RELATIVE CONTRIBUTION OF ARMS AND LEGS THROUGH REPETITIVE ASSISTED SIT-TO-STAND MOTION IN INDIVIDUALS WITH INCOMPLETE SPINAL CORD INJURY

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FACULTY OF ENGINEERING
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DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING SCIENCE

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RELATIVE CONTRIBUTION OF ARMS AND LEGS THROUGH REPETITIVE ASSISTED SIT-TO-STAND MOTION IN INDIVIDUALS WITH INCOMPLETE SPINAL CORD INJURY

ABSTRACT

Sit-To-Stand (SitTS) exercise is one of important prerequisites to achieve some functional independence goals in everyday life especially for individuals undergoing rehabilitation In general, the execution of SitTS in spinal cord injury (SCI) patients involves motor function in both upper and lower extremities. The use of arm support in particular is a very significant element while executing SitTS movement for SCI population. In addition, application of functional electrical stimulation (FES) onto the quadriceps muscles is one of the prescribed management for incomplete SCI to improve muscle action for simple lower limb movements. However, the relative contribution of upper and lower extremities during SitTS has not been studied thoroughly. Therefore, the objective of this study is to determine the contribution of arm and leg during repetitive SitTS in incomplete SCI participants with and without FES. Two motor incomplete SCI participants performed repetitive SitTS-to fatigue exercise challenge. Three sets of SitTS test were completed with five-minute resting period were allocated in between set, with mechanomyography (MMG) sensors attached over the belly of the quadriceps muscles bilaterally. A total of 399 and 463 SitTS trials were completed without and with FES respectively by both participants. A SitTS cycle can be divided into three phases; Phase 1 (Preparation to stand), Phase 2 (Seat-off) and Phase 3 (Initiation of hip extension) which contributed to 23 ± 7%, 16 ± 4% and 61 ± 6% of the SitTS cycle respectively. Overall, the mean time to complete each FES-SitTS cycle between early trials for each set was identified to be significantly shorter compared to the final trials in each set (p<0.0005). The contribution of leg and arm during SitTS movement varied in different participants based on their legs Medical Research Council (MRC) muscle grade. During early Phase

2 of voluntary and assisted SitTS, in terms of percentage of total participant's body weight, both participants showed higher arms percentage contribution compared to their legs. Meanwhile throughout the end of Phase 3 in the SitTS activity, the percentage of arms contribution increased only for Participant 1 due to his right leg condition that was weak. For Participant 2, the percentage of arms contribution decreased as the contribution of leg percentage increased. For both conditions, there were significant average differences in the percentage of total body weight contribution between early Phase 2 and the end of Phase 3 for arm ($p<0.001$) and leg ($p<0.001$). This study highlighted the relative contribution of arm support in SitTS activity in two individuals with motor incomplete SCI. The finding might serve as a reference for SCI individuals to do a safe SitTS protocol hence future rehabilitative SitTS exercise where strength training of arm and leg can be emphasised.

Keywords: Standing, Functional Electrical Stimulation, Paraplegia

PENGLIBATAN RELATIF LENGAN DAN KAKI SEMASA PENGULANGAN AKTIVITI DUDUK KE BERDIRI SECARA BERBANTU BAGI INDIVIDU YANG MENGALAMI KECEDERAAN SARAF TUNJANG

ABSTRAK

Peralihan dari posisi duduk ke berdiri (SitTS) ialah salah satu aktiviti yang penting bagi mencapai kebebasan dari segi fungsi kendiri dalam kehidupan seharian terutamanya kepada individu yang menjalani proses pemulihan. Ringkasnya, pelaksanaan SitTS bagi individu yang mengalami kecederaan saraf tulang belakang (SCI) melibatkan fungsi motor di kedua-dua bahagian atas dan bawah badan. Sokongan lengan secara khususnya adalah unsur yang sangat penting ketika melaksanakan gerakan SitTS untuk populasi ini. Stimulasi elektrik berfungsi (FES) pada anggota kaki adalah antara rawatan alternatif yang diberikan kepada individu SCI bagi meningkatkan daya otot dan pergerakan anggota badan yang asas. Walau bagaimanapun, penglibatan relatif dari bahagian atas dan bawah badan ketika SitTS masih belum diterokai. Objektif kajian ini adalah untuk menentukan penglibatan lengan dan kaki ketika SitTS secara berterusan bagi peserta SCI dengan tidak menggunakan FES dan sebaliknya. Dua orang peserta SCI melakukan latihan SitTS berulang kali sehingga mencapai cabaran keletihan. Tiga set ujian SitTS dengan tempoh rehat lima minit diperuntukkan antara setiap set telah dijalankan dengan menggunakan peranti pengesan mekanomiografi (MMG) yang dilekatkan pada permukaan kulit otot kuadriseps di kaki. Secara keseluruhan, terdapat 399 percubaan SitTS tanpa menggunakan FES dan 463 percubaan SitTS dengan menggunakan FES. Pergerakan SitTS boleh dibahagikan kepada tiga fasa; Fasa 1 (Persediaan berdiri), Fasa 2 (Peralihan dari tempat duduk) dan Fasa 3 (Permulaan pemanjangan otot dibahagian belakang pinggul) yang masing-masing menyumbang sebanyak 23 ± 7%, 16 ± 4% dan 61 ± 6% daripada kitaran SitTS. Secara keseluruhannya, purata masa bagi kitaran setiap set FES-SitTS pada percubaan awal menunjukkan perbezaan jauh lebih pendek berbanding percubaan di akhir kitaran dalam setiap set (*p*<0.0005). Penglibatan antara kaki dan lengan ketika pergerakan SitTS bervariasi bagi setiap peserta berdasarkan gred otot bawah badan mengikut Majlis Penyelidikan Perubatan (MRC). Pada awal Fasa 2 SitTS, dari segi peratus sumbangan jumlah berat badan peserta, peratus sumbangan lengan kedua-dua peserta lebih tinggi daripada kaki mereka. Sehingga ke penghujung Fasa 3 SitTS, hanya sumbangan dari lengan Peserta 1 meningkat disebabkan oleh keadaan kaki kanan Peserta 1 yang lebih lemah. Bagi Peserta 2, sumbangan dari lengan menurun manakala sumbangan kaki pula meningkat. Bagi kedua-dua keadaan SitTS, terdapat perbezaan purata yang ketara dalam penglibatan peratusan jumlah berat badan antara awal Fasa 2 (peralihan dari tempat duduk) dan akhir Fasa 3 untuk lengan (*p* <0.001) dan kaki (*p* <0.001). Kajian ini memberi fokus kepada penglibatan relatif sokongan lengan bagi dua peserta SCI. Hasil kajian ini mungkin boleh dijadikan sebagai rujukan bagi individu SCI untuk melakukan protokol SitTS yang selamat, seterusnya latihan pemulihan SitTS bagi kekuatan lengan dan kaki dapat ditekankan pada masa akan datang.

Kata kunci: Berdiri, Stimulasi Elektrik Berfungsi, Paraplegia

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LIST OF SYMBOLS AND ABBREVIATIONS

#kg	:	Amount of weight lifted
#Reps	:	Number of repetitions to fatigue without rest interval
#RM	:	Repetitions maximal
1-RM	:	One repetition maximum
AB	:	Able-bodied
ABC	:	AIS A, AIS B, AIS C
AIS	:	ASIA Impairment Scale
ANOVA	:	Analysis of Variance
A-P	:	Anterior-posterior
ASIA	:	American Spinal Injury Association
BMD	:	Bone mineral density
BWS	:	Body weight support
CF	:	Centre frequency
CNS	:	Central nervous system
EMG	:	Electromyography
FES	:	Functional electrical stimulation
FN	:	Femoral nerve
FP	:	Force plates
FSR	:	Force sensing resistance
FV	:	Frequency variance
GT	:	Greater trochanter
GLUT	:	Gluteus maximus
HAM	:	Hamstring

ISNCSCI	:	International Standards for Neurological Classification of Spinal Cord Injury
LE	:	Lower extremities
LSD	:	Least significant difference
MAV	:	Mean average value
MDF	:	Median frequency
MMG	:	Mechanomyogram
MPF	:	Mean power frequency
MRC	:	Medical Research Council
NA	:	Data not available
NICE	:	National Institute for Health and Care Excellence
NLI	:	Neurological level of injury
NS	:	Not Significant
NTSCI	:	Non-traumatic spinal cord injury
PDS	:	Power density spectrum
PNS	:	Peripheral nervous system
PTP	:	Peak-to-peak
QUAD	:	Quadriceps
RF	:	Rectus femoris
RMS	:	Root mean square
RMS_{ave}	:	Root mean square $_{average}$
RMS_{max}	:	Root mean square $_{maximum}$
SCI	:	Spinal cord injury
SD	:	Standard deviation
SF	:	Standing frame
SitTS	:	Sit-To-Stand

SOCSO	:	Social Security Organisation
StandTS	:	Stand-To-Sit
TA	:	Tibialis anterior
TLS	:	Thoracolumbosacral
TO	:	Thigh-off
TSCI	:	Traumatic spinal cord injury
UMMC	:	University of Malaya Medical Centre
VC	:	Video camera
VL	:	Vastus lateralis
VM	:	Vastus medialis
VI	:	Vastus intermedius
VMG	:	Vibromyography
ZC	:	Zero crossing

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

This chapter discussed the brief idea of this study on spinal cord injury (SCI) individuals during Sit-To-Stand (SitTS) activity. This chapter was divided into eight sections. Section 1 and Section 2 outlined the research background and motivation for this study respectively. The problem statement and objective of the study were described in Section 3 and Section 4. The hypothesis and significance of the study were discussed in Section 5 and Section 6 respectively. Meanwhile, Section 7 elaborated the scope of the study. The last section of this chapter described the dissertation organization in brief.

1.1 Research Background

SCI is a condition arising from trauma or disease of the spinal cord with changes in strength, sensation autonomic and other body functions below the level of lesion (Kirshblum et al., 2011). It is categorised into two main categories, which are complete and incomplete injury. A complete spinal cord injury refers to total loss of function with inexistence of sensory and motor function. On the other hand, incomplete spinal cord injury indicates any lesion which spares either sensory motor function (Kirshblum et al., 2011). The prevalence of SCI is reported from 490 to 526 per million population among the developed countries to about 440 per million in non-developed countries. Incidence varies from 13 to 163.4 per million people in developed countries and 13 to 220 per million in non-developed countries (Kang et al., 2018).

Meanwhile in Malaysia, available studies showed that most persons with SCI were males, aged younger than 40 years, and had paraplegia. A related study showed a bimodal distribution of age, with peaks of incidence in the 25 to 34 and 55 to 64 age groups. The most common reason of SCI was caused by traumatic motor vehicle accident followed by fall from height. For non-traumatic SCI, it is about 40% related to tumor cases (Engkasan, Hasnan, Yusuf, & Latif, 2017)

For incomplete SCI, some of the nerves axons remain intact and signals can still be transmitted along the fibres despite of damages on the spinal cord. According to the American Spinal Injury Association (ASIA) Impairment Scale (AIS) Classification, AIS Grade C and D persons have 'motor incomplete' SCI. The motor function is preserved below the neurological level, and more than half of the key muscle functions below the single neurological level of injury have a muscle grade less than Grade 3 and Grade 4 as shown in Table 1.1 (Kirshblum et al., 2011). For this study, the target population was AIS C as they do not have the muscle strength to enable them to stand without assistance. In physical rehabilitation, SCI patients with grade AIS C have better progression and chance in recovering motor function, as compared to grade AIS B which is 'sensory incomplete' with complete motor deficits.

Table 1.1: Medical Research Council (MRC) Muscle Grading System. Adapted from (Shenaq, Armenta, Roth, Lee, & Laurent, 2005).

Muscle grade	Observation
0	No contraction
1	Flicker or trace contraction
2	Active movement with gravity eliminated
3	Active movement against gravity
4	Active movement against gravity and resistance
5	Normal power

SitTS movement is one of the most crucial basic activities for person with SCI to conduct daily routines. It is a necessary manoeuvre for their motor functionality such as standing, transfer and walking. The difficulty to perform stand-up action due to insufficient balance and leg muscle weakness was reported to be one of the common source of falls in SCI population (Amatachaya et al., 2019). In addition, this study found that episode of falls occurred when patients tried to transfer from wheelchair. Hence the ability to perform SitTS movement plays an important role and key indicator in achieving functional independence amongst SCI patients (M. Y. Lee & Lee, 2013).

1.2 Motivation for this Study

One of the functional independence in SCI individuals can be determined by SitTS exercise. To enhance the capacity of SCI patients in executing SitTS effectively, the use of arm support is shown to have a significant role (Pages, Ramdani, Fraisse, & Guiraud, 2009). The use of arm support will influence the accomplishment of SitTS. Researchers have described that it is crucial to recognise the arm contribution during SitTS, however this information is still very much unknown.

To date, arm support contribution which looks at the force generated from upper limbs during SitTS exercise after incomplete SCI remains poorly researched. Even though the biomechanics of SitTS has been widely studied to assess its kinetics and dynamics, the arm contribution during SitTS on the other hand is poorly understood yet to be definitively quantified (Yoshioka, Nagano, Hay, & Fukashiro, 2012) especially on these population.

This knowledge gap motivates the proposed study to investigate the contribution of arms and legs during repetitive assisted SitTS in incomplete SCI individuals. It is motivating to see how quadriceps muscles perform throughout assisted SitTS activity and its effects on muscle fatigue during Functional Electrical Stimulation (FES) evoked SitTS. In addition, the feedback from SCI individuals regarding the usage of FES device as a supportive tool can be explored further and these info can be used to optimise their care and treatment.

The combination of these three elements results in more information concerning incomplete SCI rehabilitative treatment in the future. These data can be used where a proper arm support system can be observed by clinicians to monitor user behaviour during

SitTS exercises. In addition, these activities can improve muscle function for both arms and legs together with rehabilitation. This regime has great value in rehabilitation field especially to enable the SCI population achieve more independence in their life.

1.3 Problem Statement

Complete execution of SitTS involves the translation of the body mass in horizontal and vertical directions from a relatively steady sitting position towards a period of relative instability. SitTS in able bodied (AB) starts with the thighs and feet acting as the base for support, until when the individual's thighs leave the seat and the feet remain as the only base for support (Carr & Shepherd, 2003). In addition, this movement is derived as a stable three-point base support with a low position of the center of mass to a two-point base of support with a high position of the center of mass (Saensook et al., 2018). In various strategy of SitTS manoeuvre, there are three prime muscles activated in these exercise which are the lumbar paraspinal, quadriceps and hamstrings muscles (Kim, Yi, Yoo, & Choi, 2011).

Individuals with AIS C SCI have difficulties in accomplishing the SitTS task due to presence of lower muscle weakness, postural instability and some possible deformities. Coupled with muscle deterioration, it is challenging for them to do the SitTS action as these conditions cause instability and increase muscle's susceptibility to fatigue. To compensate for these issues, support from the upper limbs is a very significant element while executing SitTS movement for these SCI population (Amatachaya et al., 2019). Adequate amount of force applied on upper limbs especially on the arms determines the success of the SitTS tasks.

FES has been established as an alternative treatment for persons who are paralyzed from spinal cord injury to improve muscle action for a simple limb movement (Figure 1.1) or even more complex functional movements. FES can be adapted to assist exercises in SCI individuals to perform basic manoeuvres such as bed transfer, toilet transfer and even if they want to stand up as shown in Figure 1.2. However, the use of FES has been found to be limited due to early muscle fatigue. Thus, it is necessary to establish the right stimulation pattern and minimise patients' fatigue to enable patients to perform exercises for a longer duration.

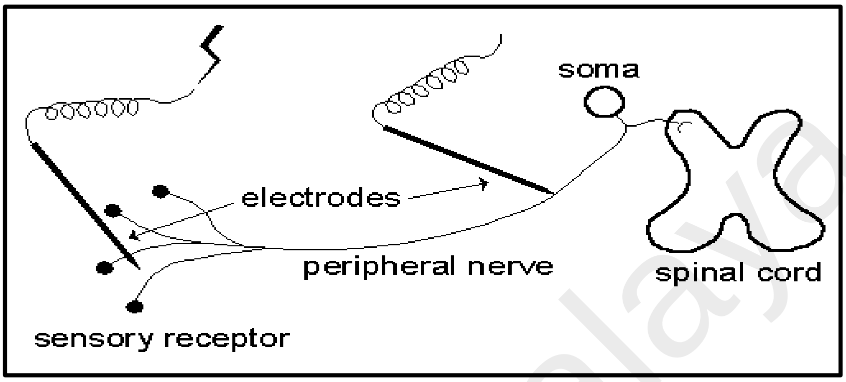


Figure 1.1: Electrical stimulation passing through the electrodes (attached to the skin) on the patient's nerve thus generating action potential and transmit to spinal cord. Adapted from (Hammarberg & Sternad, 2011).

Figure 1.2: Importance of arm support to people with spinal cord injury in basic daily activities. Adapted from ("Bathroom accommodation starts with adjustability.," 2019; "Transfer from wheelchair to bed," 2008).

Previous studies have been focused on kinematics and dynamics of SitTS exercise on SCI population. Even though arm support has been widely used in SCI SitTS movement, the contribution of the arm supports is poorly documented. Due to lack of research concerning contribution of upper limbs in SCI during assisted SitTS action, it is promising to compare both arms and legs contribution during the exercise as the association of these two parameters relationship has yet to be investigated. A combination of these two measurements may provide more information from the SCI individuals regarding their power and strength pattern during FES assisted SitTS exercise and FES assisted ambulation.

Therefore in this study, the main aim was to assess arms and legs contribution in repetitive assisted SitTS exercise in incomplete SCI participants.

1.4 Research Objective

There are three objectives that need to be met during the course of this study:

i. To measure the contribution of SCI participants' body weight (arms versus legs) during FES-evoked standing using an instrumented standing frame (SF).
ii. To evaluate the activity of quadriceps muscles in SCI individuals during SitTS motion by using Mechanomyography (MMG).
iii. To capture the SCI participants' feedback regarding the use of FES devices, particularly during the SitTS activity.

1.5 Hypothesis

As SitTS action transformed a physiological postural change from a balanced position to a vulnerable position, the contribution of arm and leg force can be determined throughout the phases of assisted SitTS exercise. It was hypothesised that the force contribution of arm and leg in SitTS action relates with the legs' muscle grade of SCI participants. The use of FES device in this study is believed to improve the number of SitTS trials among the SCI participants.

1.6 Research Significance

The relationship of relative contribution from arms and legs towards the body weight of SCI individuals during SitTS exercise is an important factor that added to the knowledge in this study. This study proposed a safe SitTS motion protocol with the use of SF and FES for the rehabilitation professionals to refer when they carry out the rehabilitation training for SCI patients.

Measuring MMG on the quadriceps muscles provided additional information regarding the muscle performance during voluntary and assisted FES. By verifying the data with the associated body weight contribution and its kinematics parameters in prolonged SitTS, these information can be used to monitor and predict the occurrence of fatigue during exercise in both condition.

Additional data on the SCI participants' views regarding the use of FES devices, particularly during the SitTS activity give supplementary information regarding the need to incorporate FES therapy into SCI rehabilitation programme. This data would serve as supporting documents to the relevant stakeholders to facilitate the FES service towards the disabled patients in hospitals and rehabilitation centre specifically in Malaysia.

1.7 Research Scope

This study aimed to verify the contribution of arm and leg during assisted SitTS exercise in SCI individuals. Since this study looks at the force generated at arm and leg, an instrumented SF was used to calculate the force exerted on the patients' upper limbs. Force on legs was observed from force plate's sensor in the Vicon Nexus motion capture system. The second scope was used to analyse the strength that was gained in SitTS prime mover muscle (i.e. quadriceps) using indirect 1-repetition maximum (1-RM) method. The muscle activity of quadriceps muscle during SitTS exercise was analysed using the MMG assessment. The third part was to observe the feedback session of the use of FES device in SCI individuals. The interview session helped researchers to develop a more user friendly FES device.

1.8 Dissertation Organization

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

Chapter 1 - Introduction. The background of this study which comprised of incomplete SCI and SitTS are briefly introduced in this chapter. The chapter also contains the problem statement, research objectives, research significance, research scope and dissertation organization.

Chapter 2 - Literature Review. The overview of SitTS is elaborated including its biomechanics, kinematics & dynamics, methods of SitTS in SCI. The introduction of FES and MMG are discussed further in this chapter. Next, a comparison of SitTS set up used in previous studies is tabulated. The chapter ends with a conclusion of findings of the reviews.

Chapter 3 - Methodology. This chapter describes in detail the protocols and materials that had been used in the study. The method of instrumentation of the SF protocol indirect 1-RM and SitTS experiment (without and with FES) are also included.

Chapter 4 - Results. This chapter reports all findings of the current study. This chapter begin with the outcome of the instrumentation of SF as well as the indirect 1-RM test. The overall result of the SitTS experiment is also included.

Chapter 5 - Discussion. This chapter discuss the findings of the current study with related previous studies.

Chapter 6 - Conclusion. This chapter concludes the findings of the study. In addition, some suggestions and recommendations are proposed to develop a better approach to achieve the goals of FES standing in individuals with SCI.

CHAPTER 2: LITERATURE REVIEW

This chapter elucidates previous studies on SCI individuals during SitTS activity. This chapter is divided into six sections. Section 1 explains the research background study of SCI. Section 2 and Section 3 describe the overview of SitTS activity and FES respectively. Section 4 elaborates on the details of MMG. Meanwhile, Section 5 focuses on previous standard set up of SitTS activity in SCI individuals. The last section of this chapter summarises the literature review.

2.1 Overview of Spinal Cord Injury (SCI)

A spinal cord is a long, thin and tubular bundle of nervous tissue protected by spinal columns. It is a part of the central nervous system (CNS) together with the brain. It acts as a bridge to connect large parts of the peripheral nervous system (PNS) to the brain. Each lesion on different levels of spinal cord causes different clinical features, as shown in Figure 2.1.

