INVESTIGATIONS ON WHEELCHAIR SEATING PRESSURE RELIEF SYSTEM FOR PRESSURE ULCER PREVENTION AMONG PARAPLEGICS

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INVESTIGATIONS ON WHEELCHAIR SEATING PRESSURE RELIEF SYSTEM FOR PRESSURE ULCER PREVENTION AMONG PARAPLEGICS

ABSTRACT

Individuals with paraplegia spend their time in a wheelchair for life. Adapting to prolonged wheelchair seating for almost all activities of daily living is challenging. The loss of abilities to sense any pain or excessive seating pressure cause them to remain seated on the wheelchair without any pressure relief activities. This situation leads to secondary complications including pressure ulcers which further degrades the individual's health. A wheelchair seating pressure relief training system (WSETs) was developed to overcome this. Optimal placement of the force sensitive resistors (FSR) as seating pressure sensors on the cushion was determined, and their responses were investigated with 5 people with paraplegia. Two different FSR orientations, A and B, were compared. Each paraplegic sat in a resting position and then performed pressure relief activities (PRA) which included whole body push-up, left and right lean and forward lean, before returning to resting position. With more forward positioned FSRs, Orientation B showed higher sensitivity, implying better capture of the high-risk areas of pressure ulcer development. The FSR sensor readings were significantly different among pressure relief activities in all subjects ($p<0.05$), indicating the validity of FSR measures for the intended application. In conclusion, the WSETs system was proven suitable as a training tool for new paraplegics to habituate themselves in performing PRA.

Keyword: Paraplegic SCI, PRA, WSET, Training tools

PENYIASATAN SISTEM LATIHAN TEKANAN TEMPAT DUDUK KERUSI RODA UNTUK PENCEGAHAN ULSER TEKANAN DIANTARA PARAPLEGIA

ABSTRAK

Paraplegia individu menghabiskan masa mereka diatas kerusi roda untuk kelangsungan hidup. Mengadaptasi untuk selamanya duduk di kerusi roda dalam kerja-kerja seharian adalah mencabar. Kehilangan keupayaan untuk merasa sakit atau tekanan yang berlebihan ketika duduk menyebabkan mereka duduk di atas kerusi roda tanpa sebarang aktiviti melepaskan tekanan. Keadaan ini menyebabkan komplikasi sekunder termasuk ulser tekanan yang dimana menurunkan tahap kesihatan seseorang. Untuk mengelakkan ini, sistem latihan tekanan tempat duduk kerusi roda (WSETs) telah dibangunkan. Penempatan optimum perintang peka daya (FSR) sebagai sensor tekanan tempat duduk di kusyen akan ditentukan, dan tindak balas sensor disiasat melalui 5 orang paraplegia. Dua orientasi FSR yang berbeza iaitu orientasi A dan B telah dibandingkan. Setiap paraplegia duduk dalam keadaan rehat dan kemudian melakukan aktiviti pelepasan tekanan (PRA) yang merangkumi menolak seluruh badan ke atas, sandar ke kiri dan kanan dan ke depan, sebelum kembali ke posisi rehat. Orientasi B, dengan kedudukan FSR yang lebih maju, menunjukkan kepekaan yang lebih tinggi, yang menunjukkan penangkapan kawasan ulser tekanan berisiko tinggi yang lebih baik. Pembacaan sensor FSR berbeza secara signifikan antara aktiviti pelepasan tekanan pada semua subjek ($p < 0,05$) yang menunjukkan kesahihan langkah-langkah FSR untuk aplikasi yang dimaksudkan. Kesimpulannya, sistem WSET terbukti sesuai sebagai alat latihan bagi orang-orang paraplegia baru untuk membiasakan diri dalam melakukan PRA.

Kata kunci: Paraplegia SCI, PRA, WSET, Alat Latihan

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LIST OF ABBREVIATION

SCI	Spinal Cord Injury
WSET	Wheelchair Seating Training System
PU	Pressure Ulcer
PRA	Pressure Relief Activity
FSR	Force Sensitive Resistance
NPUAP	National Pressure Ulcer Advisory Panel
IT	Ischial Tuberosities

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Introduction to Spinal Cord Injury

The spinal cord is a two-way conduction pathway to and from the brain where it consists of a bundle of nerves, and the spine's vertebrae protect other tissues. The spinal cord has three major functions: a conduit for motor information, sensory information, and a centre for coordinating certain reflexes. Therefore, any injuries or damage to the spinal cord could cause an individual to lose their ability to sense or reflexes of their own body.

When spinal cord injury (SCI) happens, the spine's main function as a messages pathway through the body has been disturbed, which causes the body to lose sensation and movement abilities. This permanent change has a huge impact on an individual's lifestyle, especially for individuals who have lost their capability to walk and depend on a wheelchair to continue their activities. Even though there are many types of wheelchairs and other accessories had been designed for the comfort of the wheelchair user. However, there are still issues on health conditions due to individuals' lack of knowledge to maintain their health although on wheelchair and lead to bad lifestyle.

The bad lifestyle could be worsening the health condition of SCI individuals and lead to secondary complications such as bowel and bladder issues, sexual dysfunction (Papathomas et al., 2015), cardiovascular disease(Bakkum et al., 2015), obesity and pain, and pressure ulcer(Ide-okochi et al., 2013). A pressure ulcer commonly affects paraplegic SCI individuals due to prolonged sitting on a wheelchair without any pressure relief movement. Three factors that caused the development of pressure ulcer which is pressure, friction and shear. Therefore, prolonged sitting will increase pressure between the surfaces as in this case, the buttock-thigh area and wheelchair seat area, then increase the potential of pressure ulcer development.

To avoid the development of pressure ulcers, the SCI individual usually had been suggested and exposed by physiotherapy the pressure relief activities within their capabilities to practice such as forward-leaning, side to side leaning, and push up. The pressure reading status will always be monitored by physiotherapy as a precaution to develop pressure ulcers or other secondary complications. The process could be done by using available pressure monitor systems such as Xsensor mapping pressure. Therefore, the SCI individuals will keep practicing the activities and decrease the risk of pressure ulcer development and mortality rate.

1.2 Research Background

According to World Health Organization (WHO), more than 250,000 individuals suffer from spinal cord injury (SCI) every year due to an increasing number of accidents, especially in traffic and sport. Having an SCI cause the individual to lose half or complete sensory-motor capabilities. Therefore, most SCI individuals spend most of their time on wheelchairs to mobile themselves daily.

However, the prolonged on sitting on wheelchair cause of high pressure on interface areas and decrease the flow of blood and nutrition circulation through body. Without any precautions taken, the conditions lead to secondary complications, decreasing the quality of life and increasing the mortality risk. As a step in reducing the risk of PU, a patient was being advised to perform the PRAs such as forward lean and side tilt.

The PRA activities were important as the alternative for weight shifting for the SCI patient after remaining in the same position for a long time. However, due to their lack to sense the discomfort after prolonged seated, the patient usually cannot be left alone while practicing the PRAs. They need to depend on someone to monitor and alarm them about activities, even though they are good enough to practice alone.

As the solution, a device system, WSET systems, were designed that act as an assistant to SCI patients in doing the therapies or PRA individually without depending on caregiver or physiotherapy. The device systems were created with a monitor and alarm system consisting of four unit of force-sensitive resistor (FSR) sensors as sensing element placed on both sides of the buttock-thigh area and an android application interface as a control system that acts as monitor interface and alarm count.

1.3 Problem Statement

Every year there is increment number of spinal cord injury (SCI) cases are reported. The spinal cord injury or SCI is an injury that happens on the spinal cord and disturbs the communication system of the human body. After having an injury, most SCI individuals have difficulties adapting to new situations where they start to lose mobility and sensation. Due to loss of mobility, the SCI individuals depend on accommodations to helps them to transfer from one place to another such as a wheelchair. However, spending most of the time on wheelchair without any pressure relief due to lack of sensation and only depending on rehabilitation schedule or caregiver reminder leads most SCI individuals to secondary complications such as pressure ulcers and bowel dysfunction. The pressure ulcer happens due to unrelieved pressure, which causes the blood and nutrition flow to be slow. It has been the worst condition for SCI individuals to have pressure ulcers because it takes a lot of time to treat and is very costly, which is not affordable to some patients and leads them to death. Therefore, as a precaution to secondary complications, the wheelchair seating training system (WSETs) was designed to train patients to do the pressure relief activity (PRA) accordingly to standard routine independently.

1.4 Objective

The wheelchair seating training system (WSETs) was designed to remind and train the SCI individuals to be alert on relieving pressure after sitting for a long period. However, the prototype had not been introduced and used by paraplegic individuals, especially for wheelchair users. Therefore, through this experiment, three main objectives need to be achieved: to approve the reliability of the prototype to the currently available device. Those objectives are:

1.4.1 Development of Upgraded Wheelchair Seating Training System (WSETs)

1.4.2 Determine the optimal region for FSR sensor placement on cushion based on a comparison of the pressure sensor arrangement.

1.4.3 Investigate the clinical use of wheelchair seating training systems (WSETs) for PRAs training in SCI paraplegic individuals.

1.5 Scope of Work

The wheelchair seating training system (WSETs) was designed previously using only one Force Sensitive Resistance (FSR). Thus, on this project, some modifications had been made to improve the previous design's limitations. The new design of the WSET system consists of four FSR used to represent both buttock-thigh areas. Besides that, the upgrade of the android system will also be done by displaying all four values from the pressure sensing element for monitoring purposes. Throughout this project, the optimal region on interface areas of buttock-thigh region on seating position will be determined by comparing two orientations of sensing element placement. Besides that, this project will also discuss the functionality and reliability of the WSET system as a training device toward SCI paraplegic individuals in practicing the PRAs compared to the currently available device.

1.6 Thesis Organization

The thesis comprises five chapters, including Introduction, Literature Review, Methodology, Result and Discussion, and Conclusion and Future Work.

Chapter 1: Introduction: The chapter explained the general concept of the study with three divisions: objective of project, scope of work, and thesis structure. It focused to explain the boundary of the development clearly.

Chapter 2: Literature Review covers the background of the whole idea of development. The flow started with SCI sub-topic, followed by wheelchair, pressure ulcer, prevention, and treatment. Comparisons between some earlier studies were done. Most topics were discussed in further detail, especially on pressure ulcer, stages, reverse staging, prevention and treatment, wheelchair cushion selection, pressure mapping system and current rehab technologies. All sub-topics were summarised at the end of chapter 2.

For Chapter 3: methodology mainly focused on the overall flow of the project and clinical test of system toward PRAs. Details for every sub-flow will be discussed here to allow readers to understand how the WSETs modification process takes place. Then, experiment in determine of FSR sensor optimal placement and clinical test of WSET system toward PRAs is construct.

Chapter 4: Results and Discussion will elaborate mainly on the prototyping and reliability of WSET system as training tools.

Finally, Chapter 5: Conclusion and Future Work will discuss possible work that can be applied in the future for further improvement of the project.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Every year, reports show the increment number of persons with spinal cord injury and having treatment in hospital. This situation is worrying because most spinal cord injury people lead to inactive lifestyles after injury, leading to secondary complication diseases such as pressure ulcers. Most people with spinal cord injury (SCI) will be affected by pressure ulcers due to prolonged use of the wheelchair. This is the reason that healthcare management after an injury is very important and been highlighted by many researchers. As for this project, the wheelchair training seating system is designed to train people with SCI by reminding them to relieve their pressure and reduce the risk of secondary complications. To develop an efficient system, the previous work done by researcher related to SCI, wheelchair technologies, healthcare management and existing prototype will be discussed in this chapter.

2.2 Spinal Cord

The spinal cord is a bundle of nerves and other tissue that the spine's vertebrae contain and protect, plus providing a two-way conduction pathway to and from the brain. The spinal cord has three major functions: as a conduit for motor information, which travels down the spinal cord, as a conduit for sensory information in the reverse direction, and finally as a centre for coordinating certain reflexes(Jackson et al., 2010). Therefore, it is very important for us to take care of our spine because all limb movement depends on the spine's messages, including the reflex action.

The spinal cord starts from the foramen magnum of the skulls to the first or second lumbar vertebrae, positioning just below the ribs where it continues as the cauda equina. The whole spinal cord was covered by three layers of meninges (pia, arachnoid and dura) and extended beyond the end of the spinal cord(Winter & Temple, 2017). The spine consists of 33 vertebrae, including: 7 cervical (neck), 12 thoracic (upper back), 5 lumbar (lower back), 5 sacral (sacrum – located within the pelvis) and 4 coccygeal (coccyx – located within pelvis) as shown in figure 2.1.

