – max) (22.4 ± 17.9 – 48.6 ± 44.3 W) and (6.7 ± 7.4 – 13.0 ± 11.2 W), respectively. The PO generated during FES cycling in SCI participants is lower than voluntary cycling in AB participants. This finding is similar to the previous reported studies (Berry et al., 2012; Duffell et al., 2010; Eser et al., 2003; Fornusek et al., 2012; Gföhler et al., 2001; Sinclair et al., 2004; Szecsi et al., 2014).

To our knowledge, no studies have yet to investigate the effect of ankle constrained movements on the PO during voluntary recumbent cycling in AB. However, a few studies had investigated the PO during voluntary recumbent cycling for 30s. Duffell *et al*. (Duffell et al., 2010) reported the peak PO achieved by AB participants was 311.6 ± 24.2 W, while, Martin *et al*. (Martin & Brown, 2009) reported the average PO achieved by well-trained AB cyclists was 540 ± 31 W. One of the reasons that the current study revealed a lower peak and average POs may be due to the ankle immobilization itself, as has been previously suggested (Ferrante et al., 2005). However, a second explanation for the lack of differences between AFO's, might be that only minimal power was required during the unloaded cycling (Gregor et al., 2002) compared to a higher resistance (Duffell et al., 2010), since changes in workload would necessarily alter PO (Gregor et al., 2002; Sinclair et al., 1996). Our study selected minimal loaded cycling to allow more direct comparison to data of SCI participants (Gregor et al., 2002). Well-trained cyclists (Martin & Brown, 2009) might also have led to the contribution of higher PO compared to the untrained participants in this study. However, the previous studies on recumbent cycling focused on lower total POs (30 – 65 W) (Gregor et al., 2002) which was almost similar with the peak pedal PO in the current study.

Previous studies also have investigated the peak and average pedal POs during FES cycling in individuals with SCI. To our knowledge, no studies have yet to investigate the effect of fixed- and free-ankle on the pedal PO during FES cycling in individuals with SCI. However, a few studies had investigated the PO during FES cycling in individuals with SCI. The PO reported in previous studies were ranged within 10 to 25 W (Mutton et al., 1997), 5 to 10 W (Theisen et al., 2002), and 8 to 35 W (Duffell et al., 2010). Besides that, Gföhler *et al.* (Gföhler et al., 2001) reported the peak and average POs as 15 W and 8 W, respectively. On the other hand, Berry *et al.* (Berry et al., 2008) reported the peak PO of 20.82 W after 6 months of training. Berry *et al.* also reported the highest SCI individual peak PO value of 35.6 W after 12 months of training (Berry et al., 2008). The present study revealed higher peak and average pedal POs of FES cycling. The first reason may be due to the addition of the shank muscles stimulation (TA and TS) during FES cycling. Stimulation of more muscles groups can contribute to a larger PO production (Fornusek et al., 2012). The second reason may be due to the medium resistance applied in all FES cycling modes and thus may contribute to the higher PO production (Duffell et al., 2010) as changes in workload would alter PO (Gregor et al., 2002; Sinclair et al., 1996).

The present study also reported that there was no significant difference in the peak and average pedal PO values amongst the different types of AFOs constrained ankle movements and stimulation modes in recumbent and FES cycling, respectively. The results refuted our initial hypothesis that the ankle movements might alter the cycling PO as ankle pattern affected movement kinematics (Gregor et al., 1991; Haapala et al., 2008). This may be because the main components of PO are the knee and hip extensors and flexors, but not the ankle movements (Szecsi, Straube, & Fornusek, 2014; Trumbower et al., 2006). The ankle acts primarily to transmit force produced from the upper leg to the crank and less as a power generator (Duffell et al., 2009; Gregor et al., 2002; Trumbower & Faghri, 2005).

Despite the non-significant PO production difference, the present study however observed that DPF AFO produced highest normalized peak and average pedal POs. Therefore, FP AFO and free-ankle movement was chosen to be further investigated in FES cycling in individuals with SCI. Free-ankle movement in FES cycling was similar to the DPF AFO movement in recumbent cycling as DPF AFO allows the ankle to move from the neutral position to dorsi-plantarflexion.

