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Field measurement of hand forces of palm oil harvesters and evaluating the risk of work-related musculoskeletal disorders (WMSDs) through biomechanical analysis

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ABSTRACT

Hand force data is critical in evaluating work-related musculoskeletal disorders (WMSDs). Nevertheless, earlier studies on oil palm workers relied on estimated or laboratory measurements, which may not accurately reflect the actual hand forces. This study is the first report on the field measurement of hand forces for palm oil harvesters using a chisel and sickle to harvest low and tall palm trees, respectively. The dynamic hand forces and ground reaction forces were measured using instrumented harvesting tools and force plates, while wearable motion (IMU) and electromyography (EMG) sensors were incorporated for quantifying postural angles and muscle activations, respectively. Additionally, the spinal loadings, continuous Rapid Entire Body Assessment (REBA) scores, and subjective pain scores were determined to evaluate the risk of WMSDs. A total of 10 harvesters were recruited to perform the palm pruning tasks using a chisel and sickle. Resultantly, the sickle and chisel recorded a maximum cutting force of 1601.23 ± 424.26 N and 420.80 ± 96.00 N, respectively. All pruning tasks were found to be highly risky to harvesters, with a peak REBA score of 12. Likewise, all investigated muscles were activated for over 40% MVC, thus inducing moderate pain in the muscles. The peak L5-S1 compression forces for all tasks exceeded the safety threshold (>3400 N), but the values were not significantly different. The shear force of the L5-S1 was extreme in pruning with a sickle (1446.10 ± 411.00 N) compared to using a chisel. In conclusion, palm harvesters were at a high risk of developing WMSDs following poor postures, high physical exertion and muscle activity, and excessive spinal loads.

Relevance to the industry

This study presents a comprehensive risk analysis that may assist in developing ergonomics interventions for the working conditions in palm plantation environments.

1. Introduction

Malaysia is among the largest palm oil producers worldwide. Thus, there is a growing demand for a high number of plantation workers to meet up with the high volume of production in the country. The actual number of palm plantation workers in Malaysia may be difficult to determine as the industry is dispersed and most workers are employed in small and informal plantations. In 2016, 429,351 field workers worked in the oil palm plantation sector, and the number kept increasing over the years (Ismail et al., 2016). In 2019, the estimated number of palm plantation workers in Indonesia was approximately 4.42 million (ILO Podcast, 2022). The high population of palm plantation workers reflects a high level of human involvement and manual handling. Despite the availability of automated cutting tools, the high maintenance costs contribute to their limited use in the industry (Mohd Nawi et al., 2014). Meanwhile, traditional cutting tools resembling the chisel and sickle are commonly employed by palm workers to harvest fresh fruit bunches (FFBs). In harvesting practice, the harvester will initially extract the fronds to restrict the cutting tool from reaching the FFB. The act of cutting out the fronds is known as palm pruning.

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The cutting force required to cut palm fresh fruit bunches (FFBs) and fronds depend on the size and maturity of the bunches and fronds, cutting techniques, and the cutting tool used. Reportedly, a cutting force per frond area of 12.8 kg/cm^2 is required to cut the fronds using a sickle powered by an actuator in a laboratory setting (Jelani et al., 1998a). The high cutting force requires the harvesters to exert the equivalent hand forces for cutting the fronds, thus leading to extensive physical exertion that may cause fatigue. Meanwhile, the harvesters must exert the cutting force manually and repeated cutting attempts are required to cut a frond or FFB in the actual palm environment (Saibani et al., 2015). The repetition is prevalent since the number of hand forces capable of delivering differs between machines and humans, as well as between individuals. Hence, quantifying hand forces in the actual palm harvesting conditions is important for a better risk exposure assessment. Additionally, hand forces are essential for estimating the harvester's lumbar spinal loadings when performing the cutting tasks.

Manual and labour-intensive cutting tasks necessitate the workers to use their strength in applying push or pull force to cut the palm frond and FFB. High physical exertion is necessary to handle the cutting tool, considering the tool's weight and the required cutting force (Jelani et al., 1998b). Additionally, the harvesters are exposed to extreme working postures and repetitive cutting action when manoeuvring the cutting tool and cutting down the FFB (Syuaib, 2015). The factors contributing to the risk of experiencing work-related musculoskeletal disorders (WMSDs) are high physical effort, extreme working postures, and repetitive movement (Aptel and Cnockaert, 2001). Previous studies revealed a high prevalence of extreme lower back and upper back pain among palm plantation workers (Henry et al., 2015; Sukadarin et al., 2013a). The intense pain might have resulted from spinal loads, which induce vertebral stress and lead to various back disorders (Glowinski et al., 2021). L5-S1 was reported to bear the most compression forces compared to other lumbar regions (Arjmand and Shirazi-Adl, 2006). Nevertheless, none of the reviewed studies related to palm pruning quantified the force exerted on the lumbar spine during related tasks. The estimation of spinal loadings requires determining the hand forces and ground reaction forces, where the gathered data could analyse the loads at the spinal disc.

Generally, the working conditions of palm harvesters heighten their susceptibility to various injuries. A study conducted among 100 harvesters found that the common injuries were particles in the eyes (40%), hand injuries from harvesting tools (28%), and body pain (27%) (Decker et al., 2021). Body pain may have resulted from WMSDs, which are prevalent among palm harvesters (Henry et al., 2015; Tewtow et al., 2019; Bhuanantanondh et al., 2021). Similarly, in a study of 52 FFB harvesters, more than half of them experienced lower back pain (71.2%), neck pain (63.5%), shoulder pain (59.6%), and hand pain (40.4%) within the past year (Bhuanantanondh et al., 2021). Lower back, shoulder, neck, and hand pain were also identified as the most frequently reported symptoms (Ng, 2015). These findings emphasise the urgent need for comprehensive research on factors contributing to WMSDs among palm harvesters.

To determine the risk of WMSDs among palm workers, most studies employed an indirect measurement and qualitative approach to identify the pain distribution (Syuaib; Parra et al., 2018; Ng et al., 2013; Sukadarin et al., 2013). The indirect measurement method is conducted using ergonomic assessment tools based on video recording and interviews, where the main assessment element is the target's body angle. In palm harvesting, researchers employ ergonomic assessment tools, such as Rapid Upper Limb Assessment (RULA), Rapid Entire Body Assessment (REBA), and Ovako Working Posture Analysis System (OWAS) (Syuaib, 2015; Ng, 2015; Mohd Nawi, 2016). Nonetheless, qualitative measurement is limited to only the descriptive and individual perception regarding pain (Annett, 2002), while indirect measurement depends on the researcher's interpretation of the video and photograph.

In the recent advancement of wearable sensor technology, the inertial motion unit (IMU) allows a direct measurement of human motion parameters, joint positions, velocities, and angles (Caputo et al., 2019). Wearable surface electromyography (EMG) can also measure the electrical activity produced by a skeletal muscle. The EMG technology can improve the efficiency of WMSDs risk analyses and also act as a complementary element to the existing ergonomic assessment tools. The wearable IMU has been included in some studies related to WMSDs. For instance, Merino et al. (2018) employed a wearable IMU and EMG to assess the risk of WMSDs among banana harvesters. The result elucidated the specific movements and duration that expose the harvester to risk. Another study reported that the IMU systems are highly accurate in identifying and managing the risk of WMSDs (Filippeschi et al., 2017). Additionally, some researchers take advantage of the IMU to develop automated ergonomic assessment tools. Vignais et al. (2013) and Huang et al. (2020) linked the wearable IMU sensors to a biomechanical model, where the output from the model served to compute the RULA and REBA scores for each second of the movement. This procedure allows full-time evaluation without requiring the researcher to manually select the posture needed in the assessment.

Integrating the postural and biomechanical evaluation tools permits researchers to comprehensively investigate the risk of activity on the human body. This study conducted quantitative and qualitative measurements of the WMSDs' risk exposure to palm harvesters. A deeper comprehension of WMSD risk in palm pruning activities can be derived by considering the following factors: the measurement of cutting force, human posture, REBA scores, muscle efforts, rated pain scores, and spinal loads.

2. Methodology

2.1. Participants

A total of 10 male harvesters (n = 10; Age: 26.3 ± 9.07 years; Height: 167.4 ± 3.40 cm; Weight: 60.95 ± 4.35 kg) were recruited as study participants upon fulfilling the inclusion criteria. Two participants had more than a year of experience in palm harvesting, while the other eight had less than a month of experience but were familiar with the harvesting methods. All participants willingly complied with all aspects of the research protocol by signing the consent form. Before providing written consent, the participants were verbally informed of the overall study protocol. Each participant was equipped with proper clothing, a safety helmet, and other safety measures. The guideline and regulations were approved by the Human Research Ethics Committee Universiti Sains Malaysia (USM) (code number: 21100665).

