WORK-RELATED MUSCULOSKELETAL RISKS AND ELECTROMYOGRAPHIC ANALYSIS OF THE UPPER BODY MUSCLES DURING OIL PALM PRUNING ACTIVITIES

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UNIVERSITI SAINS MALAYSIA

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by

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidate for any degree.

Signed………………………………………… (Nadiah Aqilahwati Binti Abdullah)

Date……………………………………………………………………... (12/7/2021)

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This thesis is the result of my own investigations, except where otherwise stated.

Other sources are acknowledged by giving explicit references.

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LIST OF ABBREVIATIONS

3D	3-Dimensional
EMG	Electromyography
FFB	Fresh Fruit Bunch
FFT	Fast Fourier Transform
GRF	Ground Reaction Force
IMU	Inertial Measurement Units
MDF	Median Frequency
MNF	Mean Frequency
MSDs	Musculoskeletal Disorders
MVC	Maximum Voluntary Contraction
MTw	Motion Tracker
NMQ	Nordic Musculoskeletal Questionnaire
OWAS	Ovako Working Posture Assessment
REBA	Rapid Entire Body Assessment
RMS	Root Mean Square
RMSE	Root Mean Square Error
ROM	Range of Motion
RULA	Rapid Upper Limb Assessment
sEMG	Surface Electromyography
SENIAM	Surface Electromyography for the Non-Invasive Assessment of Muscle
STFT	Short Time Fourier Transform
WHO	World Health Organization
WMSDs	Work-Related Musculoskeletal Disorders

LIST OF APPENDICES

GANGGUAN MUSKULOSKELETAL BERKAITAN DENGAN PEKERJAAN DAN ANALISIS ELEKTROMIOGRAFI PADA OTOT BAHAGIAN ATAS BADAN DALAM AKTIVITI PEMANGKASAN PELEPAH KELAPA SAWIT

ABSTRAK

Risiko gangguan muskuloskeletal yang berkaitan dengan pekerjaan (WMSDs) sering berlaku dalam kalangan pekerja kelapa sawit. Namun, teknik pemerhatian digunakan dalam penyiasatan risiko dimana ianya bergantung pada tafsiran penyelidik. Kajian ini menyelidiki kelaziman WMSD yang berkaitan dengan pelbagai faktor, pola pengaktifan otot, dan kelesuan otot semasa melakukan pemangkasan menggunakan kaedah pengukuran langsung. Dua subjek dengan tahap pengalaman yang berbeza dalam pemangkasan sawit direkrut untuk melakukan tugas pemangkasan menggunakan pahat dan sabit. Unit Pengukuran Inersia (IMU) daripada Xsens digunakan dalam analisis gerakan subjek. Penilaian Keseluruhan Badan Pantas (REBA) yang automatik berdasarkan data kinematik dari IMU digunakan untuk mengenal pasti postur yang berisiko yang tinggi secara komprehensif. Pengaktifan otot bahagian atas badan dianalisis menggunakan sensor elektromiografi (EMG) daripada iMotions. Elektrod EMG dalam susunan bipolar dipasang pada tujuh otot badan bahagian atas (trapezius atas, trapezius tengah, bisep brachii kiri dan kanan, deltoid tengah kiri dan kanan, dan ereksi spinae longissimus). Tanggapan mengenai kesakitan diperoleh melalui Soal Selidik Muskuloskeletal Nordic (NMQ) yang diubahsuai. Dari kajian ini, postur kerja yang bahaya dan pergerakan yang sangat berulang dikenal pasti sebagai faktor risiko kepada WMSD. Analisis REBA menunjukkan purata skor risiko yang sederhana hingga tinggi. Semua skor tertinggi dalam aktiviti pemangkasan berada dalam kategori risiko tinggi hingga sangat tinggi. Semua otot digunakan secara aktif semasa melakukan tugas dengan penggunaan otot yang tinggi adalah pada trapezius atas, trapezius tengah, dan bisep brachii. Manifestasi kelesuan pada otot adalah jelas dimana subjek yang tidak berpengalaman mempunyai kadar kelesuan yang lebih tinggi daripada subjek yang berpengalaman. Subjek mengalami kesakitan di semua bahagian badan yang disiasat. Penambahbaikan dalam persekitaran kerja diperlukan untuk mengurangi risiko WMSD dan kelesuan dikalangan pemotong sawit. Kajian lebih lanjut dengan lebih banyak bilangan pekerja di ladang kelapa sawit adalah disarankan untuk ukuran kesan yang lebih baik dalam menggambarkan pendedahan kepada WMSD, penggunaan otot, dan manifestasi kelesuan otot.

WORK-RELATED MUSCULOSKELETAL RISKS AND ELECTROMYOGRAPHIC ANALYSIS OF THE UPPER BODY MUSCLES DURING OIL PALM PRUNING ACTIVITIES

ABSTRACT

Work-related musculoskeletal disorders (WMSDs) risks are prevalent among oil palm workers. However, investigating the risks mainly relies on observational techniques that depend on the researcher's interpretation. This study investigated the prevalence of WMSDs associated with various factors, muscle activation patterns, and muscle fatigue induced during the pruning tasks using reliable direct measurement methods. Two subjects with different levels of experience in palm pruning were recruited to perform pruning tasks using chisel and sickles. Xsens wearable inertial measurement units (IMU) were utilised in the motion analysis of the subjects. An automated Rapid Entire Body Assessment (REBA) based on the kinematic data acquired from wearable IMU was employed to identify postures exposed to a high-risk level comprehensively. Activation of the upper body muscles was analysed using iMotions wearable surface electromyography (EMG) sensor. Bipolar surface EMG electrodes were attached to seven upper body muscles (upper trapezius, middle trapezius, left and right biceps brachii, left and right middle deltoid, and erector spinae longissimus). A subjective perception regarding pain was obtained using a modified Nordic Musculoskeletal Questionnaire. From this study, extreme working postures in various articulations and highly repetitive movements were identified as the risk factors of WMSDs. REBA analysis showed medium to high-risk mean scores with all peak scores within the tasks fell in the high to very-high risk category. All muscles measured were activated together during the tasks with the greatest demand during the pruning using both cutting tools were on the upper trapezius, middle trapezius, and biceps brachii. Manifestation of fatigue on muscles was evidence in all pruning tasks, with the inexperienced subject had a higher rate of fatigue than the experienced subject. Regarding the subjective perception of pain, both subjects experienced pain in all selected body parts. Improvement in the working environments is required to reduce the risk of WMSDs and fatigue among the palm cutters. Further investigation with more sample sizes in an actual palm plantation is suggested for better effect size in portraying exposure to WMSDs, utilisation of muscles, and the manifestation of fatigue in muscles.