To our knowledge, no studies have yet to investigate the effect of fixed- and free-ankle FES cycling on the pedal PO in an experimental setting (Soest et al., 2005). The present study revealed that free-ankle FES cycling with QH stimulation produced lowest normalized peak and average pedal POs compared to other FES cycling modes. While, free-ankle FES cycling with QHT stimulation produced the highest normalized average pedal PO. One of the reasons might be due to the power loss at the ankle joint during free-ankle FES cycling without the stimulation of the shank muscles. Theoretically, releasing the ankle joint may elevate the PO by 14%. But only with the tuning of contact point between the foot and pedal to the relative strength of the ankle plantar flexors, and with the addition of TS and TA muscles stimulation (Soest et al., 2005). In the present study, the normalized average pedal PO between free-ankle FES cycling with QHT stimulation and free-ankle FES cycling with QH stimulation was elevated by 10%, slightly lower than reported in the previous study. Therefore, the present study refuted that the shank muscles stimulation of TA and TS during FES cycling contribute almost zero PO (Berkelmans, 2008) and did not affect the peak PO (Berry et al., 2008). Shank muscles stimulation is very important to maximize the peak and average pedal PO during power phase of free-ankle FES cycling.

On the other hand, the present study revealed that free-ankle FES cycling with QHT stimulation produced highest normalized peak pedal PO with 1% elevation from fixed-ankle FES cycling with QHT stimulation. This finding was similar to the previous study, where it was expected that there is no difference in PO production between fixed- and free-ankle FES cycling if it is uphold reality (Soest et al., 2005).

The present study also revealed that the normalized peak and average pedal POs of fixed-ankle FES cycling with QH and QHT stimulations having only small elevation of PO (3% and 2%, respectively). This may be due to the stimulation of TA and TS in the fixed-ankle FES cycling that does not elevate the PO as reported in the previous study (Ferrante et al., 2005).

In addition, the present study revealed that there was only small PO elevation between fixed-ankle FES cycling with QHT stimulation and free-ankle FES cycling with QHT stimulation. Fixed-ankle FES cycling did not cause the lower pedal PO production. The present study refuted that fixing the ankle joint during FES cycling causes the low power production (Haapala et al., 2008).

The present study also revealed that there was significant difference in the normalized pedal PO between FES cycling modes at every 20° of crank angle during the power phase of cycling (20° to 100°, when HAM and TS muscles are stimulated). Free-ankle FES cycling with QH stimulation produced lowest normalized pedal PO compared to the other FES cycling modes. One of the reason may be due to the loss of the pedal power at the ankle joint during power phase of FES cycling. Releasing the ankle joint without the stimulation of shank muscles negatively affect the kinematic relation between the crank and joint angles (Soest et al., 2005) during power phase of cycling. The second reason may be due to the absence of TS muscles stimulation. Stimulation of TS muscles is important to transfer the power generated in the whole limb to the pedal (Zajac et al., 2002). Therefore, stimulation of the shank muscles is very important during free-ankle FES cycling to ensure direct kinematical relation between the crank and joint angles to maximize the pedal PO as reported in the previous study (Soest et al., 2005). Besides that, fixing the ankle joint can become the alternative way to minimize the power loss at the ankle joint (Martin & Brown, 2009) during the power phase of FES cycling. Overall, the present study showed that QUAD muscles produced the highest normalized power compared to other muscles of all FES cycling modes, as reported in the previous study (Haapala et al., 2008; Martin & Brown, 2009; Szecsi et al., 2007; Trumbower & Faghri, 2004). The present study revealed that the stimulation of TS muscles is important during free-ankle FES cycling to prevent power loss at the ankle joint. TS muscles work to transmit the force from the hip and knee to the crank and pedal during cycling (Zajac et al., 2002). On the other hand, TA muscles produce the least power, due to its small volume (Martin & Brown, 2009). This finding is important to help researchers and clinicians to wisely choose which muscles have to be stimulated during free-ankle FES cycling. The stimulation of QUAD, HAM, and TS muscles should be sufficient to maximize the pedal PO during free-ankle FES cycling with 6-channels stimulator.