2.2. Wearable motion capture and surface electromyography

Wearable motion capture in full-body configuration was performed in this study using Xsens (Xsens Technologies BV, Enschede, The Netherlands). Sensors were placed on the head, sternum, shoulder blades, upper arms, lower arms, hands, pelvis, upper legs, lower legs, and feet (Fig. 1a). The sensors were attached to the body using a set of straps and Velcro patches on the suit. Each participant used a different size of the suit based on their comfortability and the level of fastening. Suitable fastening is compulsory for dynamic movements to ensure that the motion tracker follows the movement of the underlying body segment. The sampling frequency for full-body configuration was fixed at 60 Hz for all tasks.

The harvester's muscle activation was measured using surface electromyography (EMG) from iMotions (iMotions, Copenhagen, Denmark). Meanwhile, 24 mm diameter disposable Ag/AgCl surface electrodes were placed in bipolar configurations on the left and right biceps brachii (LBB, RBB), left and right middle deltoid (LMD, RMD), right upper trapezius (RUT), right middle trapezius (RMT), and right erector spinae (RES). The right-side muscles were preferred for the harvesters' dominant side. The muscles were chosen based on the reported pain regions by palm harvesters from earlier studies. The subject's skin was cleansed


[redacted] [redacted] [redacted] [redacted]

Fig. 1. (a) Xsens IMU sensors setup on the harvester in full-body configuration. (b) Surface EMG electrode placement.

with an alcohol wipe to remove dead skin and ensure good electrode-to-skin contact, before placing the electrode. The electrode was pre-gelled with an adhesive, attached directly to the skin, and secured with a medical bandage as a precaution. The centre-to-centre inter-electrode distance was set at 20 mm to avoid the risk of crosstalk from nearby muscles. In addition, the EMG electrode placement was based on the guideline provided by Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) (Hermens et al., 1999) (Fig. 1b). A maximum voluntary contraction (MVC) exercise was conducted for each muscle as described in the previous (Halaki and Ginn, 2012; Ekstrom et al., 2008; Rainoldi et al., 1999), with the sampling rate for the EMG measurement set at 1024 H. The data were band-pass fourth-order Butterworth filtered (20–300 Hz), full-wave rectified, and low-pass filtered (10 Hz).

2.3. *Experimental setup and instrumentation*

The two types of tools commonly used in palm plantation harvesting, a 164 cm length chisel (Fig. 2a) weighing 10.84 kg and a 367 cm sickle (Fig. 2b) weighing 20.30 kg were selected as the cutting tools during the experiment. Thereafter, an S-Type S9M load cell (HBM, Germany) was placed on each pole of the tool for hand forces measurement (Fig. 2c). As for the chisel, the load cell was placed 54 cm from the tip of the cutting tool. As for the sickle, the load cell was placed at a distance of 219 cm from the top of the blade. Fig. 2d illustrates the full view of the load cell position within the cutting tools. Each load cell was connected to the Signal Conditional Unit (SCU), NI–N114 (National Instrument, Hungary). The SCU was plugged into Data Acquisition (DAQ), NI cDAQ-9174 (National Instrument, Hungary), and LabVIEW 2021 was used as the software for data recording and processing. The load cell sampling rate for the chisel and sickle was set to 2000 Hz. To calibrate the load cell, the cutting tool was held upright, and the reading was set to zero. This calibration was performed to eliminate the weight of the tool above the load cell, leaving only the reading of push or pull force being applied by the harvester during the task.

The technical datasheet revealed that the load cell weighed 1.4 kg. In comparison to the overall weight of the chisel and sickle, the load cell accounted for 12.92% and 6.90%, respectively. This result indicates that adding the load cell would require little effort when handling both tools. The mounting location was selected based on previous testing to ensure the comfort of the harvester and to closely replicate the conditions of actual palm harvesting. Thus, the performance of the tools was preserved.

Furthermore, two pieces of 60 cm × 40 cm triaxial force plates (Bertec Corporation, Columbus, OH) were employed to measure the subject's ground reaction forces (GRF) while performing the cutting tasks (Fig. 2d). The force plates were placed on a flat platform to minimise movement or vibration on the plate, and the sampling rate was set to 500 Hz. The GRF outputs consisted of forces and moments in the x, y, and z directions.

2.4. *Description of the harvesting tasks*

The experimentation was split into two categories based on the height of the palm fronds. The first category (tool: chisel) was a frond location of below 3 m, usually occurring during the early harvesting year while the second category (tool: sickle) was for fronds locations of more than 3 m.

The first category was split into three tasks based on the height of the target: less than 1 m (Task A), within one to 2 m (Task B), and more than 2 m (up to 3 m) (Task C). In the tasks, pruning with a chisel demanded the harvester to apply sudden push forces to cut the fronds. With five cutting shots, the harvesters were asked to cut the fronds as naturally as possible. The palm trees were marked with a red spray to distinguish the tasks, thus indicating different target areas.

For the second category, the pruning task was set for the palm fronds

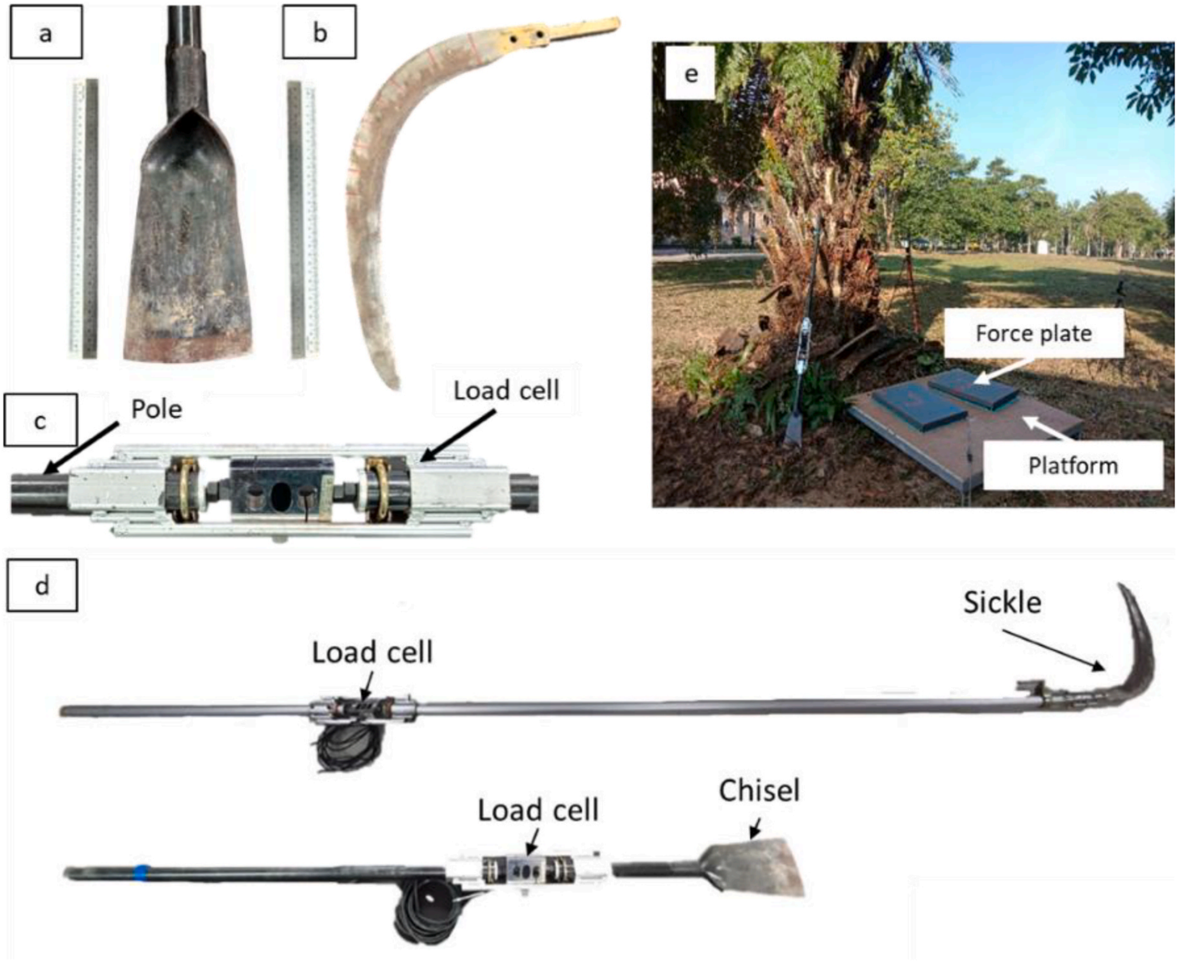


Fig. 2. The instrumented cutting tools used in the pruning tasks are (a) chisel, (b) sickle, and (c) load cell attached at both cutting tools, (d) full view of the cutting tools mounted with a load cell and (e) placement of force plates on a flat platform near the targeted palm tree.

higher than 3 m height (up to 5 m) (Task D). The harvesters were provided with five cutting shots to cut the fronds as naturally as possible. Pruning with a sickle required the harvester to manoeuvre, point the sickle to the palm frond, and apply sudden pull forces to cut it down. Fig. 3 depicts the overview of all pruning tasks. Overall, the measurement timeframe of each task, involving five attempts to cut the fronds, was approximately 2 min.