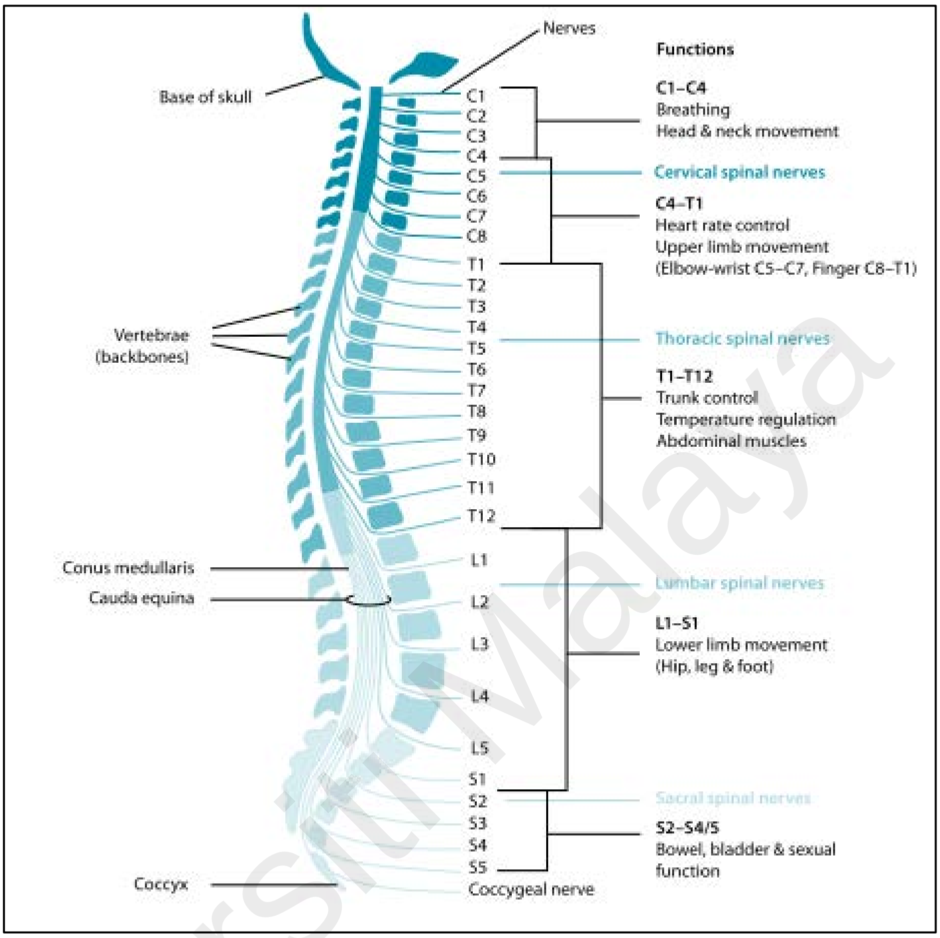


Figure 2.1: Illustration division of spinal cord. Source: International Perspective on Spinal Cord Injury (SCI)(Jerome et al., 2013)

The spinal cord functions primarily in the transmission of neural signals between the brain and the rest of the body and contains neural circuits that can independently control numerous reflexes and central pattern generators. Most spinal neuronal cell bodies were located through the central areas (gray matter) surrounded by spinal tracks (white matter) in a longitudinal orientation. The gray matter of the spinal cord is divided into two posterior projections and two anterior projections where both end projection roots fuse together to form the spinal nerves.

It also contains the neuron with specific functions, and injury at this point may cause flaccid paralysis. As for the white matter, the shape is divided into three regions, and each region contains a number of fiber tracts. This tract conducts the sensory impulse to and from the brain. If any injury happens to this matter, the body's movement could be involuntary and not controllable, plus lack of mobility(Marieb, 2012). Both matters are reflected in each other to stabilize the spine and protect the spinal cord. As the shield to the spinal nerve, the vertebrae's body acts as the primary weight-bearing component of the spine.

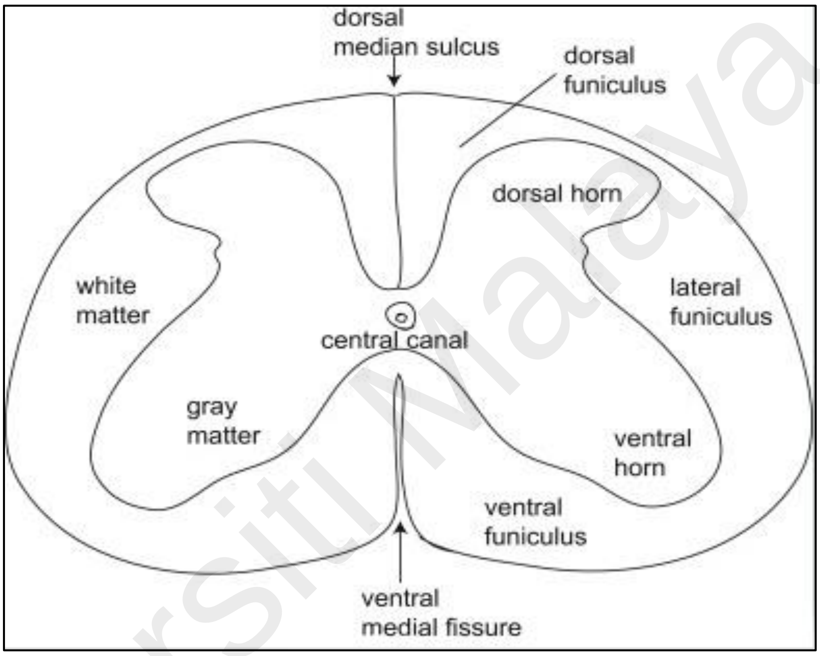


Figure 2.2: The illustration of white matter of the spine. Source from Spinal Cord (Sengul & Watson, 2012)

As mentioned earlier, the spine plays an important role in the body movement controller. The spine allows motion in three planes of movement: anterior, posterior and lateral aspect plus a range of motion (ROM) allowed at each motion is governed by the anatomical constraint that is different through the cervical, thoracic and lumbar region of the spine(S.J.hall, 2012). Every action applied to the body left impacts spine flexion, extension, and compression, especially active routine such as playing sports.

2.1.1 Spinal cord injury

Having an injury to the spinal cord affects the conduction of sensory and motor signals across the injury sites. It also may cause some permanent changes in body autonomic function, stability, strength, and sensation below the injury site (Li et al., 2015). The injury happens due to a violent attack (Perspectives, n.d.), diving into shallow water, a huge car and sport accident, and severe twisting of the middle portion of the torso(Hall, 2012). Besides common activities like repetitive lifting load during work can cause an injury to the spine due to a great amount of force or tension acting on it. The other factors affecting the spine are body weight, aging, tension from surrounding muscles, and intra-abdominal pressure.

The spinal cord injury (SCI) is sorted into two types: complete or incomplete (paralysis), depending on the level of injury. The complete SCI means that all the communication function, either sensory and ability to control body movement below the injury, are totally off while having some or part communication function of body loss after the injury known as incomplete SCI(Tominaga et al., 2015). The standard of American Spinal Injury Association Impairment Scale (AIS) as shown in figure 2.3 is used for determining the class of injury, including the test on the strength of individuals muscle which been graded by the clinician to six-point scale which is 0 (total paralysis), 1 (palpable or visible contraction), 3 (active movement, full ROM with gravity eliminated), 4 (active movement, full ROM against gravity, moderate resistance), and 5 (active movement, full ROM against gravity, full resistance) (Winter & Temple, 2017).

The incomplete SCI is divided into three classes that consist of quadriplegia, triplegia, and paraplegia. The neurological level of injury refers to the lowest of the spinal cord that function after injury. To determine the class of injury, some neurological examination had to be done toward the patients to check the performance of motor and sensory. The ability to control limbs after injury depended on 2 factors: the place of the injury along your spinal cord and the severity of injury to the spinal cord. As for people with SCI, the dysfunction of body system determines by the level of injury and the high level of injury cause the more dysfunction of body system.

American Spinal Injury Association (ASIA) Impairment Scale (AIS)

A — **Complete.** No sensory or motor function is preserved in sacral segments S4 — S5.
B — **Sensory incomplete.** Sensory but not motor function is preserved below the neurological level and includes the sacral segments S4—5 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 have a muscle grade less than 3.
D — **Motor incomplete*.** Motor function is preserved below the neurological level, and at least half of key muscle functions below the neurological level of injury have muscle grade >3.
E — **Normal.** This is only allocated if the patient had a previously documented SCI.
In order to receive a C or D grade, they must have either voluntary anal sphincter contraction or sacral sensory sparing at S4/5 with sparing of motor function more than three levels below the motor level for that side of the body.

Figure 2.3: American Spinal Injury Association Impairment Scale (AIS). Adapted from Spinal Cord Injury. (Winter & Temple, 2017)

The worst class of SCI level is quadriplegia (four), where the injury causes the impairment or loss of motor and sensory function in the cervical segments of the spinal cord. The impairment of function occurs at all for limb, which is arm, trunk, leg, and pelvic organs plus it also affect chest muscle and difficulty to breath. Then for triplegia (three), the injury involved three limbs with sensational loss in one arm and both legs. Different from paraplegia (two), the injury causes the loss of motor or sensory function in the thoracic, lumbar, or sacral segment of the spinal cord, which means only two limbs get affected either the arm, trunk, leg and pelvic organs function depending on the level of injury(Kirshblum et al., 2011).

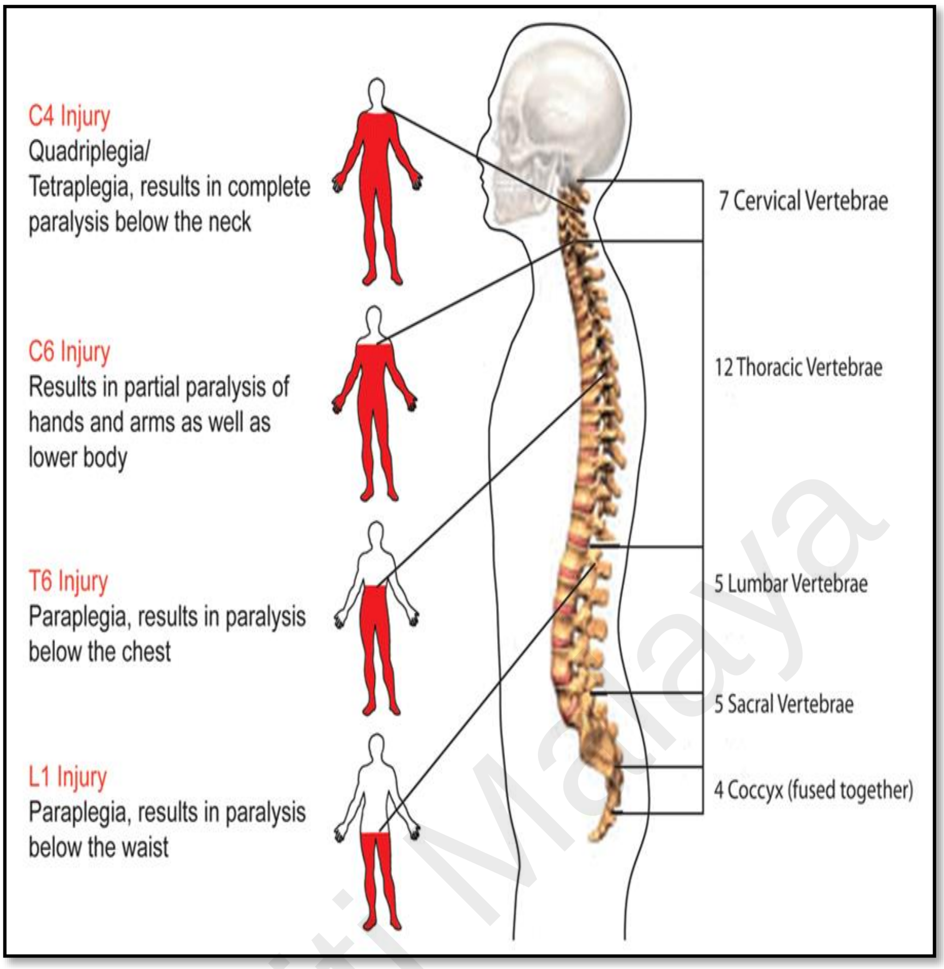


Figure 2.4: Class of SCI based on the stages of injury. Adapted from Spinal Cord Injuries (David, 2016)

There are common signs or symptoms of SCI: loss of movement and sensation, loss of control of bowel or bladder, changes in sexual function, sensitivity and fertility, pain, difficulty to breath, and weakness and incoordination of any part of the body. Therefore, without any planning about rehabilitation program after injury, the SCI individuals are exposed to secondary complications that risk their lives and are difficult to treat. This situation is worrying because it threatens SCI individual health condition and their daily routine, economic condition, and social relationship.

2.2 Secondary Complication after SCI

The health conditions after SCI are more worsening if the preventive measure were not been practiced regularly. The secondary health conditions such as neuropathic pain, spasticity, urinary tract and pulmonary infections, bowel and bladder dysfunction were complications that happen among people with SCI. This condition leads to a bad lifestyle that could reduce life satisfaction and emotional well-being and diminish life expectancy and mortality(Brinkhof et al., 2016).

Cardiovascular disease, bowel dysfunction, and pressure ulcer have a higher prevalence among SCI individuals, and it occurs at an accelerated rate (Mishori et al., 2016). In the early stage of SCI, most patients spend their time resting on a bed or wheelchair that cause to low level of physical activity and cardiovascular activity. When a person with a low level of physical activity, it also decreases the combination of cardiovascular and musculoskeletal systems ability to react at a given level of activity called physical ability(Zbogar et al., 2017). This is why physical activity and rehabilitation are very important for the patient to increase the functionality of the musculoskeletal system.

2.2.1 Pressure Ulcer

The development of pressure ulcers (PUs) is a serious problem that is most prevalent among SCI people. According to latest edition of NPUAP guidelines, the pressure ulcer or injury is defined as localized damage happen to skin or underlying tissue due to pressure with combination of shear(Kottner et al., 2020). The PUs happens due to three mechanical factors: the unrelieved pressure, shear, and friction, where their combination created localized damage to the skin and underlying deeper tissue(Smit et al., 2012). People with SCI are normally sitting in a wheelchair for a longer time due to a lack of control and sensation. Even for healthy people, it is very bad for a person to remain seated without any pressure relief. By sitting more than 8 per day, the person could increase mortality and negatively affect body activities(Paleg & Livingstone, 2015), leading to more disability than repair the weakness.

As for SCI people, they do not realize once the pressure ulcer is develop, the surrounding tissue is also affected and becomes necrotic due to the failure of blood pressure (Tominaga et al., 2015). However, the time of effect and level of pressure that could start damage varies depending on the individual pressure threshold, location, and disease development (Gehin et al., 2006). As in seated position, the most affected area by PUs were ischial tuberosities (Smit et al., 2012) because of the high pressure exerted on them as the transition of upper body weight. The position of Ischial tuberosities are shown in figure 2.5.

Figure 2.5: Position of human Ischial tuberosity. Source from Ischial Tuberosity Tuberculosis: An Unusual Location and Presented as Chronic Gluteal Abscess (Krishnan et al., 2010).

The pressure acts perpendicularly to the skin and increases the sore development while shear acting parallels to the skin surface, adding pressure by reducing flow through the blood vessel (Gehin et al., 2006). Based on previous research, when the pressure is not being relieved greater than capillary closure pressure, which 32 mmHg, the skin will start to break down and develop a pressure ulcer.

There is two class of factors that cause PUs which is extrinsic and intrinsic. Other than the three mechanical factors mentioned above, the extrinsic factors are poor skin hygiene (Trewartha & Stiller, 2011), arteriolar pressure, emotional stress, and interstitial fluid flow (Verbunt & Bartneck, 2010) while intrinsic factors were included prolonged immobilisation, nutrition, age, smoking, skin temperature. It usually happens in weight-bearing bony prominences (Vaisbuch et al., 2000) because most of body weight were act on it and increase the thermal conductivity.