5.1.1 Summary

In summary, there was no significant difference in the normalized peak and average pedal POs between all constrained-ankle movements in AB participants and between fixed- and free-ankle FES cycling in SCI participants. However, DPF AFO and free-ankle FES cycling with QHT stimulation contributed to the highest normalized average pedal PO compared to the other cycling modes. DPF AFO and the fixed-ankle FES cycling with QHT stimulation produced highest normalized peak pedal PO compared to the other cycling modes. It can be concluded that releasing the ankle joint can maximize the pedal PO during voluntary and FES cycling in AB and SCI participants, respectively. In addition, both fixed- and free-ankle FES cycling maximize the pedal PO in SCI participants. Fixed-ankle FES cycling with QH and QHT stimulation also maximize the pedal PO with small PO elevation between them.

On the other hand, free-ankle FES cycling QH stimulation contributed to the lowest normalized peak and average pedal POs compared to the other FES cycling modes. Releasing the ankle joint without the stimulation of shank muscles causes the loss of power produced from the leg to the crank at the ankle joint during the power phase of cycling. Therefore, the stimulation of TS muscles is important to prevent the loss of power during free-ankle FES cycling in SCI participants. TS muscles help to transmit the power produced from the leg to the crank, while maintaining the kinematic between the crank and leg joint angles.

The present study found that QUAD, HAM, and TS muscles stimulation are important to maximize the pedal PO during free-ankle FES cycling. The stimulation of QUAD and HAM muscles only are enough to maximize the pedal PO during fixed-ankle FES cycling.

5.2 Kinematics of Leg Joints

To our knowledge, there is limited number of studies that have investigated the influence of ankle joint excursions on the PO production during cycling (Gregor et al., 2002; Pierson et al., 1997). Trumbower *et al.* (Trumbower & Faghri, 2005) has suggested to allow the ankle joint to move in sagittal plane during FES cycling in individuals with SCI to resemble AB semireclined leg cycling (Trumbower & Faghri, 2005). Therefore, the pedaling effectiveness of free-ankle FES cycling can be improved (Faghri et al., 2001).

It is important to note that the FP, DPF, DF, PF, free- and fixed-ankle movements did not express any influence on the hip and knee joint excursions change during recumbent and FES cycling. Previous study reported the same finding as the hip and knee joint excursions were not significantly affected by releasing the ankle joint (Soest et al., 2005). This further justified that the changes in PO generated during cycling was more associated with ankle movements. In this study, it was revealed that ankle plantarflexion for DFP and PF AFOs occurred at mid to late power phase. While the ankle dorsiflexion for DPF and DF AFOs occurred at mid to late recovery phase. These current findings were similar to the previous study where Trumbower *et al.* (Trumbower & Faghri, 2004) reported that the ankle plantarflexion and dorsiflexion occurred at mid to late power phase and mid to late recovery phase of cycling, respectively, during voluntary cycling with ankle mobilization. In addition, Gregor *et al.* (Gregor et al., 2002) also reported that the knee is extended during the first 90° of pedal revolution as the hip continued to extend until the end of power phase, which was similar to the present study. In addition, the present study also revealed that all participants were able to control their cadence within the set cycling cadence with the DF AFO compares to the other AFOs. Therefore, the DF AFO might be effective for the cycling training, if the goal of the training was speed-performance.

The present study also revealed that there was no significant difference in the hip and knee joint ROMs between FES cycling modes. Besides that, the present study revealed that there was no hyperextension of the knee occurred during free-ankle FES cycling with QH and QHT stimulations. This finding refuted that freeing the ankle joint during FES cycling may cause hyperextension of the knee.

In addition, the present study revealed that there was significant difference in the ankle ROM between FES cycling modes. Fixed-ankle FES cycling with QH stimulation contributed to the lowest ankle ROM. While, free-ankle FES cycling with QHT stimulation contributed to the largest ankle ROM. One of the reason is free-ankle FES cycling increases the ankle excursions as reported in the previous study (Fornusek et al., 2012). Besides that, QHT stimulation increases the ankle excursion compared to the traditional muscles stimulation alone (QH stimulation) as reported in the previous study (Fornusek et al., 2012).