The subjects were reminded to limit their movements within the force plates for a better recording of the ground reaction forces. A new recording session for all measuring equipment was generated for each subject and activity.

2.5. Data processing

Selection of postural data

This study selected the frames containing practical actions for further analysis. Thus, unwanted scenes in the recordings, such as the subject walking to the force plate and post-experiment random motion were eliminated, leaving only the critical posture of harvesting movements.

3.5.2. Rapid Entire Body Assessment (REBA)

The REBA score was evaluated automatically, frame-by-frame, based on joint angle data from the MNVX file using an automated REBA tool (Xsens Based Automated WMSDs ergonomic assessment system), which was developed by KAIST, Human Factors and Ergonomics Lab (Huang et al., 2020). There were three load options of less than 5 kg, 5–10 kg, and more than 10 kg, which align with the REBA scoring method. Nevertheless, when the score was evaluated, it was presumed that the constant load was applied along the entire frame. This assessment resulted in incorrect data since the subject only carried the load at specific frames. Hence, the data from three load options were collected and synced with force plate data (GRF) using Python coding. The force plate data and Xsens MVN postural data were synchronised by pairing their timestamps using a Python programme. The force plates recorded a sampling rate of 500 Hz, while Xsens MVN had a rate of 60 Hz. In this study, Xsens time stamps were set as a reference. To match the timestamps of the postural data, cubic interpolation was applied to the force plates data, providing a GRF value for every line of Xsens data. Finally, the various REBA scores according to the load applied at each timestamp were obtained based on the synced data. By syncing with the force plate data, the correct proportion of REBA based on the actual load carried by the subject could be acquired (Law et al., 2022).

3.5.3. Spinal loadings (compression and shear forces)

The estimation of spinal loads was performed using a 3D Static Strength Prediction Programme (3D SSPP), which requires information on gender, height, weight, postural angles, and hand loads. The postural angles and hand loads were obtained from the measurement using Xsens and load cell, respectively. Since 3D SSPP can specifically measure spinal loads from a static posture, only the posture from the maximum REBA score of each task and each subject was chosen for evaluation.

The reported shear force is the resultant of shear components in the anteroposterior and lateral directions. Both peak compression and shear forces at the L5-S1 disc were compared to the widely-used compression

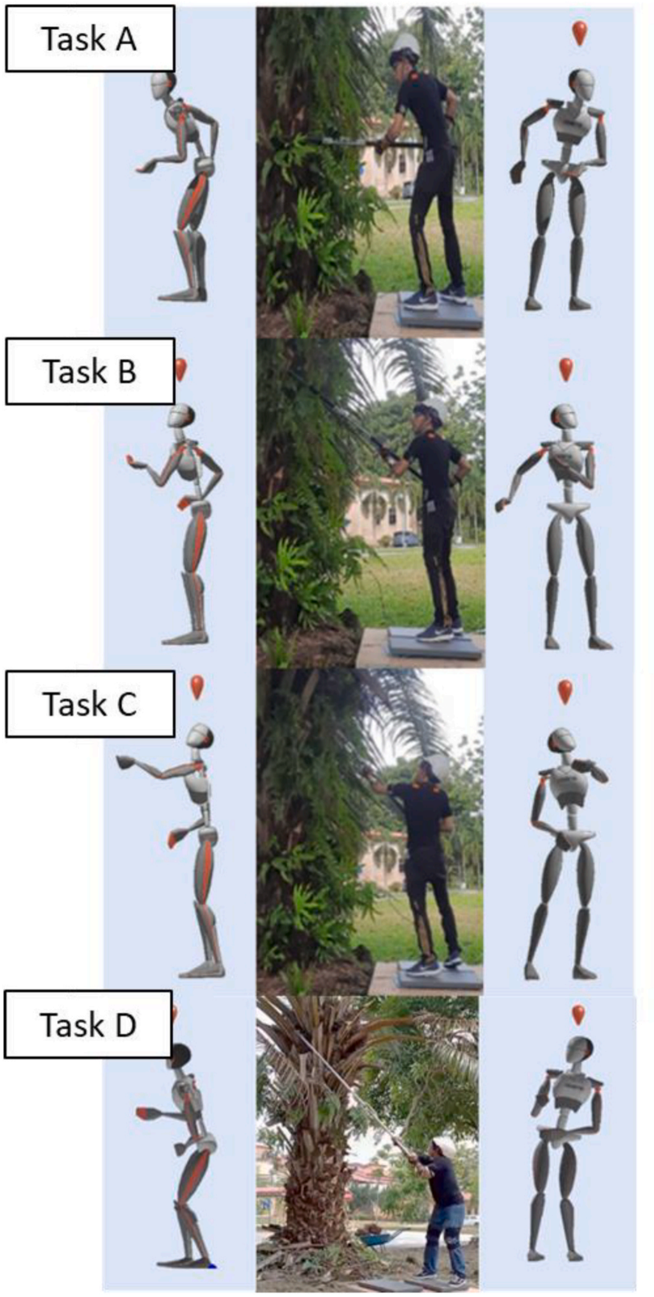


Fig. 3. The designated pruning tasks with different cutting heights and tools.

and anteroposterior shear safety limits proposed by the National Institute of Occupational Safety and Health (NIOSH), which were 3400 N (Waters et al., 1993) and 1000 N (Gallagher and Marras, 2012), respectively. The comparison was performed to evaluate whether the pruning tasks posed a risk for developing low back disorders.

2.6. *Body pain questionnaire*

After each pruning task, the harvesters were interviewed using a questionnaire based on the pain experienced on specific body parts and their relative pain score (Appendix A). The score ranged from 0 to 10 and was categorised as no pain (0), low pain (1–2), moderate pain (3–6), high pain (7–9), and extreme pain (10). The interview sessions were recorded for the experimenter's further reference. The questionnaire served to investigate the subjective perception of the pain experienced by the harvesters. Furthermore, the questionnaire was developed based on the placement of EMG electrodes to investigate the correlation between the reported pain and the muscle activation level.

2.7. *Statistical analysis*

The difference in the cutting force, REBA scores, and spinal loads as a function of pruning tasks was determined using analysis of variance (ANOVA). In other words, ANOVA was used to ascertain if the mean values of any parameter based on the cutting tools and various heights applied significantly varied. Post-hoc analyses were performed using the Bonferroni correction. A p-value of less than 0.05 was considered statistically significant. An eta-squared (η^2) effect size was calculated based on the results of the ANOVA. Additionally, Pearson correlation was used to determine the relationship between the peak REBA and cutting force with the L5-S1 compression and shear forces. A correlation analysis was also performed between the muscle activations and the reported pain scores using a non-parametric statistical test (Spearman's correlation). All inferential analyses were conducted using IBM SPSS Statistics 27 software (SPSS Inc., Chicago, IL, USA). For descriptive analysis, the mean, and standard deviation (SD) of all selected variables were reported in the results.

3. Results

This study entailed biomechanical and postural ergonomic assessments during different approaches of palm pruning tasks, comprising low back compression and shear forces and REBA scores. The measurements and evaluations allowed for the quantitative identification of potential injury risks. Additionally, several working factors that may pose a risk of WMSDs were identified.

3.1. *Cutting force*

Fig. 4a, b and 4c illustrate the cutting force patterns exerted by a harvester to complete a pruning cycle using a chisel for Task A, Task B, and Task C, respectively. The peak value was the maximum pushing force exerted by a harvester towards the fronds, whereas the valley is the pulling force recorded while the harvester retracted the chisel. In Fig. 4d (Task D), the valley on the graph was the maximum pulling force applied by the subject to cut the targeted frond, while the peak value was the pushing force applied by the harvester to reposition the sickle upward.

