Original Article

Ergonomic Hose Roller Tool for Firefighter: Design, Fabrication, and Fatigue Study

Mohammad Luqman Hakim Bin Mustapha,[1] Salwa Mahmood,[1] Helmy Mustafa El Bakri,[1] Ismail Abdul Rahman,[2] Mohd Rizal Buang[3],

[1] *Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Campus Pagoh, 84600 Panchor, Johor, Malaysia*
[2] *Ergonomic Excellence Centre, National Institute of Occupational Safety and Health (EEC, NIOSH), Southern Regional Office, Taman Teknologi Johor, 81400 Senai, Johor, Malaysia*
[3] *Bahagian Perancangan dan Penyelidikan, Pusat Penyelidikan Kebombaan, Lengkok Teknologi Bandar Enstek, 71760 Nilai, Negeri Sembilan.*

Corresponding author: msalwa@uthm.edu.my

Article history

Received 30/08/2024
Accepted (Panel 1) 22/10/2024

ABSTRACT: *The safety and health of firefighters are vital considerations during physically intensive tasks like hose rolling. Prior research has identified that firefighters face significant ergonomic risk factors (ERFs) and a heightened risk of developing low back disorders (LBDs) due to awkward postures, static positioning, vibrations, forceful exertions, and repetitive motions during hose rolling activities. This research proposes an ergonomic hose roller design aimed at reducing LBD risks. The study conducts a fatigue analysis to determine the effectiveness of the newly designed tools in mitigating ERF and LBD risk. The Industrial Lumbar Motion Monitor (i-LMM) equipment was used in this research to measure the LBD risk value from lumbar spine motions. The equipment, which comprises body harnesses with spinal area motion sensors, is worn by firefighters during hose rolling. Data from these sensors can be captured and evaluated using BALLET software, providing insights into spinal loading and postural strain during hose rolling activities. Results show that the manual hose rolling method poses a 57.67% risk of LBD, whereas the ergonomic hose roller tool significantly reduces this risk to 27%. The LBD risk data were statistically analyzed using the Design of Experiments (DOE) method to identify critical variables influencing the design's effectiveness. This research offers a novel approach by incorporating ergonomic considerations into firefighting equipment design, with the potential to greatly reduce LBD risks and improve the well-being of firefighters. The ergonomic hose roller presents a significant advancement in firefighter safety by addressing both physical and ergonomic risks associated with hose rolling operations.*

Keywords: *Ergonomics, Low Back Disorders, Hose Roller, Firefighter*

1.0 INTRODUCTION

Prior to the introduction of mechanical tools, firefighters typically employed the two-man hose-roll technique, which was originally thought to safeguard their lower backs. However, this technique still required firefighters to assume awkward postures, which can lead to musculoskeletal disorders (MSD) [1]. The fire station normally operates for 24 hours and requires two shifts; the 12- and 24-hour shifts involve the maintenance of vehicles and rescue equipment, emergency training, rescuing victims, and attempts to salvage the content of buildings [2]. Data from the Social Security Organization (SOCSO) revealed a significant increase in reported MSD among Malaysian workers and employers, with cases increasing from 10 to 675 between 2005 and 2014 [3]. The incident related to manual handling activities also led to a rise in the number of MSD cases from 2009 to 2014 [4]. According to a recent study by a Canadian urban fire association, MSD occurrence was higher at stations (30.8%) and training locations (27.7%) than during fire or non-fire emergency responses (both at 18.2%) [5]. These findings are expected to increase awareness in Malaysian workplaces.

To create awareness among firefighters regarding MSDs, this study proposes the design of an ergonomic hose-rolling tool that is lightweight and easy for firefighters to operate. To effectively execute the fabrication process, it is essential to select superior tools, operating systems, and materials that are both robust and user-friendly. This study also aims to evaluate the efficiency of the hose-rolling system during fatigue analysis by utilising Industrial Lumbar Motion Monitor (i-LMM) tools, which can be assessed using the BALLET software. The efficiency and safety measures of firefighting tools are the most important factors influencing firefighter performance.