CHAPTER 1
INTRODUCTION

1.1 Brief Overview

Malaysia and Indonesia are the top producers for producing more than 80% of the global crude-palm-oil (CPO) production [1]. As the second-largest palm oil producer globally, Malaysia's palm oil industry contributed 4.5% to the Malaysia Gross Domestic Product (GDP) and RM 67.5 billion of export earnings to the country in 2018 [2]. An increase in production required an increase in the input, especially in the number of workers on the plantation. In 2010, there were 413 137 field workers, with 192 973 (46.71%) hired as fruit harvesters and collectors [3]. A total of 417 247 labourers worked in the oil palm plantation sector as field workers in 2014, where 174 472 (41.82%) were hired as fruit harvesters and collectors [4]. Both data were gathered through census technique, and the data showed a trend of increment in the number of palm plantation workers. However, a slight reduction can be seen in the number of workers hired as harvesters and collectors, which might be due to the country's dependency on foreign workers where most locals refused to work on estates as harvesters [4].

The significant number of workers involved in oil palm plantations revealed the high reliability in human involvement and manual handling. For harvesting tasks which are cutting the palm fronds and the fresh fruit bunches (FFB), manual cutting tools are widely used among the palm workers. In some cases, there is an automated cutting tool, but the utilisation is minimal among palm workers, considering the high machine and maintenance price [5]. For sustainable practice in cutting the FFB, the harvester must first eliminate the fronds around it that restrict the cutting tool's reach to the FFB [6]. From this, harvesting of FFB required the harvester to cut both the FFB and the palm frond. The act of cutting out the fronds is also known as palm pruning [7].

For the early harvesting season, in which the height of the palm tree is less than three meters, the most acceptable practice is to use a chisel mounted to a wooden or iron pipe handle. Chisel is related to the push-cutting technique in which a push force is applied to cut the palm frond and fruit bunches. Meanwhile, a sickle mounted to bamboo or an Aluminium pole is widely used to harvest the oil palm fruit bunch from a tree of more than three meters in height [8]. In common practice, the pole can be adjusted according to the tree's height, and a pull-cutting technique where a sudden pull force is applied to cut the fronds and FFB needs to be implemented. Figure 1.1 shows the cutting tools and their usage according to the tree's height.

Figure 1.1 (a) Chisel, (b) Sickle, (c) Palm tree < 3 meters, (d) Palm tree > 3 meters

Manual and labour-intensive cutting tasks required the workers to employ the strength of their body in applying push or pull force to cut the frond and FFB. High physical exertion is needed to handle the cutting tool, considering the tool's weight and the cutting force required [9]. In addition, the harvesters are exposed to extreme working postures and repetitiveness in cutting action while harvesting the FFB and manoeuvring the cutting tool [10]. Extreme working postures and repetitive movement lead to musculoskeletal disorders (MSDs) among the harvesters [11, 12]. MSDs are a condition affecting the tendons, nerves, muscles, and supporting structures of the body, which generally occurs when one or more related body tissues worked harder than they are designed to [13]. Work-related musculoskeletal disorders (WMSDs) are conditions in which the work environment and execution of work have a significant role in MSDs. World Health Organization (WHO) has reported that from 2006 to 2017, almost 1.71 billion people globally have musculoskeletal conditions that cause early retirement from the workforce [14].

A number of studies highlighted the prevalence of WMSDs among palm harvesters. A previous study, through video recording and face-to-face interviews with 52 FFB cutters, reported that the prevalence of WMSDs in any nine body parts during the past 12 months of FFB cutters was 96.2%, mainly at the lower back (71.2%), neck (63.5%), and shoulder (59.6%). In addition, the top three 7-day prevalence of WMSDs were in the lower back (32.0%), shoulder (20.0%), and elbow (12.8%) [15]. The assessment of the body parts was based on the modified Nordic Musculoskeletal Questionnaire (NMQ). From this study, the palm harvesters' pain was mainly focused on the upper extremities.

Most of the studies in determining the risk of WMSDs among palm workers used an indirect measurement and qualitative approach to identify the pain distribution [8, 10, 11, 16-19]. The indirect measurement method to evaluate the risk of WMSDs usually performed using ergonomic assessment tools based on video recording and interviews. Ergonomic assessment tools such as Rapid Upper Limb Assessment (RULA), Rapid Entire Body Assessment (REBA), and Ovako Working Posture Analysis System (OWAS) are broadly used among researchers in palm harvesting [10, 12, 20]. The tools are low-cost observational approaches capable of evaluating physical effort based on posture, force, and static or repeated load, which results in the risk level associated with the observed condition[21]. However, qualitative is only limited to the descriptive and individual perception regarding pain [22], while indirect measurement relies on the researcher's interpretation of the video and photograph. Therefore, quantitative and reliable direct measurements such as wearable sensors should be included in the investigation for a better accuracy assessment as they are able to produce real-time measurement and reduce the variability resulted from individual's perception.

As far as the author knew, no study used direct measurements in determining the prevalence of WMSDs among the palm harvesters. As WMSDs are closely related to working in extreme postures, the postural angles of the harvester can be measured using inertial motion capture technology, allowing a three-dimensional real-time measurement to be done. Furthermore, as the pain on the muscle is as well related to WMSDs, it can be detected by quantifying the muscle activity of the palm harvester using a surface Electromyography (sEMG) system and evaluate the fatigue indicator through the downward shift of the frequency spectrum of the EMG signals being measured [23, 24].

1.2 Problem Statement

Malaysia is one of the largest producers of palm oil in the world. Nevertheless, this achievement is still overshadowed by the harvesting method, which is primarily conventional and labour-intensive. Many studies have shown that palm workers are exposed to awkward postures during cutting tasks [10, 16-18, 25, 26]. Repetitive movement along with awkward posture increases the tendency to experience muscle fatigue and WMSDs [27]. However, no study has been done in assessing the risk of WMSDs among palm workers through direct measurement methods. In this study, the muscle activation patterns and the postural angles of the subjects while performing the pruning tasks are quantified and evaluated by employing equipment for direct measurement of biomechanical load, which are iMotions surface Electromyography and Inertial Motion Units from Xsens Awinda. The findings from this study can be beneficial to provide reference material for ergonomic interventions to reduce the risk of WMSDs in palm harvesting and pruning.

1.3 Research Objectives

The main objectives of this study were to:

1. Quantify the joint range of motion of the harvester during the pruning tasks for different cutting heights and cutting tools to evaluate the ergonomic risk and the prevalence of work-related musculoskeletal disorders.
2. Quantify muscle activation patterns from the neck, shoulder, upper and lower back during the harvesting tasks using different cutting tools to evaluate the manifestation of fatigue and their association with the muscle pain experienced by the harvester.

1.4 Scope of Research

In this project, two healthy subjects were selected to perform the actual palm pruning practices [6]. The iMotions sEMG electrodes in bipolar configurations were placed on the subject's muscles to measure their activation patterns in determining the intensity of muscle activity during the study. The investigated muscles during the pruning tasks are biceps brachii, middle trapezius, upper trapezius, erector spinae, and middle deltoid for push-cutting technique and pull-cutting technique. The selection of muscles under investigation was based on a thorough review of previous studies related to WMSDs in palm pruning and harvesting. The selection followed the reported prevalence of musculoskeletal disorders[12, 17, 20, 28, 29].