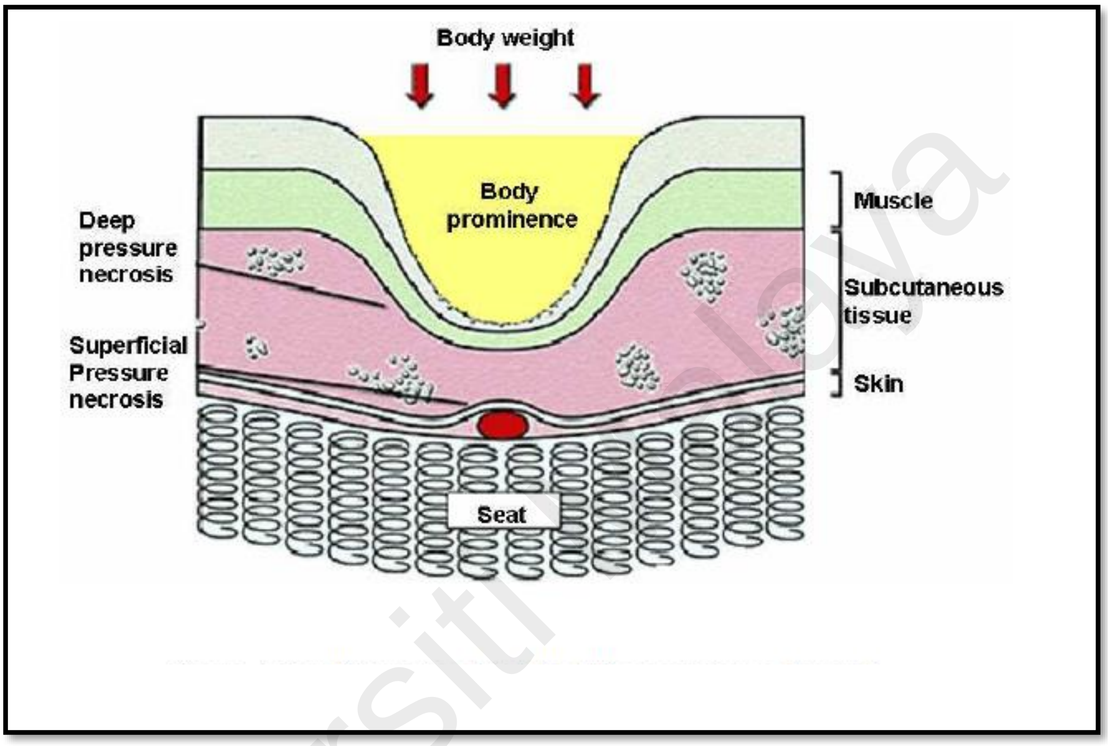


Figure 2.6: Condition of development of PUs. Adapted from Experimental Seat for the Study of the Effects of Random Pneumatic Stimulation for the Prevention of Pressure Ulcers (González et al., 2005)

2.2.1.1 Stage of pressure ulcer

PU was classified using the degree of tissue damage by National Pressure Ulcer Advisory Panel, NPUAP, in 1989. Staging is an assessment method used to classify PU according to anatomic features, such as wound depth, and to describe soft tissue damage. Wounds are constantly changing. Therefore, it is like a snapshot of the wound at a single point in time. Staging is the only appropriate method for documenting the depth of tissue damage. The process included removing necrotic tissue to get accurate definition of staging and allow complete visualization of ulcer bed(NPUAP (National Pressure Ulcer Advisory Panel), 2016). In latest NPUAP guidelines, there are three stages of pressure ulcer ranging from nonblanchable erythema to full thickness of skin loss as defined in figure 2.7.

NPUAP/EPUAP International Classification (2009, 2014, 2019)	NPUAP Classification (2016)	WHO ICD-11 (2018)
Category/Stage I pressure ulcer: Nonblanchable erythema Intact skin with non-blanchable redness of a localized area usually over a bony prominence. Darkly pigmented skin may not have visible blanching; its color may differ from the surrounding area. The area may be painful, firm, soft, warmer or cooler as compared to adjacent tissue. Category/Stage I may be difficult to detect in individuals with dark skin tones. May indicate "at risk" individuals (a heralding sign of risk).	Stage 1 Pressure Injury: Non-blanchable erythema of intact skin Intact skin with a localized area of non-blanchable erythema, which may appear differently in darkly pigmented skin. Presence of blanchable erythema or changes in sensation, temperature, or firmness may precede visual changes. Color changes do not include purple or maroon discoloration; these may indicate deep tissue pressure injury.	EH90.0 Pressure ulceration grade 1 Pressure ulceration grade I is a precursor to skin ulceration. The skin remains intact but there is non-blanchable redness of a localized area, usually over a bony prominence. The area may be painful, firm, soft, warmer or cooler as compared to adjacent tissue. It can be difficult to detect in individuals with dark skin but affected areas may differ in colour from the surrounding skin. The presence of pressure ulceration grade 1 may indicate persons at risk of progressing to frank ulceration.
Category/Stage II pressure ulcer: partial thickness skin loss Partial thickness loss of dermis presenting as a shallow open ulcer with a red pink wound bed, without slough. May also present as an intact or open/ruptured serum-filled blister. Presents as a shiny or dry shallow ulcer without slough or bruising.* This Category/Stage should not be used to describe skin tears, tape burns, perineal dermatitis, maceration or excoriation. *Bruising indicates suspected deep tissue injury.	Stage 2 Pressure Injury: Partial-thickness skin loss with exposed dermis Partial-thickness loss of skin with exposed dermis. The wound bed is viable, pink or red, moist, and may also present as an intact or ruptured serum-filled blister. Adipose (fat) is not visible and deeper tissues are not visible. Granulation tissue, slough and eschar are not present. These injuries commonly result from adverse microclimate and shear in the skin over the pelvis and shear in the heel. This stage should not be used to describe moisture associated skin damage (MASD) including incontinence associated dermatitis (IAD), intertriginous dermatitis (ITD), medical adhesive related skin injury (MARSI), or traumatic wounds (skin tears, burns, abrasions).	EH90.1 Pressure ulceration grade 2 Pressure injury with partial thickness loss of dermis. It presents as a shallow open ulcer with a red or pink wound bed without slough or as a serum-filled or serosanguinous blister which may rupture. This category should not be used to describe skin tears, tape burns, incontinence associated dermatitis, maceration or excoriation
Category/Stage III pressure ulcer: full thickness skin loss Full thickness tissue loss. Subcutaneous fat may be visible, but bone, tendon or muscle are not exposed. Slough may be present but does not obscure the depth of tissue loss. May include undermining and tunneling. The depth of a Category/Stage III pressure ulcer varies by anatomical location. The bridge of the nose, ear, occiput and malleolus do not have subcutaneous tissue and category/Stage III ulcers can be shallow. In contrast, areas of significant adiposity can develop extremely deep Category/Stage III pressure ulcers. Bone/tendon is not visible or directly palpable.	Stage 3 Pressure Injury: Full-thickness skin loss Full-thickness loss of skin, in which adipose (fat) is visible in the ulcer and granulation tissue and epibole (rolled wound edges) are often present. Slough and/or eschar may be visible. The depth of tissue damage varies by anatomical location; areas of significant adiposity can develop deep wounds. Undermining and tunneling may occur. Fascia, muscle, tendon, ligament, cartilage and/or bone are not exposed. If slough or eschar obscures the extent of tissue loss this is an Unstageable Pressure Injury.	EH90.2 Pressure ulceration grade 3 Pressure ulcer with full thickness skin loss. Subcutaneous fat may be visible but bone, tendon or muscle are not exposed. Slough may be present but does not obscure the depth of tissue loss. There may be undermining and tunneling into adjacent structures. The depth varies by anatomical location: grade 3 pressure ulcers can be shallow in areas with little or no subcutaneous fat (e.g. bridge of the nose, ear, occiput and malleolus). In contrast, grade 3 pressure ulcers can be extremely deep in areas of significant adiposity

Footnote: Tables comparing various pressure ulcer classification systems are available in the free Quick Reference Guide (QRG) and the full Clinical Practice Guideline (CPG), available at https://guidelinesales.com/.

Figure 2.7: Stage of pressure ulcer definition comparing from NPUAP 2016 and 2019 guidelines and WHO 2018 pressure ulceration guidelines. Retrieved from (European Pressure Ulcer Advisory Panel et al., 2019).

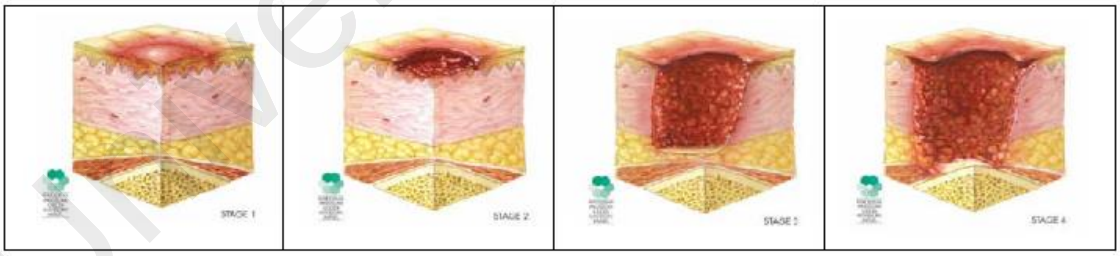


Figure 2.8: Overview stages of pressure ulcer. Reprinted from the AHCPR Publication No. 92-0050, Pressure Ulcers in Adults: Prediction and Prevention.

2.2.1.2 Reverse Staging

In 1989, due to a lack of research-validated tools to measure PU healing, clinicians resorted to the PU staging system in reverse order to describe improvement in an ulcer (Black et al., 2007). The NPUAP cautions that the PU staging system should not be used to "reverse stage" (or "down stage") pressure ulcers. Reverse staging is inappropriate because it implies that as PU heals, they go back through the stages of wound advancement. This is not what happens physiologically in a healing ulcer. A healing pressure ulcer fills with granulation tissue and becomes progressively shallower but does not replace lost muscle, fat, or dermis.

According to the NPUAP, the reason behind this is that pressure ulcer heals to progressively more shallow depth, they do not replace lost muscle, subcutaneous fat, or dermis before they re-epithelialize(Xakellis & Frantz, 1997). Instead, the ulcer is filled with granulation (scar) tissue composed primarily of endothelial cells, fibroblasts, collagen, and extracellular matrix. Therefore, reverse staging does not accurately characterize the ulcer's physiologically occurring (Sanada et al., 1997). A combination of specialized cushions for reducing pressure and pressure-relief movements, in which the patient performs "push-ups" or "leans forward," is considered the best option for PU prevention in people with SCI(Coggrave & Rose, 2003).

Therefore, the latest NPUAP guidelines (Kottner et al., 2019) had recommended good clinical practice that could be used by healthcare professional as guidelines to individuals on risky or affected group and their caregiver such as PI assessment and monitoring of healing, pain management besides the surgery.

2.3 Healthcare Management After SCI

The biggest challenge for SCI people is to adjust themselves to their body condition and manage themselves with less help from caregivers. They also need to socialise with the community and work for their life onward. So, people with SCI need to train their bodies to move again through attending rehabilitation and self-management training. If the individual does not regularly exercise, the poor mobility and poor posture during sitting will develop, which high the risk of pressure ulcers.

By regularly practicing the activity, the SCI individual will slowly improvise their quality of life. The prevention strategies such as regular repositioning, pressure relief activities, and stabilized posture during sitting effectively reduce the risk of pressure ulcers by maintaining the good nutritional status, good blood flow, and moisturizing the skin.

2.3.1 Pressure relief activities

In this thesis, the technique to prevent PU is used is pressure relief activity. Pressure Relief Activity (PRA) is a method to prevent pressure ulcers by conducting exercise from time to time. There are many techniques to perform PRA: lateral trunk shift, forward trunk lean, and shoulder depression (Figure 4). Every 30 minutes, the patient should perform repositioning activity or PRA and then stay in that position for at least 60 seconds(Sonenblum et al., 2014) because the pressure is not fully relieved if the PRA only be done for 15 to 30 seconds. The PU recovering time will be efficient if the individual regularly practices PRA and the time of pressure relief is longer.

The techniques chosen are dependent on the level of injury and patient capabilities. Lateral trunk shift can be done by hooking the upper extremity over the back or side of the wheelchair and leaning to one side. This technique is recommended for a patient with a level of injury of C4, C5, or C6. Next, forward trunk lean is done by leaning forward and the hand reaches towards the feet until the buttocks clear the wheelchair seat. This technique is suitable for patients with a level of injury of C6 because it requires less effort to maintain(Coggrave & Rose, 2003). Lastly, shoulder depression or also known as "wheelchair push-up". In this technique, the patient will place his/her hand onto the wheel or the armrest and then push the hand down to lift the entire buttock in mid-air. Since adequate energy is needed to push our body upward, thus this technique is suitable for patients with a level of C6 or below that have the strength to push their body upwards.

(a) (b) (c)

Figure 2.9: Techniques in performing PRA. (a) lateral trunk shift, (b) forward trunk lean, (c) shoulder depression or wheelchair push-up. Adapted from Posture, Proper Wheelchair Fit and Seating Posture(Good, 2013)

2.4 Wheelchair technologies

An estimated 1.6 million Americans residing outside of institutions use wheelchairs, according to 199495 data from the National Health Interview Survey on Disability (NHIS-D). Most (1.5 million) use manual devices, with only 155,000 people using electric wheelchairs. Wheelchair users are among the most visible members of the disability community, which experiences the highest activity levels and functional limitations. They also create the lowest number of employments.

The wheelchair is an assistive device used by an individual for mobility purposes. Mobility is the ability to move oneself from one place to another. A person with a physical disability that impedes functional mobility often require a wheelchair to augment or replace the function of walking. Wheelchair mobility has existed since at least the nineteenth century. Early examples were ordinary chairs to which wheels were attached. Designs progressed through the early part of the twentieth century, and use became more prominent in rehabilitation veterans returning injured from the two world wars and subsequent conflicts. Use of more advanced materials was adopted through the second half of the twentieth century, and the knowledge of the concept of posture as related to the wheelchair began to take off. Variations of the basic chair are available for amputees, hemiplegics, and others, but the basic chair of proper dimensions is generally the most suitable for paraplegic patients (Figure 10). The range of dimensions of the basic wheelchairs available in the United States are shown below (Figure 11).