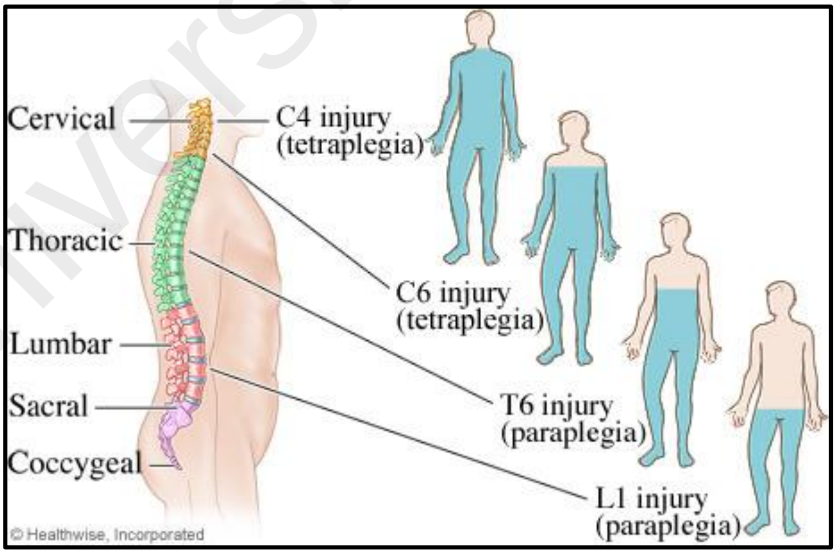


Figure 2.1*: Level of spinal cord injury. Adapted from (Griffinreynoldslaw, 2019).*

Tetraplegia, also known as quadriplegia, refers to an impairment or loss of motor and/or sensory function on the cervical segments of spinal cord which essentially results in loss of neural feeds to major four extremities (arms and legs), trunk and pelvic organs.

Paraplegia is a medical condition of loss of either or both motor and sensory function on thoracic, lumbar or sacral segments of the spinal cord. In paraplegic cases, neural functions on arms are preserved, however depending on the level of injury, the trunk, legs and pelvic organs might be affected. Based on the magnitude of spinal cord injury related to spinal columns, SCI can be divided into 5 groups of AIS classification (Table 2.1).

Table 2.1: AIS designation used in grading the degree of impairment. Adapted from (Kirshblum et al., 2011).

AIS grade	Description
A = Complete	No sensory or motor function is preserved in the sacral segments S4-S5.
B = Sensory incomplete	Sensory but not motor function is preserved below the neurological level and includes the sacral segments S4-S5, and no motor function is preserved more than three levels below the motor level on either side of the body.
C = Motor incomplete	Motor function is preserved below the neurological level, and more than half of key muscle functions below the single neurological level of injury (NLI) have a muscle grade less than 3 (Grades 0–2).
D = Motor incomplete	Motor function is preserved below the neurological level, and at least half (half or more) of key muscle functions below the NLI have a muscle grade >3.
E = Normal	If sensation and motor function as tested with the ISNCSCI are graded as normal in all segments, and the patient had prior deficits, then the AIS grade is E. Someone without a SCI does not receive an AIS grade.

*ASIA Impairment Scale = AIS, International Standards for Neurological Classification of Spinal Cord Injury = ISNCSCI, NLI = neurological level of injury

2.1.1 Epidemiology of SCI

For the past 30 years, descriptive SCI epidemiology has been studied extensively which generally focused on the incidence rates, gender, race, cause and level of SCI injury. It was reported that the range of Asia and Europe SCI incidence is from 12.06 to 61.6 and 10.4 to 29.7 per million respectively. Meanwhile SCI incidence in North America ranges between 27.1 and 83 per million (Ning, Wu, Li, & Feng, 2012). Based on these data estimation, one of the factor contributing North America to have the largest range of SCI incidence is due to the difference attribution to economic and social development from these continents. North America is known to have higher number of nondeveloped countries compared to Asia (Ning et al., 2012). Meanwhile the mortality of SCI patients was still high in recent years as the estimations of SCI mortality among developed countries varied from 3.1%7 to 22.2%,39 while mortality in nondeveloped countries ranged from 1.4%18 to 20.0%19 (Kang et al., 2018). These mortality rate is highest within 1 year after SCI where the increasing age is one of the factors contributed to the death. Elderly population (aged above 60 years) with a more risk factors for death (diabetes, cigarette smoking and heart diseases) is highly exposed to these contribution (Kang et al., 2018).

Based on studies of SCI survivors, one of the major post-injury sequelae is musculoskeletal defects including bone fractures and decrease in bone mineral density (BMD) (Chiodo et al., 2007). These conditions leads to osteodegenerative diseases such as osteopenia and osteoporosis. The same research reported that 61% of men with SCI has met the criteria for osteoporosis in World Health Organization, with 19.5% were osteopenic and 19.5% had normal BMD. 34% male SCI patients were reported with 14 cases of bone fracture occurred after SCI episodes (Chiodo et al., 2007). Individuals with SCI lose 60% of their BMD due to progressive thinning of bone cortical wall and destruction of the trabecular epiphyses (McHenry & Shields, 2012). Most commonly seen in SCI cases is muscle weakness in both arms and legs as they lose sensation and motor function. It can negatively affect the quality of life by confining and eliminating daily activities for example standing, walking, and driving.

2.1.2 Rehabilitative Management of SCI

The incidence of SCI cases is increasing thus it is crucial for medical practitioners and researchers to understand better and improve the current treatment to treat SCI (Kang et al., 2018). Management of SCI survivors include supportive treatment, pharmacotherapeutic approach, rehabilitation programme and a new lifestyle adaptation. Due to legs paralysis, most individuals with SCI undertake new exercises or participate wheelchair sports and recreation for fitness training of maintenance. Upper limb exercises, particularly arm training however have been somehow to have lesser effectiveness than lower body exercise in preserving peripheral and central elements of cardiovascular fitness (Thomas, Zaidner, Calancie, Broton, & Bigland-Ritchie, 1997). With regard to spinal injury, suitable exercises are very important for SCI individuals to improve their fitness and promote healthy lifestyle (Nash, 2005).

2.2 Introduction to a Standard Sit-to-Stand (SitTS) Activity

SitTS movement is a postural transition from seating position to vertical, upright standing position which involves movement of the whole body. More specifically, it involves motor function of both upper and lower extremities.

2.2.1 SitTS as a key indicator for rehabilitation management of SCI

SitTS is a basic indicator for SCI rehabilitation management as it demonstrates the degree of motor function post- SCI. SitTS activity is beneficial in the management of spinal cord injury to prevent or reduce secondary legs musculoskeletal complications and spasticity (NICE, 2009). However, this important manoeuvre may be restricted due to insults on the nervous system resulting in paralysis of the legs and its consequences (Hasnan, Fornusek, Husain, & Davis, 2012). Thus, any external mechanism which helps SCI patients to perform this movement like the FES is useful to enable lower body exercises (Bakkum et al., 2015; Hunt et al., 2004; Thijssen, Ellenkamp, Smits, &

Hopman, 2006). The ability to do a functionally-independent SitTS movement is influenced by a few factors, which are chair seat height, feet position, and use of armrests (Janssen, Bussmann, & Stam, 2002). Janssen et al suggests that higher chair seat height results in lower moment at knee level up to 60%, and hip level up to 50%. In contrast, decreasing the chair seat height has increased the need for higher momentum production or feet repositioning to reduce the moment required. Meanwhile, individuals associated with knee extensors muscle weakness was suggested to use additional compensatory mechanism for example an arm assistance (Bahrami, Riener, Jabedar-Maralani, & Schmidt, 2000). The use of armrest has shown reduction to the moments needed at the hip, probably without altering the range of joint motion. On another hand, feet repositioning affects SitTS motion's strategy and powering lower maximum mean extension moments at the hip which is 148.8 Nm as compared to 32.7 Nm when the foot repositioned from anterior to posterior position (Janssen et al., 2002).

2.2.2 Biomechanical aspects in SitTS

According to established studies, most biomechanical aspects in SitTS were focused on movement along sagittal plane studied with motion analysis system (Bahrami et al., 2000; M. Y. Lee & Lee, 2013). However, when involve with SCI individuals, basic fundamentals of SitTS can be grouped by their ability to stand up without and with arm assistance (Bahrami et al., 2000). A common biomechanics of SitTS can be defined as a shift in horizontal movement towards vertical movement of the body mass, led to vulnerability in postural stability when the thighs lift off the seat (Figure 2.2). At this point, an angular displacement from large upper body (head, arms and trunk) which revolves at pelvic joints, is changed from flexion to extension, and linear momentum of body mass is then changed from horizontal to vertical. Braking force needs to be applied to ensure stable transition from horizontal to vertical movement with controlled horizontal momentum (Carr & Shepherd, 2003). In addition, legs muscles have important role in providing support and balance for total body mass, and propelling the body mass vertically.

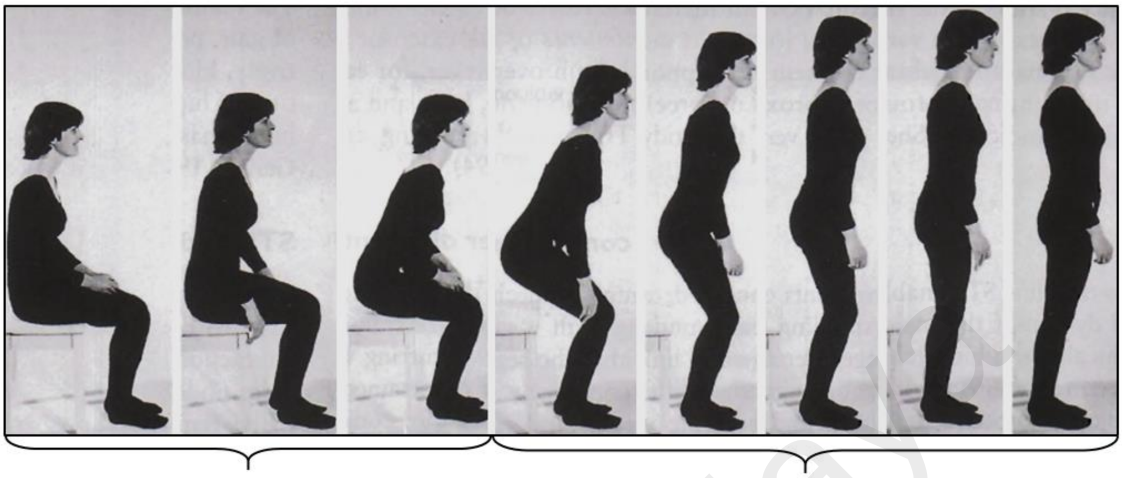


Figure 2.2: A transition from SitTS. Horizontal movement of the body mass: forward rotation of the trunk at the hips and shank at the ankles. Vertical movement: extension of hips, knee and ankles. Adapted from (Carr & Shepherd, 2003).

Different studies have discussed several phases that occurred during SitTS. Studies on four mechanically-distinct phases on SitTS activity have shown that full flexion of trunk in the early stages of rising was the most essential part of complex compensatory mechanism adapted by patients with gross muscle weakness. This strategy was used in healthy geriatric patients and the main one was to achieve better postural stability (M. Lee, Wong, Tang, Cheng, & Lin, 1997). According to few studies on different phases of SitTS, this action can be divided into a few phases which are pre-extension, an extension, and transition occurring at thighs-off (TO) phase (Carr & Shepherd, 2003). Carr and Shepherd believed that this is the simplest division for clinical purposes.

2.2.3 Muscle activated during SitTS

SitTS activity consists of complex movements of whole body and these movements include postural and executional activities (Goulart & Valls-Solé, 1999). On execution of ordinary SitTS manoeuvre, the quadriceps (QUAD) and paraspinal muscle are proven to be the prime movers, as these muscles have been activated throughout the SitTS activity (Goulart & Valls-Solé, 1999; Kagaya et al., 1995). Two studies have shown that the tibialis anterior (TA) has peak muscle activation during SitTS action in disabled patients as to protect them from falling (Cheng, Chen, Wang, & Hong, 2004; Kagaya et al., 1995; Pages et al., 2009).

2.2.4 Kinematics & dynamics of SitTS

i. Chair height

The height of chair is an essential factor in deciding the highest achievable angles of lower body parts, the range of motion of body segments, and the torque developed in the legs joints. Raising seat height enables individuals with weak muscles to practise SitTS (Carr & Shepherd, 2003). Meanwhile lowering the height of the seat makes the SitTS movement becomes more demanding or even unsuccessful (Janssen et al., 2002). A standard height chair is described following to the individual's leg length (Nadeau, Desjardins, Briere, Roy, & Gravel, 2008). Based on other SitTS studies, the chair's height commonly used was in between 0.44m to 0.46m (Anglin & Wyss, 2000; Bahrami et al., 2000; Kagaya et al., 1995).

ii. Translocation of body mass centre

The movement from sitting position to an upright posture requires translocation of the centre of mass, from a steadfast and stable position towards a position with lesser stability via extension of lower extremities. Any impairment on this biomechanical movement increases the risk of falling (M. Lee et al., 1997). Clinical data suggests that body weight is distributed evenly between legs bilaterally in healthy participants, however in patients who suffered from stroke, the body weight is distributed unevenly throughout this manoeuvre. When knee flexion is increased with a range of angle between 70° to 110°, it results in wide displacement of the centre of pressure (M. Y. Lee & Lee, 2013).

2.2.5 Methods of SitTS for SCI Individuals

Generally, an accomplishment of SitTS in SCI individuals involve the arm support contribution. The use of arm assistance has been widely involved in previous studies' protocol as these arm instrument provided the research to study the SitTS biomechanical analysis and other determinants during these exercise (Bahrami et al., 2000; Saensook et al., 2018). The common arms assistance was presented as parallel bar that had been located fix in front of SCI participants during a sitting position.

There are also different routines of SitTS training to improve SitTS independence after SCI. One of the methods developed for SitTS manoeuvre is 'partial body weight support' (BWS) (Figure 2.3). When a participant performs a SitTS movement, the weight stack gets lower and the participant would sustain a fixed anterior-superior force at the pelvis of the movement (Boyne, Israel, & Dunning, 2011). In this study, two participants had manifested an improvement from moderate assistance (25%-50%) for SitTS to independent SitTS on post-testing and resulted the time taken for three repetition of SitTS have reduced by 53% and 47% respectively (Boyne et al., 2011).

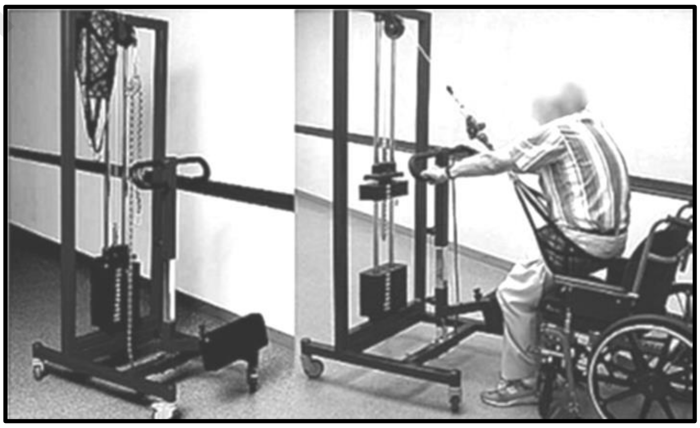


Figure 2.3: Neurogym sit to stand trainer for partial BWS. Adapted from (Boyne et al., 2011).

SitTS mechanism also can be found in smart mobile walkers (Jun et al., 2011) shown in Figure 2.4. In this case study, the participant has demonstrated better SitTS execution particularly on the body balance. This improvement is achieved by body trunk inclination. Moreover, this inclination has lowered the load on knees in SitTS movement.

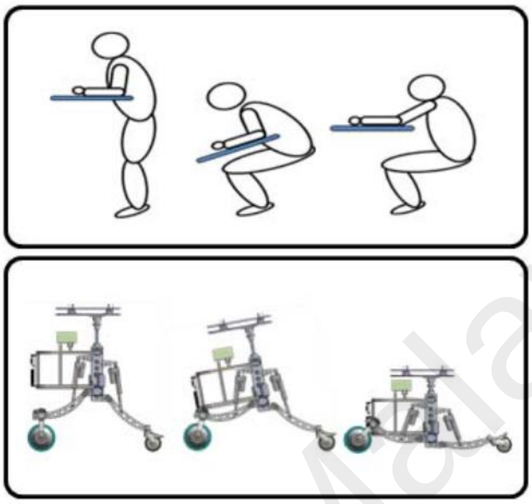


Figure 2.4: Basic concept of SitTS support in smart mobile walker. Adapted from (Jun et al., 2011).

2.2.6 Effect of neurological disorders on SitTS

In post stroke recovery period, patients would spontaneously avoid from bearing body weight on the affected leg, once the patients are able to stand up and sit down. Lack of backrest and angled seat are the causes of persistent strain in the thighs to remain on the seat, which then explains frequent complaints of fatigue (Chester, Rys, & Konz, 2002). The rate of fatigue in patients performing prolonged SitTS exercise is greatly affected by body weight distribution in arms and legs. Hence, the relationship between arm support and total body fatigability and stability need to be understood to establish its therapeutic effect when it is used with FES device.

2.2.7 Importance of arm assistance in SitTS for SCI participants

The use of arm support in SitTS routine is used as index for impaired activities in daily living and impaired mobility in elderly (Saensook et al., 2018). For SCI individuals, the use of armrest helps them to support their body to become more stable when executing SitTS. It also provides lower centre of mass by providing their upper limb posture at the SF during the initial phase of SitTS movement. An existing study showed the arm support as an assistive tool for the SitTS method in SCI population (Kagaya et al., 1995; Pages et al., 2009). Meanwhile, other study has highlighted the ability of arm support to unload the force applied on the knees while providing sufficient lifting force and assuring body balance in paraplegic participants (Kamnik, Bajd, & Kralj, 1999). The mean maximum hip moment during SitTS was reduced by 50% when arm assistance was implemented during the task (Saensook et al., 2018).

2.3 Functional Electrical Stimulation (FES)

FES is a device that enable the activation of paralysed muscles (Bajd, Kralj, Štefančič, & Lavrač, 1999) through small electric currents and it can be used to stimulate weakened muscles. The main purpose of FES is to evoke muscle contraction and functional movements of extremities (Askari, Chao, & de Leon PhD, 2013). There is achieved evidence that it helps in restoring muscles function and strengthening paralysed muscles (Askari et al., 2013; Bajd et al., 1999), regaining mobility (Hamzaid, Pithon, Smith, & Davis, 2012) and rehabilitation therapy (Davis, Hamzaid, & Fornusek, 2008). FES is widely used in the rehabilitation field with different approaches which entries depend on the individuals personalised needs including patients with SCI, stroke, traumatic brain injury, multiple sclerosis, Parkinson's disease and other neurological diseases.

2.3.1 Overview of FES

FES has been developed for more than 40 years as a neuroprosthesis and it has been used for artificial generation of short electrical signal to contractions in paralysed muscles via skin surface or implanted electrodes (Lynch & Popovic, 2008). In recent years, FES technology has been adapted as an approach device to be used in rehabilitation therapy particularly in voluntary motor function training regime such as hand grasping, reaching, SitTS manoeuvre, walking and daily activities. In addition, FES has been shown to decrease muscle spasm and increases blood flow on stimulated areas in neurological patients (Nightingale, Raymond, Middleton, Crosbie, & Davis, 2007). Nowadays, there are several systems available such as open-loop FES system and closed-loop FES system which is used commercially (Figure 2.5).

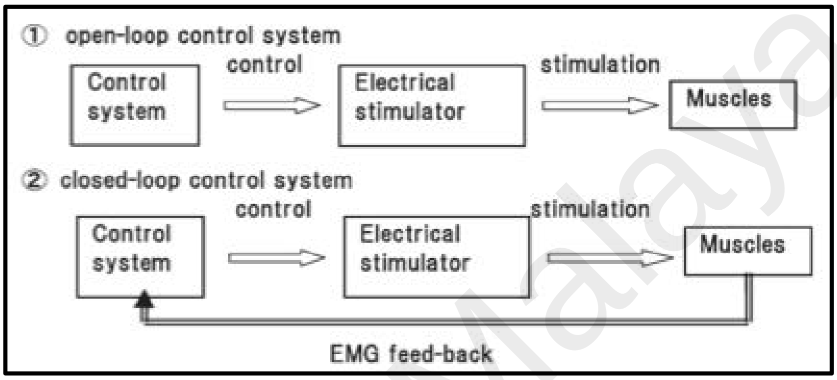


Figure 2.5: Open and closed loop FES systems. Adapted from (Hara, 2008).

Based on study from Crosbie et al, involvement of FES technology in SCI individuals comprised the electrical stimulation during a cycling exercise. SCI participants were shown advancement on their ability to generate greater support through the feet after training with 35Hz frequency FES stimulation. Meanwhile with a training of 10**0**Hz high frequency in FES stimulation, the rate of its force production was increased (Crosbie, Tanhoffer, & Fornusek, 2014).

Besides that, a study by Naeem et al. reported that the use of FES displayed a significant contribution for SCI individuals throughout the cycling exercise. This study demonstrated the differentiation of fatigued and non-fatigued muscles throughout the exercise (Naeem, Hamzaid, Islam, Azman, & Bijak, 2019). Another study by Naeem also displayed the FES application in SCI population during a standing exercise (Naeem, Hamzaid, Azman, & Bijak, 2020). The outcome explored a real-time MMG-based FES monitoring system in order to prevent the onset of critical muscle fatigue for SCI individuals in prolonged FES standing sessions.

2.3.2 Major concepts of FES and its therapeutic effects

The SCI individual suffers from huge decrease in neuronal connection on different level of spinal cord lesion manifested by skeletal muscles supplied by the nerves. In tetraplegic patients, the connection between spinal cord to peripheral nerves which innervate specific dermatomes and skeletal muscles, are totally severed. Without artificial stimulation on these muscles to mimic synaptic conduction on neuromuscular junction, these skeletal muscles lose its tone, reflex, coordination and motor functions. Other complications such as muscle spasm and skeletal muscle atrophy are also related to neuronal disconnection between injured spinal cord and peripheral nerves. According to a randomised controlled trial reported by National Institute for Health and Care Excellence (NICE) in the United Kingdom, there is 23% increase in walking speed in 14 patients treated by implanted FES as compared to 3% improvement in 15 patients who had conventional therapy over 26-week follow-up period. The key outcomes of FES implementation are improvement in gait on top of reduction in pain, discomfort, and effort during walking. However, it is challenging to interpret this data as the existing clinical evidences are based on studies with different methodologies and device applications such as skin surface (transcutaneous), percutaneous, or nerve cuff. In addition, ankle foot orthosis can be used with FES to increase optimum treatment outcome (NICE, 2009).