A conventional chisel was used for pruning the fronds located at three different heights, following the real conditions in pruning the short palm tree that is less than three meters. For the pull-cutting technique, a conventional sickle and an intervention sickle were used for pruning height of more than three meters. From the electromyography measurements, the muscle activation pattern and trends of muscle fatigue are identified. In addition, the postural angles of the harvester while pruning the palm tree were measured using Xsens inertial motion capture. From the postural angles, the risk factors associated with musculoskeletal disorders are presented using the ergonomic assessment tool. The pain areas associated with muscle activation and the trends of muscle fatigue for every muscle will then be discussed. These data can bring additional insight into the physical exertion required by the palm harvester and contribute to the identification of risky activities for WMSDs in the industry.

1.5 The Organisation of the Thesis

The thesis comprises five chapters: introduction, literature review, methodology, results and discussions, and conclusion with future works recommendation. Chapter 1 starts with a brief description of palm harvesting, the WMSDs in palm harvesting, and the limitations of the current methods in determining them. The objectives and the scopes of this research are then highlighted. This chapter ends with the significance of the study.

Chapter 2 discusses ideas, facts, and the information related to this study. This chapter consists of nine subsections: human musculoskeletal system, mechanism of muscle contractions, measurement of human motion, risks of WMSDs in palm harvesting, ergonomic assessment tools, principles of the surface electromyography, maximum voluntary contraction, muscle fatigue, and the detection of muscle fatigue in dynamic contraction. In each subsection, the facts and findings from previous studies are discussed.

Chapter 3 explains in detail the methodology applied in this study. In the first subsection, the inclusion criteria of the subject and the approaches to selecting the investigated muscles are highlighted. Within the field setup, the arrangement of equipment and the preparation of cutting tools is explained. Brief explanations regarding the features of Xsens motion capture and iMotions sEMG, including the placement, setup, and calibration, are presented in the third subsection. In data collection, the maximum voluntary contraction (MVC) protocol for EMG, the study protocol including the precautions taken, harvester's subjective perception of pain, and the REBA scores are clarified. In the fifth subsection, the approaches in analysing the data from all trials to meet the study's objectives and the signal processing for all sensors are discussed. Finally, the statistical analysis consists of descriptive and inferential analysis are described.

Chapter 4 presents and discusses the results related to the study's objectives. The joint angles and ergonomic risk score are reported at the beginning of this chapter. The chapter continues with the analysis of the muscle activation patterns and muscle fatigue for all subjects. This chapter ends with a discussion on the effect of pruning activities on the risk of WMSDs, including muscle effort and the trend of muscle fatigue in all pruning activities. Chapter 5 presents the conclusion of the findings. The chapter ends with some suggestions and strategies for future research to improve the quality of the proposed technique.

CHAPTER 2
LITERATURE REVIEW

This chapter reviews the existing literature that mainly discusses the overview and fundamental concepts related to the study. It begins with discussing the prevalence of musculoskeletal disorders (MSDs) and work-related musculoskeletal disorders (WMSDs) in various industries. The discussion narrowed to the risk factors of WMSDs in palm harvesting and pruning. The review continues to technologies developed to measure human motion and the utilisation of ergonomic assessment tools in identifying the prevalence of WMSDs. Furthermore, the overview of surface electromyography, maximum voluntary contraction, and muscle fatigue are presented. The suitable analysis for detection of muscle fatigue for dynamic contraction is as well discussed. The chapter ends with a summary of the reviewed literature.

2.1 Musculoskeletal Disorders and Work-Related Musculoskeletal Disorders

Musculoskeletal Disorders or MSDs are injuries and disorders that affect the body movement or musculoskeletal systems such as muscles, tendons, ligaments, and spinal discs. On the other hand, Work-Related Musculoskeletal Disorders (WMSDs) occur due to work conditions where there is an imbalance between the human body's physical capabilities and the task's physical demands [30]. The causes of WMSDs are diverse, involving the biomechanical factors and psychosocial factors in the workplace [31]. Aptel et al. [32] and Das et al. [33] stated that extreme joint postures, strenuous physical efforts, repetitive motions, and vibration are the key risk factors of the biomechanical WMSDs. Strenuous efforts and inappropriate body postures may cause pain and stress to the joint and muscle, especially when it comes to manual handling of tools and improper lifting of load. Improper manual lifting with extreme forward flexion brings pain to the erector spinae muscle and the lumbar joint [34]. Repeated actions in extensive periods could result in muscle and tendon tension and fatigue. In agricultural settings, repeated movements and extreme postures are typical. For instance, a study related to tomatoes harvesting revealed that the lower back, hand, and wrist are the most exposed body regions to experiencing WMSDs due to forceful, repetitive cutting, and prolonged stooping conditions [35].

Work requiring repeated motion increases the muscles' stress and pain due to the quick shortening and lengthening of the muscle fibre where the muscle experienced insufficient recovery time [30]. Repetitive movements are also known to cause a muscle to experience fatigue [36]. Psychosocial factors such as stress and high mental loads due to job demands may affect the individual performance at work and increase the tension in the body system [32]. MSDs such as tendonitis, carpal tunnel syndrome (CTS), tension neck syndrome and back pain are closely related to repetitive movements, sustained extreme postures, and prolonged forceful exertion to the musculoskeletal systems [30, 37]. A report made by the European Agency for Safety and Health at Work stated there were various sectors that reported a high prevalence of MSDs. Some of them are skilled traded occupations, agriculture, construction, human health, and social work activities [31]. A study on the Global Burden of Disease in 2019 revealed that out of 1.7 billion reported MSDs globally with low back pain contributed the most to the burden of MSDs, followed by fracture, osteoarthritis, other injuries, neck pain, and rheumatoid arthritis [38]. MSDs cause an early retirement from the workforce, work absenteeism, and loss of productivity, where prevention steps need to be implemented to reduce the prevalence of MSDs in the workplace [14].

2.2 Risks of Musculoskeletal Disorders in Palm Harvesting

Work conditions such as performing repetitive forceful tasks, working in an extreme range of motions, and lifting heavy objects can lead to MSDs [30]. In the agricultural environment, repetitive movements and awkward postures are typical among the workers[19, 39]. Different postures will lead to different workloads and risk factors depending on the postural angles. In palm harvesting, the harvester needs to manually handle the cutting tool, especially targeting the FFB and cutting down the fronds that restricted access to FFB. Different postural angles are required depending on the location of the FFB and the height of the palm tree. As palm harvesting demanded the ability to handle the cutting tools according to the height of palm tree, the most significant part of the body that needs to be controlled during the harvesting tasks is the harvester's upper extremities [28]. A push cutting technique by using a chisel is commonly used for the early harvesting stage. On the other hand, pull cutting techniques by using sickle mounted to a long pole is common among FFB harvesters to cut the FFB from a tree more than 3 meters. For fronds and FFBs located at more than three meters height, extreme postures in the upper extremities, which are neck, shoulder, trunk, and upper limbs, are the most observed trend in previous studies (Figure 2.1) [8, 10, 12, 16].