Even when sensation is present, the hammock-type seat is seldom used without cushions, which are needed to better distribute pressure over the thighs and buttocks for comfort, if for no other reason. The importance of selecting the most appropriate chair and seat cushion cannot be over emphasized. The chair's dimensions must distribute the body's forces properly while also placing the user in a position with respect to the driving wheels, to provide maximum efficiency during propulsion. If the wheelchair was not chosen properly, the discomfort during sitting will affect the pressure applied and increase the risk of pressure ulcers.

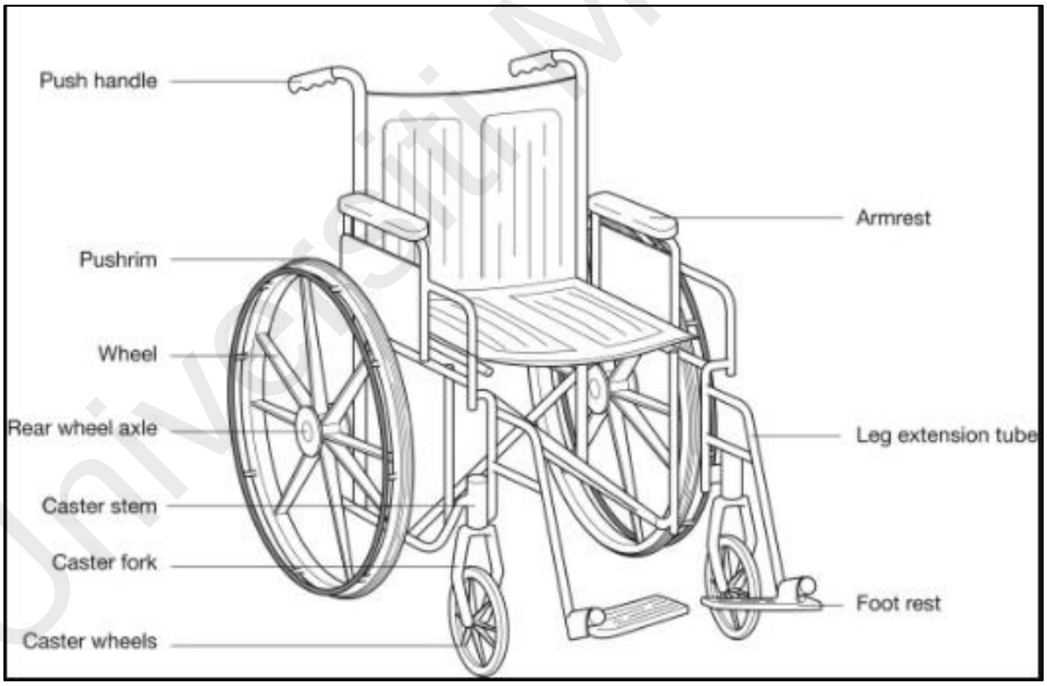


Figure 2.10: The basic wheelchair. Source from Wheelchair and Seating System (M. Koontz et al., 2015).

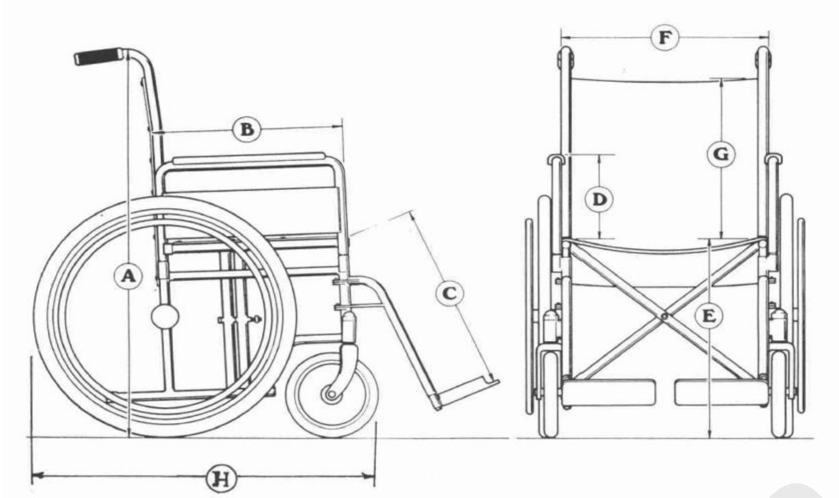


Figure 2.11: Dimension ranges for the basic adult wheelchairs. Source from Types of Wheelchair (Wilson & McFarland, 1990)

Table 2.1: Dimension ranges for the basic adult wheelchair. Source from Types of Wheelchair (Wilson & McFarland, 1990).

Label	Part	Dimension ranges (inches)
A	Overall height	36 - 37
B	Seat depth	16 - 17
C	Footrest support (adjustment range)	16 ½ - 22
D	Armrest height from seat rail (adjustment range)	5 - 12
E	Seat height from floor	19 ½ - 20 ½
F	Seat and back width	16 - 22
G	Back height from seat rail	Essentially as required
H	Overall length (without front rigging)	30 ½ - 32

In this thesis, we are focusing on the seating system on the wheelchair in order to investigate the pressure ulcer that occurs around the buttock region. Figure 2.11 and table 2.1 described the appropriate measurement for the height, width, and depth of seat according to categories of users stated in the designation. This is because the ergonomic of human is different as we grow older. Besides that, there are also many types of seats used.

2.4.1 Cushion

Besides the wheelchair, the choice of the cushion also affected the development of pressure ulcers. The primary use of cushion is to reduce the excessive pressure located on bony prominences and maintain tissue integrity (D. et al., 2010). There are several cushion selections in the market, including foam, viscoelastic, solid gel, viscous fluid, and air cushion (Trewartha & Stiller, 2011). Compared to all the cushions, the most effective cushion is based on the high degree of immersion and envelopment.

The foam, typically polyurethane or latex is most common material used in cushion today. It is lightweight, but susceptible to damage from light and moisture. Foam can be compresses heavily which allows it to be good cushion material. Viscoelastic foam has distinct time-dependent qualities. If you push on quickly, it will resist deformation more than if you push on it slowly.

Different from foam, Solid gel cushions are also vicious in nature, but they can be compressed lightly rather than foam. Instead, gel deforms and displace as a person sits on it. The gel is heavier than foam and must be encased as it can dry out if exposed to air. The viscous fluid cushion has replaced water cushion, which was prevalent several years ago. The material is a thick polymer or grease-like fluid that is displaced when a person sits on it, and lastly, the air cushion has an air-tight container that holds the gas and prevents leakage.

Table 2.2: Comparison of cushion with different fill. Source from Wheelchair Selection (Dudgeon et al., 2014)**.**

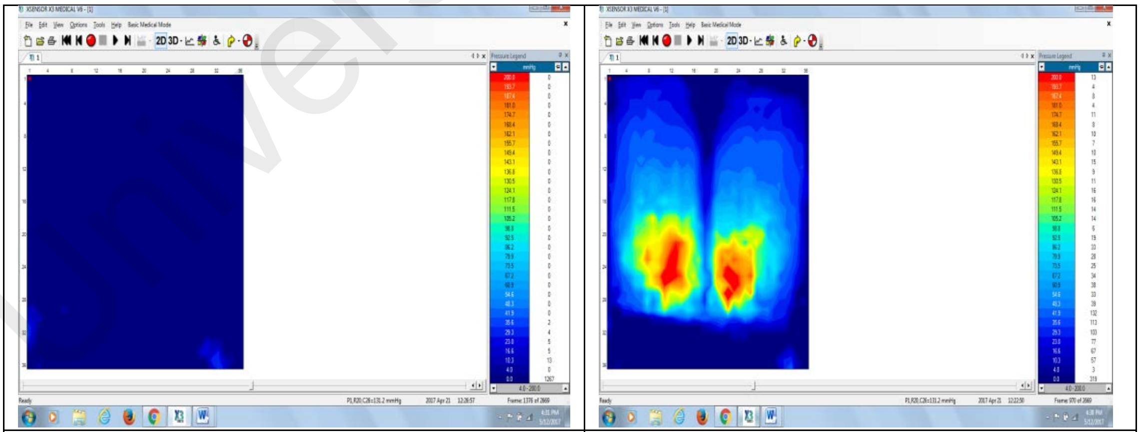
Foam 	➢ Good envelopment ➢ High shear ➢ Good dynamic properties (damping) ➢ Good long- and short-term resilience ➢ Poor thermal characteristic

Viscoelastic foam 	➢ Good envelopment ➢ High shear ➢ Mixed dynamic properties (cannot absorb impact loads) ➢ Mixed resilience ➢ Good thermal characteristics
Solid gel 	➢ Poor envelopment (does not compress) ➢ Low shear ➢ Mixed dynamic properties (damps) ➢ Good thermal characteristic.
Viscous fluid 	➢ Variable envelopment depending on container. ➢ Low shear ➢ Poor dynamic properties (poor long and short-term resilience), good thermal properties.
Air 	➢ Envelopment depends on design and proper inflation, ➢ shear depends on design and cover. ➢ good dynamics properties ➢ Thermal properties depend on cover.

2.5 Pressure Mapping System

The pressure mapping system is one of the tools currently used by many physicians or SCI individuals to visualize the contact pressure between the interface area of the human body and support surface such as wheelchair seat, cushion, or mattress(Yih-Kuen Jan & M. Brienza David, 2006). Through the pressure mapping system, the analysis of pressure, shear and heat on the interface can be known, and a precaution step could be planned by physiotherapy for SCI individuals. It is important to keep the pressure distribution on the interface area within the threshold, which is 32mmHg to 100mmHg.

Through pressure mapping system, the effectiveness of weight shifting can be exposed, which means the performance of SCI individuals in practising weight shifting can monitor either it completely off-loaded on interface area(Stinson et al., 2018). One of the pressure mapping systems widely used is the Xsensor mapping pressure system, which consists of pressure sensing mapping mat is connected to the computer as a display interface. Its display interfaces is graphically designed with a range of pressure values from 1mmHg to 300mmHg as shown in figure 2.12.



Off-Loading	On-loading

Figure 2.12: The interface display of Xsensor mapping pressure during off-loading and on-loading.

2.6 Current application prototypes

Over the years, the number of SCI individuals affected by pressure ulcers has increased and this situation has been worrying, especially among medical practitioners. Due to that, much researchers have been done related to SCI, PUs, and the prevention method. However, the medical report still shows an incrementing number of patients every year. Therefore, the attention of research had switched to healthcare management, self-management, and prototyping tools that educate patients to do the exercise or pressure relief individually without depending on the caregiver.

Table 2.3 Current application prototypes of training tools on pressure ulcer prevention

Pressure Mapping System for Physiological Measurements,(Janeiro, 2006)	In this paper, the researcher was discussing physiological measurements of a commercial Xsensor pressure mapping system. The physiological measurements involved reliability, sensitivity, temperature sensitivity, and hysteresis of the pressure sensor. As a results, only hysteresis showed poor results while the other properties were showed satisfactory. Therefore, pressure mapping systems were good tools for monitoring and analyzing the pressure condition on exerted areas. It also helps the physiotherapy and caregiver to alert the patient on taking the preventive measure.
Wireless Solution to Prevent Decubitus Ulcers: Preventive Weight Shifting Guide, Monitor, and Tracker App for Wheel Chair Users with	In this paper, the researcher had developed the idea of monitoring the pressure through the android application. The purpose of the app is walking the

Spinal Cord Injuries (Phase II),(Khan et al., 2016)**.**	patients through the weight shifting process. It also can track any movement activity through an accelerometer to verify the weight shifting activity. Besides that, the app is also responsible for saving and analysing the data from weight shifting activity. For every 15, 30, or 45 minutes, the app will notify about shifting activity according to patient preference.
Evaluation of a new sitting concept designed for prevention of pressure ulcer on the buttock using finite element analysis.(Lim et al., 2007)**.**	In this paper, the 3D finite element was designed for monitoring the pressure distribution on the buttock. The data are gathered from normal sitting to the off-loading sitting posture, where the ischial support is partially removed to reduce pressure under the buttock. This idea helps redistribute pressure on the buttock-thigh area, decreasing the risk of development of PUs at ischial tuberosities (Its). The data were compared between four regions at the buttock area, which is distal-medial (DM), distal-lateral (DL), proximal-medial (PM) and prosterial-lateral (PL)
Clinical Benefits and System Design of FES-Rowing Exercise for Rehabilitation of Individuals with Spinal Cord Injury: A Systematic Review(Ye et al., 2021)	Functional electrical stimulation or FES is one of the alternative methods that many researchers have discussed. The FES is an act stimulator that induces the paralysed muscle system and generates contractions. It also helps in improving and

	restoring the functional loss due to spinal cord injury. There are many FES types that SCI individuals can practice, as in this paper, FES-rowing is used as the main activity. The FES-rowing activity combines voluntary of the upper body and electrical stimulation of the lower body, which means it involves all four limbs in moving. It is proven that by practicing the FES-rowing exercise, cardiovascular performance improved and reduced bone density loss.

2.7 Conclusion

In conclusion, there are many studies on the consequences of having spinal cord injury and awareness to prevent any secondary complication such as pressure ulcer after the injury. It starts by discussing on the method of pressure ulcer prevention, wheelchair technologies design, cushion as a supportive element, and additional assisting tools such as pressure mapping system. The development of upgrade assisting tools has been discussed to help the SCI individual continually upgrade their lifestyle.

CHAPTER 3: METHODOLOGY

3.1 Introduction

In this chapter, the development of Wheelchair Seating Pressure Relief Training System (WSET) design, experimental procedure in determine best option for sensor placement and clinical test of WSET were discussed.