Fig. 4e illustrates the boxplot of the cutting force exerted by the harvesters for all tasks. The pruning task using sickle (Task D) recorded the highest average value of 1601.23 ± 424.26 N, followed by Task C (420.80 ± 96.00 N), Task B (390.07 ± 53.60 N), and Task A with a value of 377.00 ± 110.50 N. Task D differed significantly from all pruning tasks using chisel [$F(3,36) = 56.94$, $p < 0.001$, $\eta^2 = 0.86$]. The effect size indicates a large effect between the variables.

3.2. *The pattern of continuous REBA scores*

Fig. 5a illustrates a graphical representation of the continuous REBA patterns from one of the harvesters while performing Task C for one pruning cycle, which comprises aiming, swinging, cutting, and retracting the chisel from the fronds. Fig. 5b denotes the postures of the harvester for a complete pruning cycle. The peak scores within the cycle were obtained during the aiming (Fig. 5c(ii)) and cutting (Fig. 5c(vi)) positions, while the lowest scores were obtained when the harvester stood straight to reposition the cutting tool on the palm frond (Fig. 5c [iii]).

3.3. *Average of peak REBA scores*

Fig. 6a depicts the mean value of the peak REBA score for each task. Using REBA, the body postures revealed that the mean (SD) of the peak risk scores of Task A, Task B, Task C, and Task D was 11.00 ± 1.05, 11.00

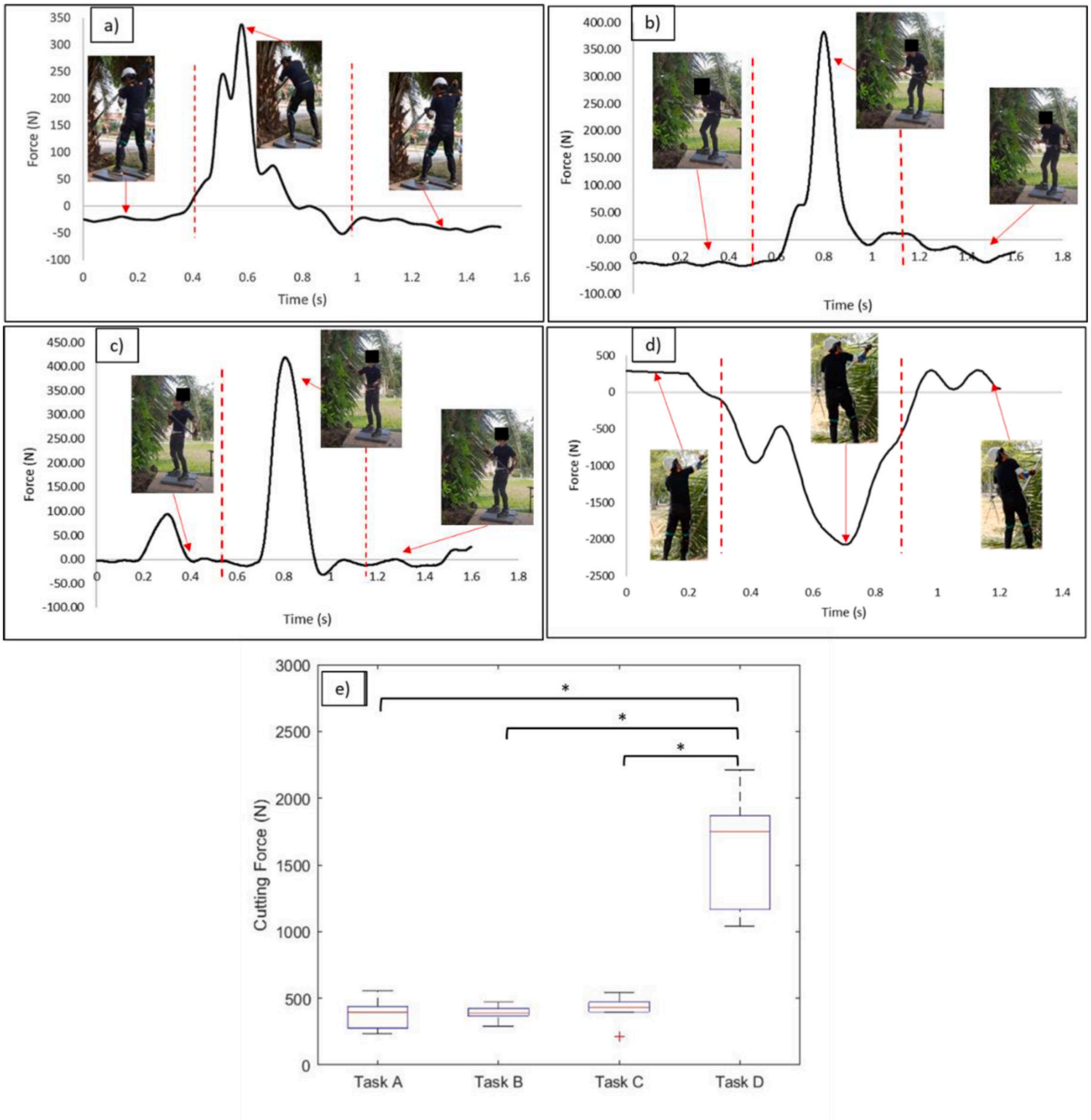


Fig. 4. Pattern of peak cutting forces for (a) Task A, (b) Task B, (c) Task C and (d) Task D. (e) Boxplot diagram of the cutting force for all pruning tasks. * Significant difference at $p < 0.001$.

± 1.05, 10.70 ± 1.06, and 10.30 ± 1.16 respectively. According to the REBA classification, the scores were classified as high risk since they were greater than 8, where immediate changes to the working conditions are required. The highest recorded score of all tasks was 12, which falls under the very high-risk category. Fig. 6b displays the respective high-risk postures for every task. Furthermore, there was no significant difference between the tasks [F (3,36) = 0.80, p = 0.534, $\eta^2 = 0.07$]. This indicates that the working postures in all pruning tasks regardless of the cutting tools or pruning heights are strenuous for the harvesters.

3.4. L5-S1 compression and shear forces

The L5-S1 disc loads were quantified to investigate the forces exerted on the spine of the palm harvesters during the palm pruning activities. Fig. 7a depicts the mean lumbar (L5-S1) compression force of the harvesters at all pruning tasks. The mean low back compression forces were lower than the safety threshold of 3400 N, where Task A, Task B, Task C, and Task D produced an average of 2981.40 ± 761.20 N, 2598.70 ± 604.59 N, 2686.20 ± 562.92 N and 2493.20 ± 1349.48 N, respectively. Nonetheless, the peak compression force of all tasks exceeded the limits recommended by NIOSH, with Task D recording the highest value of 5023 N, followed by Task C (3845 N), Task A (3739 N), and Task B (3647 N). The statistical results revealed no significant difference [F (3,36) = 0.57, p = 0.638, $\eta^2 = 0.04$] in the lumbar compression forces between the tasks, hence revealing that all pruning tasks imposed an intense compressive force on the L5-S1 joint.