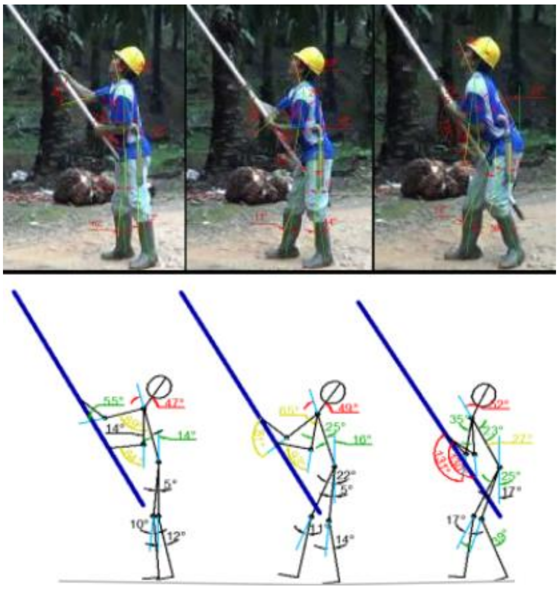

Figure 2.1. Body postures while cutting FFB located at a height more than 3 meters [10].

For the later harvesting stage, in which the palm tree high is more than 6 meters, FFB harvester needs to continuously tilt their head upward to aim and maintain the sickle's position [11]. Extreme neck postures while head up to locate the FFB is common among harvesters. The upper limbs experienced excessive flexion in manipulating the pole during the cutting task [8]. Flexion and extension of the shoulder usually exceed the normal range of motion, 90° and 31°, respectively. Trunk extension is observed to be more than 20°, exceeding the normal limit of the range of motion while handling the cutting tool to cut the FFB [10]. The trunk flexion's degree varies according to several factors: the harvester’s height, the height of the FFBs on the palm trees, and the work environment [11].

In terms of force exertion, excessive force and high grasping force are required to move the cutting tool from tree to tree and pull the pole repeatedly to cut the FFB [39]. Repetitive strikes are most of the time a must to cut a frond and FFB in which muscular use and load are significant[10, 23]. Targeting the FFB located at more than six meters requires the harvester’s arms to be above the shoulder (more than 50° shoulder flexion) while sustaining the load of the cutting tool (Figure 2.2). A three-meter-long sickle can weigh around 10 kg [23] and increases as the length of the pole increases. High force in handling the cutting tool and cutting the fronds and FFB can lead to muscle fatigue, especially when required to be done repetitively [24, 27].

Figure 2.2. Body posture while cutting a frond located more than 6 meters in height.

From previous studies, body postures, repetitive work, and forceful exertion are the main factors contributing to the high prevalence of WMSDs among FFB harvesters while applying push and pull force to cut the FFB. Rapid Upper Limb Assessment (RULA) analysis on 7 FFB harvesters shows that 83% of the FFB harvesters have scored seven (very high risk) during harvesting work while 17% of FFB harvesters have scored 5 (medium risk) [18]. Besides, a study that used the Nordic Musculoskeletal Questionnaire to determine the prevalence of WMSDs during the early harvesting stage shown that 86% of the 446 respondents complained of experiencing pain, discomforts, or disorders at any of the nine anatomical body parts [12]. The highest number of complaints reported were lower back disorders (58%), followed by the knee (40%), shoulder (28%), and neck (26%). Most studies revealed that the upper part of the body is the most exposed part to WMSDs among the palm harvester for both early and later harvesting stages [11, 12, 16, 19, 26, 39].

2.3 Measurement of Human Motion

The evaluation of human movement is essential in investigating physical activity and its effects on the body. It provides insight into the role of physical activity in the prevalence of musculoskeletal disorders and designing the prevention and management to avoid it. In ergonomic, measurement of human movements is mainly done to quantify the joint angles involved while performing a specific task [10, 24, 40, 41].

Kinematics measurement of human motion is widely used to measure the normal and pathological movements, assess the effect of various interventions, and assess the ergonomics and the risk of musculoskeletal disorders in conducting certain tasks [42]. There are a variety of methods being applied in the analysis of human movement. At present, the most common methods for accurate capture of three-dimensional (3D) human movement require a laboratory environment and the attachment of markers or sensors to the body's segments [43]. In addition, video-based measurement is also used for quantifying the human joint angle, usually in a two-dimensional (2D) configuration [10, 44]. Common laboratory systems are electromagnetic systems and video-based optoelectronic systems. These systems are expensive and complex where it required the study to be conducted in a laboratory setup.

On the other hand, a manual video-based technique quantifies joint angle by referring to a photo, constructing the line of reference for each joint and measure them using simple mathematical equipment such as the ruler, protractor, and compass [10]. These techniques are a cheap but time-consuming process where every interest posture required the researchers to measure the joint angles repeatedly. Softwares equipped with an image processing algorithm are suitable for measuring body angles through a video recording approach. However, it is only applicable and accurate for motion in the sagittal plane [44, 45]. Kinovea is one of the open-access video analysis software that available for analysing 2D human motion angles based on video recording[46].

Another approach in quantifying the variety of data from human movement is attaching the inertial motion unit (IMU) to the body’s segments. It is one of the direct methods in quantitative biomechanical measurement. The direct method provides detailed and accurate values for jobs with varied work tasks. IMU uses an accelerometer, a gyroscope, and a magnetometer to provide calibrated measurements on the motion of the object to monitor the specific 3D acceleration, angular rate, and magnetic field of a moving object [47]. The accuracy of the IMU system is sufficiently high to assist in the identification and management of the risk of WMSDs [48].

Xsens Awinda (Figure 2.3) is a well-established and accurate wearable IMU system developed for full-body human motion measurement. A study was conducted by comparing the joint angles obtained from Xsens and optoelectronic system for whole-body motion analysis where the results show the root mean square error (RMSE) of 2.8° for a long complex task (32 minutes manual material handling) and 1.2° for short simple functional (flexion/extension) movement task [49]. The findings showed that Xsens has a good accuracy to produce a reliable result in assisting the kinematic measurement of human motion in an actual working condition.

Figure 2.3. Xsens MVN motion tracker system for 3D real-time human motion measurement [50].

In performing a biomechanical evaluation to investigate the risk of certain activities, the protocol usually combined IMU system with surface Electromyography (sEMG) technology. For instance, studies related to manual material handling [40, 41], banana harvesting [24], and manufacturing assembly activity [51] utilised the combination of IMU and sEMG in identifying the biomechanical load of each study. The combination of these wearable sensors allowed for comprehensive biomechanical measurements in the matter of human kinematic and muscle activation patterns while performing certain tasks. In fact, muscles are the essential component in providing human with the ability to voluntarily performed any desired movements.