3.2 Designation chronology of Wheelchair Seating Pressure Relief Training System (WSET)

The conceptual ideas in designing the Wheelchair Seating Pressure Relief Training system or WSET prototype are to help monitor the pressure exerted on SCI individual buttocks while sitting on wheelchair and remind them about prepositioning or Pressure Relief Activity (PRA). Most SCI individuals spend more than 8 hours in a wheelchair for mobility. Thus, prolonged sitting increases the thermal conductivity and pressure on the buttock, especially on the bony prominences area. This situation is dangerous and leads to death if no action such as pressure relief are done. However, most SCI individuals do not sense any pain or irritation that urges them to do the pressure relief.

Therefore, the whole system of WSET was designed for the SCI individual to do the pressure relief without depending on the caregiver regularly. This prototype is built with a set of monitoring sensors installed inside the cushion and application as an alarm system. Many researchers designed the alarm system's timing according to standard recommendation time (Coggrave & Rose, 2003). The cushion was used to help redistribute the force acting on the buttock and decrease the pressure on bony prominences (Mcclure et al., 2014). The use of a cushion is also more comfortable and ease the patient to do the pressure relief activity.

3.2.1 First generation of Wheelchair Seating Pressure Relief Training System (WSET)

At first, the WSET was fully designed through PIC microcontroller software, including the indicator sensor and alarm control system. The Light Dependent Resistor (LDR) is used as a sensing element where it reacts to the light presence and stimulates the control system to function. Eight LDR are being embedded into the cushion surface. When the user seating on the cushion, the LDR is automatically covered by buttock. The absence of light through LDR starts the timing of the control system to countdown according to the selected time. After a few minutes, the alarm system will activate to remind the user to relieve pressure. Then, the control system will reset and standby for another round (Hazmi, 2014). However, this design does not show any value of pressure that exerted on the interface area.

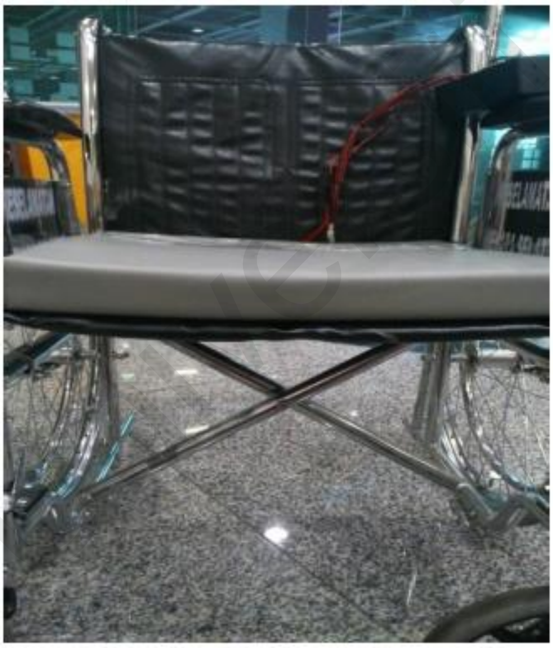
	
Front view	Upper view

Figure 3.1: First designation of WSET. Source from Development of seating pressure ulcer prevention training system for individual with spinal cord injury(Hazmi, 2014)

3.2.2 Second generation of WSET

To occupy the first-generation limitation, the second designations of WSET were built by using force sensing resistance (FSR) as a sensing element. The system also completes with an android application that acts as a control system where all sensor values can be monitored, aside from the alarm system. The FSR was embedded inside the cushion. When the user is seated on the cushion, the FSR will start to detect the load exerted on it(Hashim, 2015).

The FSR Interlink model 402 has a nominal thickness of 0.46 mm, active area's diameter of 14.68 mm, and length of 56.34±0.15 mm. The function of FSR was to monitor the force acting on the area. It also acts as an indicator to prove that the pressure relief had been done correctly. For the very first step, the functionality of FSR will be tested by monitoring the analogue value through the serial monitor on Arduino software. The connection between FSR sensor to Arduino controller are shown in figure 3.2. The value will increase when there is a squeeze on FSR and decrease when the FSR is in the normal state or not squeezed (Last & Edt, 2013). This test had been done to all FSR sensor use.

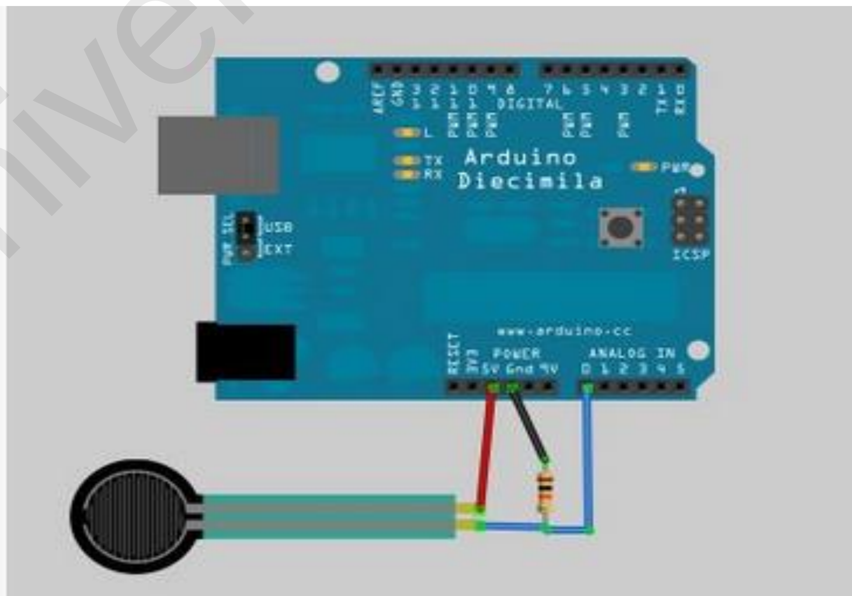


Figure 3.2: Connection of FSR to Arduino

Through the second generation of WSET, the android application was introduced. The android application was designed by using MIT Apps software. The purpose of existence on the android application as figured in figure 3.3 was to upgrade the functionality of the control system where the user or caregiver can just install the application through their phone. The android applications were built with a monitoring and alarm system. The analogue value produced by FSR can be monitored through the application by connecting to Bluetooth devices. Thus, it's easy to access for the user and caregiver to monitor the interface pressure from time to time.

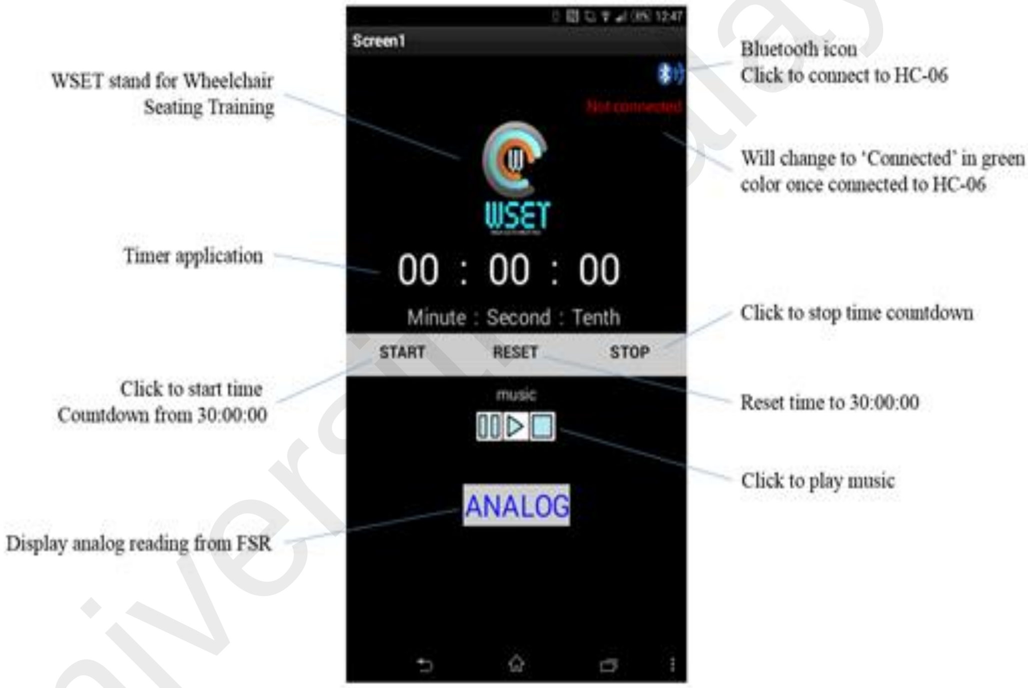


Figure 3.3: Android application interface

However, there limitation on second generation of WSET is lower number of sensor to represent the whole affected area where only one FSR is used to represent the interface pressure of whole buttock-thigh area. Therefore, the upgraded WSET is being design with more FSR which represents each interface defined region.

3.2.3 Upgraded of Second Generation WSET

In this version, the FSR sensor is added from one to four FSR to represent each region on the buttock-thigh interface area. The two FSR were placed at the Ischial Tuberosities region, while the other two represented the thigh area. All four FSR were embedded inside the cushion, and the values can be monitored through an android application that is wirelessly connected by Bluetooth devices.

On the android application, all FSR values are present in colours to indicate the level of pressure. The colours are yellow, light blue, dark blue, light red, and dark red. The yellow indicates the lowest level of pressure, and as the values increase, the colour also changes accordingly to light blue, dark blue, light red, and lastly, dark red, which indicates the most dangerous stage of unrelieved pressure. The pressure range was from 0-300 mmHg, same as Xsensor pressure mapping.

Four FSR embedded on cushion

Android application interface

Figure 3.4: Upgraded of second generation of WSET

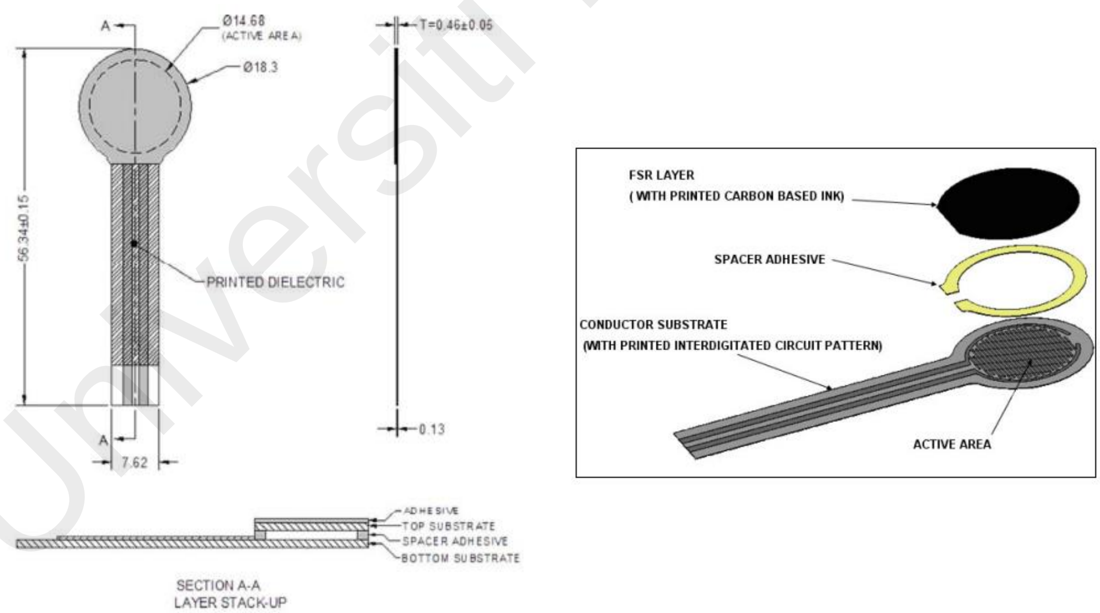
3.2.4 The software, application and sensing element used in WSET development

3.2.4.1 Arduino software

The arduino software was used as a microcontroller or “the brain” of the system where all systems or applications were connected. The connection between sensing element, Bluetooth device and android application, including the time interface between all systems, are being manageable by Arduino software. The coding of reading the values from FSR and changing the values from analogue reading to mmHg unit, all were written on the software.

3.2.4.2 Force Sensitive Resistance (FSR)

The force-sensitive resistance or FSR acts as a sensing element in WSET. The FSR will detect any force or load exerted on it. The FSR concept is that when the load is applied, the resistor values will decrease as the load value increases. FSR is used in WSET as a pressure indicator that senses the user's presence on the cushion by detecting load applied. Although pressure differ depending on individual body condition but it can analyse the pressure exerted on interface area, beside exposed to user if they were doing PRA correctly as recommended.



(a) (b)

Figure 3.5: Force Sensitive Resistor (FSR), (a) Mechanical Data of FSR, (b) FSR construction. Adapted from Data Sheet Interlink Electronics - Sensor Technologies (Interlink Electronic, 2015).

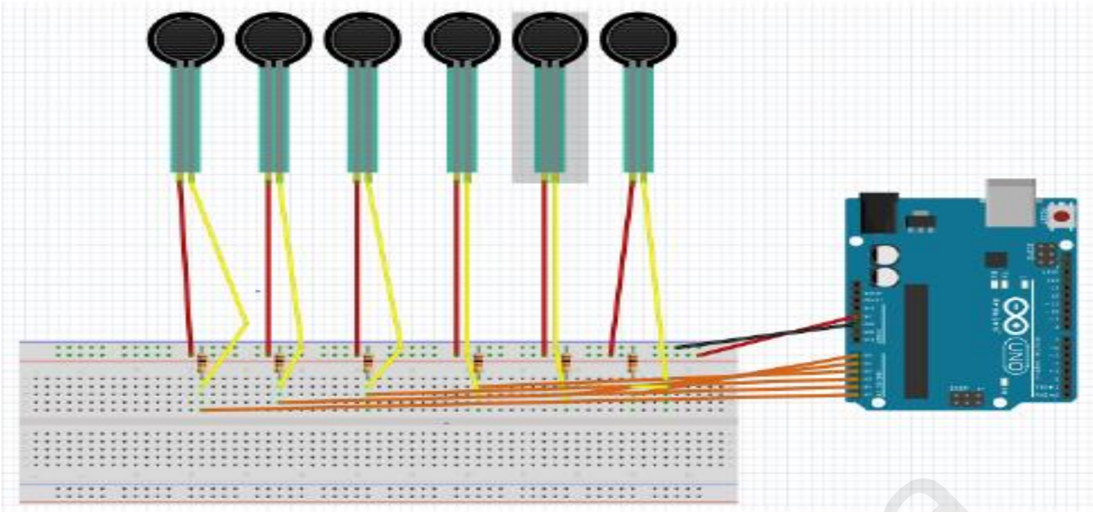


Figure 3.6: Connection between FSR and arduino software

3.2.4.3 Android application

For WSET's android application, the system were designed by using MIT II Apps. MIT App Inventor is a blocks-based programming tool that allows the building fully functional apps for Android devices. The android application's purpose was developed to ease the user, caregiver or physicians to monitor the exerted pressure and as an alarm system that reminds the user about pressure relief.