2.3.3 FES in SitTS activity

For a person with SCI injury, the ability to stand is one of the primary indications to access and enhance mobility and independence. However, the execution of standing up activity is restricted due to legs paralysis. FES SitTS is an effective exercise for SCI individuals to regain their confidence to get into standing position by placing electrodes on several targeted sites on the legs. One of the FES device used is *Rehastim 2®* as shown in Figure 2.6. During preparation phase of STS, the participant is required to bring his body to an initial pose, while the upper body leaned forward with the arms supported by the SF. At the same time, the hip joints resting on the chair were pulled forward with feet brought backward (Kamnik et al., 1999). The same study also discuss about the *start of rising* where a voluntary stimulation is triggered with the help of the stimulated quadriceps muscles and arm support.

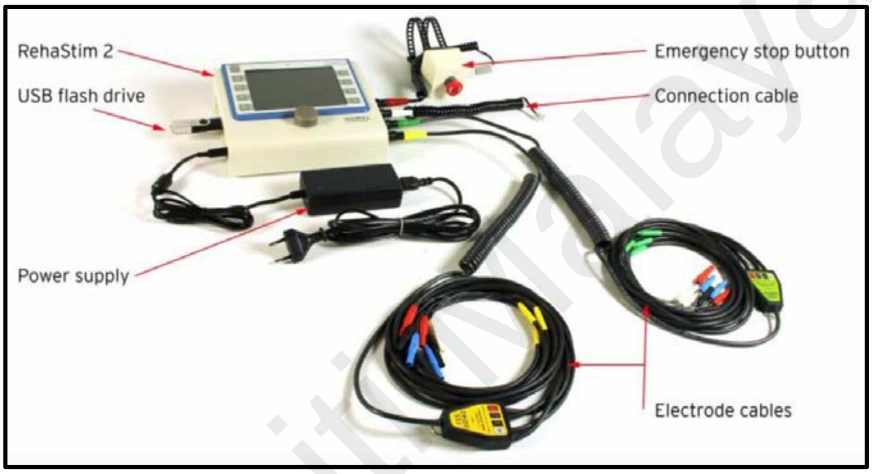


Figure 2.6: RehaStim 2 is a portable electrical stimulation device that generates impulses, on up to 8 channels simultaneously. Adapted from (RehaStim 2 operating manual, 2012).

2.3.4 FES muscle stimulation

With reference to Section 2.2.3, the quadriceps muscles have the highest contribution during SitTS activity. In fact, the quadriceps alone is consisted of four separate muscles which are the rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM) and vastus intermedius (VI). Based on Kagaya, H., et al study, RF demonstrates the peak muscle activity of SitTS which indicates that strong hip flexion is necessary during hands-assisted standing-up (Kagaya et al., 1995). In FES-evoked SitTS, an artificial stimulation is commonly applied to quadriceps (Bahrami et al., 2000; Kamnik et al., 1999; Pages et al., 2009) and gluteus maximus (GLUT) (Pages et al., 2009) via surface electrodes (Figure

2.7). Stimulation of these muscles will assist knee extension and avoid buttock from falling during the propulsion phase (Kagaya et al., 1995). The stimulation of gluteus muscle is required to support the upper body and avoid front-facing falls during standing.

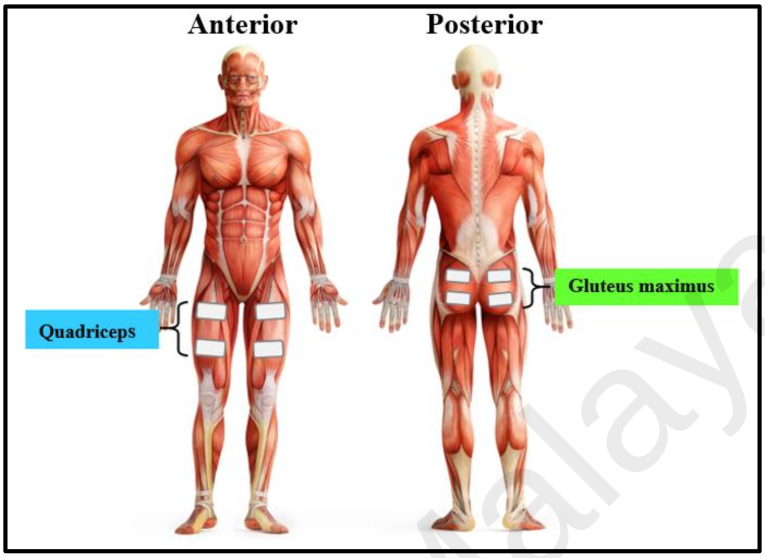


Figure 2.7: Standard muscles stimulation and placement of electrodes during FES standing.

2.4 Mechanomyography (MMG)

Vibromygraphy (VMG) or known as MMG is a tool that has been used to study mechanical signals from a muscle in the human body. MMG is a non-invasive technique commonly used to record and quantify low-frequency lateral oscillations produced by active skeletal muscle fibres (Ebersole & Malek, 2008; Kawakami et al., 2012). The use of MMG has been applied in the clinical field and experimental practices to examine muscle characteristics. These characteristics of muscle include muscle function, prosthesis and/or switch control, signal processing, physiological exercise, and medical rehabilitation (Islam, Sundaraj, Ahmad, & Ahamed, 2013).

2.4.1 Working principle of MMG

Essentially, MMG signal is generated by "slow bulk movement of the muscle" fibre vibrations of muscle or due to the pressure waves produced by muscle fibre dimensional changes (C. Orizio, 1993). During muscle skeletal contraction, MMG gets inputs from three primary mechanisms, (i) a slow bulk movement of the muscle at the initiation of the contraction, (ii) smaller subsequent lateral oscillations which occur at the resonant frequencies of the muscle, (iii) a pressure waves produced by dimensional changes of active muscle fibre (T. W. Beck et al., 2007; C. Orizio, 1993) shown in Figure 2.8. The MMG signal summates the activity of the muscle fibre's motor unit as each motor unit contributes to the pressure waves produced by the activated muscle fibres during muscle contractions (C. Orizio, Gobbo, Diemont, Esposito, & Veicsteinas, 2003).

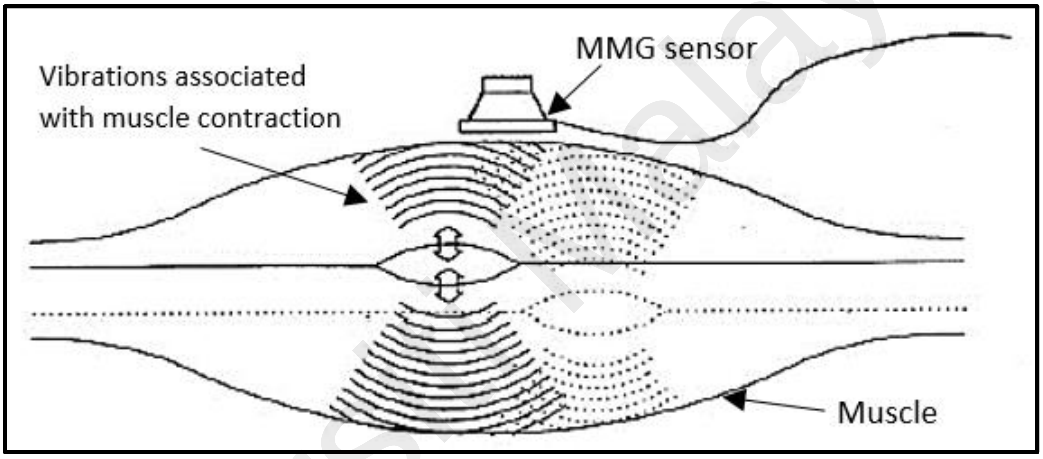


Figure 2.8: Schematic representation of the hypothesised MMG generation process. Adapted from (C Orizio, 2004).

In the diverse applications of MMG, specific transducers are used to detect and record the signals. There are a few types of transducers available for laboratory and clinical settings such as piezoelectric (Travis W Beck, Housh, Johnson, et al., 2005; Ebersole & Malek, 2008), microphones (Kawakami et al., 2012), accelerometer (Scheeren, Krueger-Beck, Nogueira-Neto, Nohama, & Button, 2010; Zuniga et al., 2010) and laser distance sensors (Claudio Orizio, Solomonow, Diemont, & Gobbo, 2008). MMG signal is commonly measured by a physical sensor such as accelerometer shown in Figure 2.9 (Cescon, Farina, Gobbo, Merletti, & Orizio, 2004). It integrates low noise accelerometer with band-pass filtering to eliminate most motion artefacts and pre-amplify the signals.

Figure 2.9: Example of accelerometer transducer, Sonostics VMG BPS-II Transducer for BIOPAC Systems.

When skeletal muscles start to contract, MMG signals may be acquired on the surface of the skin in the form of acceleration, vibration or sound signal (C. Orizio, 1993). In short, even though MMG signals can be collected by a variety of physical transducer, accelerometer-based sensors have been widely recommended due to their suitability for integration into a neurostimulator, in comparison with other sensing modalities (Cescon et al., 2004).

2.4.2 Characteristics parameters of MMG

By analysing MMG signal, there are some features and parameters that can be observed by operators in time and frequency domain. For time domain, there are root mean square (RMS), peak-to-peak (PTP), amplitude, and mean average value (MAV). Meanwhile in frequency domain, mean power frequency (MPF), median frequency (MDF), centre frequency (CF), and frequency variance (FV) can be studied (Ibitoye, Hamzaid, Zuniga, Hasnan, & Wahab, 2014). In the same study, it was believed that these parameters offered valuable information about contractile properties of skeletal muscles' motor units and these properties can be used to estimate the force capacity and fatigability. The amplitude of MMG signal is related to force production of the muscle. It is very sensitive as it is able to detect small changes of force which can be portrayed in the amplitude (Barry, Hill, & Im, 1992). In addition, both time and frequency domains may provide beneficial information on motor control strategies; motor unit recruitment and firing rate of selected muscles during both isometric and dynamic muscle contraction (C. Orizio et al., 2003).

2.4.3 Skeletal muscle condition following incomplete SCI

As mention earlier in Section 2.1.1, SCI leads to the difficulties or inability of individuals performing daily tasks. Subsequent to incomplete SCI, individual's skeletal muscle become paralysis and developed to an atrophic condition. These condition involves the morphological changes as well as contractile changes in incomplete SCI individual's muscles (Biering-Sorensen, Kristensen, Kjaer, & Biering-Sorensen, 2009). Moreover, the skeletal muscle atrophies was revealed to be associated with a shift from type I slow oxidative to type IT fast glycolytic fibers within several months after SCI (Qin, Bauman, & Cardozo, 2010). Approximately 6 weeks post injury, it had been shown that a cross sectional area of individual's thigh was stated to be 35% smaller meanwhile intramuscular fat was 126% greater compared to the control groups (Biering-Sorensen et al., 2009). However, when electrical stimulation was induced to a selected paralysed muscles, a significant increment in its cross sectional area was observed. Of note, the muscle atrophy demonstrated a reversed state after applying the electrical stimulation (Biering-Sorensen et al., 2009).

2.5 Standard Setup of SitTS for SCI

Standard setup of FES for SitTS is necessary to ensure that patients receive maximum benefits from the exercise regime. The standard setup, or also known as traditional setup involving FES and muscles stimulation are further discussed in the next sub section.

2.5.1 Comparison of SitTS Setup used in previous study

In general, there are only a few studies regarding on the incomplete SCI individuals for SitTS activity. Thus, in this section certain previous studies involving the stroke condition was also included in order to compare and improve the research protocol of the current SitTS study. One of the studies by Bahrami et al. discussed the SitTS performance in paraplegic participants. It was observed that paraplegic individuals did the SitTS action in a quasi-static manner. A study by Roy et al. revealed the SitTS exercise in hemiparesis reduced knee extensor moments on the affected side compared to the unaffected side.

Meanwhile, Pages et al. studied the contribution for restoring standing in paraplegia while using the FES by designing a closed-loop control during the activity. Similarly, study from Kamnik et al. discussed the joint moments in lower and upper extremities during SitTS exercise in paraplegia participants. Table 2.2 summarised the SitTS setup in previous studies involving the SCI and stroke individuals.

In the recent study by Saensook et al., he studied the lower limb loading during SitTS exercise in SCI individuals. He found that SCI participants who did not use the hand assist have the similar pattern of lower limb loading with the AB participants. Yet the pattern was not consistent among the trials. For SCI participants who managed to do SitTS with the support of hand assist, the outcome validated that the first peak force and maximal lower limb loading were significantly lower than those SCI individuals who did not use the hands (Saensook et al., 2018).

Table 2.2: Review on Comparison of SitTS setup used for SCI and stroke individuals in previous study.

Author	Participant	Phases of SitTS movement	Muscles stimulated on FES	Equipment used	Markers position	Determinants
(Bahrami et al., 2000)	10 healthy, 2 paraplegic	2	QUAD	Instrumented chair, VC, FP, FES	Ankle, knee, hip, shoulder, elbow, and wrist	Healthy 1. Arm crossed the chest 2. Normal assistance of the arms, 3. Strong assistance of arm support. Paraplegic 1. Arm support with/without FES
(Roy et al., 2007)	12 hemiparesis	NA	NA	Instrumented chair, FP	Feet, legs, thighs, pelvis, trunk and head	Foot position 1. Spontaneous 2. Symmetrical: both feet placed at 15° of dorsiflexion 3. Asymmetrical with the affected foot dorsiflexed at 15°, positioned behind the unaffected foot 4. Asymmetrical with the unaffected foot behind the affected foot.

Table 2.2, continued

Author	Participant	Phases of SitTS movement	Muscles stimulated on FES	Equipment used	Markers position	Determinants
(Pages et al., 2009)	3 healthy, 4 SCI (ASIA A, T5-T12)	NA	QUAD, GLUT, TA, HAM(needed for some subjects)	Flexible pressure insole, Vicon, FES	NA	Observational study with arm support
(Jun et al., 2011)	2	NA	NA	FP(seat, foot), EMG	NA	Observational study
(M. Y. Lee & Lee, 2013)	15 hemiparesis	NA	NA	Matscan System	NA	Height of chair (knee flexion)
(Kamnik et al., 1999)	8 paraplegic	NA	QUAD	Instrumented chair, FP, armrest, FES	NA	Observational study (preferable way at a preferable speed)
(Kagaya et al., 1995)	12 healthy, 2 paraplegic	3	FN, RF, VL, VM	EMG, FP, FES	Lateral malleolus, lateral knee, GT, acromion of the shoulder.	With /without hand-assist

*ASIA = American Spinal Injury Association, EMG = electromyography, FES = Functional Electrical Stimulation, FN = femoral nerve, FP = force plates, GLUT = gluteal maximus, GT = greater trochanter, HAM = hamstring, NA = data not available, QUAD = quadriceps, RF =rectus femoris, SitTS = Sit-To-Stand, SCI = spinal cord injury, TA = tibialis anterior, VC = video camera, VL = vastus lateral, VM = vastus medialis

2.6 Summary

SitTS activity is a basic indicator of motor capacity in AIS C SCI individuals to improve their quality of life. The biomechanics of SitTS have been discussed to establish robust understanding of behaviours which occur throughout SitTS manoeuvre. FES has been developed as a device which can help to activate paralysed muscles of neurological patients such as SCI and provides better performance in terms of movement.

In section 2.2.5, two different methods occurred in SitTS manoeuvre for affected persons are clarified. The BWS demonstrates the weight stack lowers and sustains a fixed anterior-superior force at the pelvis of the movement. Meanwhile in smart mobile walker, this instrument proves better SitTS execution by improving patients' balance during the inclination of body trunk. Moreover, the inclination of trunk lowers the load on patients' knees in SitTS movement. Both studies have shown a similarity on the use of arm support as an assistance tool during the SitTS task (Bahrami et al., 2000; Pages et al., 2009).

As the quadriceps muscle group need to be stimulated by FES for SitTS, it is important to observe and analyse its activity during the manoeuvres. MMG is a tool that has been used by researchers previously to observe the mechanical activity of the quadriceps. As these muscles have significant role on SitTS action, hence their activity must be recorded and analysed further with the other outcomes of the study. Previous study by Islam et al. (2013) stated that measuring certain muscle activity allows researchers to determine muscles fatigue in related to the prolonged exercise.

Table 2.2 shows there are previous studies on SCI patients performing SitTS exercise, however there is no study that has looked at the relative contribution of both arm and leg simultaneously during the exercise. It was hypothesised that contribution of arms relates with the legs' muscle grade and joint condition of participants. The use of FES device is theorised to help participants perform better during this exercise.

CHAPTER 3: METHODOLOGY

This chapter describes the process and protocols used in the study. It explains the participants' information, experimental setup, data collection, processing and analysis for SCI participants. The method of using arm supports during SitTS is advantageous for SCI individuals to help them in trunk control and stability. Two SCI participants with impairment level of grade AIS C were selected to do the SitTS activity in order to measure their arms and leg contribution during SitTS with instrumented SF.

3.1 Participants selection

3.1.1 Able-Bodied (AB) Participants

Ten volunteers with different body weight ranged from 36kg to 45kg were recruited in this research. Volunteers were students from primary schools and University Malaya. They participated in this study only in validation of instrumented of SF which is occurred during PART I of the study protocol, The mean ± standard deviation (SD) body weight of the AB participants were 42 ± 2.18kg

3.1.2 SCI Participants

Three SCI individuals with motor incomplete lesion (AIS C) volunteered to participate in this study. They participated only in PART II and PART III of the experiment. All SCI volunteers could stand up independently and were able to follow verbal instructions. All participants provided written informed consent before taking part in the study **(Appendix A)**. Participants were excluded from this study if they presented with pre-existing bone conditions (i.e. osteoporosis, fractures) or any other medical conditions that would contraindicate medically safe participation in the study. Unfortunately, Participant 3 was unable to continue this research as he had neuropathic pain during FES test current stimulation. Two other SCI participants' (45 and 49 years old) physical characteristics are shown in Table 3.1. All participants were untrained and unfamiliar with the setup of SitTS experiment and FES.

Table 3.1: Physical Characteristics of SCI study participants.

Participant	Gender	AIS level	Height (m)	Body weight (kg)	NLI	Months since injury	LE muscle grade
1	M	C	1.63	54	T12	95	L-4 R-2
2	F	C	1.52	77.5	L4, L5	33	L-4 R-4

*AIS = ASIA Impairment Scale, F = female, L = left, LE = lower extremities, M = male, NLI = Neurological level of injury, R=right

Participant 1 was used to have flaccid right leg with absent knee and ankle reflexes indicating a lower motor neuron injury. Not unexpectedly his right leg did not show any response to FES. Both participant have good trunk control.

3.2 Quadriceps muscle strength assessment

One of the ways to access muscle strength is by using a method termed '1-RM' which is a reliable method for a novice weightlifter or trained individuals (Reynolds, Gordon, & Robergs, 2006).

3.2.1 Adaptive prediction of 1-Repetition Maximum (1-RM)

1-RM refers to the weight maximum that can be lifted at one time (Dohoney, Chromiak, Lemire, Abadie, & Kovacs, 2002). In another approach, the maximum strength can be determined by estimating 1-RM. Estimation of 1-RM is the number of repetition performed up to the point of temporary muscle failure, known as repetition to fatigue (Mayhew, Johnson, LaMonte, Lauber, & Kemmler, 2008). Based on Exercise Physiology Laboratory Manual 6th edition, there are direct and indirect estimate measurement of 1-RM (W. Beam & Adams, 2010).

Direct method of 1-RM involves a traditional trial-and-retrial routine. However, for indirect estimation of 1-RM, its calculation is based on either linear relationship or curvilinear relationship between %1-RM and Repetitions Maximal (#RM). #Repetitions (#Reps) is defined as the number of repetitions to fatigue without rest interval. The % 1-RM is estimated for a set of submaximal repetitions as in Equation 3.1. Then, 1-RM can be estimated by factoring in the weight lifted as in Equation 3.2 (W. Beam & Adams, 2010). For a successful of both direct and indirect 1-RM, quadriceps muscle needs to move in a dynamic contraction by doing a knee flexion. Hence, an adaptive prediction of 1-RM is necessary in order to understand the maximum muscle strength of quadriceps in SCI individuals.

$$\%1 - RM \; = 100 \; - (\#Reps \; \times 2.5) \tag{3.1}$$

$$1 - RM \quad = \; (\,Weight\; lifted/(\%1 - RM/100)\,) \tag{3.2}$$

3.3 Mechanomyography

As mentioned in Section 2.4, MMG is a technique applied in this study to investigate muscle performance during SitTS and Stand-To-Sit (StandTS) activities. The single axis MMG, TSD250A sensors (Sonostics VMG BPS II Transducer, operational frequency response = 20-200 Hz, sensitivity 50V/g, maximum range = 2000g) was used. The transducer as shown in Figure 3.1, has a round shape and can be attached to the human skin to monitor muscle vibrations. It is used with two acquisition unit (BP150 and HLT100C, BIOPAC System Inc., USA) to record and store the raw MMG data for SitTS and StandTS on a computer for off-line analyses.

The BIOPAC system recorded the MMG signal at sampling rate of 2 kHz then the raw data was relayed and transformed by a finite impulse response band-pass filter between 20Hz to 200Hz which has been recommended by BIOPAC for assessment of muscle effort ("Assess Muscle Effort with Vibromyography,"). All MMG signals recorded were obtained from vibration of quadriceps muscle in the exercises.

Figure 3.1: VMG transducers and BIOPAC Vibromyography system.