2.4 Ergonomic Assessment Tools

Bringing the ergonomic assessment in assessing a physical activity helps identify the ergonomic risks such as repetitive tasks, improper work area setup, postural loading, the effect of vibration, coupling, awkward postures, frequency of movements and its duration, and its duration use of tools [52]. Ergonomic risks can lead to WMSDs, common among field workers [18, 28, 35, 53]. Some assessments were developed for specific industrial scope, while others are generalised tools that can be used in any field of study. Some of the generalised tools are Rapid Entire Body Assessment (REBA) [54], Rapid Upper Limb Assessment (RULA) [55], and Ovako Working Posture Analysis System (OWAS) [56]. These tools are widely used in the form of assessment sheets.

RULA provides an assessment of the musculoskeletal system's burden due to the postures of the neck, trunk, upper limbs, muscle function, and external loads exerted. It has four action levels indicating the severity of the action to be taken. The OWAS classifies work postures into seven for the lower limbs, four for the back, and three for the arms, and three weight classifications for the loads sustained. The final score includes the combinations of these four categories based on their influence on the musculoskeletal system.

REBA included the upper arms, lower arms, wrist, trunk, neck, knees, and legs. The method reflected the extent of the external load or forces exerted, muscle activity caused by static, dynamic, rapidly changing, and unstable postures. The coupling effect, which is an essential variable in handling loads, is counted in REBA. RULA and REBA share almost similar postures analyses. However, REBA has more coverage of the postural angle for each body category. REBA has five actions categories based on the severity of the final score. Table 2.1 summarises the comparison between the three ergonomic assessment tools based on the covered risk factors.

Table 2.1: Comparison between the risk factors covered by RULA, REBA, and OWAS

Ergonomic Assessment Tool	**Risk Factor**			
	Posture	**Forceful Exertion**	**Repetition**	**Coupling**
RULA	X	X	X	
OWAS	X	X		
REBA	X	X	X	X

Despite using the ergonomics assessment tool alone, several studies included Nordic Musculoskeletal Questionnaire (NMQ) to determine the prevalence of WMSDs in the workplace. In palm harvesting, some researchers utilised the NMQ alone and NMQ combined with the REBA and OWAS [12, 26, 28, 29]. Table 2.2 summarises some of the previous studies utilising ergonomic tools. NMQ is a general questionnaire that allows the evaluation of pain symptoms in nine parts of the body (neck, shoulders, elbows, wrists/hands, upper back, lower back, hip/thighs, knees, and ankles/feet) based on the subject’s perception on the pain that they experienced. However, the obvious limitations of the mentioned ergonomic assessments are their manual approach, and some even missed the important elements in evaluating the risk factors of WMSDs for palm harvesting. For instance, posture duration and repetitive works are unavailable in OWAS [39], whereas RULA excludes the coupling element that is important for tasks that involved the handling of tools. If the job involved dynamic movements and researcher is interested in the overall postures risk, the manual assessment needs to be performed all over again.

Table 2.2: Summary of ergonomic assessment approaches taken in previous studies.

Research	Measurement Tools	Results
Syazwani et al. (2016) [25]	Modified NMQ and Rapid Entire Body Assessment (REBA)	The 12-month prevalence of MSD was reported as shoulder 60%, upper back 52%, neck 48%, and lower back 44%.
Hani et al. (2016) [26]	Nordic Musculoskeletal Questionnaire (NMQ), Interview, Video Recordings, Direct observation	Most reported pain area among palm harvesters was neck, upper back, and lower back.
Syuaib (2015) [10]	Questionnaire, Motion Analysis, RULA	Waist (28.52%), Shoulder (27.82%), Lower Limbs (14.44%), Upper Limbs (14.08), Back (10.21%), Neck (4.93%).

Mokhtar et al. (2013) [18]	Face-to-face structured interviews, Video Recording, Rapid Upper Limb Assessment (RULA), Questionnaire for Demographic	83% (5 out of 6) of the FFB harvesters have scored 7 during harvesting work & 17% (1 out of 6) FFB harvesters have scored 5 for wrist & arm, neck, trunk & leg.
Henry et al. (2015) [28]	Standard Nordic Musculoskeletal Questionnaire (SNMQ), Quick Exposure Check (QEC)	The prevalence of work-related musculoskeletal disorders (WMSDs) among palm oil workers was 58.3%. Back pain was the most prevalent WRMD (63.5%), but the neck was the most exposed to risk based on QEC.
Ng et al. (2015) [12]	NMQ, Ovako Working Posture Assessment (OWAS)	Self-reported prevalence of MSD: 86%, the prevalence of acute (7 days) MSD: 45%. Most complained about areas were lower back, followed by knee, shoulder, and neck.

2.4.1 Automated Ergonomic Assessment Tools

In investigating the prevalence of WMSDs, self-reported questionnaires (NMQ) and ergonomic assessment tools (RULA, REBA, OWAS) are widely used among researchers [28, 57, 58]. However, the self-reported questionnaire is based on the subject's or investigator's perception of pain symptoms. The repeatability might be poor, as the results may vary between different person's understanding. On the other hand, ergonomic assessment tools are based on the observational method in identifying the risk based on the tool's standard parameters (body postures, load applied and repetition/duration). The observational process requires an ergonomic expert to perform the assessment, where different interpretations are possible [59]. These methods are as well a time-consuming practice.

As the mentioned ergonomic assessments above require postural angles data, some researchers take advantage of the advancement of human motion measurement technology such as wearable motion capture based on IMU to develop automated ergonomic assessment tools. Automated tools can provide rapid and accurate results for better risk identification. For example, Vignais et al. linked the wearable IMU sensors to an upper-body biomechanical model, in which the output from the model was used to calculate a real-time RULA score[60]. The score was feedback simultaneously to the user. Figure 2.4 shows the concept of the system.

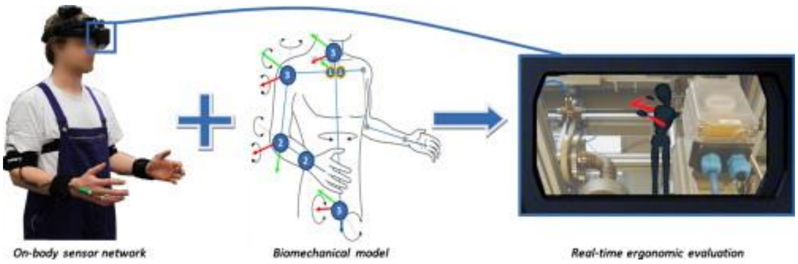

Figure 2.4. Conceptual design of the automated RULA assessment [60].

In addition, Huang et al. developed an automated RULA and REBA assessment based on the kinematics data obtained from Xsens MVN Link as the input [61]. The input was then integrated with the RULA and REBA's analysis. The results are presented in the form of segment's score, overall score, and plots on a simple and easy to use Graphical User Interface (GUI). The results from the automated system are validated through different levels of complexity experiment and compared with the ergonomic experts' results. The mean absolute difference was lower than 0.5 and 1.0 for RULA and REBA, respectively. The automated assessment allows for an effective and comprehensive evaluation where every posture could be investigated without having to manually choose only a certain posture.