Since the pruning tasks involved pushing and pulling the cutting tools, the shear forces of the L5-S1 are equally pertinent as the compressive force. Fig. 7b presents the mean shear forces exhibited by the subjects during the pruning tasks. Task D attained a mean value of 1446.10 ± 411.00 N, the highest among all tasks, and exceeded the tolerance limit for lumbar shear force. Nonetheless, pruning tasks using a chisel remained below the safety borderline, with Task A producing 505.30 ± 90.20 N of force, followed by Task C (496.10 ± 93.32 N) and Task B (455.30 ± 79.20 N). Statistically, the mean shear forces for Task D were significantly different compared to Task A, Task B, and Task C [F

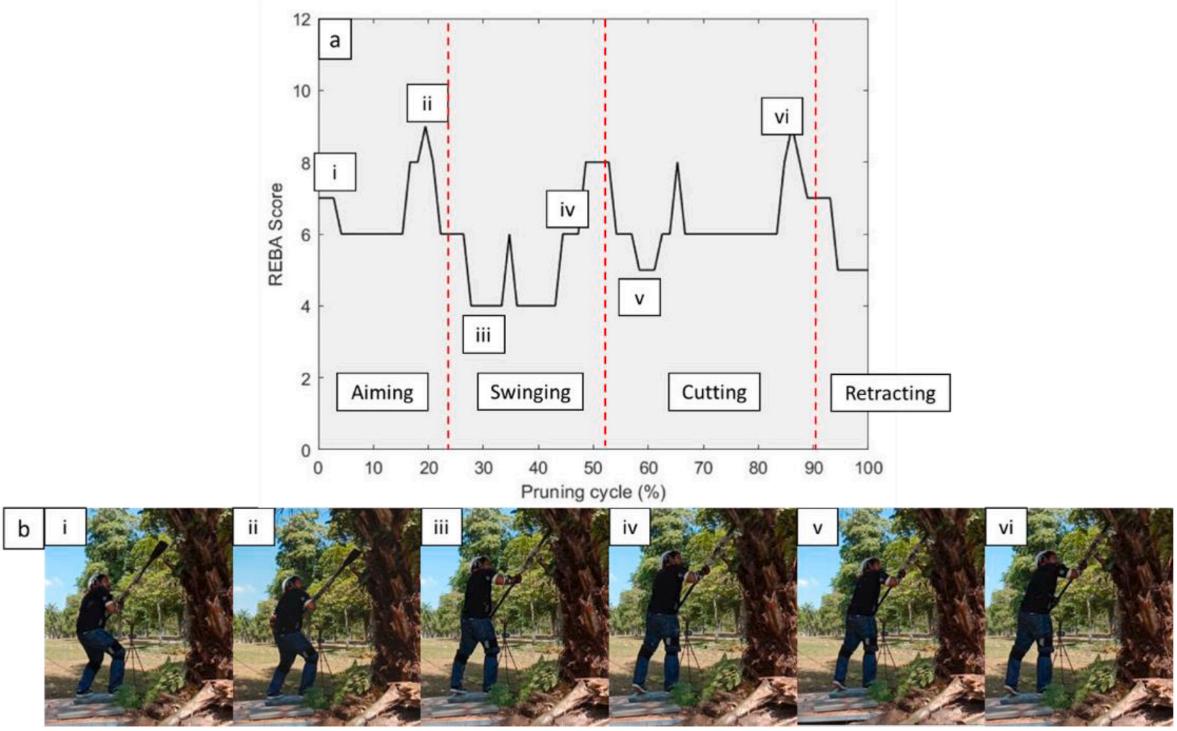


Fig. 5. Representative continuous REBA scores graph based on Xsens IMU data. (a) REBA scores for five cutting strikes, (b) REBA scores for one cutting strike and (c) postures of the harvester while performing Task C.

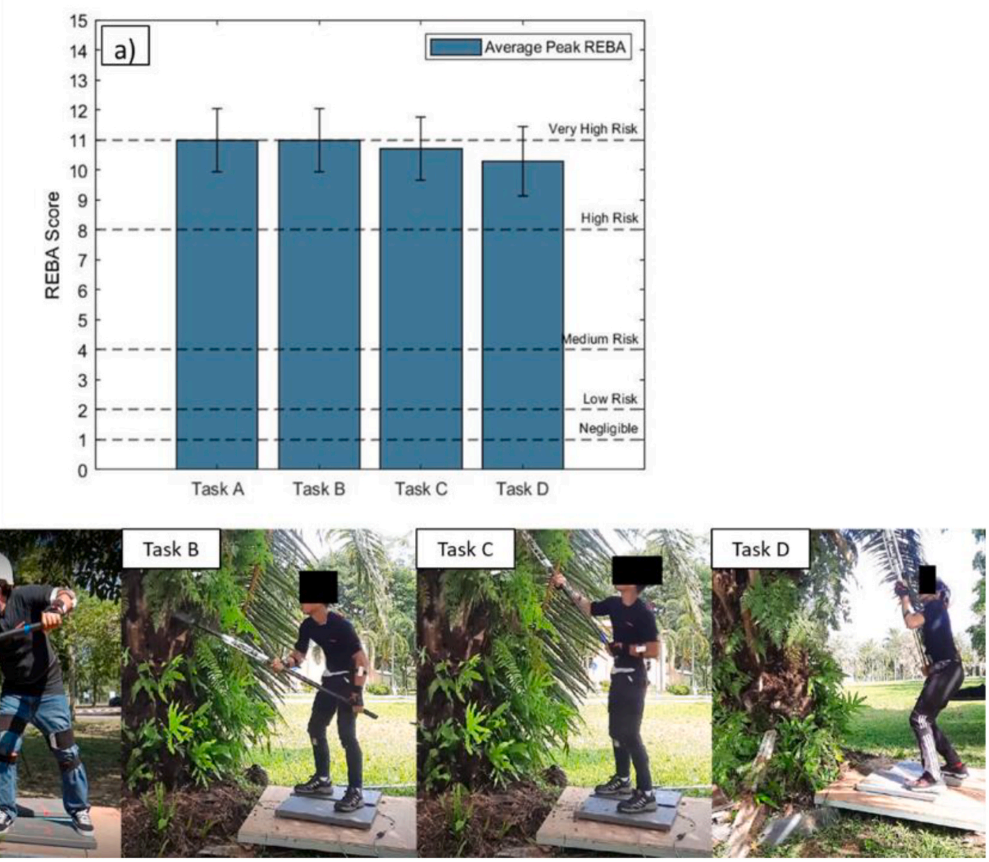


Fig. 6. (a) Average of peak REBA scores for each pruning task with (b) its respective postures.

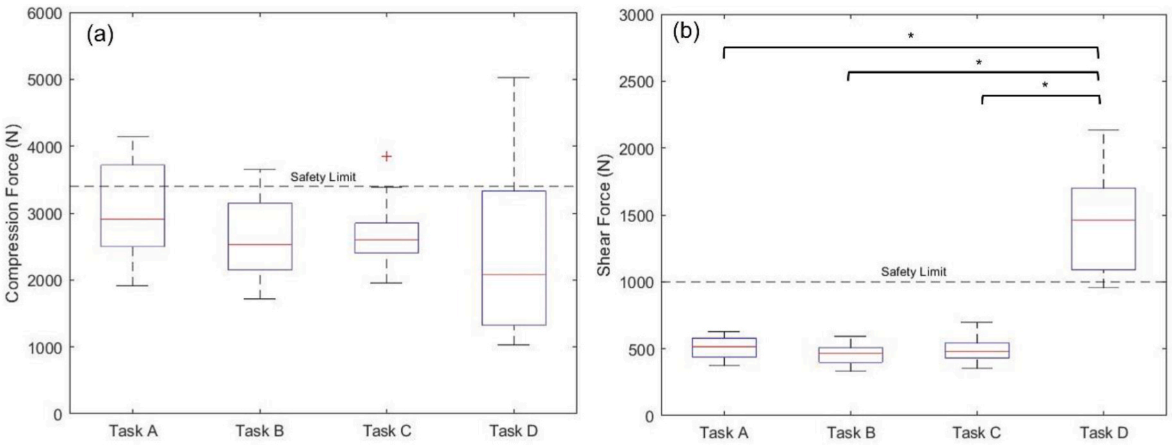


Fig. 7. (a) Average compression forces at the L5-S1 joint of each pruning task. (b) Average shear forces at the L5-S1 joint of each pruning task. * Significant difference at $p < 0.001$.

$(3,36) = 48.14$, $p < 0.001$, $\eta^2 = 0.80$]. As such, pruning with a sickle at a height of more than 3 m exerted a high shear force on the L5-S1 disc compared to using a chisel for a height of lower than 3 m.

3.5. *Effect of REBA score and cutting force on L5-S1 loadings*

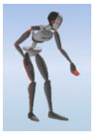
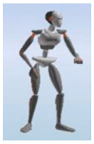
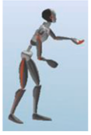
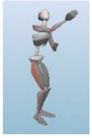
Table 1 summarises the average cutting force and average peak REBA score of the selected postures with their respective compression and shear forces. Table 2 denotes the correlation analysis between the variables presented in Table 1. Resultantly, the compression force had a significant moderate positive correlation with the REBA score ($r = 0.600$, $p < 0.001$). The shear force also exhibited a significantly strong positive correlation with the cutting force ($r = 0.879$, $p < 0.001$).

3.6. *Muscle activation patterns*

The biceps brachii, middle deltoid, upper trapezius, middle trapezius, erector spinal, and rectus femoris were investigated to evaluate the physical demands on the harvester during the palm frond pruning. The EMG activation was considered moderately activated if the value was within 20%–50% MVC and was highly activated if the muscle activity was >50% MVC (Cools et al., 2014). Fig. 8 presents the activation of different muscles for all pruning tasks. All muscles in every task were highly activated except for Tasks A, B, and C in RES.