In figure 3.7, the application interface was shown where the user could view all the information such as sensor value, alarm counting, and PRAs procedure. In the alarm system, the apps were designed to alert the patient every 15 minutes to do the PRAs and countdown for 1-2 minutes before its starts to reset back to 15 minutes. Once the counting system hit 0 seconds after 15 minutes, the sound with activated to alarm the patient for PRAs and the alarm only stops after the patient is done with PRAs, as shown in the flow chart in figure 3.8.

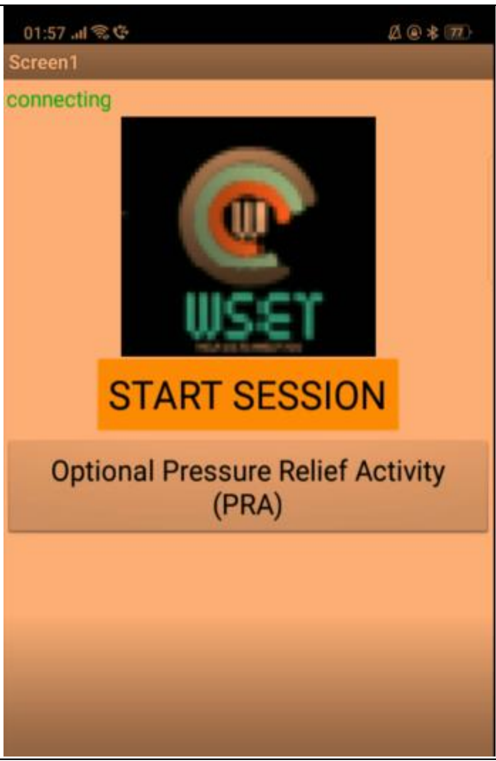
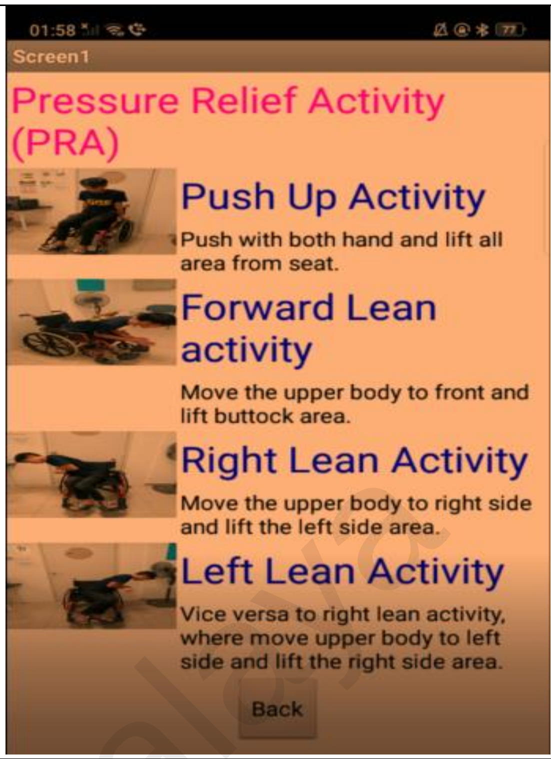
	
WSET front screen of apps	PRAs informations screen

Figure 3.7: WSET Apps interfaces

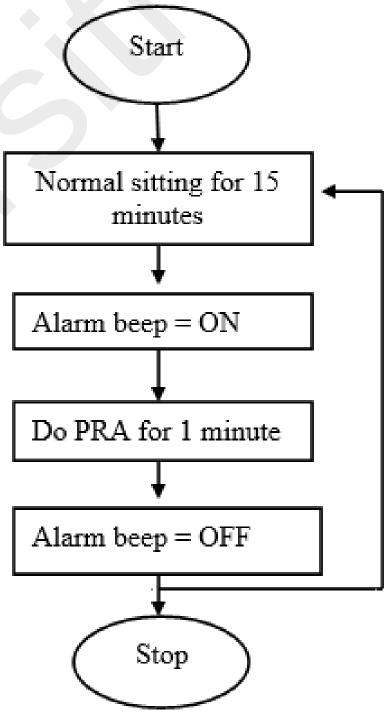
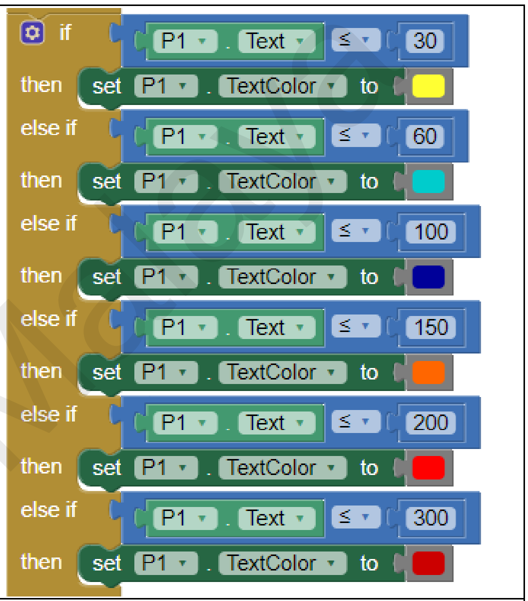


Figure 3.8: Flow chart of alarm system in WSET apps

In the sensor value display section, as shown in figure 3.9, every patient was capable of monitoring the pressure value along the time through the apps. The differences in colours of sensor values indicate the pressure level as yellow for the lowest pressure with a range of 0-30 mmHg and red for higher pressure with a range of 200 – 300 mmHg. The PRAs techniques were briefly introduced in the apps as a reference for patients, especially for patients new to the techniques.



Differ of colour for value display on apps	Colour level set on apps

Figure 3.9: Value display on WSET apps

3.3 Determine the optimal region in placing the FSR

The system was built up with four FSR installed inside the cushion. During sitting position, the most affected area was both of ischial tuberosities and thigh area. Two FSR sensors were placed on the right and left ischial tuberosity where the distance is 135 mm, while the other two FSR sensors were placed at the left and right thigh area(Chen & Yang, 2016). However, there is no exact position of buttock on the cushion for placing all four FSR. Therefore, initial test had been done to determine the suitable position for installing all the sensors.

3.3.1 Orientation of FSR

In this experiment, there are 2 design orientations of FSR introduced. The FSR sensors are placed accordingly to a high-pressure area based on the experimental result compared to Xsensor mapping pressure. The sensor orientation is placed on a high-density gel-foam cushion with foam thickness of 8.9 cm and 44 cm on width distance, 36 cm on length, as shown in figure 3.10.

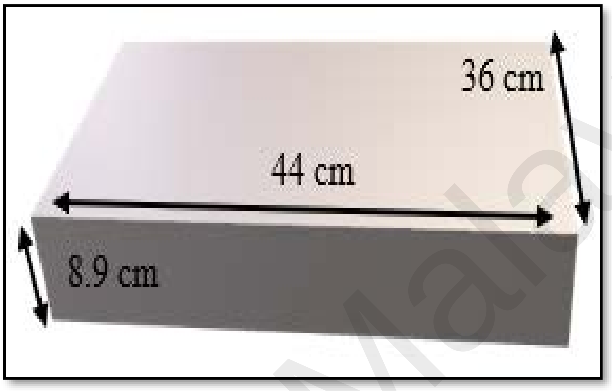


Figure 3.10: Dimension of cushion's surface

Referring to figure 3.11, the distance in Orientation A between the cushion's edges to the buttock sensors is 15 cm on the side and 8 cm to the back side. While on the thigh region, the distance between sensors to side edge is 10 cm and 18 cm to back side. Then, the distance between sensor on the buttock and thigh area is 10 cm.

Meanwhile, the Orientation B is being constructed by rearranging all sensors to the centre of the cushion. The distance between sensors on thigh and buttock regions remains the same, which is 10 cm while changes are made between sensors to the back side of cushion where the distance is 13 cm for both regions. Based on Figure 3.10, Symbol 'x' represents the location of the FSR meanwhile, the number beside the X represents the FSR numbering.

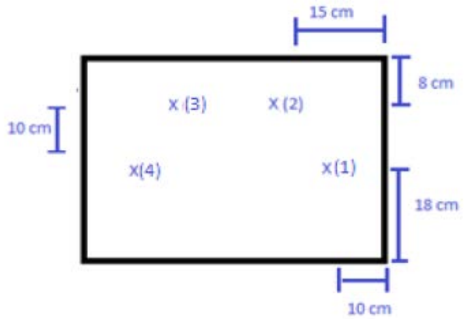
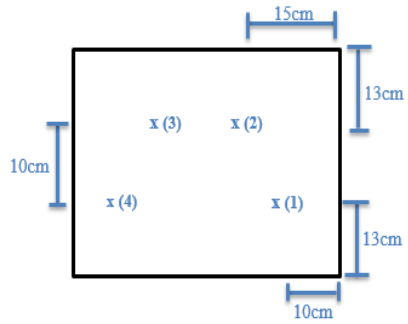
	
Orientation A	Orientation B

Figure 3.11: Measurement on orientation A and B

Figure 3.12: Position of cushion on wheelchair

3.3.2 Sensors calibration

Before experimenting, all FSR is being calibrated first by using load. The purpose of the calibration process was to determine the sensitive range within four sensors. The calibration is done from 1 N of load up to 100 N and applied to all sensors. Based on figure 3.13, its shows that all FSR sensors had almost the same sensitive range, which is within 5 N to 60 N.

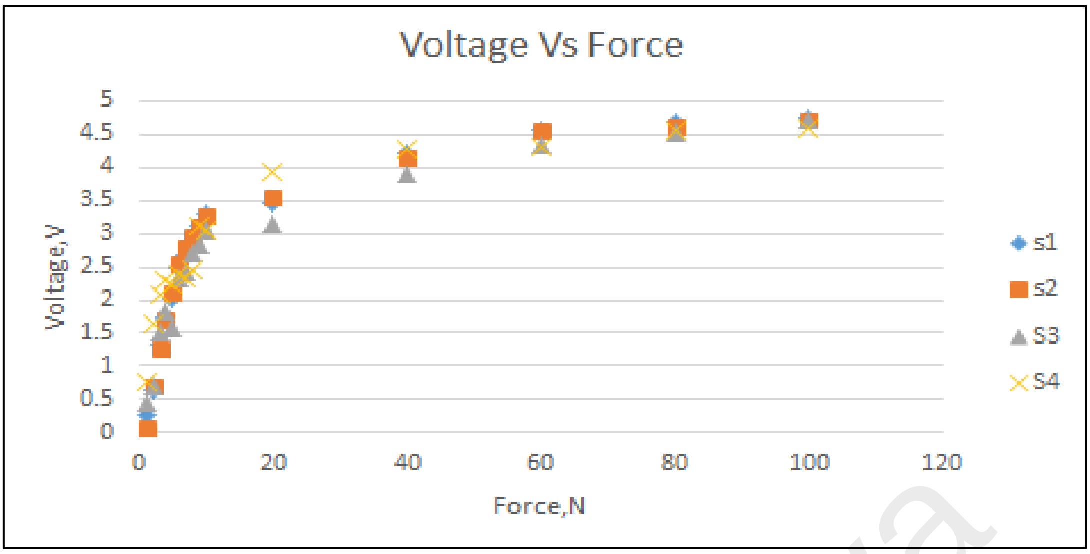


Figure 3.13: Calibration graph between 4 FSR

3.3.3 Experimental procedure

In comparing both orientations, pilot experiment had been done with 2 able-bodied person and 2 SCI paraplegic individuals as describe on table 3.1. Both of SCI paraplegic individuals are the fulltime wheelchair. The experiment all been done by using the same type of cushion and standard wheelchair.

Table 3.1 Description of subjects

Subject	Age	Weight (kg)	Gender	Health condition
1	24	85	Female	Healthy
2	22	63	Female	Healthy
3	32	86	Male	Paraplegic
4	25	55	Male	Paraplegic

In this experiment, all subjects had two sessions of the same routing protocol but different sensor orientations. The orientation A and B shown in figure 3.11 was applied to each subject and the result is compared between subjects based on each orientation. The experiment started by installing a cushion placed between the subject buttock and wheelchair seating area.

The routine for this experiment was that the subject needed to remain in a static position on the cushion that installed the WSET system comfortably without any movement for 15 minutes. During the session, the pressure applied on the interface area is recorded within the time.

3.4 Clinical experiment

In the clinical experiment, the prototype reliability, functionality, and suitability of WSET system to paraplegic SCI individuals was checked. Therefore, the WSET system were tested to 5 paraplegic individuals from University Malaya Medical Center (UMMC). Besides the WSET system, each subject's interface pressure also be recorded on Xsensor pressure mapping to compare the pressure reading between two systems and prove the reliability of the WSET system.

Xsensor mapping pressure system as shown in figure 3.14 is an assistive tool that monitors and analyzes the interface pressure commonly used by medical practitioners and physiotherapy to check SCI individuals' condition. The Xsensor consistss of thousands of sensor cells that could measure pressure continuously in real time and cover 30” x 74”. The sensors could detect the interface pressure from 5 mmHg – 200 mmHg with the accuracy of +/-2 mmHg.