2.5 Surface Electromyography

Electromyography (EMG) is an electrodiagnostic technique to measure the electrical activity produced by skeletal muscle during voluntary and involuntary contraction. In common, there are two types of EMG, which are invasive and non-invasive EMG. Invasive EMG involved inserting the needle electrode or a needle containing two fine-wire electrodes into the targeted muscle. The invasive technique is considered painful and requires the subject to be anesthetised. Due to this, surface electromyography (sEMG), a non-invasive, is preferable to be used primarily in quantifying the muscle activation in real-time dynamic movement [24, 41, 57]. There are numbers of sEMG available in the market, such as iMotions and Delsys.

sEMG is widely applied in monitoring and evaluating electrophysiological changes induced by sport, rehabilitation, ergonomic, agricultural, and harvesting. For instance, Park et al. utilise sEMG in conducting movement and activation analysis of the upper and lower limb muscles during five common gardening tasks [62]. They found a series of muscles that were significantly activated during each task which could help in designing a gardening-based rehabilitation exercise. Another study was from Skals et al. that assessed physical efforts required by supermarket workers by analysing the body angles and muscle activities for trapezius descendens and erector spinae longissimus [41]. The study comprehensively evaluated the risk factors in manual material handling, especially those involving awkward working postures and highly demanded muscle usage. Moreover, Merino et al. placed the sEMG on the extensor carpi radialis, upper trapezius, flexor carpi radialis and biceps brachii muscle of two workers to quantify their muscle activation and the trend of muscle fatigue in banana harvesting [24]. These studies showed the ability of wearable surface electromyography to be utilised for investigating the subject’s muscles activity in an actual working environment, including the harvesting field.

In terms of the sEMG electrode placement, an active electrode should be placed on the muscle belly area [63]. Figure 2.5 shows the anatomical guide for correct placement of active electrodes at the superficial muscle belly. In contrast, the ground electrode must be placed on the electrically quiet site, usually a bony landmark [64]. The preferred configuration sEMG electrode is bipolar, where two active electrodes and one ground electrodes are required to avoid unwanted electrical signals from being detected other than from the investigated muscle [65]. One well-known project describes the recommendations for electrodes placement procedures for sEMG, known as SENIAM or Surface Electromyography for the Non-Invasive Assessment of Muscles [66]. SENIAM covers 30 individual muscles from the shoulder, neck, trunk, lower back, hand, leg, and foot. A number of studies referred to SENIAM in placing the electrodes on their investigated muscles, such as the skin preparation, inter-electrode distance and orientation, and the location of the muscles [24, 41, 67].

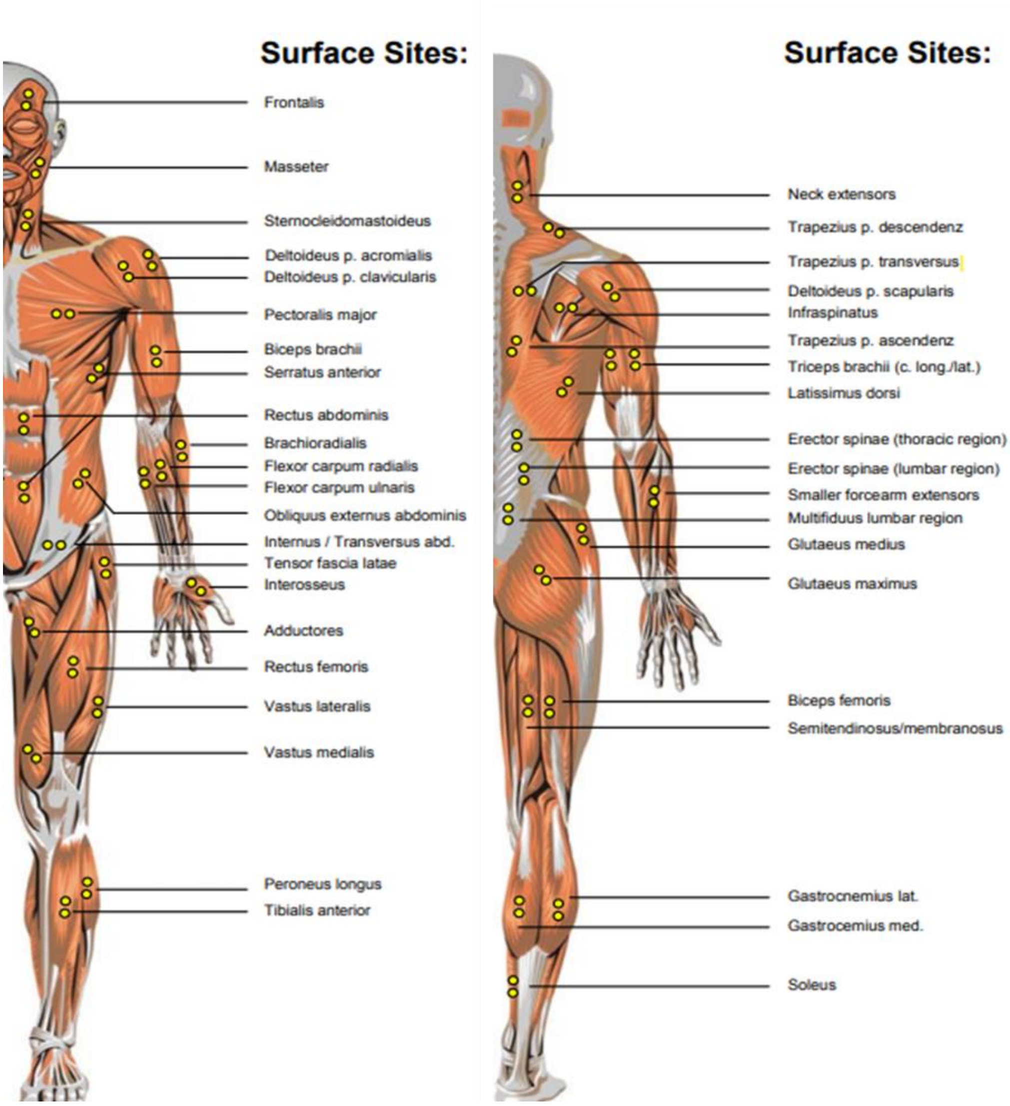

Figure 2.5. Frontal (left) and Dorsal (right) view of human anatomy with point for placing surface EMG electrode over the superficial muscles [68].

Signal obtained from sEMG needs to undergo filtering and, usually a high-pass and low-pass filter. The high-pass filter will remove motion artifacts and other low-frequency noise from the EMG signal, while the low-pass filter will remove unwanted high-frequency noise [65]. Most EMG data is high pass filtered at 10-15 Hz or higher, and low pass filter at 300 to 600 Hz, depending on the activity [69]. Several parameters used to describe the EMG are linear envelope, root mean square (RMS), mean frequency and median frequency. The linear envelope is a combination of rectification and low pass filtering, while RMS is the root mean square of the signal. Both are used to describe the intensity of the EMG signal [24, 36]. Mean and median frequency is typically beneficial for evaluating muscle fatigue [70].