Considering the RBB and LBB, the tasks exhibiting the highest activation were Task D (68.90 ± 20.00%) and Task C (73.04 ± 18.24%), respectively. Task D also provided the highest activation of 68.46 ± 19.53% for RMD, while Task C recorded a value of 68.90 ± 19.09% for LMD. Meanwhile, Task B recorded the highest activation on both RUT and RMT, with a value of 57.68 ± 11.47% and 51.06 ± 19.88%,

Table 1
Summary of the cutting force, average peak REBA score, compression force, and shear forces of each pruning task.

Xsens Posture	3DSSPP Posture	Cutting Force (N)	Average Peak REBA	L5-S1 Compression Force (N)	L5-S1 Shear Force (N)
Task A 		377.00 ± 110.50	11.00 ± 1.05	2981.40 ± 761.20	505.30 ± 90.22
Task B 		390.07 ± 53.60	11.00 ± 1.05	2598.70 ± 604.59	455.30 ± 79.18
Task C 		420.80 ± 96.00	10.70 ± 1.06,	2686.20 ± 562.92	496.10 ± 93.32
Task D 		1601.23 ± 424.26	10.30 ± 1.16	2493.20 ± 1349.48	1446.10 ± 411.00

*Values in the table are presented as Mean ± SD.

Table 2
Correlation between peak REBA score, cutting force, compression, and shear forces.

Variable		Peak REBA	Cutting Force	Shear Force (N)	Compression Force (N)
Peak REBA	Pearson's r	–			
	p-value	–			
Cutting Force (N)	Pearson's r	−0.338	–		
	p-value	0.059	–		
Shear Force (N)	Pearson's r	−0.210	0.879	–	
	p-value	0.248	<.001	–	
Compression Force (N)	Pearson's r	0.600	−0.283	0.015	–
	p-value	<.001	0.116	0.933	–

respectively. Regarding the low back muscle (RES), Task D reflected the maximum average value of 50.18 ± 25.18%. No obvious difference was observed in all tasks within the same muscle.

3.7. Reported body pain

Based on the EMG electrode placement, the pain experienced by the harvesters after each pruning task was evaluated using a customised pain questionnaire. Fig. 9 presents the average pain score reported by the harvesters for each muscle region. In Table 3, spearman's correlation between the muscle activations and the reported body pain score was determined, thus revealing a significantly strong positive correlation between both variables for all muscle regions.

Table 3
Correlation between reported body pain assessment and muscle activation measured by surface EMG.

Muscle	Correlation (rs)	p-value
Right Biceps Brachii (RBB)	0.948	<0.001
Left Biceps Brachii (LBB)	0.947	<0.001
Right Middle Deltoid (RMD)	0.974	<0.001
Left Middle Deltoid (LMD)	0.964	<0.001
Upper Trapezius (RUT)	0.954	<0.001
Middle Trapezius (RMT)	0.944	<0.001
Erector Spinae (RES)	0.949	<0.001

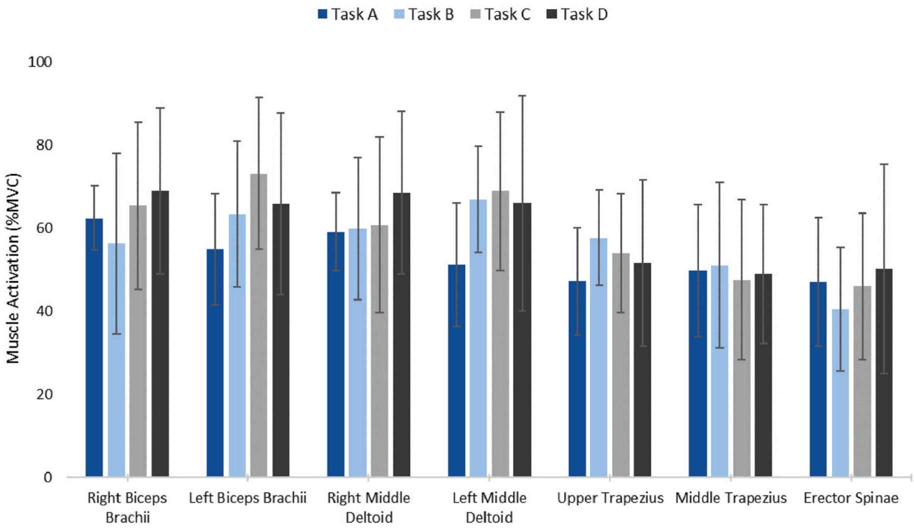


Fig. 8. Average maximum muscle activation in all pruning tasks. Task A (Chisel, <1m), Task B (Chisel, 1–2m), Task C (Chisel, 2–3m), Task D (Sickle, > 3m).

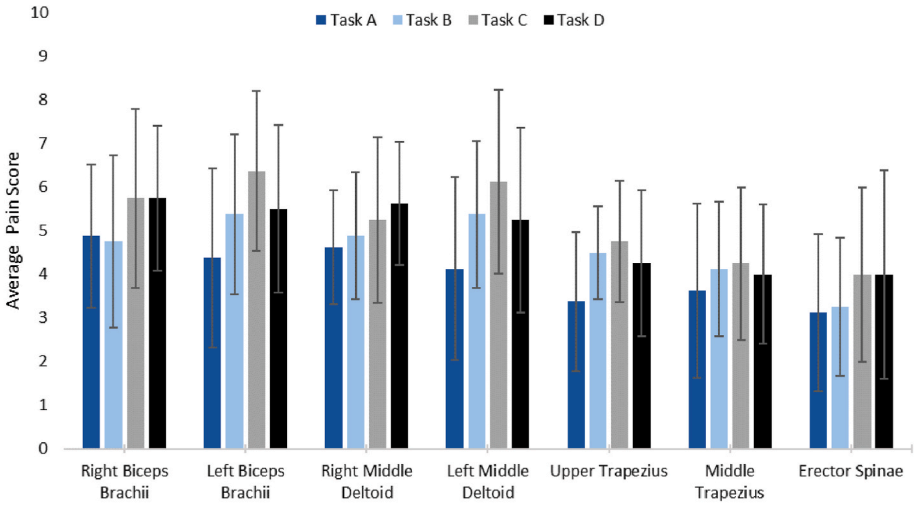


Fig. 9. Average reported body pain in all muscle regions of all tasks.

4. Discussion

In this study, the postural risk, low back compression forces, and muscular efforts during palm pruning tasks were analysed based on the IMU and EMG measurements. This study aimed to provide a comprehensive analysis of the risks and physical efforts required to complete the tasks based on the selected variables. The result of this evaluation will provide a reference for ergonomic interventions aimed at reducing WMSD risks.

The cutting force required to cut the fronds in all tasks was measured in an actual pruning environment. Resultantly, a significantly higher cutting force (1601.23 ± 424.26 N; max: 2662.30 N) was required when using a sickle to prune the fronds at more than 3 m of the target height. A previous study (Jelani et al., 1998b) investigated the cutting force using a sickle cutter in a laboratory setting with a value of 12.2 kg/cm^2 (1196411 N/m^2) (force per frond area); however, the force was delivered by an actuator without human involvement. Meanwhile, a maximum specific cutting force of 735498.8 N/m^2 was obtained when an average measured fronds area of approximately 35.84 cm^2 for sickle (cut fronds) was considered (Ishak, 2021). The conditions could thus exceed the required force in the field, including the force capable to be delivered by a human. Nevertheless, factors involving fronds moisture, fronds maturity and cutting angle that may affect the cutting force should be considered (Ahmad et al., 2020).

The REBA analysis was conducted to reveal the rating of awkward posture and musculoskeletal risks in various conditions of the pruning tasks. As presented in Section 3.2, this study measured a continuous REBA score, which facilitated the evaluation of every posture along the pruning cycle without missing any risk. Previous studies that employed ergonomics sheets in measuring the risk of WMSDs among palm harvesters only manually selected the posture based on the interpretation of the researcher (Ng et al.; Mohd Nawi et al., 2013). The determination of the postural angles was traditionally calculated as the input, which might raise reliability issues (Kucera et al., 2009). Despite requiring minimal instrumentation, the observational methods relied on the involvement of ergonomics experts. The variability between the ergonomics experts may result in discrepancies between the conclusions drawn by various experts (Fagarasanu and Kumar, 2002; Wang et al., 2015). Hence, continuous measurement of risk score with inputs from an accurate wearable motion capture can comprehensively analyse the working conditions.