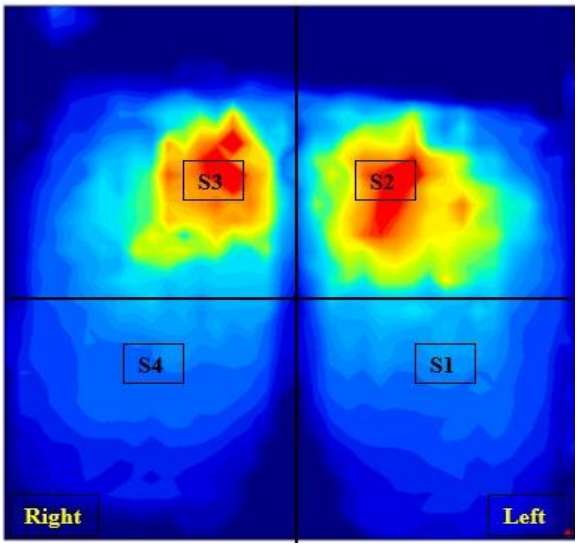


Figure 3.14: Xsensor Pressure Mapping and FSR sensor placement

3.4.1 Subject Characteristics

In this experiment, five paraplegic SCI individuals from the UMMC rehabilitation center had been recruited to experience the functionality of the WSET system. All the subjects are required to fulfill the subject's condition, where most importantly, they must be a full-time wheelchair user and capable of performing all types of PRA. In table 3.2, the inclusive and exclusive criteria of subjects were stated.

Table 3.2 Description of subjects on clinical experiments

Subject	Age (years)	Weight (kg)	Gender	Health condition	Years since Injury
1	28	86	Male	Paraplegic	2 years
2	25	55	Male	Paraplegic	2 years
3	32	60	Male	Paraplegic	5 years
4	35	63	Male	Paraplegic	4 years
5	35	70	Male	Paraplegic	6 years

Table 3.3 inclusive and exclusive criteria of subjects

Inclusion	Exclusion
• Traumatic & Non-traumatic SCI. • Admission to any participating centre. • Initially classified as incomplete SCI (paraplegic). • Wheelchair user. • Informed consent, given by the subject, where applicable. • Participants needed to be able to follow simple instructions. • Persons who have demonstrated a willingness to use the device long-term. • Participants could not have a skin allergy to electric stimulation or electrodes. • Age 18-80 years old.	• Pre-existing bone conditions (e.g. fractures, osteoporosis). • Participants were excluded if they had autonomic dysreflexia, any other conditions that could potentially affect the study results, or if they had a history of other neurological or psychiatric disorders. • Participants must be applicable to do the pressure relief activity such as bending forward and leaning sideways. • The upper limb must be in the condition. • Orthopedic conditions that affect function (e.g., pain in lower limbs or spine)

3.4.2 Experimental procedure

The experiment started by introducing the WSET system device and briefly explained every procedure, including their awareness of Pressure Relief Activity (PRA). As shown in figure 3.15, each subject needs to practice during the experiment according to the guidelines. Then, subjects were required to fill up on consent form to agree on understanding and willingness to experiment. After that, they were asked to place themselves on a WSET system installed cushion and Xsensor pressure mapping before the experiment was started and data were recorded.

In the first 15 minutes, the patients are needed to be seated quietly without any disturbance or movement to detect the pattern of normal seating posture and pressure of each subject. After 15 minutes of seating, the patients were required to do the push-up activity for 1 minute as PRAs before back to seat position for another 2 minutes. Then, the subject needs to practice the second PRA, which is right side leaning activity, before resting for 2 minutes.

After that, the activity was repeated until all the PRAs had been practiced according to our suggested sequences: push up, right lean, left lean, and forward lean. Lastly, the subject was back to a normal seated position for 15 minutes before completing the experiment. Through figure 3.16, the guidelines of the experimental procedure are shown in the flow chart.

Figure 3.15: Pressure Relief Activities (PRA)

Consort Flow Diagram

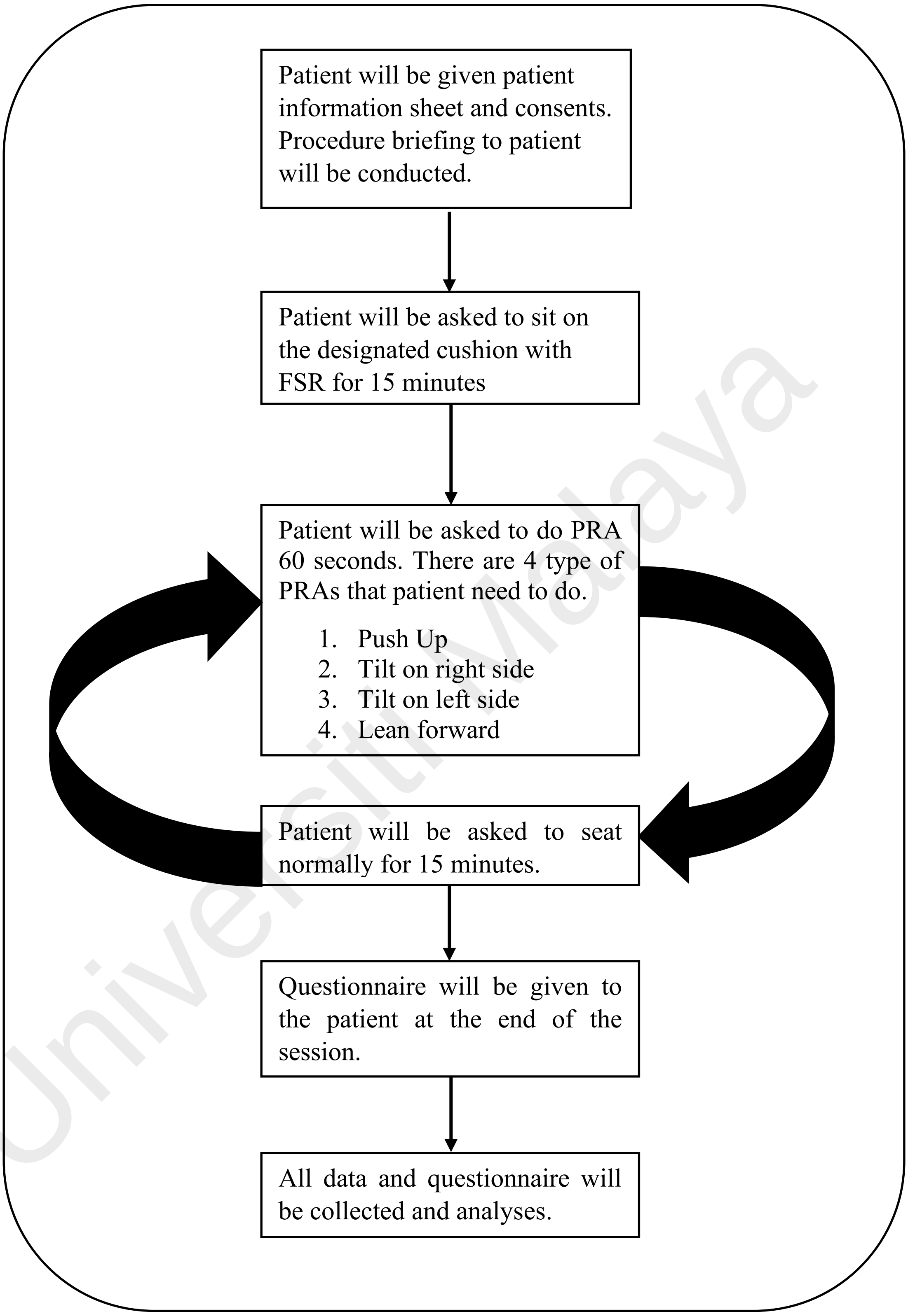


Figure 3.16: Flow chart diagram of procedure guidelines.

3.5 Data collection and analysis

On each experimental procedure, the data were collected through a computer before analysing process. All the data collected from FSR sensors and Xsensor pressure mapping during both experimental procedures were analysed through analytic software such as Microsoft Excel and SPSS. In justification of sensor placement, the orientation was selected based on the high-risk area representing both sides of buttock area (ischial tuberosities) and thigh area with a difference of 10 cm between the area.

In SPSS analysis, the significant between the sensors reading in both of orientation was analyzed through an independent T-test analysis. While in comparing the FSR sensor reaction between PRAs activities, the Anova analysis is used. As for determining the accuracy between FSR and Xsensor Mapping pressure, the method of linear regression is applicable. In this method, the statistical coefficient of determining, R-squared, and mean percentage error is analyzed to measure the proportion and precision of variance between dependent and independent variables(Tofallis, 2013). All the results were explained and presented in figures, tables, and the SPSS analysis method explained in chapter 4.

3.5 Conclusion

In conclusion, this chapter begins with the designation of the WSET system and upgraded prototyping development. Then, the experimental procedure in finding optimal region for FSR placement and clinical test procedure of WSET system with paraplegic SCI individuals is also explained in this chapter.

CHAPTER 4: RESULTS

4.1 Introduction

In this chapter, the outcome of the study will be discussed. The chapter begins with presenting the outcome of prototyping and development of the Upgraded Wheelchair Seating Training System (WSETs). The result of WSETs FSR sensors placement and clinical test with paraplegic SCI individuals will also be explained here.

4.2 Development of Upgraded Wheelchair Seating Training System (WSETs) Outcome

On WSET's second generation, the FSR sensor is introduced as a sensing element replacing the LDR sensor used on the prototype of the first generation. However, using only one FSR sensor was not enough to represent the whole buttock area, especially on the high-risk area of PUs development. Therefore, as to occupy the limitation of WSETs second generation, the new prototype was designed by adding the number of FSR sensors. The additional FSR sensors also affected the whole process of WSET designation, including placing of FSR sensors, monitoring system through android software, and Arduino controller.

To determine the suitable number of FSR sensors added on the prototype, a pilot study was done (Nurliyana Farzana Zamrut, 2017). Through the pilot study, the WSET system was tested using 2, 4 and 6 units of FSR sensors and each configuration came with 4 suggested orientations. The placement of FSR focused on ischial tuberosities (ITs) area and thigh area. As a result, the best orientation with 4 FSR sensors was chosen as the final configuration to the WSET system. Two sensors were placed to represent both sides of ITs and another two sensors represent both sides of the thigh area. In figure 4.1, the configuration and placement of FSR in WSET system is shown.

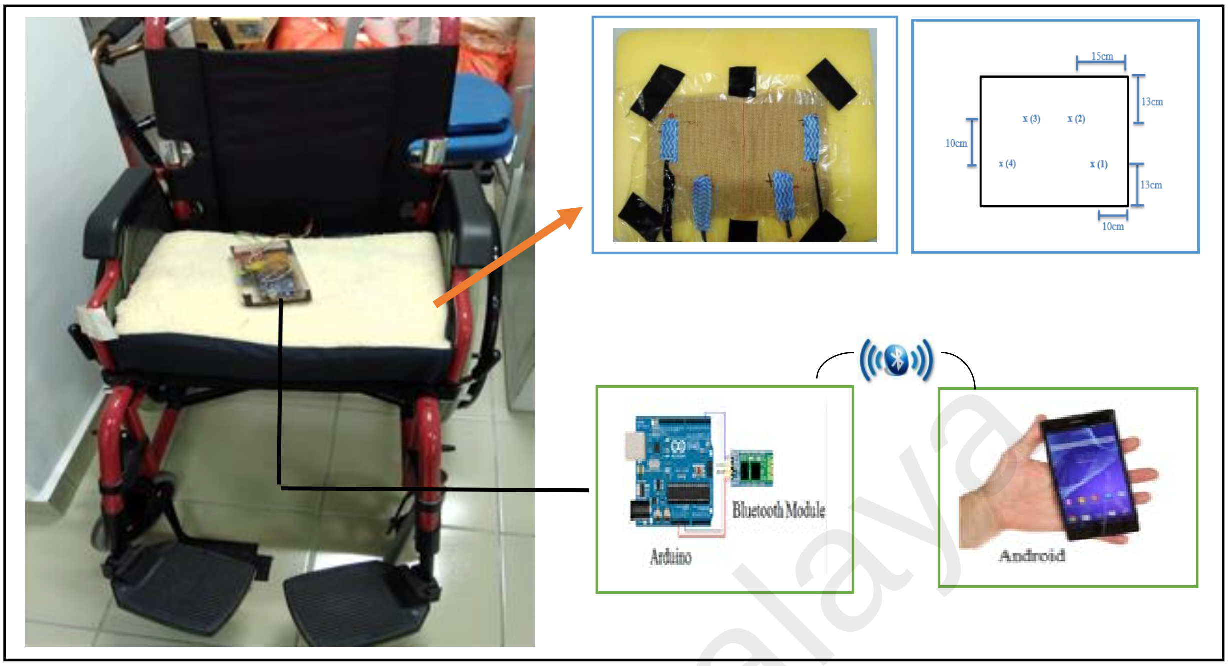


Figure 4.1: The FSR sensors dimension and monitoring systems connection.

For the monitoring system, the medium used for displaying value from FSR sensors is through the android system because to ease the user to monitor the condition of pressure wirelessly through personal phone and alarm the user to relieve the pressure. The android system was connected to the WSET system through a Bluetooth connection. The display shows the placement of the sensor accordingly to the position of FSR sensors at the cushion. Each sensor value was analysed through time and displayed in the apps with different colours to indicate different pressure levels in monitoring functions.

In reducing the risk of pressure ulcer development, it is very important to control the interface pressure lower than 32 mmHg(Gehin et al., 2006). However, the interface pressure for each individual is differs depending on body weight and health conditions. For an overweight person, the interface pressure during seating is higher compared to normal-weight person. Therefore, as the best option to standardize for each individual, WSET systems were designed with alarm system based on time countdown and stop once movement of subject doing PRAs is detected based on the value of FSR sensors.

Table 4.1: The behaviour of FSR sensors during pressure relief techniques based on the placement of FSR.