In the time domain, the voltage values represented as amplitude of the MMG signals retrieved as RMS. This parameter is important to monitor motor unit recruitment during muscle contraction (C. Orizio et al., 2003). For zero crossing (ZC), this parameter signified as the repetitions of muscle contraction during the exercise. Both RMS and ZC equation as followed:

$$RMS = \sqrt{\frac{1}{N}\sum_{k=1}^{N-1} x_k^2}\ , for\ k = 1, \dots, N \tag{3.3}$$

$$ZC = \sum_{k=1}^{N} sgn(-x_k x_{k+1}), for\ k = 1, \dots, N \tag{3.4}$$

$$sgn(x) = \begin{cases} 1\ if\ x > 0 \\ 0\ otherwise \end{cases}$$

where x_k is the raw signals of the segment and N is the number of samples (Dzulkifli, Hamzaid, Davis, & Hasnan, 2018).

Meanwhile in frequency domain, MPF parameter generally related to frequency variables that reflect the changes in global firing rate of unfused activated motor unit during contraction. MPF equation was as below:

$$MPF = \frac{\int_0^{fs/2} f.s(f)df}{\int_0^{fs/2} s(f)df} \tag{3.5}$$

where S(f) and fs are the power density spectrum (PDS) of the signal and the sampling frequency respectively (Ibitoye et al., 2014).

3.4 Study Protocol

This study protocol is divided into three parts. Each part of experiment are presented. All participants provided written consent voluntarily after verbal information from the primary investigator. Participants were provided with a participant information sheet, in accordance with the requirement of Medical Ethics Committee, University of Malaya Medical Centre (UMMC). This study protocol was approved by UMMC Medical Ethics Committee (Reference No.: 2017119-4828). Figure 3.2 shows the overall flowchart of the methodology.

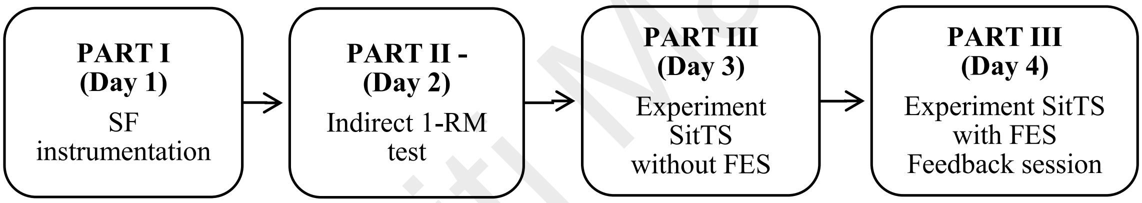


Figure 3.2: Overall flowchart of the SitTS experiment.

3.4.1 PART I: Instrumentation of the standing frame (SF)

In this study, four FlexiForce A201 sensors (Figure 3.3) were used to elucidate the force measured at the handle of calibrated SF, as it has been shown in previous study that it has higher precision in terms of its repeatability compared to Force Sensing Resistance (FSR) and LuSense PS3 (Hollinger & Wanderley, 2006). The sensors were supplied from Tekscan, Inc., USA. One important procedure in using any type of sensor is calibration. During the calibration test, the value of force was established by measuring the value of its voltage. Thus, a sensor needs to be calibrated with a known force using 'dead weight method' and its voltage is then measured. The study design protocol was adapted from datasheet of FlexiForce A201 sensor. Modification was done to suit the experimental exercises.

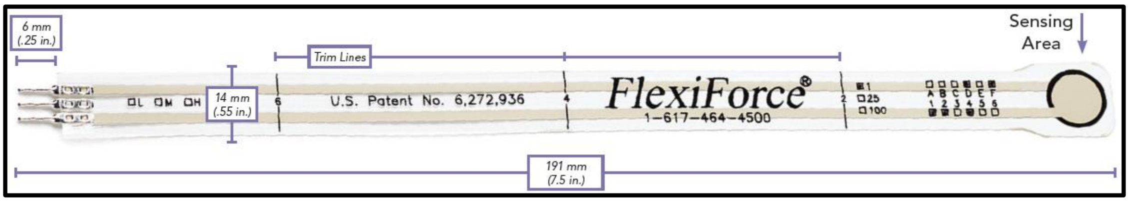


Figure 3.3: FlexiForce sensor A201 used in the SitTS experiment. Adapted from ("FlexiForce A201 Sensor," 2014).

The foldable SF shown in Figure 3.4 with adjustable height works as an arm support during the assistance of SCI participants in SitTS activity. These SF had been supplied from Limb Brace Rehab Appliance, Kuala Lumpur. A single steel cross brace placed in front of the SF was meant to provide stability for the device. It was equipped with shaped hand grips for comfort and anti-slip rubber feet. The one-button fold system in this standing frame design makes it easy to store. The SF weighted 2.3kg. The height of SF is 70cm and it can be adjust up to 90cm.

Figure 3.4: Foldable standing frame used in SitTS experiment.

<u>Study design/Protocol (Day 1)</u>

Hanging test

Experimental set up: Four FlexiForce sensors were calibrated individually. Each sensor is capable of measuring force up to 11kg. A weight, starting from 1kg was placed on top of each sensor and kept in the position for 5s (the predicted time for SCI patient to do a cycle of SitTS activity with SF). This step helps to minimize drift error. Each weight was then increased progressively until 11kg. Then, these four sensors were placed at the bottom leg of the standing frame (Figure 3.5). Ten AB participants with different body weight (36kg to 45kg) lifted their whole body while holding onto the arm support of the SF. This would allow their whole body weight to be distributed among the four sensors at the base of the SF.

Data collection: Each set of data (sensor output/voltage versus force exerted) was collected and data were plotted on a graph. The equation for the line of best fit and the sensor output was used to determine the total body weight exerted on the participant during hanging test on the standing frame.

Figure 3.5: (a) Flexiforce sensor was placed at the bottom part of the rubber stopper of the standing frame leg. (b) The placement of four Flexiforce sensor.

3.4.2 PART II: Indirect 1-RM & FES current test

The purpose of this experiment was to measure the maximum amount of force that can be generated by one knee extension contraction 1-RM using the indirect 1-RM method with and without FES in SCI participants. Apart from that, the other objective of this test was to obtain the maximum RMS-MMG of the SCI participants' quadriceps that next will be used to normalize the RMS-MMG of their quadriceps muscle from the SitTS experiment. In addition, this experiment was done to get the participant become habituated to the use of FES as well as to get the participant become acclimatised to the hardware and experiment venue.

The study protocol of indirect 1-RM test for SCI participants was adapted from Exercise Physiology Laboratory Manual Sixth edition (W. C. Beam & Adams, 2011). Modification had been done to suit the experimental exercises in this study.

Study design/ Protocol (Day 2)

Indirect 1-RM test

Initial Evaluation: Brief medical history of the participant was taken. Information pertaining to the participant's spinal cord injury level of paralysis and weakness and personal experiences were noted down. Responses to FES was also recorded from the participant. Physical parameters such as participant's weight and height were recorded. A physiotherapist had assessed the participant to determine legs muscle strength grade, range of motion of joints.

In this study, the term 'leg' refers to the whole lower limbs i.e. from the highest point of the thigh to the foot ("Cambridge Online Dictionary," 2019).

Participant Preparation: The participant was informed of the requirement to wear fit trousers on the day of the experiment. The participant was asked to sit on a chair while his trunk should lean on the back rest of the chair and his hands and arms crossed the chest. Two VMG sensors were placed at quadriceps (i.e. rectus femoris) of both legs. The participant wore an ankle weight on his right ankle and knee positioned in 90 degree. The weight prescribed for the participant was determined by asking his verbal feedback if weight was too heavy or too light to lift. Three pairs of adjustable ankle load (Kettler Adjustable Ankle Weight, 2.5kg per pair) were used as the weight prescribed in this experiment (Figure 3.6). For one pair of ankle load, there are 2 straps of ankle weight. Each strap consists of 10 cylinder slots which can be fitted with 0.125kg load for each slot. The participant was directed to practice the knee extension at the end of countdown until his performance is satisfactory. A warm –up set was conducted at 8-10 repetitions according to the previously prescribed weight. A minute rest with active recovery was allowed before continuing with the left leg.

Figure 3.6: A pair of adjustable ankle load strap. Each strap consist of ten removable cylindrical weight slot

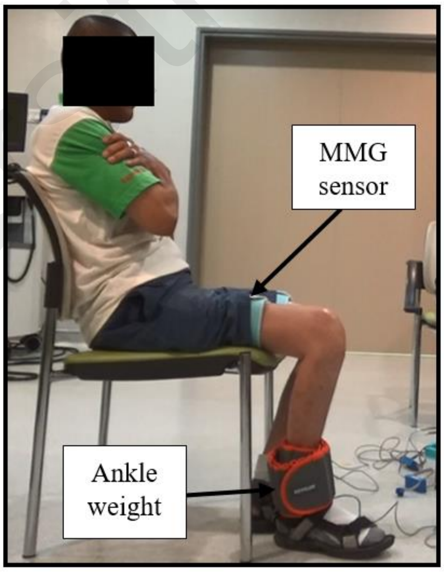


Figure 3.7: Set up of indirect 1-RM experiment.

Performance strength: Again, the participant was asked to sit on a chair while his trunk should lean on the back rest of the chair and his hands and arms crossed his chest (Figure 3.7). Two VMG sensors were placed on the quadriceps (i.e. rectus femoris) of both legs. The participant wore the prescribed ankle weight on his right ankle and the knee positioned in 90 degree. This weight was recorded as Trial 1. The participant was directed to make an attempt of knee extension at the end of countdown. The participant was asked to repeat the knee extension as many times as possible at a comfortable pace, but without any rest interval. Ideally, the goal of the test is to lift the weight about 3-12 times up to fatigue. (3-12 RM). 1-RM of the participant will be estimated using number of repetitions to fatigue (#RM) and the amount of weight lifted (#kg). If the participant becomes fatigued in 3-12 repetitions, it was acceptable and the test was considered complete. The test continues with the same procedures for the left leg. The number repetitions with the weight lifted for Trial 1 was recorded. The 1-RM was calculated based on formula in Equation 3.1 and Equation 3.2.

Next, for indirect 1-RM with assistance of FES, the performance strength was repeated in both sides by putting the electrodes on the quadriceps. The FES stimulation was set initially at 20mA. The FES current was determined by getting his verbal feedback to reach a particular tolerable current. This current was recorded in order to define the minimum tolerable FES current for the SitTS experiment in PART III.

The FES was switched on when the participant started to do the knee extension movement. As the participant's knee was extended position, the FES is then switched off.

3.4.3 PART III: SitTS without and with FES

The study protocol of SitTS test for SCI participants was adapted from an article entitled "Quantitative analysis of sit to stand movement: Experimental set-up definition and application to healthy and hemiplegic adults" (Galli, Cimolin, Crivellini, & Campanini, 2008). Modifications were made to suit this experimental exercises.

<u>Study design/protocol (Day 3) - Voluntary SitTS Experiment</u>

SCI participant was tested on their regular methods of transitioning from a seated position to a standing one without the assistance of FES.

Hardware Set Up: Two force plate in Vicon Nexus motion capture system was calibrated. The MMG system and sensors for standing frame were set up.

Participant Preparation: The procedure was explained to the participant. The VMG sensors were placed on quadriceps (i.e. rectus femoris) on both legs (Figure 3.8). The participant was instructed to sit on the chair provided. A standard height of chair was used in this experiment which is 0.45m (Mazza, Benvenuti, Bimbi, & Stanhope, 2004). With reference to Figure 3.9, a custom made chair was designed for SitTS experiment following the dimension of the force plate in the motion analysis laboratory.

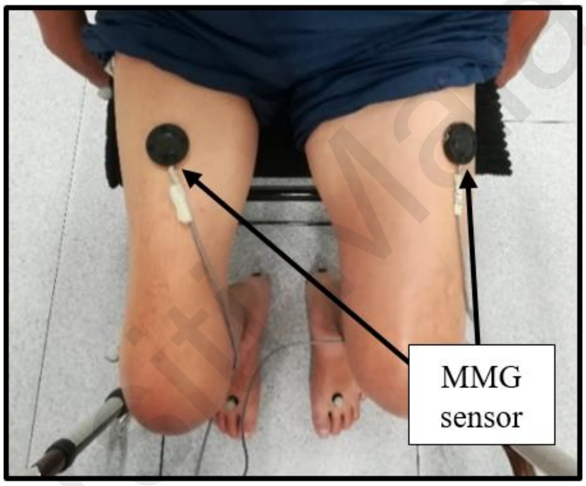


Figure 3.8: MMG were put on both side of quadriceps RF muscle belly.

Experimental set up: The participant was directed to attempt stand up movement using a standing frame as the arm support from seated position at the end of a countdown. Before the countdown ends, the data captured from Vicon Nexus, MMG and sensors of standing frame were activated. Then, the participant performed transition from sit to stand (Figure 3.9). The participant safety while standing was monitored throughout the test. Three seconds after the participant achieved full upright standing (full knee extension), the participant was directed to sit down. Five second resting intervals were given before the same manoeuvre was repeated until they were unable to perform the same routine further. Then, the participants were allowed to take a five minute rest. These steps were repeated for three sets. The frame work of SitTS experiment was illustrated in the Figure 3.10. A 48-hour rest was given to the participant before the next test day.

<u>Study design/protocol (Day 4) - FES Assisted SitTS Experiment</u>

The participant was tested on their ability to transition from a seated position to a standing one with the assistance of FES.

Hardware Set Up: Two force plate in Vicon Nexus motion capture system was calibrated while the MMG system and FES device and sensors for standing frame were set up.

Participant Preparation: The procedure was explained to the participant. The FES electrodes were placed on gluteal muscles as well as the quadriceps bilaterally. MMG sensors were placed on the quadriceps (i.e. rectus femoris) on both legs. The participant was instructed to sit on the chair given.

Experimental set up: The FES stimulation was programmed to pre-set parameters and the current was set to the maximum tolerable current (Figure 3.9). The participant was directed to attempt stand-up manoeuvre from the seated position at the end of countdown by an investigator. Before the countdown ends, the data capture functions from Vicon Nexus, MMG and sensors of SF were activated. The participant then did transition from sit to stand. The participant safety while standing was monitored throughout the test. Three seconds after the participant achieved full upright standing (full knee extension), the stimulation were switched off. Feedback was taken from the participant on his ability to tolerate higher intensity of stimulation. Five second resting intervals were given before the same manoeuvre was repeated until they were unable to perform the same routine further. Then, the participants were allowed to take a five minute rest. These steps were repeated for three sets.

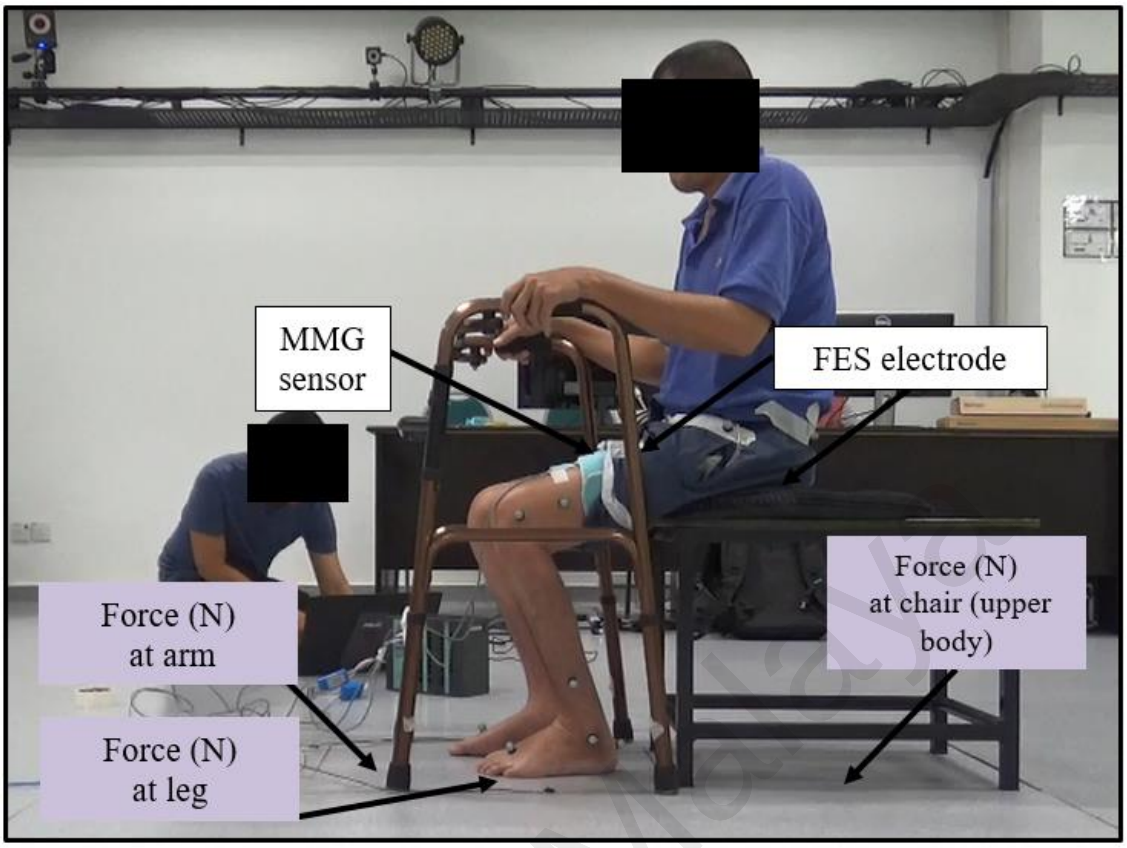


Figure 3.9: The setup of SitTS experiment during FES session. The custom made chair was placed inside force plate 1. Both feet were assigned to be put on force plate 2.

Feedback session: This session was divided into two parts. The first part was started by giving four simple questions regarding the stability and fatigue experienced by participants during the accomplishment of SitTS in Day 3 and Day 4. In this section, stability was observed as the highest balance achieved meanwhile fatigue was detected as the lowest performance retrieved after SitTS exercise. Then, the participants were interviewed in the second part to capture their views on the use of FES device in SitTS activity throughout the experiment. The interview session was recorded for future transcription of the content. Open questions and prompts were used to gather information in relation to their experience, knowledge, benefits, problems or difficulties, and thoughts about FES. The list of questions attached in **Appendix D** acted as basic guidelines for the interview which was lasted for 20 -30 minute.

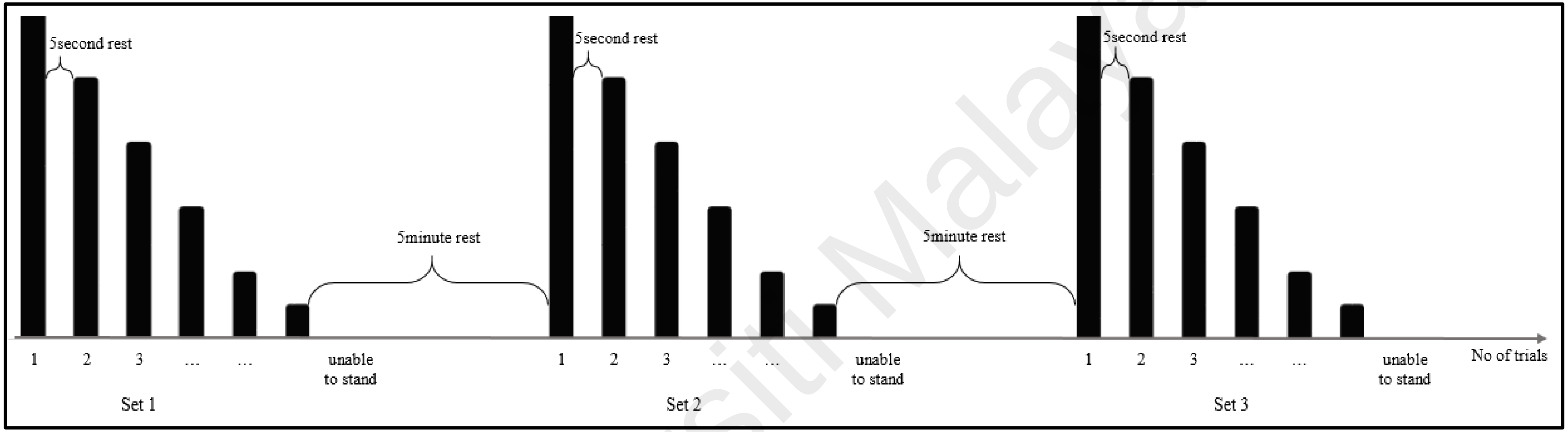


Figure 3.10: Experimental frame work of SitTS activity in one session.

3.5 Data analysis

In order to meet the first research objective, the contributions of arms and legs during SitTS activity were evaluated from the instrumented SF and force plates of Vicon Nexus motion capture system respectively. For upper limbs contribution, the voltage values from Flexiforce sensors were converted into a force values by using equations as below:

Sensor 1; $$y_1 = 0.2974x_1 + 0.2281 \tag{3.6}$$

Sensor 2; $$y_2 = 0.2827x_2 + 0.4817 \tag{3.7}$$

Sensor 3; $$y_3 = 0.2823x_3 + 1.76 \tag{3.8}$$

Sensor 4; $$y_4 = 0.3042x_4 + 0.6428 \tag{3.9}$$

where y is the value of voltage (V) and x is the value of force (N).