2.6 Maximum Voluntary Contraction

The normalisation of EMG signals is usually performed by dividing the EMG signals during a task by a reference EMG value obtained from the same muscle**.** Normalisation needs to be done if the EMG activity is to be compared in the same muscle on different days or in different individuals or compare EMG activity between muscles [71]. There are various methods to normalise the EMG signal, but the Maximum Voluntary Contraction (MVC) is widely used to obtain the reference value for investigated muscle. Maximum voluntary contraction (MVC) is a standardised method for the measurement of muscle strength. A reference test or muscle test must be performed to obtain a maximum contraction in the muscle of interest. According to a review of MVC tests by Halaki et al., the findings indicate that using a single MVC test to identify maximum activity in a muscle is not valid and that sets of tests are required to ensure maximum activity for a given muscle is recorded from all subjects [72].

In addition, in a previous study where eight shoulder muscles were evaluated using 12 MVC tests, a minimum of 30 s of rest between each trial and three minutes of rest between each test was applied to avoid fatigue [73]. The study has shown that exercises must be performed to determine the highest value of the EMG signal. The value will then be used as MVC values, where all readings of the selected muscles will be referred to their respective MVC value and presented as %MVC. The muscle activation expressed in %MVC allows comparing the muscle activity between different muscles for similar cutting techniques and similar muscle in different cutting techniques. Table 2.3 shows several superficial muscles with respect to the MVC tests obtained from the previous research.

Table 2.3. List of MVC exercises for different muscles

Muscle	**MVC Protocol**
Upper Trapezius	• shoulder abducted to 90º with the neck side bent, rotated to the opposite side, and extended [72]
Middle Trapezius	• shoulder horizontally abducted and internally rotated [72]
Middle Deltoid	• shoulder abduction at 0º abduction [72]
Biceps Brachii	• shoulder flexion 0°, elbow flexion 90° in the supine position [74]
Erector Spinae (Longissimus)	• prone extension with the upper and lower extremities lifted (Superman exercise) [75]

2.7 Muscle Fatigue

The skeletal muscle that is subjected to voluntary control is used in the study of muscle fatigue. Skeletal muscle tissue is composed of muscle fibres, as the muscle fibres contract, an electrical current or the action potential (AP) is transferred down the nerve fibre. When a motor unit (MU) fires, the electrical impulse or the AP is carried down the motor neuron to the muscle. The result of this electrical activity is known as motor unit action potential (MUAP), where it can be measured by using electromyography (EMG) [68].

There are two types of focus in the localised muscle fatigue research, which are non-fatigued and fatigue. Fatigue refers to the onset of fatigue after a muscle contraction, while non-fatigue refers to the state of the muscle after the contraction that takes place before fatigue starts. Fatigue is a phenomenon linked to the duration of reduction of the maximum force-generating power or as a degradation of the maximum voluntary contraction (MVC) [76]. The larger the force a muscle exerts, the faster it fatigues and approaches the point of failure or the inability to maintain the required strength [27]. As the characteristics of a muscle varied between humans, there are no specific features in terms of load or timing in determining the occurrence of fatigue [77]. However, in muscle fatigue research, fatigue is usually related to the task or time, especially when evaluating fatigue based on the muscle's inability to reach or maintain a certain level of maximum voluntary contraction over time [76]. The physiological processes behind the decline in the capacity to generate force are unique to the task's specifications (the strength of contraction, group of muscles and angle of joint) [78].

The electrical activities of a muscle or also termed as myoelectric, are measured to evaluate muscle activity and the trend of muscle fatigue. By performing the electrical current measurement in the muscle, the myoelectric manifestations of fatigue can be detected. This measurement can be done by placing the non-invasive surface electromyography electrodes over the skin on the targeted muscle region. The changes in the signal's frequency can be further evaluated to observe muscle fatigue [70, 79]. In sports-related situations, fatigue can lead to injury. A muscle strain or injury occurs when a muscle is overstretched or torn, and it is most commonly caused by fatigue and overuse of the muscle.

Several studies accounted fatigue analysis to evaluate the manifestation of fatigue on muscles while performing the investigated task. For instance, in the harvesting field, Merino et al. suggested that a less experienced banana harvester tends to experience a higher rate of fatigue than years of experience harvester. They also found that repetitive movements lead to insufficient recovery time for the muscle as the harvester who cut more bunches has a higher fatigue rate.

2.8 Detection of Muscle Fatigue in Dynamic Contraction

Muscle fatigue occurs when the muscle ability is deteriorating over time. It can be detected through EMG analysis in several domains, which are time domain, frequency domain, and time-frequency domain. Harvesting activity required dynamic motion. Due to this, specifically for fatigue in dynamic contraction, the time-frequency domain is the most suitable for analysing the shift in the frequency spectrum of the signal [34, 80]. The time-frequency domain represents the time and frequency of the EMG signal, leading to higher accuracy than the time domain or frequency domain alone. Two frequently used features in the frequency domain are mean frequency (MNF) and median frequency (MDF) [24, 70, 81, 82]. Muscle fatigue can be detected by observing the decreasing trend in the signal's mean or median frequency. Time dependence of the MDF and the MNF can be computed using several methods such as Short Time Fourier Transform (STFT) and Spectrogram [34, 82].

STFT allows for simultaneous time and frequency estimation by providing the spectral information for a distinct time slice of the signal [34].

$$\boldsymbol{STFT_X(t,w) = \int_{-\infty}^{\infty} x\,(\tau)\, w\,(\tau - t) e^{-2\pi f \tau} d\tau} \qquad (2.1)$$

From equation (2.1), $x(\tau)$ is the EMG signal, $w\,(\tau - t)$ is the observation window, and t is the variable that slides the window over the signal, $x(\tau)$. The selection of the window function in STFT is crucial for obtaining correct results. The window should be narrow enough to ensure that the portion of the signal that falls within the window remains stationary. However, it should not be too narrow as it would result in poor frequency domain localisation.

On the other hand, the spectrogram is the squared magnitude of the STFT [34].

$$\boldsymbol{STFT_X(t,w) = \left[\int_{-\infty}^{\infty} x\,(\tau)\; w\,(\tau - t) e^{-2\pi f \tau}\right]^{2} d\tau} \qquad (2.2)$$

A spectrogram can be used to determine the power and energy distributions of a signal in a frequency direction at a particular time. The MNF and MDF can be calculated from the power distribution of the frequency obtained from either through STFT or Spectrogram.