Position /FSR Sensor	FSR 1 (front left)	FSR 2 (back left)	FSR 3 (back right)	FSR 4 (front right)
Pre-Rest	X	X	X	X
Push Up	0	0	0	0
Right Lean	0	0	X	X
Left Lean	X	X	0	0
Bend Forward	X	0	0	X
Post-Rest	X	X	X	X

X = with reading   0 = zero reading

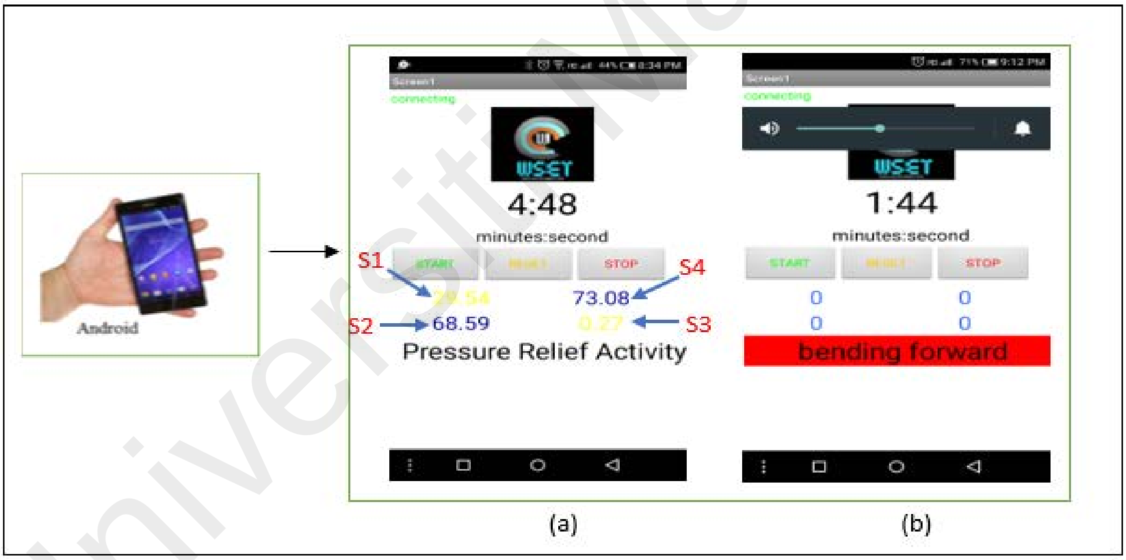


Figure 4.2 The monitoring system display on WSETs apps (a)reading normal seat position. (b) reading bending forward position.

By referring to the expected FSR sensor behaviour during PRAs shown in table 4.1, the WSET system could detect the subject movement. For example, if the subject has remained static for more than 30 minutes, the WSET system will start the alarm count until the subject is doing PRAs. Along the time, the display on the WSET system will continuously read the FSR sensor and the activity done by the subject, as shown in figure 4.2.

4.3 Determine of Optimal Region for FSR Sensors

In this finding, the important area that needs attention is ischial tuberosities (ITs) area represented by sensor 2 and 3. This is because the ITs area had to hold most of upper body weight during sitting position. There are significant differences ($P<0.05$) of FSR sensors behaviour between orientation A and orientation B. Through figure 4.3, the FSR sensor 2 and sensor 3 among paraplegic individuals in orientation B show high-pressure reading compared to orientation A. There are also significant differences where $P<0.05$ for sensors 1 and 4.

This shows that the ITs area covered by sensors in orientation B is at high risk in the development of pressure ulcers compared to the area covered at orientation A. Besides, the position of sensor placement in Orientation B is more centred toward cushion dimension and more defined in division of buttock and thigh area compared to Orientation A. Therefore, orientation B placement of the FSR sensor is chosen as the optimal placement of the FSR sensor and finally becomes the last configuration for the WSET system. The orientation is very important for the WSET system as the placement of FSR plays the biggest role in detecting the most affected area by high pressure and eventually could be the point of pressure ulcer.

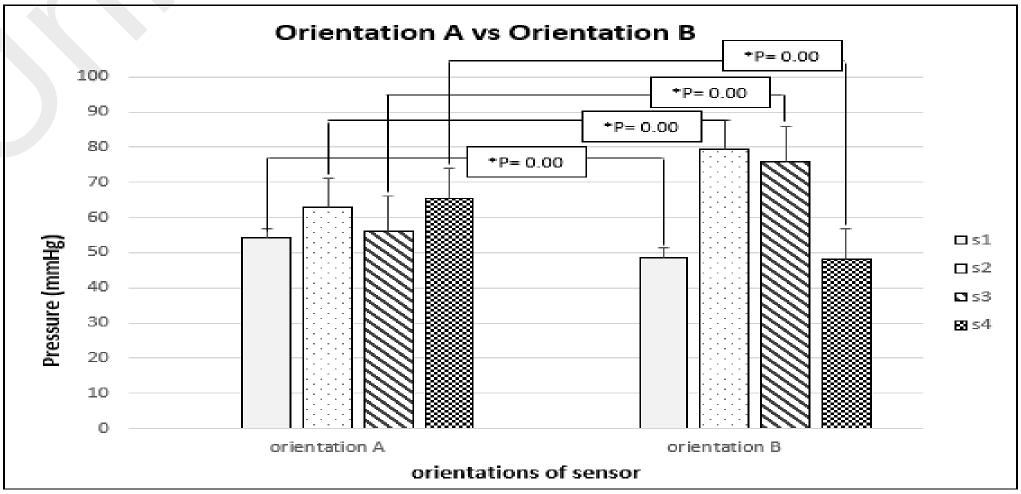


Figure 4.3: Different of FSR behaviour between orientation A and orientation B.

4.4 Investigate the Wheelchair Seating Training System (WSETs) for SCI Paraplegic Individuals

WSETs system was designed as physiotherapy devices for SCI individuals in increase their quality of life (Hazmi, 2014). This device is specialized for paraplegic SCI who commonly spend most of their time in a wheelchair for preventive secondary complications and life continuity. Therefore, this experiment is set up to test the WSET system device to SCI individuals clinically.

In this clinical experiment, each subject was required to do all five routines of PRAs alternately with 2 minutes rest between routines. All FSR sensors behaviour was recorded through both the WSET system and Xsensor mapping pressure. Through the experiment, results from each technique were compared based on figure 4.4, and it is proven that push-up activity is the most effective technique in relieving pressure. This is because when practicing the push-up activity, the subject will use all strength in the upper limb to push up the buttock area from seating and show zero pressure points. However, this technique is not very suggested by many researchers to be practicing regularly because it could lead to fatigue and injury to upper limb area(Coggrave & Rose, 2003).

Compared to other techniques, push up technique had significant differences where $P<0.05$ in all sensors to the other activity, shown in figure 4.4. While for forward technique, there are significant differences ($P<0.05$) on sensor 2 and 3 at the buttock area between the forward bending technique to pre-rest and post-rest activity as the transition of body weight from buttock area to thigh area (Lim et al., 2007). However, there is no significant increment of pressure in sensors 1 and 4 at the thigh area between a push-up and pre-rest and post-rest.

Other than forwarding bending, side-leaning techniques are also suitable for those with weak upper limb strength and limitations in performing the push-up activity (Engineering

& Technology, 2008). In this activity, when the subject is leaning toward the left side of the body, all the pressure is also shifted to the left side of the body along with body weight, and this same goes to the right side leaning(Coggrave & Rose, 2003). This technique required less effort and was much easier to practice regularly but needed to be done alternately between both sides.

Based on figure 4.4, the significant difference where P<0.05 can be seen on sensor 1, 2 and 3 between the left lean towards pre-rest and post-rest activity on the left side leaning. However, for sensor 4, there are no significant differences in sensor reading between the activity to pre-post rest. The same goes for right lean, and there are significant differences where P<0.05 in sensors 2, 3, and 4 except for sensor 1 between the right lean activity to pre-post rest activity.

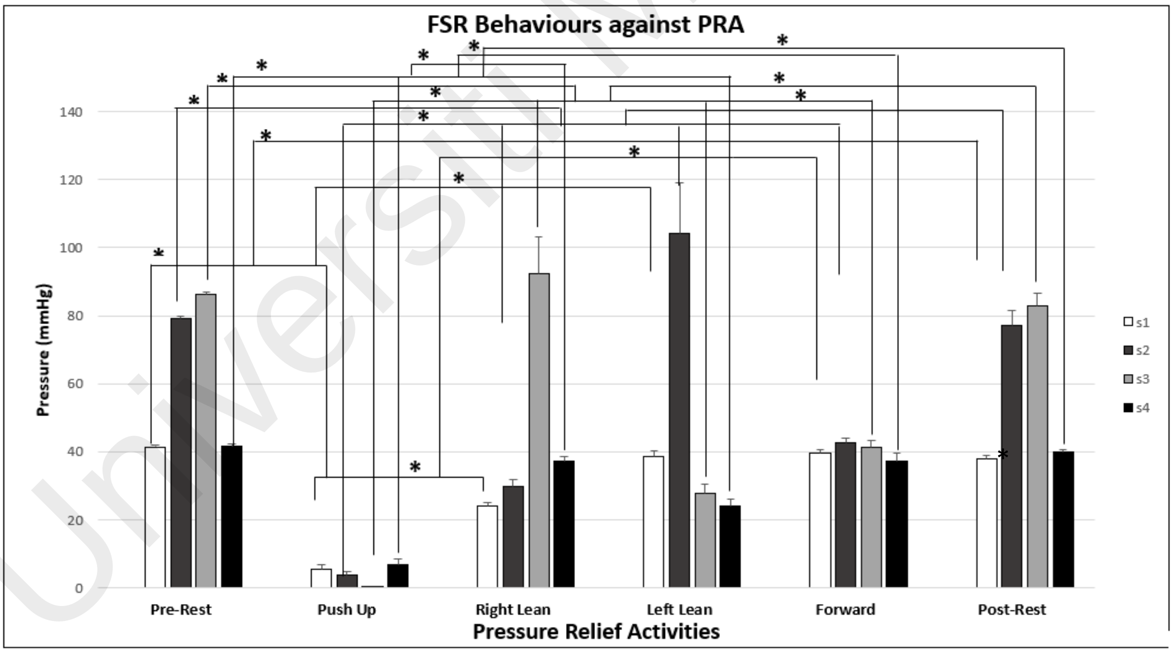


Figure 4.4: Graph showing post-hoc analysis based on Bonferroni between pressure amount with pressure relief activities

As for pre-rest and post-rest activity, post-hoc analysis shows no significant difference between all sensors in both activities. However, it can be seen in figure 4.4 that there is a slight decrement of pressure between the activities. Therefore, pressure reading can be achieved by regularly and maintaining pressure relief activities(Saliba et al., 2003).

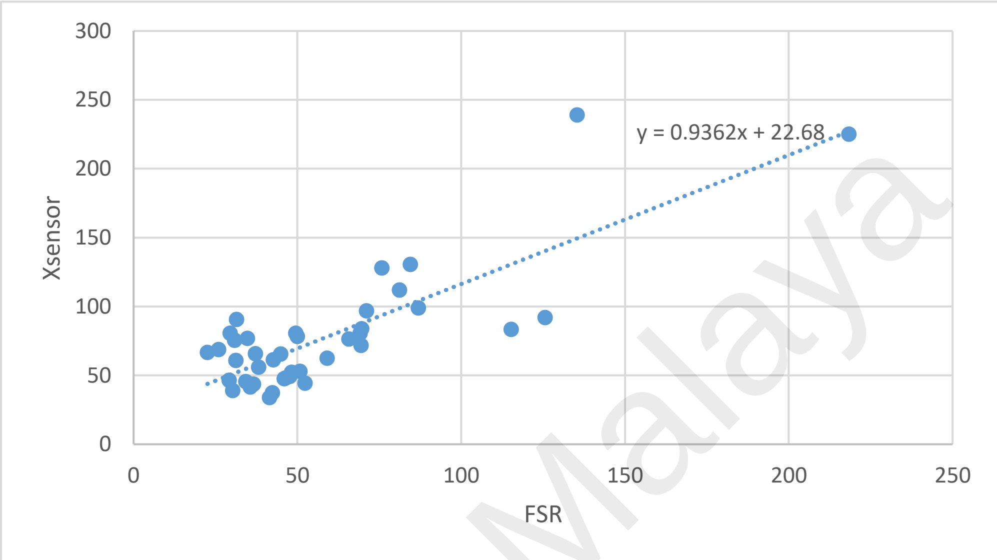


Figure 4.5: The correlation between Xsensor Pressure Mapping and WSETs system

In this study, the validity of WSETs responses toward paraplegic SCI individual seating routine were a very important part to be investigated. A WSET system was designed for paraplegic individuals as a training assistive tool that reminds them to perform pressure relief activity (PRA). Therefore, WSETs measurements were validated using Xsensor pressure mapping system commonly used by medical practitioners to monitor the pressure among patients. The WSETs sensors readings strongly correlated with Xsensor pressure map readings (r = 0.9362, Figure 4.5), confirming its reliability as a pressure measurement system. The R-squared value can be between 0 to 1 and the percentage of R-squared close to 1 indicates a better fit for a model(Henseler et al., 2009). This means that the WSETs system can monitor the interface pressure with only 4 point of sensors, without needing the pressure mapping of the whole buttock area as the Xsensor system.

4.5 Conclusion

In conclusion, this chapter begins with the result of the development and designation upgraded WSET system where all the functionality of systems was being tested. Then, the optimal region of FSR placement is also being experimental. Based on the result, orientation B is considered as final configuration of WSET. In determining the WSET system's validity, the result shows that the WSET system had a positive correlation to Xsensor mapping pressure, which means the WSET system is suitable to be practiced by SCI individuals. In the effectiveness of WSET during all PRAs, the pressure reading was compared and showed significant differences between the sensor in most of PRAs.

CHAPTER 5: CONCLUSION

5.1 Summary

In conclusion, an upgraded WSETs system was developed to provide an automated training system for pressure relief activity. In the long run, it is hoped that this development could improve the lifestyle of paraplegics who spend most of their time sitting on wheelchairs without any pressure relief activities. The WSETs system device is designed with 4 FSR sensors that represent the exerted region during sitting position on both sides of the buttocks and thigh. The paraplegics and their therapists can access all the pressure changes through the Android application connected to the WSETs system through Bluetooth connection. Additionally, the user would be reminded through an alarm system in case of a prolonged seating position detected through the android application.

5.2 Limitation

As the WSET system uses FSR sensors, the region's limitations can be monitored through the FSR sensor due to the small sensing element size. Besides that, the capabilities of the android application in detecting the movement where the alarm only mutes the sound after detecting zero reading on certain FSR sensor accordingly to the technique used which quite possible for some subject that had difficulties in performing the PRA well. Then, the alarm will continuously beep even the subject has already done the PRA.

5.3 Future Work

In the future, the use of FSR sensors can be changed to another sensor element with a more wide range of sensing elements than FSR. Another suggestion is to use the current applicable pressure sensor such as Xsensor mapping pressure and added to the android application, which may ease the user to access and monitor the pressure plus always alert of PRA.

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