Next, the force values from the four sensors were added following to the Equation 3.10 to sum the total arms' force contributed by the instrumented SF during SitTS experiment. Equation 3.10 was generated during the body weight validation of ten AB participants in the hanging test procedure.

$$Total\ Force\ of\ Arms = Sensor1 + (2 * Sensor2) + Sensor3 + (2 * Sensor4) \tag{3.10}$$

Meanwhile, legs contribution during the SitTS exercises was represented by the force value generated on the force plate 2 in Vicon Nexus motion capture system (see Figure 3.9). The total contribution of forces in arms and legs were assessed thoroughly in a complete cycle of SitTS (voluntary and assisted FES) which consist of three phases. During early to mid-phase of SitTS motion, force acted on upper body which generated from the force plate 1 in Vicon Nexus system was also included (see Figure 3.9). The weight of the customade chair on the force plate 1 was deducted in order to compute body weight acted on the force plate 1 during the SitTS experiment. Equation 3.11 showed the total forces acted on the body during the SitTS motion.

$$Total\ Forces\ acted\ on\ the\ body = Total\ Force\ of\ Arms + Total\ Force\ of\ Legs + Total\ Force\ of\ Upper\ Body\ from\ the\ Chair \quad (3.11)$$

In both condition, the forces acted on the body in each phases were analysed for every initial and final trial of three sets of SitTS activity. Paired sample t-test was done to observe the significant changes of forces contribution in arms and legs. Besides that, Vicon Nexus motion capture system also able to capture knee angles parameters during the SitTS exercise. The RMS-$MMG_{(maximum(max)/average(ave))}$ parameter was obtained from the SitTS motion and these data was normalised with the maximum value of RMS-MMG from the indirect 1-RM test. The calculation to determine the normalised RMS-MMG data as shown below:

$$\text{Normalised RMS-MMG}_{(max/ave)} = \frac{\text{value of } RMS{-}MMG_{(max/ave)} \text{ during SitTS motion}}{max\ value\ of\ RMS{-}MMG\ during\ indirect\ 1{-}RM\ test} \quad (3.12)$$

All these forces (arms and legs), knee angle and normalized RMS-MMG parameters during a cycle of SitTS were plotted and data are presented and compared only between initial trial of Set 1 and final trial of Set 3 for both condition.

In addition, time taken to execute a cycle of SitTS was also calculated. Prior to these parameter, the mean of first five initial and the mean of last five final trials in every set were observed and the data were tabulated. An independent sample t-test was done to observe the significant difference in mean time between two conditions.

For the second objective, evaluation of quadriceps muscles during SitTS motion were identified by using MMG. In this study, four parameters from MMG were observed in time and frequency domain. The parameters comprised of RMS_{ave}, RMS_{max}, ZC and MPF.

The raw MMG signals of quadriceps muscles were plotted and viewed in AcqKnowledge 4.3 software. Then, the raw MMG data was relayed and transformed in the same software by a finite impulse response band-pass filter. For further analysis of these parameters, the MMG signals were computed for every 25th centile from the total number of the trials produced in each set by the participants (see Figure 3.11). The parameters were computed by using the Equation 3.3, Equation 3.4 and Equation 3.5.

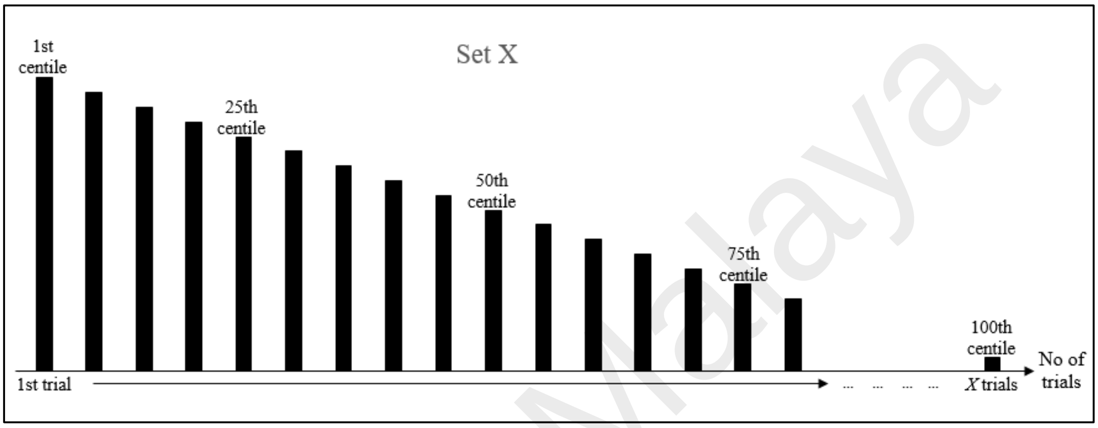


Figure 3.11: Illustration of computation of centile in every set for both SitTS session.

Two RMS-MMG parameters (i.e. RMS_{ave}, RMS_{max}) were normalized with the maximum RMS-MMG value achieved from indirect 1-RM test. The RMS_{ave}, RMS_{max} performance of quadriceps muscles from both sides of the legs in each condition were observed. The data were tabulated and presented as mean ± SD. An independent sample t-test was conducted to determine the significance difference between performances of both legs sides. Besides that, these four MMG parameters of quadriceps muscles performance were observed between initial and final trials of SitTS in every set. All data from the initial and final trials of all subjects were tested for significance difference with an independent sample t-test. Next, one-way ANOVA test was performed to analyse the difference among mean value of these four MMG parameters in every sets of SitTS activity.

In addition, these four MMG parameters of voluntary SitTS and voluntary StandTS activities were analysed and compared to observe the behaviour of MMG pattern during both events. Furthermore, difference between two sides of legs with MMG parameters were observed during these events. These data were tabulated and presented as mean ± SD. Then an independent sample t-test was conducted to determine the significance difference between sides of legs and four MMG parameters. Additionally, one-way Analysis of Variance (ANOVA) test was performed on every 25th centile of sets to analyse the difference among the mean value of MMG parameters on every 25th centile. The same one-way ANOVA analysis was also conducted to analyse the difference of mean among sets of both events (SitTS and StandTS) with the MMG parameters. All statistical analyses were conducted using IBM SPSS Statistics 24 (SPSS Inc., USA) software.

To answer the third objective, data on SCI participants' views regarding the use of FES device, particularly during the SitTS activity were transcribed verbatim. Thematic analysis was used in this study as it provides the method for identifying, analysing and reporting the themes in between the data. It is very systematic, flexible and very useful for qualitative analysis (Braun & Clarke, 2006). Besides that, analysis on stability and fatigue experienced by participants during accomplishment of SitTS were conducted. The data were tabulated and presented following the questions regarding the stability and fatigue based on the five events occurred during SitTS action.

3.6 Summary

This chapter provides information regarding the participants' characteristic and a full study protocol for each part of the experiments. This chapter also gives an overview on the procedures s and devices used in the study. The first part of the experiment included the protocol of calibration of FlexiForce sensor and its validation on instrumented SF. The second part consisted of indirect 1-RM protocol for SCI individuals. The last part of the study protocol comprised of the SitTS experiment and the feedback session. The data analysis conducted to obtain the research findings was elaborated.

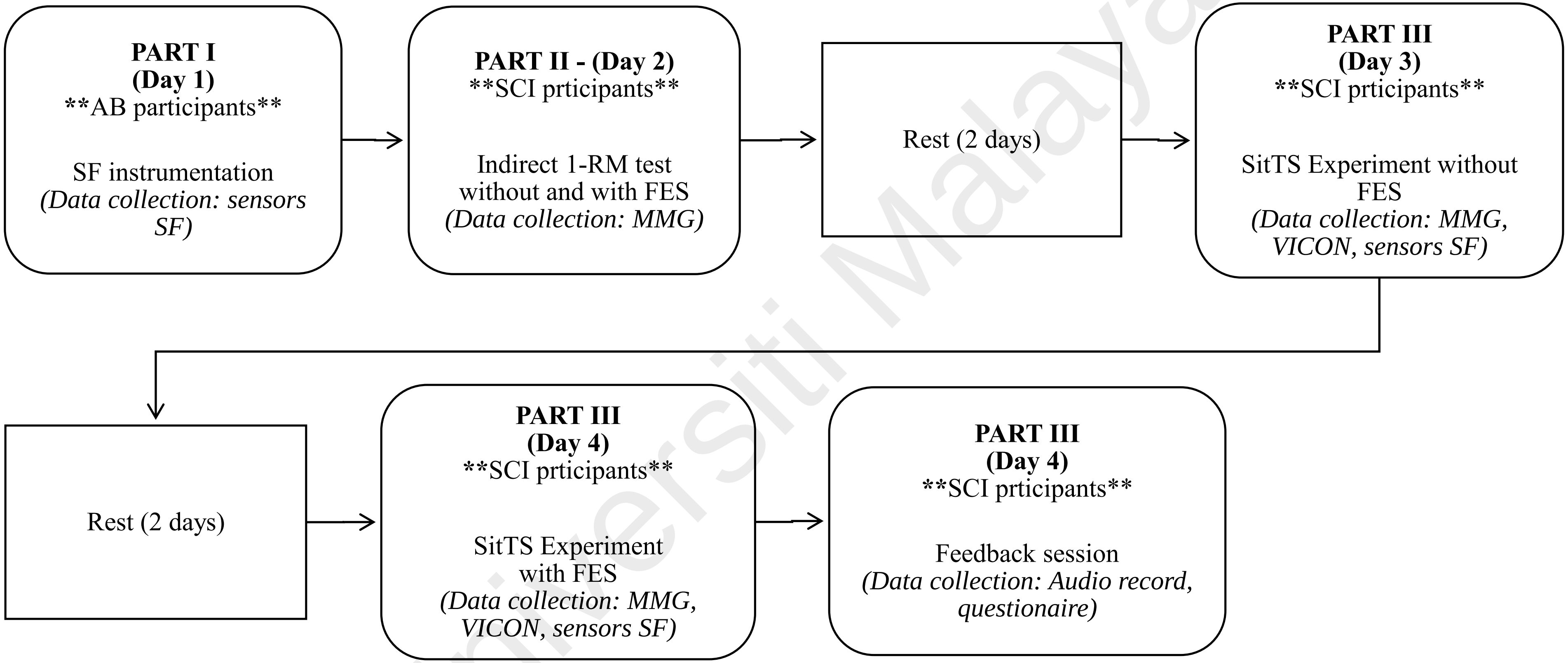


Figure 3.12: Overall flow chart of experiment and data collection of SitTS study.

CHAPTER 4: RESULTS

According to the study protocol described in the previous chapter, the results of the SitTS study were divided generally into three main parts. For PART I, the results regarding on the instrumentation of SF were provided. These part, only AB participants were involved. Next, in PART II, the outcome of the indirect 1-RM test were displayed among the SCI individuals. In specific, results from the experiment PART III was classified following to the arrangement of the data collection and analysis of the study. Data analysis from all interested parameters of leg force, knee angle (Vicon Nexus motion capture system), RMS,MPF, ZC (MMG) and arm force (instrumented SF) were then matched and compared in the study. Figure 4.1 shows the overall flowchart of the results presented in this chapter.

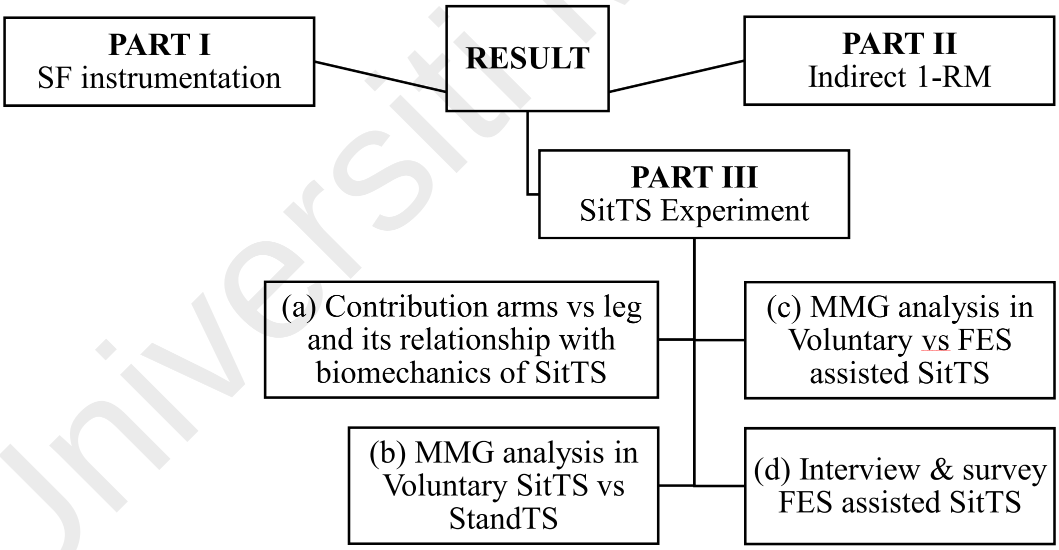


Figure 4.1: Flowchart of the results tabulated based on the SitTS methodology.

4.1 PART I: Instrumentation of the standing frame

Four FlexiForce sensors were calibrated individually by putting a load with known weight at 10N intervals. The graph of voltage versus force was plotted as shown in Figure 4.2. A line of best fit was drawn to find a linear equation of each sensor.

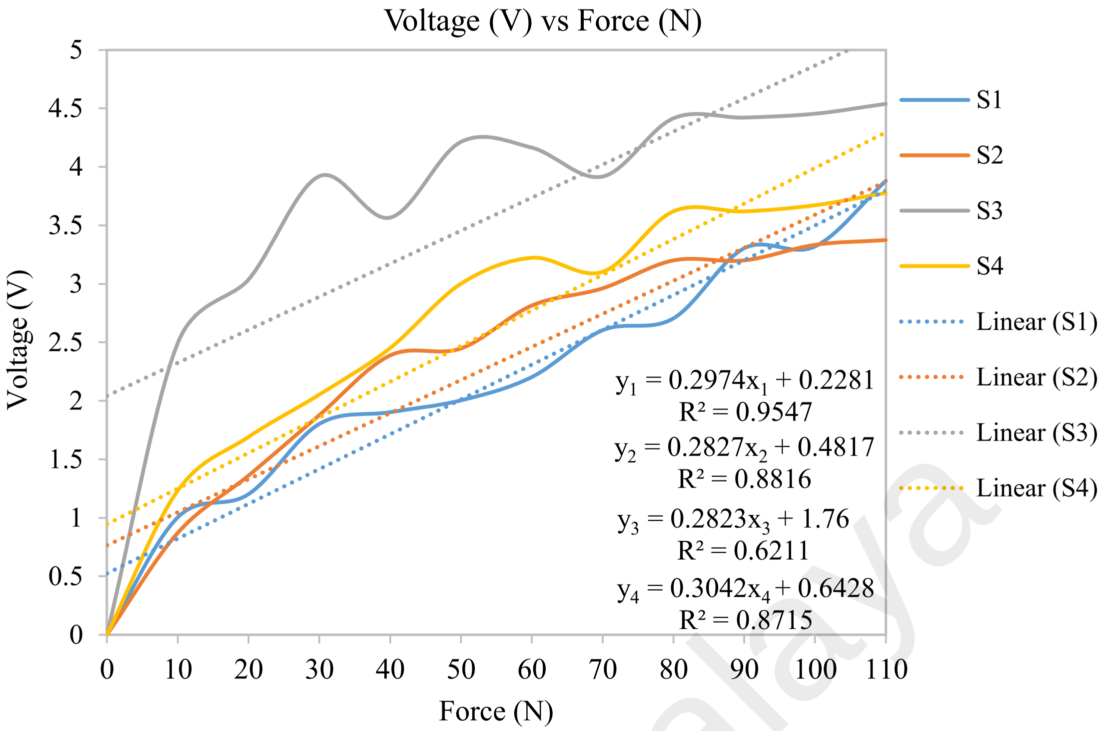


Figure 4.2: Individual FlexiForce sensors calibration.

Hanging test with ten AB participants were done to validate the distribution of weight through the instrumented standing frame. The characteristic of net body weight of each participant at standing frame was determined with this formula:

$$Net\ body\ weight\ = Sensor1 + (2 * Sensor2) + Sensor3 + (2 * Sensor4) \quad \textbf{(4.1)}$$

The percentage of net body weight was calculated using the formula:

$$Percentage\ of\ body\ weight = \frac{Net\ body\ weight}{Actual\ net\ weight} * 100 \quad (4.2)$$

The hanging test showed the instrumented standing frame setup had **minimum 85% accuracy** in comparison with the actual total body weight of the participant. In the next part of the SitTS experiment, Equation 4.1 was applied in order to provide value of the arms force applied at SF during the event.

4.2 PART II: Indirect 1-RM without and with FES

The indirect 1-RM tests were successfully performed. Both participants managed to lift the adjustable load and did the knee extension until they were tired. However for Participant 1, his right leg was not able to lift any loads with and without the presence of FES. The result of indirect 1-RM for Participant 1's left leg was 4.286kg without FES assistance meanwhile 7.5kg was recorded when stimulation of FES was given. There was a 75% increment of indirect 1-RM when Participant 1 did his left knee extension with the assistance of FES compared to the voluntary left knee extension.

For Participant 2, her voluntary indirect 1-RM for the right and left leg were 6.25kg and 7.17kg respectively. When FES was stimulated at the Participant 2's quadriceps, her indirect 1-RM was 9.48kg on the right leg and 10.34kg on the left leg. This result showed that with the given current stimulation, there were increments of 51.7% and 44.2% on right and left leg respectively as compared to the voluntary indirect 1-RM. The results were summarised and shown in Table 4.1.

Table 4.1: The results of indirect 1-RM for SCI participants.

Participant	Leg	FES	FES current (mA)	No of rods (n)	Weight lifted (n x 0.125kg)	No of reps	Indirect 1-RM
1	R	No	-	-	-	-	-
		Yes	-	-	-	-	-
	L	No	-	24	3.00	12	4.29
		Yes	40	45	5.63	10	7.50
2	R	No	-	35	4.38	12	6.25
		Yes	40	55	6.88	10	9.48
	L	No	-	43	5.38	11	7.17
		Yes	40	60	7.50	11	10.34

*FES = Functional Electrical Stimulation, L = left, R = Right

4.3 PART III: SitTS without and with FES

For this part, the results are presented in four sections. The first section is the contribution arms and leg and its relationship with biomechanics of SitTS. The second section is the observational result of MMG by comparing the quadriceps muscle performance during voluntary SitTS and voluntary StandTS activities. The third section revolved on the MMG analysis regarding on the quadriceps muscle performance during voluntary and FES assisted SitTS activity. During FES assisted SitTS session, the FES current stimulated towards the participants selected muscles were displayed in Table 4.2.The last section displayed the results of the feedback session and survey following to the use of FES during SitTS.

Table 4.2: FES current stimulation during FES assisted SitTS session.

Participant	Leg	FES current (mA)	
		Quadriceps	Gluteal Maximus
1	R	58	46
	L	46	46
2	R	35	28
	L	35	28

*FES = Functional Electrical Stimulation, L = left, R = Right

4.3.1 Contribution of arm and leg during repetitive SitTS activity without and with assistance of FES

There were a total of 399 and 463 SitTS trials completed during without and with assisted FES correspondingly as stated in Table 4.3. The participants could perform more SitTS trials with the presence of FES. In general, a SitTS cycle can be divided into three phases; Phase 1 was from the initiation of motion to the time the buttocks left the seat; Phase 2, was from the initiation of the buttocks lift-up from the seat to the maximum hip flexion; Phase 3 was from the initiation of hip extension to the end of the motion. Based on this study, these three phases (Phase 1, Phase 2 and Phase 3) contribute 23 ± 7%, 16 ± 4% and 61 ± 6% of the SitTS cycle respectively as illustrated in Figure 4.3.

Table 4.3: Summary of completed number of trials of SitTS Movement.

Participant	**Number of SitTS trials**					
	No FES			**FES**		
	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3
1	96	30	31	96	61	36
2	95	92	55	89	91	90

*FES = Functional Electrical Stimulation, SitTS = Sit-To-Stand

Overall, the mean time of FES-SitTS cycle between initial trial in each set was identified to be significantly shorter (t=1.28s) as compared to the final trials (t=1.66s) in each set (*p*<0.0005) as illustrated in Table 4.4. However there was no significance difference in mean time of non-assisted FES SitTS activity between initial and final trials (*p*=0.571). The contribution of arm and leg during SitTS movement varied among the participants based on their MRC muscle strength grade especially at the leg part. Hence in this section, the SCI participants' contribution of the arms and legs were presented individually.

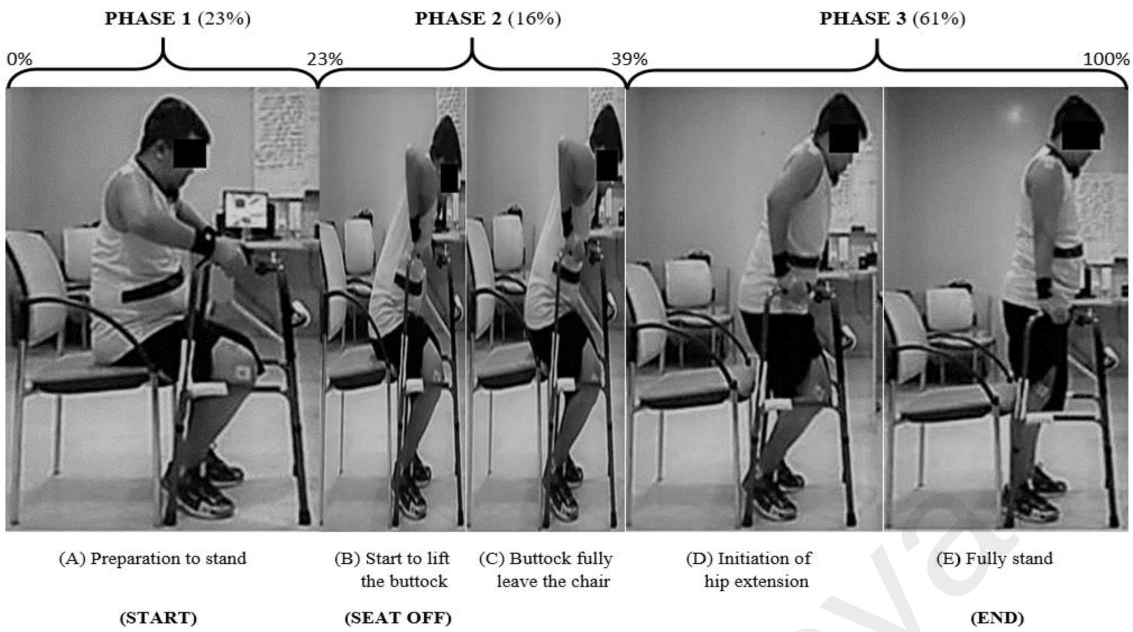


Figure 4.3: A cycle of SitTS activity assisted by SF.

Table 4.4: Time of SitTS to be completed in initial and final trials in each set.