2.9 Summary

Based on the review, it is known that WMSDs are common, involving a variety of industries. In palm harvesting, the prevalence of WMSDs is high for any cutting techniques and the height of trees. The risk factors related to WMSDs are dependent on the subject's anthropometry, the height of the tree, and the technique of cutting. Many assessments have been conducted to examine the risk factors associated with MSDs in the palm industry. However, the approaches are observational and should be further evaluated through reliable direct measurement technology. Wearable motion capture can produce real-time human kinematics data, while wearable surface EMG can be used to measure the muscle activation patterns of the investigated muscle. The investigated muscle should be based on the reported pain from the harvesters. Previous studies have shown that the neck, shoulder, lower back, and upper limbs are the most reported body parts to experience pain. The risk of WMSDs in palm harvesting can be thoroughly evaluated by utilising automated ergonomic assessment tools based on motion capture data, providing comprehensive ergonomic data without identifying high-risk postures manually. Furthermore, the manifestation of fatigue on the muscle can be identified through a series of analyses on the raw EMG data, allowing the relationship between the self-reported pain and the trend of fatigue on the muscle underlying the body regions to be investigated.

CHAPTER 3
METHODOLOGY

3.1 Introduction

The study combined quantitative and qualitative evaluation using direct and indirect measurement to fulfill the study's objectives. It starts with participants selection, cutting tools and field preparation, and continues with the setup of wearable motion capture and electromyography for biomechanical evaluation during palm pruning. The data collection involved MVC protocol, palm pruning protocol, and ergonomic assessment processes. Next, signal processing and data analysis and ended with statistical analysis (Figure 3.1).

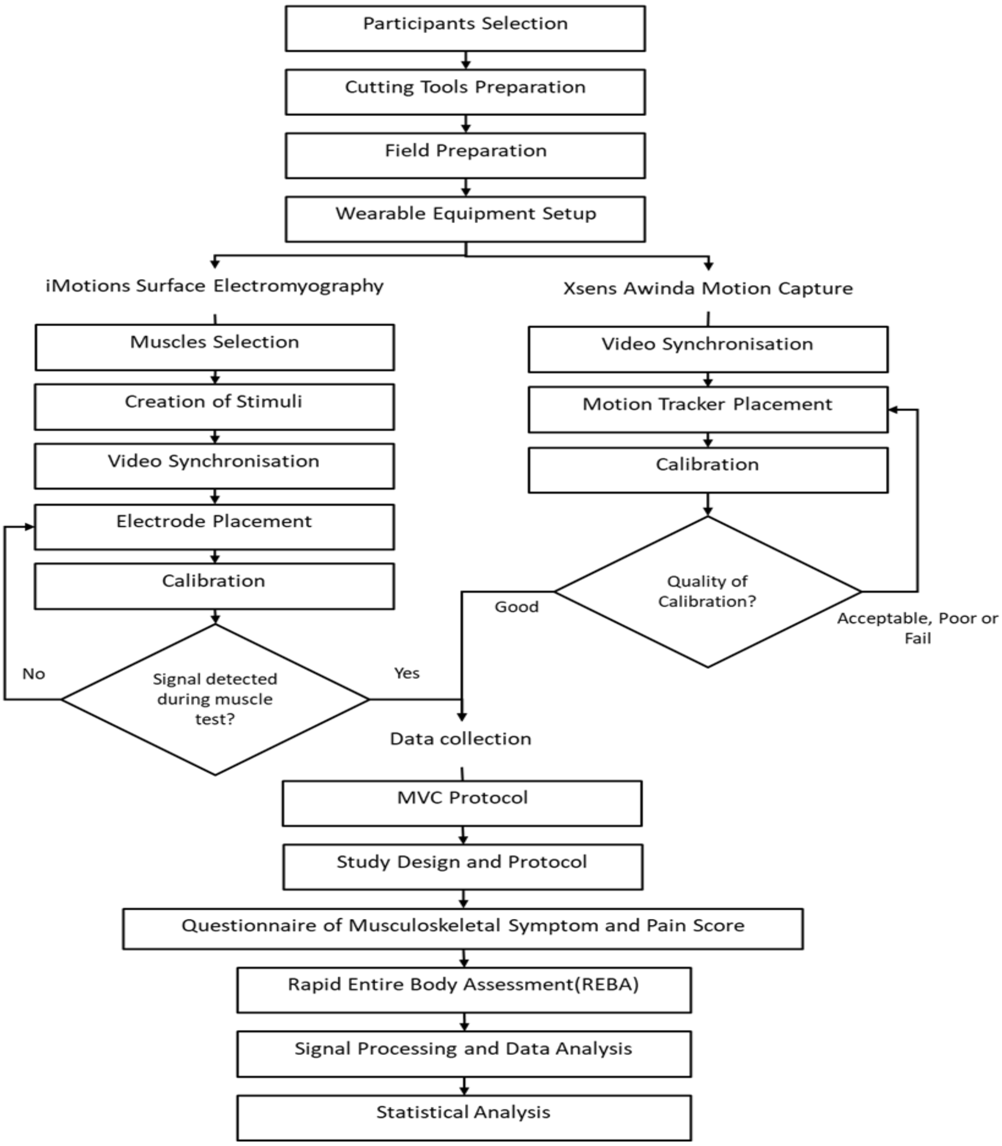

Figure 3.1: The overall framework of the approaches taken in conducting the study

3.2 Participants

Two healthy male participants (H1 & H2) were recruited for this study. Both of them met all inclusion criteria. The inclusion criteria of this study included: one individual who had experienced palm pruning and harvesting, one individual who had knowledge but no experience in palm pruning and harvesting, no health issues and major surgery, as well as consent and compliance with all aspects of the study protocol. All subjects signed an informed consent (refer to Appendix A) prior to the study. The demographic and basic information of the subjects is shown in Table 3.1.

Table 3.1: Demographic and basic information of the subjects.

Parameters	**Subject**		
	H1	**H2**	**Mean (SD)**
Age (Years)	44.0	43.0	43.5 (0.7)
Weight (Kg)	65.0	75.0	70.0 (7.1)
Height (cm)	171.0	165.0	168.0 (4.2)
Dominant hand	Right	Right	-
Experience Level	No experience	10 hours/week	10.0 (0.0)

3.3 Preparation of the Cutting Tools

In this study, the biomechanical evaluation focuses on the manual approach where two types of cutting tools widely used among the palm harvesters were chosen, the chisel and the sickle. The length of the chisel is 164 cm with approximately 11 kg in weight (Figure 3.2(a)). Considering the statue height of both subjects, the tool's length is acceptable as the study design only required the subject to cut the palm fronds at the highest height of around 2.5 meters using the chisel. For sickle, a conventional sickle (Figure 3.2(b) and an intervention sickle (Figure 3.2(c)) were selected to be used. It is to investigate the effect of using an intervention sickle in reducing the risk of WMSDs over conventional sickle. The intervention sickle able to amplify the cutting force and reduce the force exertion required to be applied by the user. Both sickles shared the same length of 164 cm, while the weight of the conventional and intervention sickle are 20.3 kg and 22.8 kg, respectively.