The present study also revealed that there was significant difference in the ankle joint ROM between FES cycling modes at each 20° of crank angle. The ankle joint ROM shows significant changes during recovery (60° to 100° - when HAM and TS muscles are stimulated, and 120° to 160° - when QUAD and TA muscles are stimulated) and power phases (280° to 300° - when QUAD muscles are stimulated) of cycling. QUAD, HAM, TA, and TS muscles are responsible in knee extension, knee flexion, ankle dorsiflexion, and ankle plantarflexion, respectively. During the recovery phase of cycling, the ankle joint tends to do dorsiflexion. Fixed-ankle FES cycling with QH and QHT stimulations however, limited the ankle dorsiflexion movement. Free-ankle FES cycling with QH stimulation also produces limited ankle dorsiflexion movement. This may be due to the absence of shank muscles stimulation (TA and TS). On the other hand, free-ankle FES cycling with QHT stimulation allows greater ankle dorsiflexion movement during the recovery phase of cycling. This may be due to the stimulation of the shank muscles that helps the ankle to move in dorsiflexion. This finding is important as it can help to treat ankle contractures, which are common complications for individuals with SCI. Contractures are likely unfavorable as this condition can hinder the performance of motor tasks (McDonald et al., 2005).

5.2.1 Summary

In summary, there was no significant difference in the hip and knee joint excursions between constrained ankle movements and stimulation modes in AB and SCI participants. Both AB and SCI participants showed the changes in ankle joint excursions between constrained ankle movements and stimulation modes. DPF AFO and free-ankle movement in recumbent and FES cycling produced greater ankle excursions in AB and SCI participants.

In addition, there was no significant difference in the hip and knee joint ROMs between FES cycling modes. Only the ankle joint ROM shows the significant difference between the FES cycling modes. Free-ankle FES cycling produced greater ankle joint ROM than fixed-ankle FES cycling. Free-ankle FES cycling with QHT stimulation produced greatest ankle ROM compared to the other FES cycling modes.

The present study also revealed that there was significant difference in the ankle ROM during the recovery phase of FES cycling. The limited ankle dorsiflexion movement produced from the fixed-ankle and free-ankle FES cycling with QH stimulation cause this significant change. Free-ankle with QHT stimulation however produced greater ankle dorsiflexion as the stimulation of shank muscles contributes to a greater ankle excursion.

It is shown that free-ankle FES cycling with QHT stimulation provided advantages to the SCI participants. The stimulation of the shank muscles (TS and TA) is found safe (Fornusek et al., 2012). Besides that, shank muscles stimulation can enhance blood flow to the lower legs, greater strength and endurance (Berkelmans, 2008; Fornusek et al., 2012) that may reduce the highly fatigable muscles of individuals with SCI. Low fatigable leg muscles could perhaps lead to the increase in PO.

5.3 Overall Summary for All Parameters Investigated

In summary, releasing the ankle joint during voluntary and FES cycling did not alter the peak and average pedal POs. The current findings were similar to the previous study, where it was expected that there is no difference in PO production between fixed- and free-ankle FES cycling if it is uphold reality (Soest et al., 2005).

Releasing the ankle joint during voluntary and FES cycling allow an increase in ankle ROM while maintaining PO productions in AB and SCI participants. However, cycling with DPF AFO during voluntary cycling and free-ankle FES cycling contributed to the greatest increase in ankle ROM while maintaining PO productions in AB and SCI participants compared to other types of ankle movements.

Free-ankle FES cycling with QHT stimulation and fixed-ankle with QH and QHT stimulations were succeed to maximize the pedal PO in SCI participants. On the other hand, free-ankle FES cycling with QH stimulation failed to maximize the pedal PO due to the loss of power at the ankle joint during the power phase of FES cycling. The present study revealed that the stimulation of TS is important to maximize the pedal PO during free-ankle FES cycling as plantar flexor muscles at the ankle joint are important to transfer power generated in the whole limb to the pedal (Zajac et al., 2002). The stimulation of shank muscles was found safe and provides more benefits to the SCI as mentioned in the previous studies (Berkelmans, 2008; Fornusek et al., 2012).

The significant difference in the ankle joint ROM between FES cycling modes occurred during the recovery phase did not affect the pedal PO produced in SCI participants. Different ankle constrained movements in voluntary recumbent cycling and FES cycling did not affect the hip and knee joint ROMs in both AB and SCI participants.