Trials	**N**	**No FES**	**FES**
		Mean time (s)	**Mean time (s)**
Initial	60	1.57 ± 0.244	1.28 ± 0.123[a]
Final	60	1.84 ± 0.210	1.66 ± 0.295[a]

Values were given as mean ± SD (N=60). Means with superscripts ‘a’ were significant (p<0.01).
*FES = Functional Electrical Stimulation

<u>Participant 1</u>

Generally, based on the Figure 4.4(a), and Figure 4.5(a), the graph of legs and arms contribution displayed the same pattern between voluntary and FES assisted SitTS session. Participant 1’s arms and legs contribution were tabulated according to the three phase of SitTS activity (Table 4.5). During early Phase 2 (seat-off) of SitTS, Participant 1’s arm contributed 21.4% (without FES) and 28.3% (with FES) meanwhile his legs contributed -5.3% (without FES) and -6.18% (with FES). However, throughout the end of Phase 3, percentage of Participant 1's arm contributed 79.2% (without FES) and 86.7% (with FES) meanwhile his leg contributed 20.8% (without FES) and 13.3% (with FES).

In addition, the negative values on the legs % during SitTS activity were illustrated in Figure 4.4(a), Figure 4.5(a). Participant 1 was observed to use lesser force on his leg towards the end of the assisted FES SitTS session compared to the voluntary SitTS session. Based on the Figure 4.4(b) and Figure 4.5(b), towards the end of the SitTS cycle, the right knee angle did not achieve the normal knee extension range of motion.

Table 4.5: Contribution of Participant 1's arms and legs during accomplishment of SitTS activity.

Contribution	Session 1 - no FES			Session 2 - FES		
	Start (Phase 1)	Seat off (Phase 2)	End (Phase 3)	Start (Phase 1)	Seat off (Phase 2)	End (Phase 3)
Arms %	11.6	21.4[a]	79.2[a]	25.2	28.3[a]	86.7[a]
Legs %	-0.3	-5.3[a]	20.8[a]	-2	-6.18[a]	13.3[a]
Upper body % from the chair	88.7	84	0	76.78	77.86	0

Means with superscripts 'a' were significant (p<0.01).
*FES = Functional Electrical Stimulation

Voluntary SitTS activity

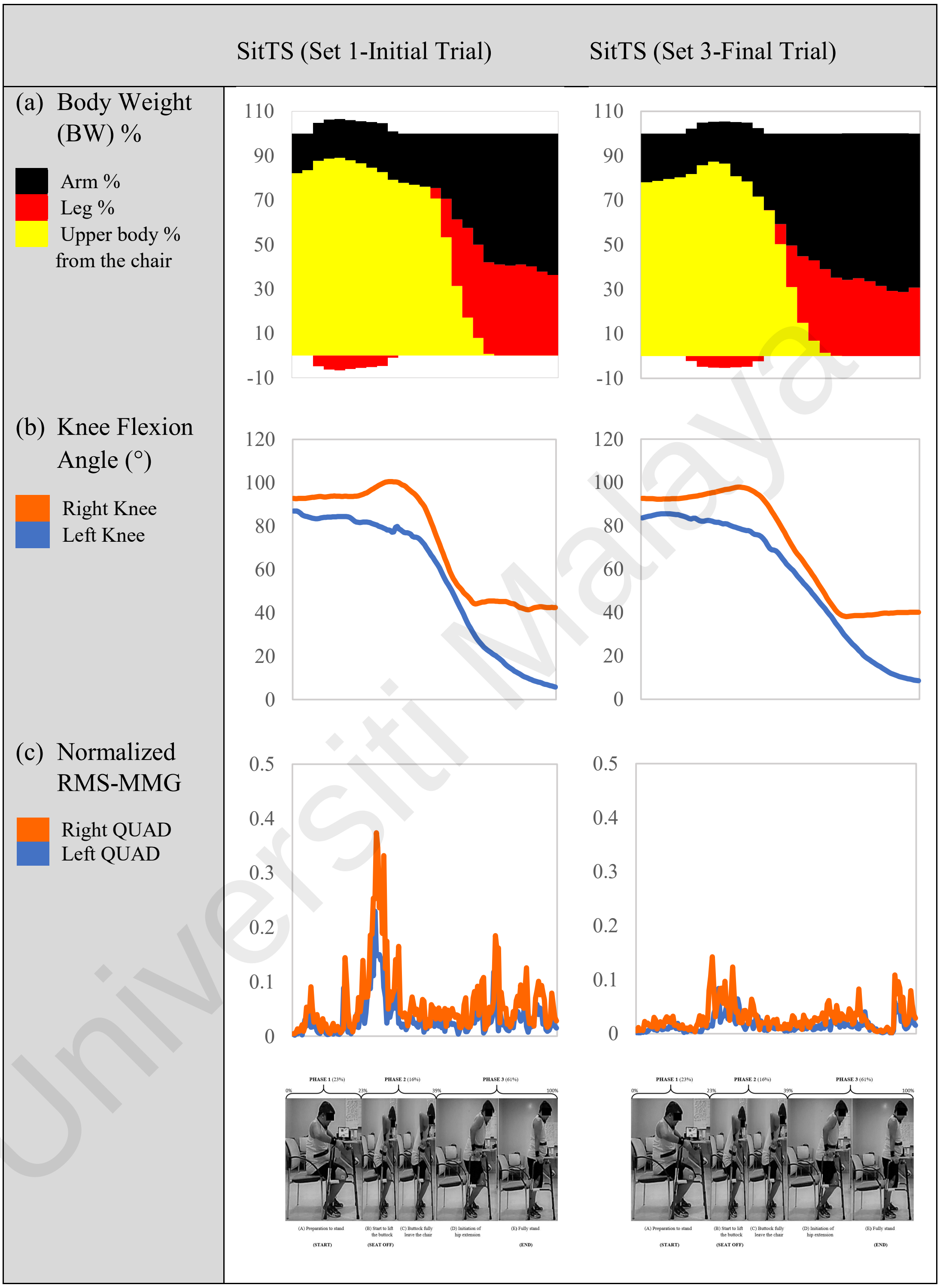


Figure 4.4: Participant 1's body weight contribution, knee flexion angle and normalized quadriceps RMS-MMG during voluntary SitTS (Set 1-Initial Trial versus Set 3-Final Trial).

Assissted FES SitTS activity

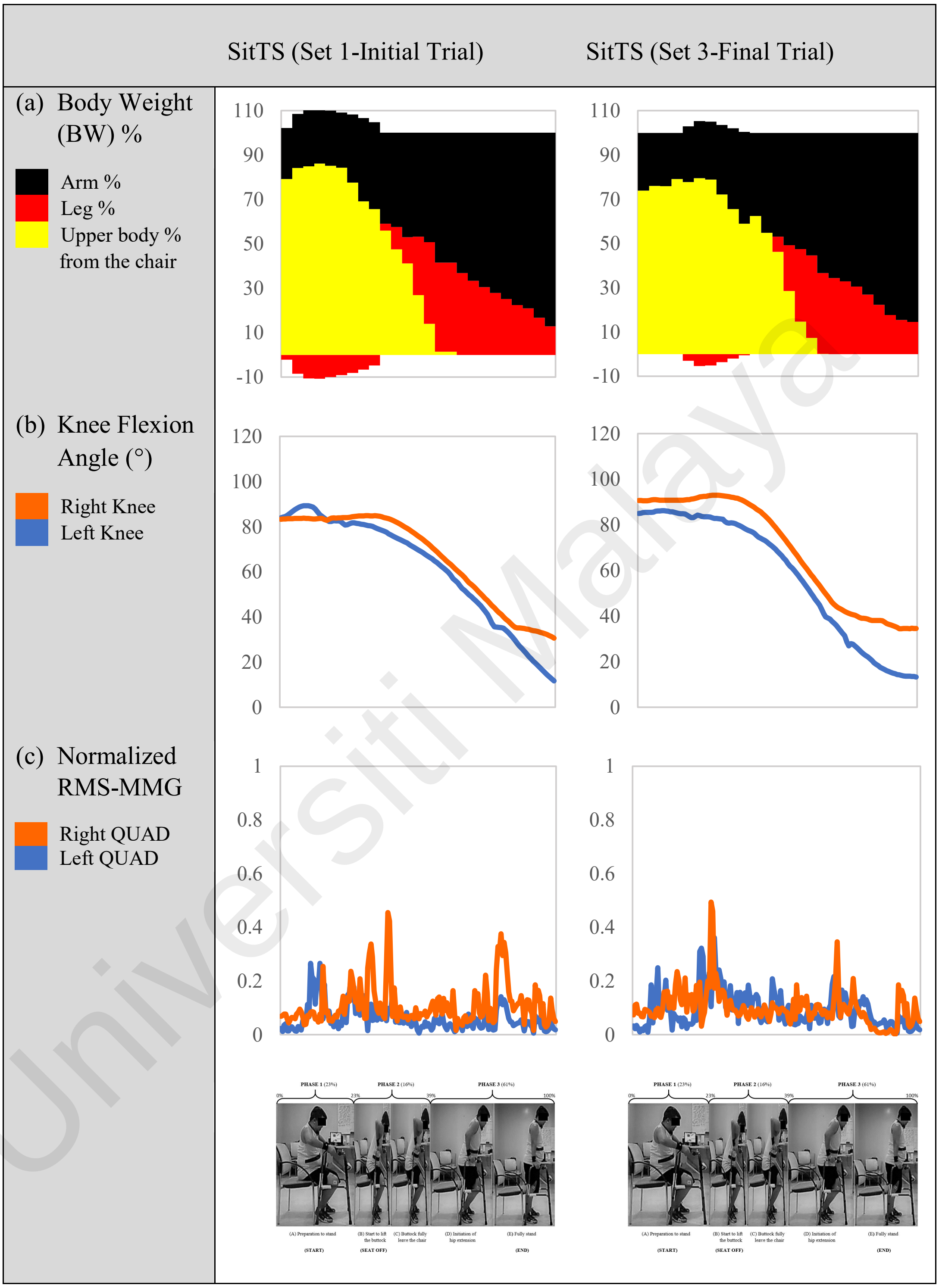


Figure 4.5: Participant 1's body weight contribution, knee flexion angle and normalized quadriceps RMS-MMG during assisted FES SitTS (Set 1-Initial Trial versus Set 3-Final Trial).

Participant 2

In general, the graph of legs and arms contribution between voluntary and FES assisted SitTS session displayed the same pattern as shown in Figure 4.6(a), and Figure 4.7(a). Participant 2's arms and legs contribution were tabulated according to the three phase of SitTS activity (Table 4.6). During early Phase 2 (seat-off) of SitTS, Participant 2's arm contributed 15.9% (without FES) and 13.9% (with FES) meanwhile her legs contributed -2.8% (without FES) and -2.2% (with FES). However, throughout the end of Phase 3, percentage of Participant 2's arm contributed 20.5% (without FES) and 21.2% (with FES) meanwhile her leg contributed 79.5% (without FES) and 78.8% (with FES).

In addition, the negative values on the legs % were illustrated in Figure 4.6(a) and Figure 4.7(a). Participant 2 was observed to use lesser force on her arms towards the end of both SitTS session. From Figure 4.6(a), during final trial of SitTS, Participant 2 presented decrement of knee angle values at the early phase of SitTS.

Table 4.6: Contribution of Participant 2's arms and legs during accomplishment of SitTS activity.

Contribution	Session 1 - no FES			Session 2 - FES		
	Start (Phase 1)	Seat off (Phase 2)	End (Phase 3)	Start (Phase 1)	Seat off (Phase 2)	End (Phase 3)
Arms %	16.7	15.9[a]	20.5[a]	15.8	13.9[a]	21.2[a]
Legs %	-1.2	-2.8[a]	79.5[a]	-1.3	-2.2[a]	78.8[a]
Upper body % from the chair	84.5	87	0	85.5	88.3	0

Means with superscripts 'a' were significant (p<0.01).
*FES = Functional Electrical Stimulation

Voluntary SitTS activity

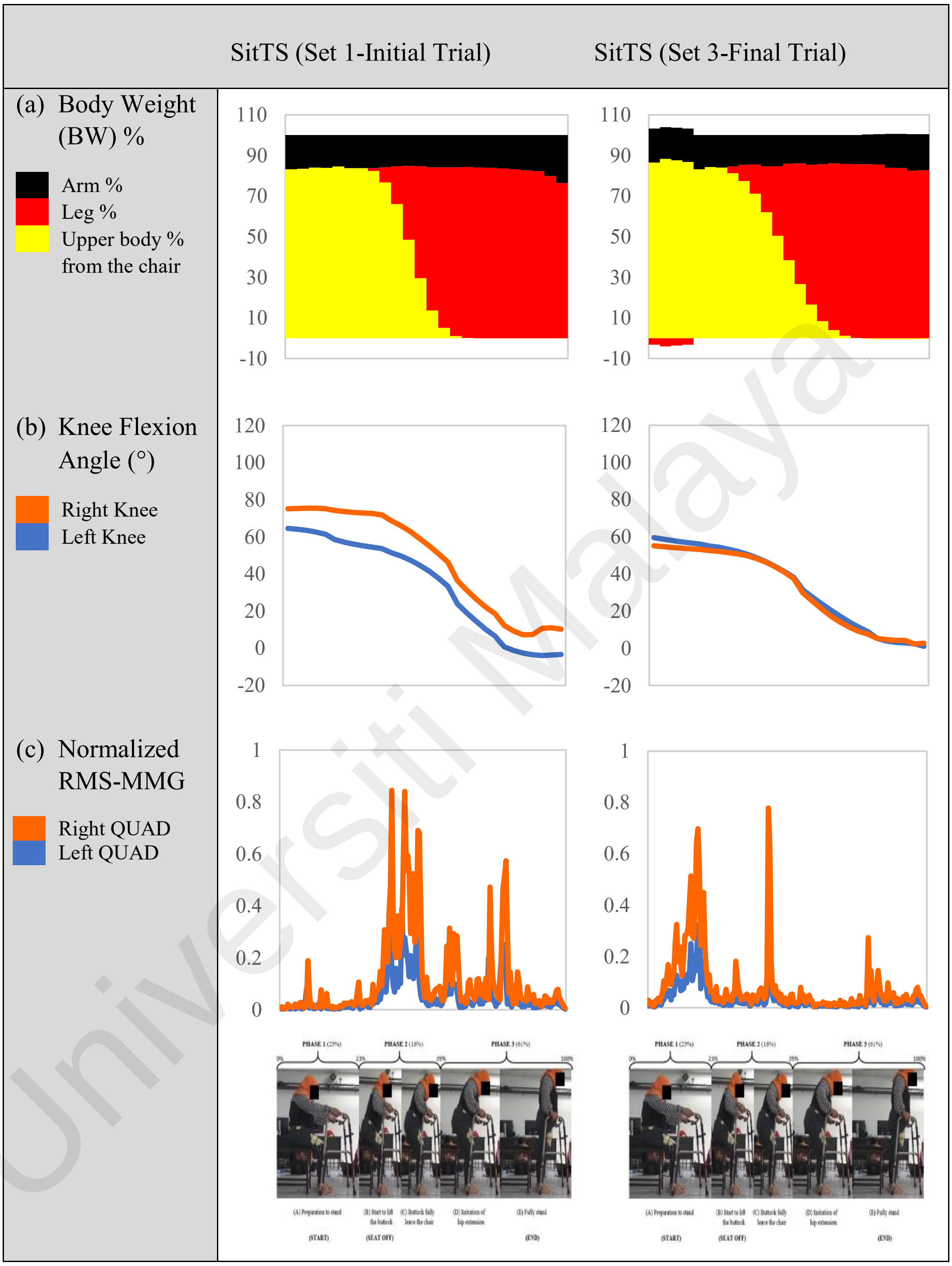


Figure 4.6: Participant 2's body weight contribution, knee flexion angle and normalized quadriceps RMS-MMG during voluntary SitTS (Set 1-Initial Trial versus Set 3-Final Trial).

Assissted FES SitTS activity

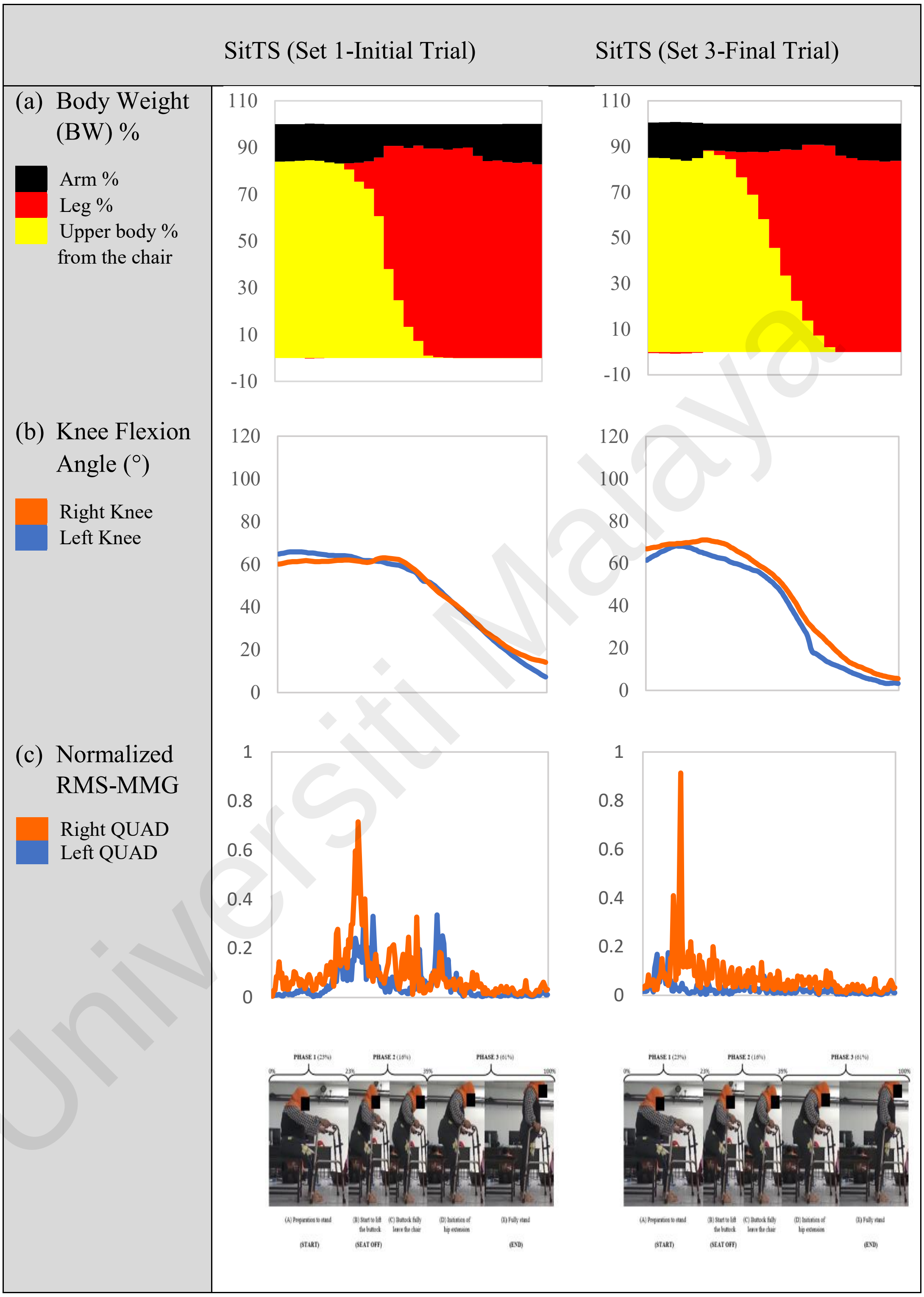


Figure 4.7: Participant 2's body weight contribution, knee flexion angle and normalized quadriceps RMS-MMG during assisted FES SitTS (Set 1-Initial Trial versus Set 3-Final Trial).

4.3.2 MMG analysis of SitTS and StandTS without FES assistance

For this section, the MMG analysis of SitTS and StandTS movements without assistance of FES are presented. The number of completed trials for both participants were recorded and shown in Table 4.7. For further analysis, the MMG data were analysed for every 25th centile from total number of trials for every set. All analysis of selected raw signal from MMG were performed in AcqKnowledge 4.3 and MATLAB software **(Appendix F)**. An example of raw data signal of MMG during a cycle of voluntary SitTS and StandTS activity was shown in Figure 4.8. These results are then compared to observe the behaviour of MMG pattern during both activities.

Table 4.7: Summary of completed number of trials of SitTS and StandTS Movement without assistance of FES.

Participant	Number of trials SitTS and StandTS		
	Set 1	**Set 2**	**Set 3**
1	96	30	31
2	95	92	55

*SitTS =Sit-To-Stand, StandTS = Stand-To-Sit

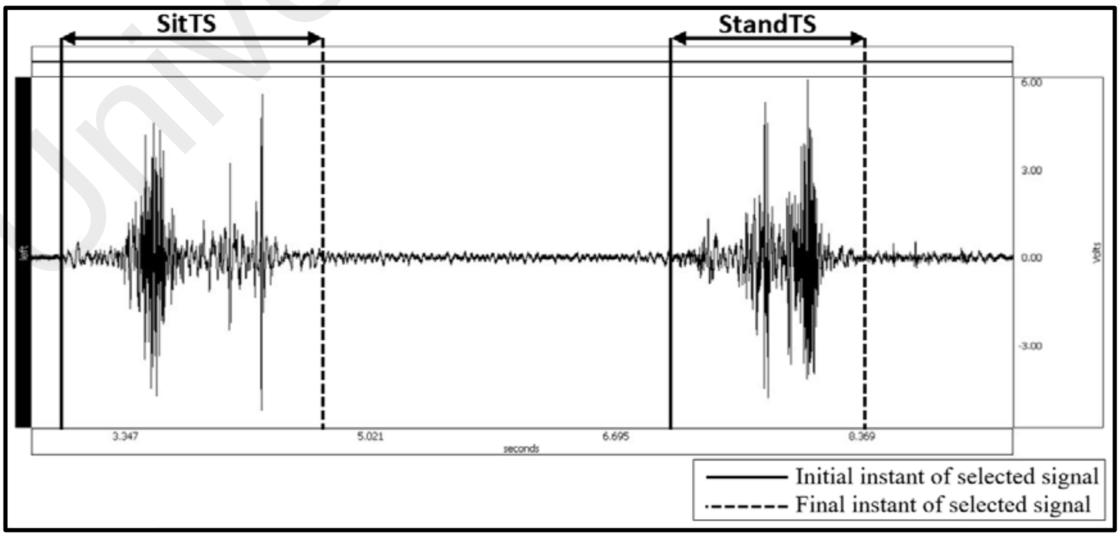


Figure 4.8: An example of raw data signal of MMG during a cycle of SitTS and StandTS activity without assistance of FES.