The mean of peak scores of all pruning tasks was categorised as high-risk (score 8–10), thus increasing the prevalence of WMSDs. Additionally, since the peak scores of each task fell under a very high-risk category (score 12), immediate actions need to be taken to ensure the health and safety of the harvesters. In the pruning task involving a chisel, the high-risk postures involved swinging the chisel towards the fronds with a combination of trunk flexion and extreme shoulder abduction, specifically in Tasks B and C. As for the lowest height of fronds (Task A), the setting demanded more knee flexion, trunk bending, and shoulder and elbow flexion, thus imposing a higher risk score. In contrast, swinging the chisel with a neutral trunk posture would lead to a lower risk score compared to those with trunk flexion or bending. The score pattern results are consistent with the report by Nawi et al. (Mohd Nawi et al., 2013), in which holding and swinging the chisel with the knees bent along with flexion of the trunk resulted in a high REBA score (score: 13) (Mohd Nawi et al., 2013). However, an additional risk posture was detected when using the chisel (Fig. 5c [vi]), whereby the harvester raised one leg with extreme neck, upper and lower arm angles while cutting the fronds despite presenting an acceptable trunk flexion. The findings highlighted the importance of considering every movement occurring in the task for a better understanding of the associated risk.

Meanwhile, a sickle was used for the highest-located fronds, which more than 3 m above the ground (Task D). The increased exposure to risk stemmed from the extensive flexion and extension of the trunk, neck, and shoulder when pulling the sickle to cut the fronds. Pruning with a sickle attached to a long poled required the hands to be above the shoulder when aiming and pulling the cutting tools for most of the cutting cycles. The over-extension of the neck was frequently necessary to search for the fronds. However, the bending of the trunk and flexion of the knee occurred naturally to exert additional power and maintain the body posture balance simultaneously, especially when the harvester cut relatively large fronds at restricted positions. A previous study reported similar results for the same posture using RULA assessment, with a very high-risk score (score: 7) (Mokhtar et al., 2013). Additionally, forceful exertion was apparent as the task required a specific level of cutting force for the tool to penetrate through the palm frond, regardless of the cutting tools utilised. In this study, the prevalence of WMSDs resulting from extreme postures and forceful exertion was evident. According to (Fathallah, 2010), extreme range of motion and repetitive actions are one of the biomechanical risk factors associated with various WMSD problems.

Aligning with the quantitative approaches used in this study, several previous studies employing qualitative methods have been conducted in palm harvesting working environments. For instance, Ng et al. (Ng, 2015) investigated palm harvesting activities during the early harvesting stage and found a high prevalence of musculoskeletal pain in the lower back, knee, shoulder, and neck. The awkward posture adopted by the FFB cutter while using the chisel was one of the factors associated with musculoskeletal pain (Ng, 2015). Henry et al. also assessed the prevalence of WMSDs among 84 palm workers from various palm plantations in Malaysia using Quick Exposure Check (QEC) and Standard Nordic Musculoskeletal Questionnaire (SNMQ) (Henry et al., 2015). Repetitive movements and awkward postures were identified as the risk factors, with QEC revealing high exposure risk at the neck (56%) and back (45.6%). Furthermore, SNMQ revealed that back pain and shoulder pain were prevalent among the harvesters.

Additionally, the muscle activation of the harvesters during the pruning tasks was measured to evaluate their physical effort. In an agricultural environment, muscle activation can be closely related to muscle functions (Teo et al., 2021; Park et al., 2014). The RUT and RMT were highly activated for all pruning heights due to the combination of the neck extension, right shoulder flexion (upwardly rotated the scapula), and abduction (elevation of the scapula) during the cutting cycle. Given the need to retract the chisel backwards and swing it back to the targeted fronds, the highest activation of RUT and RMT was at the pruning height equal to the harvesters' stature height (Task B). When using a sickle (Task D), the hands were above the shoulder, especially during the adjustment of the pole to locate the sickle at the appropriate cutting point closer to the palm trunk. This indicates the intensive use of the upper and middle trapezius function to cut the palm fronds.

Erector spinae activation was measured following the nature of palm harvesting, which necessitated the harvester to bend and sometimes, extend the trunk. The activation of RES aligned with the nature of the task, which was lowest in Task B and highest in Task D. Task B demanded minimum trunk extension and bending due to the location of the fronds, which minimised such movements. In Task D, considering the length and the weight of the pole, slight trunk flexion is usually performed by harvesters to stabilise their body while exerting a sudden pull force to cut the fronds.

The forearm flexion is performed by the biceps brachii; hence, it was highly activated on the right and left hand in all tasks. The highest activation was observed at a pruning height of more than 2 m, regardless of the tools used. This result illustrated a high physical effort of the upper limbs in pruning the fronds, especially for fronds located higher than their body height. Despite assisting the elbow flexion, biceps brachii plays a vital role in weight-bearing activity (Park et al., 2013). The harvesters are required to hold and stabilise the tool when locating the fronds. An intensive physical effort was required by observing almost equal utilisation of the upper limbs, reflecting the need to utilise the strength from both hands while pruning, especially at a height of more than 2 m. The EMG signal of the middle deltoid was also measured from both hands. Abduction of the shoulders was observed in every cutting task performed, thus leading to high activation of the RMD and LMD, irrespective of the tasks. Generally, high physical demands involving the upper body muscles are required for harvesters to perform the pruning tasks, regardless of the pruning heights and tools.

Similar to Task D in the present study, a previous work investigated the EMG activation of seven harvesters while cutting the FFBs using a sickle at the target height of three to 5 m (Teo et al., 2021). The researchers investigated similar muscles reported in the current study and discovered that the biceps had the highest peak activation (83.00 ± 7.06%), followed by the upper trapezius (72.40 ± 9.40%), erector spinae (longissimus) (70.50 ± 8.25%), and middle trapezius (60.00 ± 11.80%), where the sequence of activation amplitude is consistent with the study findings for Task D. Moreover (Teo et al., 2021), included the quantification of muscle activations in various cutting heights and discovered that the activation of upper and middle trapezius was highest in Task B (tool: chisel), despite the lower pruning height (<3 m) than Task D. The results revealed the importance of evaluating the palm cutting tasks using different cutting tools, techniques, and heights, to better portrays the physical efforts in the palm harvesting environment.

In addition to REBA and muscular effort, biomechanical evaluation consisting of the L5-S1 lumbar compression forces and shear forces were estimated to evaluate the risk of developing low back disorders associated with WMSDs. The compression force values were compared to the commonly used NIOSH safety limits, which is a generalised safety limit during lifting to prevent low back disorders (Waters et al., 1993). Low back pain is prevalent among workers in the palm plantation sector, particularly the harvesters (Henry et al., 2015; Tewtow et al., 2019; Bhuanantanondh et al., 2021). This study revealed that the harvesters sustained strenuous compressive forces on the L5-S1 joint during all tasks despite the static estimation from 3D SSPP. The burden exerted on harvesters' L5-S1 joint is expected to be larger since palm pruning activities involve repetitive movements, high muscular demands for maintaining body stability (Graham et al., 2012), as well as the frequent asymmetric postures possessed during the tasks (Zhang et al., 2022). In addition, the compressive force revealed a significant moderate correlation with the REBA score, thus reflecting that postures impact the spinal loads. Supporting the weight of the cutting tools while attempting to stabilise their bodies during the force exertion towards the frond is also crucial during the tasks, and this may lead to an asymmetric load distribution on the body.

The shear forces acting on the L5-S1 joint revealed a different pattern compared to the compression loads. Only Task D, which included pruning using a sickle, was found to have extreme shear force while all tasks employing chisels were within the safe range. In pruning using the chisel, the harvester tends to bend the trunk to cut fronds located lower than or similar to their statue height. The pruning task using a sickle requires the harvester to bend their trunk forward to apply sufficient force while pulling the cutting tool through the fronds. These situations induced high shear forces on the anteroposterior plane of the L5-S1 joint as the force of gravity acts on the upper body when bending the trunk forward (Gallagher and Marras, 2012). The lateral shear component was also accounted for in the estimated shear forces, where the lateral shear might be higher in Task D following the asymmetric alignment of the sickle while applying downward pull forces (Skals et al., 2021a). Furthermore, the externally applied forces, such as the vertical pulling forces and the weight of the cutting tools, may contribute to the extreme shear forces of Task D since externally applied forces could induce extra shear loadings to the L5-S1 joint (Kingma et al., 2007). The event is supported by the highly correlated results between the shear force and cutting force ($r = 0.879$, $p < 0.001$), where using a sickle demanded a high cutting force and imposed high shear forces on the lumbar.