CHAPTER 6: CONCLUSION

To conclude, AFOs constrained ankle movements (FP, DPF, DF, and PF) did not affect the peak and average pedal PO generated during voluntary recumbent cycling in AB individuals. Consequently, the fixed- and free-ankle ankle movements also did not affect the peak and average pedal PO generated during FES cycling in individuals with SCI. The current findings were similar to the previous study, where it was expected that there is no difference in PO production between fixed- and free-ankle FES cycling if it is uphold reality (Soest et al., 2005).

Voluntary recumbent cycling with DPF, DF, and PF AFOs constrained ankle movements and FES cycling with free-ankle movements are able to maximize the peak and average pedal PO as well as when the ankle joint is fixed throughout the cycling. Therefore, releasing the ankle joint during voluntary in AB individuals and FES cycling in individuals with SCI exercise did not lower the pedal PO generated while providing greater ankle joint movements.

The present study revealed that the stimulation of plantarflexor muscles is important during the power phase of FES cycling to maximize the pedal PO during free-ankle FES cycling. The absence of plantarflexor muscle stimulation will significantly lower the PO generated during the power phase of free-ankle FES cycling. Plantar flexor muscles at the ankle joint are important to transfer power generated in the whole limb to the pedal (Zajac et al., 2002).

Besides that, the stimulation of shank muscles was found safe and provides more benefits to the SCI as mentioned in the previous studies (Berkelmans, 2008; Fornusek et al., 2012).

Overall, our results may be useful in the field of rehabilitation therapy in eliciting increased PO during cycling training. In essence, these data could promote the development of improved lower limb training for people with musculoskeletal or neuromuscular disorders such as stroke in order to gain the benefits of therapy using FES- cycling (Fornusek et al., 2012; Szecsi et al., 2008; Soest et al., 2005). The findings of the study might also serve as a reference for future rehabilitative cycling protocols where both ankle muscle stretching and strength training are the simultaneous aim.

6.1 Recommendations for Future Work

i. Future works involving more individuals with SCI would be better as it might alter the statistical result of this study.

ii. It would be useful if the joint PO from fixed- and free-ankle FES cycling can be quantified.

iii. It would also be useful to quantify the effect of fixed- and free-ankle joint movement during mobile FES cycling in individuals with SCI, as mobile FES cycling requires higher pedal PO compared to the stationary FES cycling.

6.2 Limitations of the Study

i. For this study, all SCI participants needed to be well trained for at least 12 weeks (at least 2 times per week). However, most of them were not willing to give their full commitments during FES cycling training sessions as they have other works to do. Consequently, we have difficulty to get more participants to join the study.

ii. This study required high costs, as we need to pay honorarium to the SCI participants during their training and experiments sessions. We also need to buy electrodes for each of the participants for every 2 months of frequent training.

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LIST OF PUBLICATIONS AND PAPERS PRESENTED

List of Publications

1. Hamdan, PNF., Hamzaid NA., Usman J., Islam MA., Kean VSP., Abdul Wahab AK., Hasnan N., & Davis GM. (2017). Variations of ankle-foot orthosis constrained movements increase ankle range of movement while maintaining power output of recumbent cycling. *Biomedical Engineering - Biomedizininische Technik*. Accepted, ISI-listed (24th July 2017).

List of Papers Presented

1. Hamdan PNF., Hamzaid NA., & Hasnan N. (2016). Ankle-foot orthosis constrained movements does not alter power output during functional electrical stimulation cycling in paraplegic. In *10th International Society of Physical and Rehabilitation Medicine World Congress*. Kuala Lumpur, Malaysia.
2. Hamdan, PNF., Teo K., Hamzaid NA., Usman J., & Mohd Razman R. (2016). The effects of releasing ankle joint on pedal force and power production during electrically stimulated cycling in paraplegic individuals: A pilot study. In *3rd International Conference on Movement, Health & Exercise.* Melaka, Malaysia.
3. Hamdan, PNF., Hasnan, N., Davis GM., & Hamzaid, NA. (2016). Power output of ankle released movements during functional electrical stimulation cycling in individuals with spinal cord injury. In *International Functional Electrical Stimulation Society (IFESS) 2017.* London, United Kingdom.