There were a total of 399 trials of voluntary SitTS and StandTS activities completed by the both participants. With regards on the analyses of MMG signals, an independent samples t-test was used to know if there is a significant difference between type of activity and quadriceps performance. Table 4.8 summarised the mean ± SD of data between SitTS and StandTS activity. From Table 4.8, there was a statistically significant difference between type of activity (i.e. SitTS and StandTS) and muscle performance in terms of RMS_{max} (p=0.014) and d = 0.175.

Table 4.8: Independent sample t-test of SitTS and StandTS activity with all parameters.

Parameter	Activity		*p*-value	Effect size Cohen's, d
	SitTS	StandTS		
RMS_{ave}	1.855 ± 0.811	1.895 ± 1.030	0.103	NS
RMS_{max}	9.705 ± 4.781[a]	10.718 ± 6.623[a]	0.014	0.175
MPF	37.889 ± 9.430	35.715 ± 10.485	0.126	NS
ZC	211.848 ± 42.378	207.063 ± 35.570	0.172	NS

Values were given as mean ± SD (N=60). Means with superscripts 'a' were significant (p<0.05).
*MPF = mean power frequency, NS = not significant, RMS_{ave} = root mean square $_{average}$, RMS_{max} = root mean square $_{maximum}$, SitTS = Sit-To-Stand, StandTS = Stand-To-Sit, ZC = zero crossing.

The significance difference between the sides of leg used and muscle performance during SitTS and StandTS activities were tested using independent sample t-test as displayed in Table 4.9. Both mean values of RMS_{ave} and RMS_{max} for right leg were higher as compared to the left leg as shown in Figure 4.9. There was a statistically significant difference between both side of leg and these activities in terms of RMS_{ave} and $RMS_{max.}$ (p<0.005) and (p=0.006) respectively.

Table 4.9: Independent sample t-test of quadriceps both left and right side with all parameters.

Parameter	Quadriceps		p-value
	Left	Right	
RMS_{ave}	1.764 ± 0.525^a	1.986 ± 1.191^a	0.000
RMS_{max}	9.544 ± 4.608^a	10.879 ± 6.716^a	0.006
MPF	36.808 ± 10.000	36.796 ± 10.063	0.978
ZC	207.880 ± 36.902	211.031 ± 41.303	0.375

Values were given as mean ± SD (N=60). Means with superscripts 'a' were significant (p<0.05).
*MPF = mean power frequency, RMS_{ave} = root mean square $_{average}$, RMS_{max} = root mean square $_{maximum}$, ZC = zero crossing.

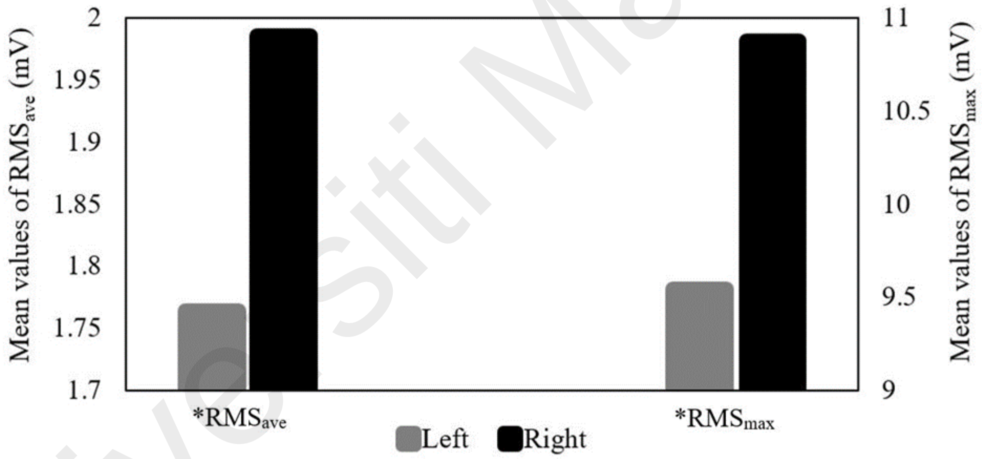


Figure 4.9: Mean Value of SitTS and StandTS activities for left and right side of leg.

Additionally, one-way ANOVA test was performed to analyse the significance difference among every centile of sets with the four MMG parameters. There was a significance difference between ZC parameter and percentile F(4,115)=9.712, p=0.000. Figure 4.10 showed the mean values of ZC for every 25th centile in all set of SitTS and StandTS activities. The 25th centile has the lowest count of ZC meanwhile 75th centile has the highest number of ZC.

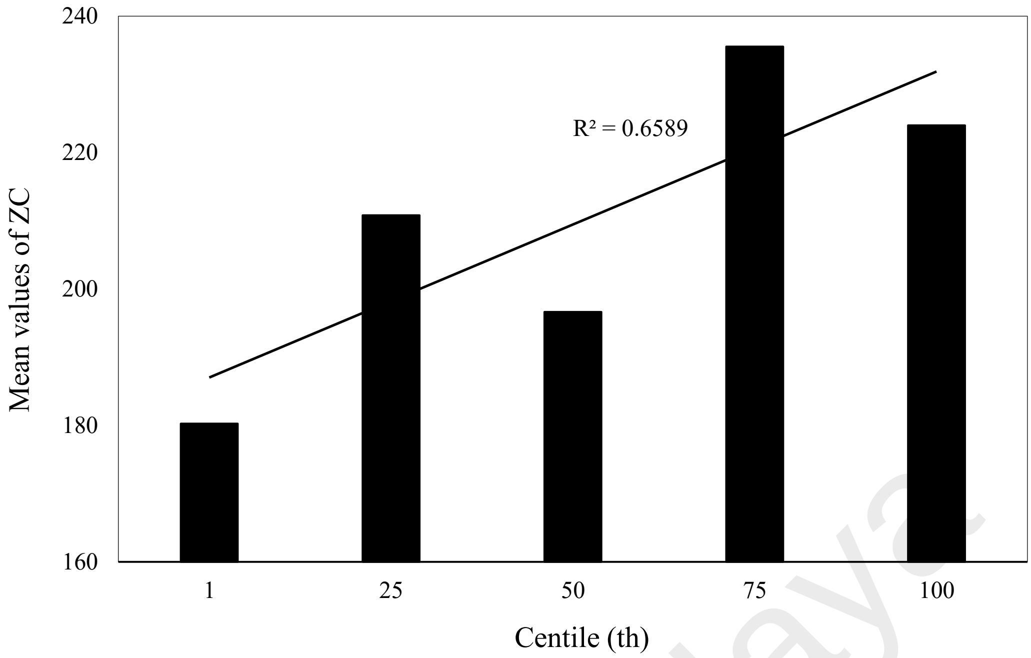


Figure 4.10: Mean values of ZC for every percentile in all sets of SitTS and StandTS activities

The significant difference of ZC by centile was analysed by the post hoc Least Significant Difference (LSD) test. From Figure 4.10 the value of ZC went up as the centile increased but significant differences were seen only between the 1st and 25th, 1st and 75th, 1st and 100th, 25th and 75th, 50th and 75th, and 50th and 100th centiles as shown in Table 4.10.

Table 4.10: *P* value of Post-Hoc Test Least Significant Difference (LSD) of one way ANOVA test.

Centile	1	25	50	75	100
1		0.003*	0.101	0.000*	0.000*
25			0.156	0.014*	0.187
50				0.000	0.007*
75					0.246
100					

*The mean difference is significant at the 0.05 level.

The same statistical analysis (ANOVA) was used to analyse the difference of mean values of MMG parameters among every sets of SitTS and StandTS activities as shown in Figure 4.11. Based on the result, MPF showed significant difference on every sets of SitTS and StandTS activities was significant, $F(2,117)=12.170$, $p<0.000$.

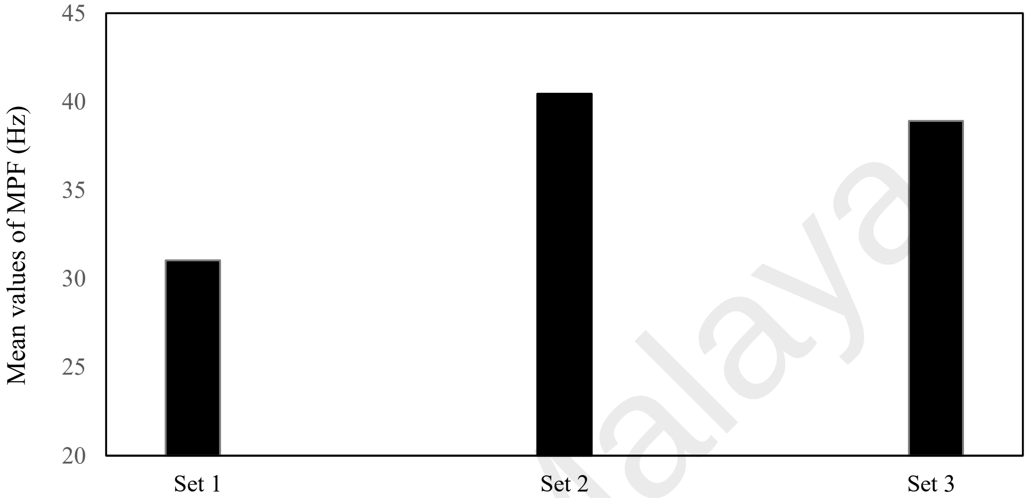


Figure 4.11: Mean value of MPF during three set of SitTS and StandTS activities.

4.3.3 MMG analysis of SitTS without and with FES assistance

In this section, MMG based-assessment in voluntary SitTS and FES assisted SitTS are discussed. Similar to Section 4.3.2, the techniques of MMG analysis for this section were achieved in AcqKnowledge 4.3 and MATLAB software. Next, the extracted RMS-MMG SitTS data were normalised with the maximum RMS-MMG value achieved in the predictive 1-RM experiment. These results are presented by Figure 4.4(c), up to Figure 4.7(c). In both SitTS conditions, the highest peak amplitude of normalised RMS-MMG pattern were observed between Phase 1 and Phase 2 as presented by Figure 4.4(c), Figure 4.5(c), Figure 4.6(c) and Figure 4.7(c).

An independent sample t-test was conducted to compare the mean of quadriceps muscle performance (RMS_{ave} and RMS_{max}) in SitTS activity for all participants. Table 4.11 summarised the mean ± SD of MMG data (RMS_{ave} and RMS_{max}, MPF, ZC) among two SitTS conditions. Based on the voluntary SitTS activity, there was a statistically significant difference between right and left quadriceps muscle performance in terms of normalized RMS_{ave} (p<0.000) and normalised RMS_{max} (p=0.011) as shown in Table 4.11. However, in frequency domain, right quadriceps has revealed a significantly higher MPF value as compared to the left quadriceps during FES-evoked SitTS (p=0.003).

Table 4.11: Independent sample t-test of voluntary and assisted FES SitTS activity with all parameters.

Parameter	No FES			FES		
	Quadriceps			Quadriceps		
	Left	Right	*p*-value	Left	Right	*p*-value
Normalized RMS_{ave}	0.103 ± 0.043[a]	0.272 ± 0.211[a]	0.000	1.68 ± 0.058	0.323 ± 0.062	0.648
Normalized RMS_{max}	0.585 ± 0.389[a]	1.355 ± 1.021[a]	0.011	0.844 ± 0.396	1.617 ± 0.574	0.224
MPF	40.078 ± 9.197	40.067 ± 9.192	0.992	34.434 ± 10.390[a]	41.265 ± 4.357[a]	0.003
ZC	200.584 ± 35.726	204.107 ± 45.620	0.403	180.210 ± 53.498	206.264 ± 40.946	0.257

Values were given as mean ± SD (N=12). Means with superscripts ‘a’ were significant (p<0.05).
*FES = Functional Electrical Stimulation, MPF = mean power frequency, RMS_{ave} = root mean square $_{average}$, RMS_{max} = root mean square $_{maximum}$, ZC = zero crossing

The significant difference of muscle performance between initial and final trials of SitTS were tested using independent sample t-test as shown in Table 4.12. MPF value for final trials in every set was statistically significance higher as compared to the initial trials. (p=0.036) with t(46) = -1.026. Furthermore, it was found that in one-way ANOVA test, there was no significance difference in all parameters on every sets of SitTS activity.

Table 4.12: Independent sample t-test of initials and final trials in every set of voluntary and assisted FES SitTS activity with all parameters.

Parameter	Trials of SitTS in every set		*p*-value
	Initial	Final	
RMS_{ave}	0.226 ± 0.163	0.207 ± 0.119	0.343
RMS_{max}	1.170 ± 0.818	1.030 ± 0.686	0.738
MPF	37.668 ± 10.643^{a}	40.256 ± 6.290^{a}	0.036
ZC	179.148 ± 42.444	216.434 ± 38.382	0.824

Values were given as mean ± SD (N=24). Means with superscripts 'a' were significant ($p<0.05$).
*MPF = mean power frequency, RMS_{ave} = root mean square $_{average}$, RMS_{max} = root mean square $_{maximum}$, SitTS = Sit-To-Stand, ZC = zero crossing

4.3.4 Evaluation of FES-SitTS activity outcome

Both participant completed the interview sessions successfully. As mentioned earlier in Section 3.4.3, stability and fatigue performance were detected after SitTS exercise. Based on the questions given in Part 1, both participants agreed that their upper limbs experience major exhaustion during early Phase 2 (Figure 4.3, Event B) of SitTS movement. This event happened when participants started to lift their buttock to stand up from the chair. In addition, they also agreed that their legs felt very tired at the end of Phase 2 (Figure 4.3, Event C) throughout the SitTS movement. By referring to Figure 4.3, the end of Phase 2 can be described as when participants' buttock fully lift-up from the chair.

Two participants however had different views in relation to stability during the accomplishment of SitTS activity. Participant 1 felt the most stable at Event C and Event E without and with assistance of FES respectively. Meanwhile Participant 2 felt the most stable during Event A for both conditions. Besides that, the least stable position felt by Participant 1 were Event E (without FES) and Event B (with FES). In contrast, Participant

2 had selected event C as the least stable posture during the SitTS activity without and with FES assistance. Table 4.16 summarised the answers given by the participant in the Part 1 regarding their experience in performing the SitTS activity.

In the Part 2 of the feedback session, all participants answered the interview questions on their experience using FES during the experiments. Three themes were identified from their interview and their responses were tabulated according to their use of FES as shown in Table 4.13 to Table 4.15.

Table 4.13: Theme 1- Perception on FES before the experiment.

	Participant 1	Participant 2
Good	1. Good, ok! 2. Expected to stand better 3. Hoping that UMMC can propose FES device to Social Security Organisation (SOCSO) so they can supply FES device to patients for personal use at home.	1. Help myself to recover faster in the walking process. 2. Can observe my leg condition. 3. Improve self-confidence and self-strength, enhance spirit.
Bad	1. It is so hard to attend rehabilitation session at hospital "If I come once in a month, the benefit would not be much".	1. Afraid that FES might be harmful or cause pain.

*FES = Functional Electrical Stimulation, SOCSO = Social Security Organisation, UMMC = University of Malaya Medical Centre

Table 4.14: Theme 2 - Experiences using FES during the experiment.

	Participant 1	Participant 2
Stability	1. Upper limbs are not utilised much during FES, feel more stable.	1. When there is FES in place, - arm not using much energy, - SitTS become more faster, - more stable.
Fatigue	1. When there is no FES, - my upper limb feel more tired. 2. When there is FES,	1. When there is no FES, - I feel tired, everything need to be done by myself. 2. When there is FES, less tired.

Table 4.14, continued

	Participant 1	Participant 2
	- I feel less tired when FES stimulation is given as it help to push my leg for SitTS.	
Good	1. So happy when attending FES session.	1. Overall, I feel happy and enjoy the session.
		2. FES make me feel stronger, my body feel lighter, more energetic and powerful to stand. 3. Satisfied, more confidence to walk
Bad	1. I experienced muscle pain during experiment when FES current is too high	1. A bit tired however I feel motivated and just ignore it.

*FES = Functional Electrical Stimulation, SitTS = Sit-To-Stand

Table 4.15: Theme 3 - Future use of FES addressing individual patient needs.

	Participant 1	Participant 2
Good	1. Depending on the cost, if it so expensive, I would ask PERKESO to buy it for me 2. Hope FES can recover my health (can walk and exercise)	1. To move independently (can jog and run) 2. Do more advance activities; driving a car/ not using a wheelchair again 3. I would like to buy if its cheap/affordable (FES helps me to instil self-confidence when walking, no need children's help at home)
Bad	- No	- No

*FES = Functional Electrical Stimulation, SitTS = Sit-To-Stand

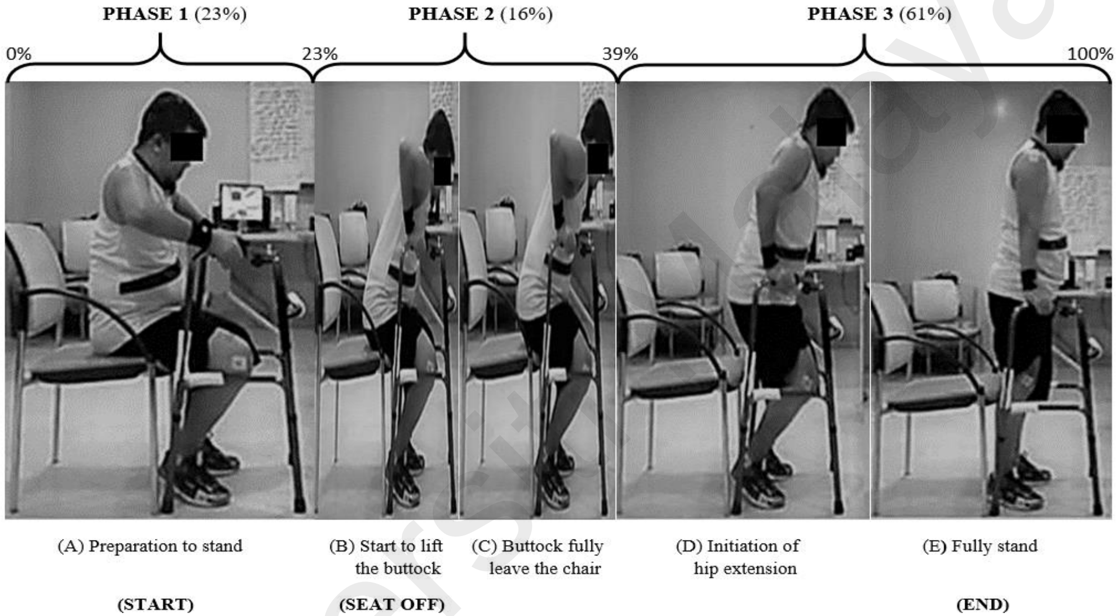
From the interview sessions, both participants felt happy and satisfied with the FES use throughout the experiment. Participants can do more trials of SitTS with FES assistance as shown in Table 4.3. Participants felt less energy were used at the ams and legs as the stimulation of FES on the quadriceps and gluteal maximus helped their legs during the SitTS movement.

4.4 Summary

In summary, instrumented SF has been calibrated and validated successfully with 85% accuracy. During FES assisted indirect 1-RM experiment, Participant 2 managed to do knee extension with 75% more load compared to voluntary knee extension. Following the SitTS experiment in both session (voluntary and FES assisted), the arm versus leg contribution during SitTS exercise depends on the legs muscle grade of every participants. The graph of legs and arms force displayed the same pattern during these two session. The MMG properties showed the quadriceps muscle performance in time and frequency domain throughout the exercise. Based on evaluation outcome of FES device, participants agreed that FES helped them in SitTS motion.

For Participant 1, arms contributed more force compared to the legs during both session of SitTS exercise. Meanwhile for Participant 2, the arms involvement showed minor contribution compared to her legs. Based on the quadriceps performance, both participants exhibited the highest force production between Phase 1 and Phase 2 of SitTS cycle. During voluntary SitTS, it was also shown that higher RMS in their right legs meanwhile higher MPF value was seen during FES assisted SitTS. Regarding on the feedback session, fatigue and stability experienced by participants were observed in a cycle of SitTS activity. The FES experienced was also jotted down. In general, participants felt FES helped their motor function to do better rehabilitation.

Table 4.16: Stability and fatigue experienced by participants during the accomplishment of SitTS activity.



	Participant 1		**Participant 2**	
	Without FES	With FES	Without FES	With FES
During the experiment;				
which event(s) was/were the most tiring for the arms?	B	B	B	B
which event(s) was/were the most tiring for the legs?	C	C	C	C
which event(s) was/were the most stable?	C	E	A	A
which event(s) was/were the least stable?	E	B	C	C

*FES = Functional Electrical Stimulation

CHAPTER 5: DISCUSSION

This chapter discussed all findings from previous chapter in greater detail. It is divided into three sections as presented in the methodology and results chapter. This chapter started with discussion the instrumentation of the SF. The outcome for the indirect 1-RM test was discussed in depth. The main findings of the SitTS study were elaborated and discussed further in the next section. The last section of this chapter summarised the presented discussion.

5.1 PART I: Instrumentation of the standing frame

Based on calibration of the instrumented SF, several identifiable random errors had reduced the results' accuracy but these errors remained constant throughout the experiment. These errors were difficult to be precisely factored in most experiments, but repetitions of calibration of instrumented SF had been done to minimise the effects of these errors on the subsequent results reliability. Thus, any reduction in accuracy did not affect the comparison between SitTS manoeuvre in both conditions.

5.2 PART II: Indirect 1-RM without and with FES

For Participant 1, his right leg was unable to do full knee extension without and with FES. This is due to the lower motor neuron injury occurred towards the right quadriceps of Participant 1. In addition, there were muscle atrophy and tightness on his right quadriceps and hamstring muscle respectively. Besides that, the experiment setup required Participant 1 to do full knee extension during sitting position which was against the gravity. Hence, Participant 1's right leg cannot do full knee extension as per requirement during the experiment as he does not have adequate quadriceps muscle strength.