High compressive and shear forces may cause low back disorders, which may be exacerbated in the case of repeated loadings (Gallagher and Marras, 2012; Kingma et al., 2007). Excessive compression and shear forces can be minimised by preventing full spine flexion and emphasising more on bending the knee when maintaining the trunk or torso as straight as possible while applying manual exertion to cut the fronds. A previous in vitro study (Gallagher et al., 2005) reported that the tendency of failed compressive load cycles increased as the torso flexion increased, indicating that a high degree of torso flexion may reduce the spinal tolerance compared to compressive forces. Factors involving upper body weight (Ghezelbash et al., 2020), the asymmetrical position of the cutting tools with respect to the body (Behjati and Arjmand, 2018), and the direction of cutting force applied (push or pull forces) may also affect the spinal loads (El Ouaaid et al., 2018). Overall, the findings quantitatively suggested that palm pruning tasks exposed the harvesters to a high risk of experiencing WMSDs with repetitiveness, forceful manual force exertion, and awkward posture as the causative factors.

Besides quantitative measurement, a qualitative investigation using a specified pain questionnaire was conducted for each harvester in all pruning tasks. The harvesters experienced moderate pain in all specified body regions. Pain at the neck (RUT) may result from extreme neck postures while looking at the target (Ng et al., 2013). Conversely, pain in the upper arms and shoulder (RBB, LBB, RMD, LMD, and MT) was associated with the extensive push and pull force along with the extreme shoulder angles while aiming and cutting the fronds (Bhuanantanondh et al., 2021). Meanwhile, low back pain (RES) was caused by the standing working conditions and the repetitive, unnatural trunk postures while performing the tasks (Sukadarin et al., 2016). It was also found that muscle activations significantly influenced the pain experienced by harvesters, where a higher activation led to higher pain intensity. All muscle regions obtained a significantly strong positive correlation between the reported pain scores and the muscle activations. No investigated body regions surpassed the moderate pain level. The unexaggerated pain can be attributed to factors influencing muscle fatigue or pain, such as the task duration (Merino et al., 2018), the intensity of the task (Iguchi et al., 2008), repetitive actions (Chowdhury et al., 2013; Luca, 1997), rest interval (Nogueira et al., 2012; Sarker and Mirka, 2020), and awkward postures (Kamat et al., 2013). Despite including repetition factors, high physical tasks, and awkward postures, this study was conducted for a short time, hence neglecting the prolonged task duration that may induce even higher pain. Overall, the physiological fatigue through the assessment of pain scores demonstrated a high tendency of experiencing muscle pain with the prolonged activation of muscles during the task.

Through an in-depth quantitative investigation, this study provides empirical evidence of the risks experienced by palm harvesters during palm pruning. Palm pruning exposes harvesters to awkward postures resulting in very high-risk ergonomic assessment scores, spinal compression forces that exceed safety limits, and high muscle activation that strongly correlates to reported pain scores. Evidently, cutting height and tool selection require distinct cutting forces and produce different ergonomic effects on the harvester. These conditions highlight the benefits of selecting the appropriate tools and methods for palm pruning, including the urgency of reducing the risk of developing WMSDs among palm harvesters. Based on the high-risk body movements results, interventions can be planned to manage the prevalence of WMSDs in the palm harvesting field.

Ergonomic interventions for working postures can be implemented by practising proper body mechanics during the harvesting tasks. The harvesters can be properly trained on correct harvesting postures based on the findings on extreme working postures, muscle usage, and burden in the low back region at different cutting heights and tools. For instance, a neutral trunk posture induces lesser compression force and ergonomic risk compared to a flexed trunk position. Cutting tools can also be modified to reduce high muscle effort and body load. The use of lightweight materials, such as composites for poles can reduce the total weight of the tool, thus reducing the burden of manoeuvring it from one target area to another. Cutting tools with comfortable grips and lightweight designs may also reduce the risk of musculoskeletal injuries, such as strains and sprains.

Several limitations of this study should be noted. Since this study was conducted with the subject standing on flat force plates, the coverage area of pruning was restricted only around the force plates. Nevertheless, the condition still allows the harvesters to perform the task as they would in normal practice. However, it eliminates the need to walk around the palm tree in search of fronds and adjusts the body posture to navigate through the short palm canopy, which may slightly reduce the time taken and risk score compared to a real palm plantation working environment. Likewise, the low back compression and shear forces in the real palm plantation activities could probably be greater than the present results, considering the canopy pattern of the plantation, which might demand a more extreme posture. Additionally, the calculation of loads acting on the L5-S1 joint was based on the static assumption, where the dynamic effect was neglected, especially the impact of acceleration and repetition. Next, the sampling of harvesters was also limited to males based on their availability and Malaysia's palm plantations profile, which are dominated by males, particularly for harvesting tasks (Yusof and Lumpur, 2021; Amkaromi, 2020). Thus, research on palm harvesting in Malaysia has primarily focused on male harvesters (Ng, 2015; Ng et al., 2013; Sukadarin et al., 2016; Mohd and Harith, 2018; Hani et al., 2016).

Magnetic disturbance from the surrounding environment (metal poles and computers) may have caused a drift in the measured kinematic data, a known issue in using IMU units (Skals et al., 2021b; Schall et al., 2016). However, the developers of the Xsens system have taken steps to address the issue of drift during measurements. This was accomplished by using an advanced Kalman filter and a post-processing tool within the software that enhances the consistency and precision of kinematics estimation (Schepers et al., 2018). As a precaution to minimise drift, frequent calibrations of the Xsens systems were performed for each task, when necessary, by the experimenter based on real-time data from the Xsens software. No noticeable distortions were observed in the real-time avatar or motion graphs during the tasks.

Despite the aforementioned limitations, this study also contains several strengths. The present research is the first attempt to measure harvesters' hand forces during palm pruning activities under an actual field condition. Instead of simulating the scenario in a laboratory setup, the actual field measurement may provide a logical and real estimation of the force required to be applied by a human for cutting the palm fronds. Furthermore, the findings complemented the limitations of previous qualitative risk evaluations of palm harvesting by quantifying the risk factors through the incorporation of advanced tools for human dynamic analyses. Apart from providing an individual risk score, the analyses yielded a comprehensive perspective of the postural angles, muscle activation pattern, lumbar loadings, and continuous ergonomic risk scores. Notwithstanding the limitations, the study framework could elucidate the risks experienced by palm harvesters in real-life or actual working conditions.

5. Conclusion

For any pruning tasks, the prevalence of WMSDs among the harvesters was proven with the risk factors of repetitive movements and extreme postural angles. The ergonomic analysis revealed a high-risk peak REBA score for all tasks, regardless of the cutting tools, technique, and height employed during the tasks. Because of these extreme postures, the harvesters were exposed to WMSDs, especially at the upper extremities, such as the neck, shoulder, and trunk. As for the L5-S1 joint, the maximum compressive forces in all tasks and shear forces during pruning using the sickle exceeded the tolerance limits for avoiding low back disorders. This result suggests a high possibility of the harvesters experiencing WMSDs related to low back pain. In the muscle evaluation, all investigated muscles were actively used in cutting activities, with most cutting tasks required a high muscle activation. Furthermore, the qualitative evaluation of body pain reflects that the intensity of muscle usage can induce pain in the muscle area. Generally, the findings revealed the urgent need for ergonomics intervention to alleviate the risk exposure and lessen human dependency on palm harvesting activities.

CRediT authorship contribution statement

Nadiah Aqilahwati Abdullah: Methodology, Software, Formal Analysis, Investigation, Writing-Original draft preparation, Visualization. **Mohamad Nazhan Mohamad Shaberi:** Software, Methodology, Formal Analysis, Investigation. **Muhammad Nor Akmal Nordin:** Software, Methodology, Formal Analysis, Investigation. **Zaidi Mohd Ripin:** Supervision, Conceptualization, Methodology, Writing-review and editing. **Muhammad Fauzinizam Razali:** Supervision, Conceptualization, Methodology, Writing-review and editing. **Wan Mohd Amri Wan Mamat Ali:** Conceptualization, Methodology, Resources. **Baharom Awang:** Conceptualization, Methodology, Resources. **Mohamad Ikhwan Zaini Ridzwan:** Project administration, Conceptualization, Methodology, Writing-review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ergon.2023.103468.

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