Apart from that, with reference to the result displayed in Section 4.2, it shows that with the presence of FES, there were improvements in indirect 1-RM test as compared to the voluntary indirect 1-RM. These demonstrate that FES stimulation provides an improvement in muscle strength to the quadriceps muscle to perform knee extension (Crosbie et al., 2014).

5.3 PART III: SitTS without and with FES

In this section, all results with regards to the research objectives are discussed and elaborated. The findings are interpreted further to analyse significant difference between the parameters and variables.

5.3.1 Contribution of arm and leg during repetitive SitTS activity without and with assistance of FES

In this study, FES is used to assist SCI participants (ASIA C) in completing their SitTS task. During FES evoked SitTS session, SCI participants did the exercise voluntarily with the assistance of FES. Overall, participants managed to perform more SitTS trials with the aid of FES. This suggests that FES helps in stimulating participants' quadriceps to execute SitTS action in a prolonged period. SitTS motion is generally divided into two or three phases as mentioned from the Table 2.2 in Section 2.5.1. Three phases of SitTS were defined in this study following the previous study by Kagaya et al. that has similar protocol of exercise in which SCI participants used the aid of hand-assists. Phase 1 displayed the highest SD of its contribution with ± 7% proving that participants recruit diverse strategies of initiation of buttocks lift-up from the seat throughout the study.

Based on the Table 4.4, mean time taken for final trials of FES-SitTS in each set was significantly longer compared to its initial trials as FES-evoked exercise caused participants to be more prone to fatigue towards the end of their SitTS action in each set. Meanwhile, non-significance difference of mean time was observed during voluntary SitTS activity p=0.571, suggests that there are several strategies of SitTS accomplishment initiated by participants throughout the voluntary SitTS session. There are some factors that might contribute to these several strategies which consume diverse time allocation. Feet placement and trunk control of participants during early phase of voluntary SitTS play a major contribution as there are few times participants tend to lift one of the feet and sway their trunk front to back first before they start leaving the chair.

Besides that, the presence of negative values at the leg % during early to middle stage of SitTS are due to the calibration procedure of force plate 2 that was taken while participants' feet were in contact on these force plate. The calibration process eliminates any significant values by giving zero reading even though the feet are positioned and already give small force on top of the force plate 2. Since both participants had the habit of adjusting their feet position by lifting the leg during early stage of SitTS, force plate 2 showed a negative magnitude of force which indicates the eliminated force that exist by the feet before the calibration process take place.

Participant 1

In order to achieve the first objective, the percentage of arms and legs contribution were observed in both condition throughout the SitTS activity. Overall, throughout the SitTS action in both session, Participant 1's arm percentage showed higher contribution in total body weight percentage as compared to his leg percentage as tabulated in Table 4.5. This result occurred as Participant 1 completely utilise his strength in both arms and left legs to bring up his upper body for standing. Both arms were used to support the left leg in providing stability for the whole body. Therefore, he endured most of his body weight using the arms and SF during accomplishment of SitTS. Participant 1 had several joint contractures at the right knee and right ankle of the leg. As a result, Participant 1 did not put his body weight onto the right leg during the exercise.

By comparing the two sessions, higher contribution of Participant 1's arm percentage was presented during FES SitTS. This result proposes that his arms are utilised to control a full right knee extension that has been stimulated by FES. Even though FES current is given to Participant 1, his right knee cannot provide full knee extension during the end phase of SitTS. This statement is validated as the right knee angle cannot reach to a normal knee extension range of motion (0° to 5°) during late phase of SitTS as shown in Figure 4.4(b) and Figure 4.5(b).

Participant 2

For Participant 2, there were huge increase of leg percentage from Phase 2 to Phase 3 of SitTS in both session. In general, Participant 2 has a better score of MRC muscle grade for legs as compared to Participant 1 as shown in Table 3.1. As a result, arms and legs contribution pattern of Participant 2's changed drastically throughout the SitTS action. Towards the end of SitTS cycle, Participant 2's leg contribute 79.5% (without FES) and 78.8% (with FES), proving that her legs provide a good weight bearing to support her whole body during standing. The results suggest that arms play a minor role in assisting Participant 2 during SitTS study.

In contrast, by comparing two sessions in Table 4.6, higher contribution of leg % during end phase of voluntary SitTS proposes that Participant 2 exerted more strength onto her legs to bear the full body weight. In addition, during final set of voluntary SitTS, Participant 2 exhibited smaller knee angle during early stage of the movement (Figure 4.6(b)). This finding suggests that towards the final set of voluntary SitTS task, Participant 2 compensated her fatigue state by positioning a smaller knee angle that provide lesser pressure at the feet (M. Y. Lee & Lee, 2013). Based on Table 4.6, FES stimulation helps Participant 2 perform SitTS by giving less strength exertion to the leg at the force plate during end phase of session 2.

5.3.2 MMG analysis of SitTS and StandTS without assistance of FES

The magnitude of the RMS is related to the muscle contraction and force produced by the muscle in the time domain of MMG (Travis W Beck, Housh, Cramer, et al., 2005). In this study, RMS_{max} of the MMG during StandTS was higher than SitTS (p=0.014, Table 4.8). This is potentially due to the higher anterior-posterior (A-P) reaction forces at the thigh produced during StandTS movement as compared to the A-P reaction forces performed during SitTS event. (Nadeau et al., 2008). This higher A-P reaction forces in StandTS has been found in spontaneous conditions i.e. no instructions are given on the placement of the initial foot position, similar to this study.

In addition, the direction of StandTS is not against the force of the gravity hence, this movement would always provide greater A-P reaction forces at quadriceps. Furthermore, this current result reflects that eccentric quadriceps contraction during StandTS activity could perform more mechanical work and generate more tension (using less motor unit activation and less energy) as compared to the concentric quadriceps contraction during SitTS activity. This phenomena suggests that the sarcomere's cross-bridges develops a greater force when they resist lengthening, rather than shortening under stress from load (Tomberlin et al., 1986).

Besides that, Figure 4.9 displayed higher muscle contraction at right leg for both participants during the SitTS and StandTS activities. Higher mean values of RMS_{ave} and RMS_{max} on the right leg explains that quadriceps muscle on right leg experienced more effort (Ibitoye et al., 2014) as compared to the left leg. This could be explained that the right leg for both subjects were most likely to be the dominant side prior to the injury, however further investigations needs to be done to validate this hypothesis. In addition, during manual muscle strength test for Participant 1, quadriceps muscles of the right leg was insensate and the right leg could not perform voluntary full knee extension. This condition due to lower motor neuron injury and muscular contracture of the right quadriceps hence full knee extension cannot be actively achieved by the right leg during the experiment. This quadriceps muscle contracture clarifies a constant muscle contraction compared to the left leg muscle, which only contracts during the SitTS and StandTS routines. Due to the contracture, this may result in muscle strength imbalance during the task. Moreover, Participant 1 also displayed compensation strategy by placing his left foot behind the right foot when he had accomplished the routines.

Higher MMG activity based on its RMS of the right leg have occurred due to the right leg having to produce more effort thus increased the force generation compared to the left leg. This is although both legs were experienced fatigued throughout the experiment. This results verify that MMG is sensitive in detecting signals that associated with contractile properties of muscles during voluntary isometric and dynamic contractions (Islam et al., 2018) in difference of muscle strength on the same incomplete SCI participant.

Based on Figure 4.10 the 75th centile had the highest value of ZC in every sets of SitTS and StandTS activities. It shows the quadriceps muscles had the fastest contraction in the 75th centile compared to the 25th centile of trials which had the lowest number of contraction. In the time domain, an increased number of ZC provides increased number of contraction thus indicates the recruitment of fast twitch muscle fiber which had less endurance to fatigue compared to slow twitch fiber (Dzulkifli et al., 2018).

This finding supports the evidence of alteration in muscle fiber of SCI paralyzed muscle. Subsequent to SCI, the fiber-type transformation occurs with downregulation of type I fiber (slow oxidative) and upregulation of type II fiber (fast glycolytic) (Biering-Sorensen et al., 2009; Qin et al., 2010) . The paralyzed skeletal muscle generally becomes atrophic, possesses lower tension generating capacity and is less fatigue resistant (Burnham et al., 1997). These explanation proves that in all sets of the SitTS and StandTS activities, as the number of trials increase, the number of ZC also increase as the muscle get more fatigue.

Meanwhile, Figure 4.11 showed that in the frequency domain, MPF mean value increased to the second set of SitTS and StandTS activities. In the third set of these activities, MPF mean value displayed a slight decrease as compared to the second set. As MPF of MMG was closely related to the mean firing rate of motor unit of quadriceps muscle, (Itoh, Akataki, Mita, Watakabe, & Itoh, 2004), this changes may have suggest fluctuation strategy of recruitment between fast twitch and slow twitch motor units in eccentric and concentric contractions. Specifically, the increased of MPF in set two suggests that motor unit firing rates increase with recruitment of fast-twitch muscle fibers. Fast-twitch motor units with short contraction times have higher initial firing rates than slow twitch motor units (T. W. Beck et al., 2007).

During the third set of the routines, elongation of motor unit twitches in the quadriceps muscles may have result in proprioceptive feedback to the central nervous system that prevent an increase in motor unit firing rates, also referred as muscular wisdom (Esposito, Orizio, & Veicsteinas, 1998). In particular, changes in the frequency content of the MMG signals could potentially reflect fatigue-induced decrease in motor unit firing rates and/or de-recruitment of fast-twitch muscle fibers (T. W. Beck et al., 2007).

5.3.3 MMG analysis of SitTS without and with assistance of FES

In order to achieve the second objective of this study, the pattern of normalized RMS-MMG were outlined between two conditions of SitTS (i.e. voluntary and FES assisted) in both participants. They exhibited similar graph pattern of RMS-MMG parameters. As mentioned in previous section, amplitude of RMS-MMG was correlated to quadriceps muscle contraction and its force production. Highest peak amplitude of normalised RMS-MMG describes the quadriceps muscles produces its highest force in between Phase 1 and Phase 2 of SitTS cycle. These highest force were generated by the participants to prepare their legs for early knee joint stabilization before its extension. Quadriceps muscles were observed to produce great muscle contraction during late phase of SitTS to help the legs to stabilize the feet and legs for standing posture.

Furthermore, Table 4.11 exhibited higher significance of muscle contraction at the right leg as compared to the left leg for both participants during voluntary SitTS action. These voluntary SitTS allows them to use all strength from their limbs especially from the legs to execute the SitTS action. Hence both participants were assumed to use more effort on the right leg during these action. In addition, with reference to the earlier section, Participant 1 has contracture of the right quadriceps muscle which results a continuous contraction thereby generating constant muscle force throughout the experiment.

Meanwhile during FES evoked SitTS session, there were no significance difference in time domain of MMG parameters for both side of the legs. This result might suggest a complex performance of both side of quadriceps contraction with the presence of FES during SitTS accomplishment. In contrast, right quadriceps revealed to be highly significant in MPF value during FES session. This outcome proposes that right quadriceps on Participant 1's has a higher proportion of Type II fibres. These affected muscles may also have lower concentration of myoglobin and mitochondria (Lai et al., 2009) which are prone to fatigue faster than Type I.

The relationship between initial trials and final trials of every set of SitTS action was investigated and found that final trials had significantly higher MPF value as compared to the initial trials. As the participants reached towards the final trials, motor unit firing rates of quadriceps increased with the recruitment of fast-twitch muscle fibers. Fast-twitch motor unit with short contraction times has higher initial firing rates than slow twitch motor units (T. W. Beck et al., 2007). In this study, ANOVA test was conducted to see the significant difference among every set of SitTS activity with the MMG parameters. There was no significance result on all parameters of MMG in each set. This result indicates that 5 minutes intermediate rest given to the participants allows the quadriceps muscles to fully recover before going to the next set of SitTS exercise.

5.3.4 Evaluation outcome of FES-SitTS activity

In an attempt to accomplish the third objective in this study, all responses from the participants were recorded and tabulated as in Section 4.3.4. Among the 3 phases which including 5 events of SitTS, both participant decided that arms were the most tired during Event B meanwhile their legs were most tired during Event C. These two events were closely related to each other as both events occurred at Phase 2 of the SitTS motion. At Event B, where the buttock lift-up was initiated, participants are assumed to use their maximum arm strength to lift their upper body from the chair. As the body was moving upward with the help of the arm support during Event B, the accomplishment of SitTS action was continued with the preparation of legs to give support and prevent the whole body from falling during Event C. These assumption are verified as both participants felt their legs were very fatigued during Event C where full lift-up of the buttocks from the chair occurred.

On the other hand, the participants had different opinions on their stability throughout the completion of SitTS activity. Participant 2 selected Event A in both conditions as the most stable position. The answer given by Participant 2 was expected as she felt secured while sitting on the chair. Conversely, without the help of FES, Participant 1 felt the most stable during Event C. This result was due to the presence of arm strength that assisted him to carry his body weight upward. By sitting on the chair without a back rest support in Event A, Participant 1 felt unstable as he felt like falling. While with the aid of FES, Event E was chosen as the most stable as he agreed that FES helped him to straighten both his knees and allowed him to stand up confidently.

Besides that, Participant 1 experienced the least stable position at Event E during voluntary SitTS due to his weak right leg (Quadriceps MRC muscle grade in Grade 2). Participant 1 felt least steady as his right leg cannot give enough support towards his body weight during the standing posture. Next, with the aid of FES, Participant 1 felt least stable during Event B which could be due to the transition of his body moving slowly from sitting to standing. However, Participant 2 experienced the least stable during Event C. As she felt she needed her trunk more than her leg during this event.

In general, FES is known as the solution for restoring muscular activity below the neurological level of injury (Guiraud, Coste, Benoussaad, & Fattal, 2014). Based on the feedback session in the second part, both participants agreed that FES device provides a great advantage for rehabilitation. In Theme 1 (Table 4.13), participants' view on FES before the experiment started were captured. Both participant were familiar with the use of FES device. Participants were aware that FES technology can help them in their recovery process.

In the second theme (Table 4.14), i.e. the experience of using FES during SitTS experiment, both participants were excited when attending the session with FES assistance. The participants believed that FES helped them to do SitTS action with lesser energy consumption. In the last theme (Table 4.15) of the interview session, the market and future use of FES device was explored. The opinion presented by the participants support that the FES market demand is expected to increase. More supplementary research and qualitative study should be done to improve the service of FES. The need to develop cheaper and more user-friendly FES device is very essential in the future.

5.3.5 Recommendation of a safe SitTS protocol

Based on this study, SCI individuals showed their capability to successfully complete the voluntary and FES assisted of SitTS procedure. A safe SitTS protocol for SCI individuals has been designed and this procedure can be a safe guideline to them in order to improve their quality of life. As a conclusion, a recommendation can be proposed to the rehabilitation specialists and physiotherapists to follow these protocol as this study is able to take into account the weight distribution of SCI individuals during three phases of SitTS motion. Furthermore, in order to do the SitTS exercise, SCI participants need to use a rigid four legs of SF and a standard height of chair. Besides that, the muscle performance experienced by the SCI participants can be monitored and examined based on the SCI individuals condition. These information are very useful for the clinicians to offer more other rehabilitative management.

5.4 Summary

In summary, it can be observed that there are varying approaches of SitTS accomplishment exercise on both SCI individuals in this study. These strategies involved the role of arms and legs contribution. As the legs experience several muscle contractures and deformities, the upper limbs specifically the arms would substitute for the main contribution of the legs during SitTS action. Even though FES was stimulated to participants' quadriceps and gluteal maximus, there was a similar pattern graph of the arms and legs contribution between voluntary and FES assisted SitTS exercise. For Participant 1, arms contributed more force compared to the legs during both session of SitTS exercise. Meanwhile for Participant 2, the arms involvement showed minor contribution compared to her legs. In addition, the SCI participants managed to perform SitTS exercise with several compensating strategies throughout the study. These strategies included the placement of feet position and trunk control during initial phase of SitTS.

On the other hand, based on the quadriceps performance by both participants, they exhibited the similar pattern of highest force production between Phase 1 and Phase 2 of

SitTS cycle. These result was caused by the early knee stabilization for the leg extension in SitTS. During voluntary SitTS, it was also shown that higher RMS in their right legs. Both participants used more effort on the right leg during voluntary SitTS. This might suggest their dominance side of leg prior to the injury. Meanwhile higher MPF value was observed on their right leg during FES assisted SitTS. These outcome proved that FES-evoked contractions more susceptible to fatigue (Travis W Beck et al., 2004) even though participants managed to do more trials in these session .

Regarding on the feedback session, fatigue and stability experienced by participants were observed in a cycle of SitTS activity. Participants felt their arms were most fatigue during event B for both session as they started to lift their buttock for the SitTS action. Hence the arms played a major role during these event to provide an early stability of the bodies from these transition. These statement was supported with the increasing of arms contribution from the early phase of SitTS up to the end of the phase. Meanwhile participants agreed that their legs were most tiring at event C where full lift-up of the buttocks from the chair occurred. These situation was related with the starting of the legs contribution at force plate 2.

On the contrary, the stability gained by participants were varies with the difference of the legs condition. As the legs have a low scoring of MRC muscle grade, the least stable experienced by them were during the event where they have to fully utilize the legs. Hence, the Event E was chosen by Participant 1 as the least sable position as he had to be in standing position for a few seconds. In conclusion to this study, the stability experienced by the participants was proved to have a correlation with the LE muscle grade and also the arms and legs contribution. The higher the leg's MRC muscle grade, the smaller the arms contribution throughout the SitTS exercise.

However, the arms and legs contribution does not affect the fatigue experienced by participants during these five events in SitTS exercise. These statement can be recognized while comparing the similar pattern contribution of both extremities for initial and final trials of the exercise for both events. Furthermore, participants agreed to have Event B and Event C as the most tiring event for the arms and legs respectively during the SitTS exercise. The experience of using the FES device during the exercise was also jotted down. In general, both participants agreed FES restored their lower limb motor function as they managed to do more trials during the SitTS exercise.

Besides that, both participants used more effort on the right leg during voluntary SitTS activity by observing MMG in quadriceps performance muscle. In contrast, FES is proposed to help in stimulating both quadriceps and gluteal maximus hence participants were able to accomplish FES-evoked SitTS with less effort. By the end of both sessions of the SitTS, quadriceps muscles were observed to be fatigued.

FES is believed to enable a lot of SCI individuals in rehabilitation exercise. The presence of FES helps in improving their quality of life. This technology provides an alternative aid towards the standing exercise and other basic activity as the SCI individuals will boost their recovering process. In a nutshell, the need of enhancing service of FES such as supplying a cheaper and more user-friendly FES device is very crucial in the future.

CHAPTER 6: CONCLUSION AND FUTURE WORK

6.1 Conclusion

In summary, the sensors on the instrumented standing frame were calibrated. At least 85% accuracy of actual body weight acting upon standing frame was obtained when normal participants bear all their body weight to the frame. Besides that, 1-RM test with and without FES can be safely tested for both legs in SCI individuals via the indirect method and can be used as a monitoring tool. In addition, this method can also provide a more objective information on the selected stimulation intensity used.

For this study, the arms and legs of SCI participants are dependent on each other as these parameters contributed to their own body weight during SitTS exercise. Contribution of arms are determined by the condition of the legs of the SCI individuals. The higher the muscle grade of the leg, the lesser the contribution of the arms. Several compensating strategies during initial phase of SitTS were discovered, for instances the placement of the feet position and the trunk control.

The present study explored the MMG behaviour of time-frequency domain during SitTS and StandTS activity. This method can provide a safer monitoring instrument to analyse muscle function performance. Moreover, the qualitative study provided deeper views regarding the need and rehabilitation of SCI requiring the use of FES devices.

6.2 Limitations

The overall findings of this study displayed a comprehensive biomechanics research study of SitTS activity for incomplete SCI individuals. Some noise was believed to be detected by the Vicon Nexus motion capture system as its infrared camera missed to capture all markers during experiment due to the complex set up of FES, MMG and SF during SitTS experiment. However, these noise did not disturb the measurement reading of force plate and the knee angle of the participants.

Due to a limited number of SCI participants with AIS grade C who can stand on their own (have at least leg muscle strength MRC of Grade 3) the recruitment of participants for this study was considerably less compared to other previous SCI study. Furthermore, one participant had knee contracture on his right leg. Larger population of these group of AIS C would contribute to a precise data and analysis of the research.

6.3 Recommendation for future work

A further series of experiments is recommended in which more SCI participants with AIS grade C should be recruited. Other SitTS determinants for example different height of chair and different initial knee angles can be added in the next study. Besides that, the other SitTS biomechanics parameters (i.e. torque and power) shall be evaluated hence these parameters can be discussed during these exercise.

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LIST OF PUBLICATIONS AND PAPER PRESENTED

The research described in this thesis has led to the presentations and publication of the following:

ISI listed Journal

1. **Abd Aziz, M.**, Hamzaid, N. A., Hasnan, N., & Dzulkifli, M. A. (2019) Mechanomyography-based Assessment during Repetitive Sit-To-Stand and Stand-To-Sit in Two Incomplete Spinal Cord Injured Individuals. Biomedical Engineering / Biomedizinische Technik (BMT)(Accepted on 3rd July 2019)(Q4).

Conference Proceedings

1. **Abd Aziz, M.**, & Hamzaid, N. A. (2017). FES Standing: The Effect of Arm Support on Stability and Fatigue during Sit-To-Stand Manoeuvres in SCI Individuals. In *International Conference for Innovation in Biomedical Engineering and Life Sciences (ICIBEL)* (pp. 67-72). Springer, Singapore. Paper presented at the ICIBEL, 10th – 13th December 2017, Penang.
2. **Abd Aziz, M.**, Selvanayagam VS, & Hamzaid, N. A. (2018). Strength Assessment with and without Functional Electrical Stimulation in a patient with Spinal Cord Injury. In *19th Asian Society for Adapted Physical Education and Exercise Symposium (ASAPE).* Presented at the ASAPE, 15th – 17th July 2018, Kuala Lumpur.