Other issues that firefighters have encountered during operations include inefficient tools that required a long time to operate. To achieve optimal functionality, hose-rolling tools must be designed with suitable dimensions and weights that allow effortless handling and space-efficient storage [6]. Previous studies have shown that aluminum is recommended as the main material for research owing to its light weight, durability, and ease of casting [7]. This study explored the construction of hose-rolling machinery to mitigate the risks encountered by firefighters in their operational and inspection tasks.

However, most existing research has rarely conducted fatigue analyses regarding fabricated tools [1]. As part of the fatigue analysis, this study analysed the efficiency of the fire hose roller in reducing ergonomic risk factors (ERFs) and low back disorders (LBD) risks by obtaining the percentage of LBD chances using i-LMM tools and BALLET software. The data obtained from the fatigue study were analysed using the Design of Experiments (DOE) method, a statistical tool that enhances data accuracy and clarity, to analyse the LBD risks across different hose-rolling methods.

2.0 MATERIALS AND METHODS

Aluminum is used as the main component in the fabrication of the hose roller tool; it is as durable as mild steel, lightweight, and matches the characteristics of ergonomic tools [13]. Building on the findings of earlier research, enhancements to the hose roller tool have also been implemented, emphasising the use of durable, weather-resistant, and corrosion-proof materials in its construction. Additionally, the incorporation of polyurethane wheels enhances the longevity and movement stability of the hose roller. Testing protocols were executed to confirm the effectiveness of the tool in fatigue analysis.

The testing procedure was essential for determining whether the developed hose roller tool could support the weight of the fire hose. In addition, drawing the hose roller tool is important for guiding the entire fabrication and its improvement process. The hose roller tool design was illustrated using SolidWorks software. The average chance of potential LBD danger for firefighters was calculated using fatigue analysis under several hose-rolling methods and conditions. To obtain more accurate data regarding LBD risks, the DOE statistical method was applied. A methodological flowchart of the current study is shown in Figure 1.

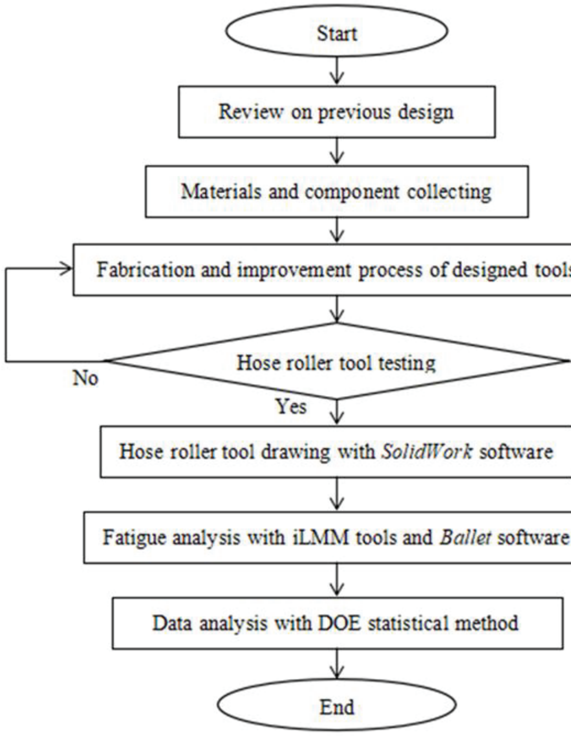

Figure 1: The Methodology Flowchart of the Project

2.1 Fabrication

Since most the components and materials of the ergonomic hose-rolling tool are made of aluminum and steel, metal fabrication techniques form the core of the hose roller production process. Metal fabrication, which refers to the procedure of casting or moulding a raw or semi-finished metal workpiece, involves processes such as forming, shaping, bending, and cutting. When fabricating hose rollers, fitting and shaping are more preferrable than welding. This is because welding may result in a permanent junction, making hose roller maintenance virtually impossible. The design proposed in a previous study is used to develop the outer and inner hose roller systems [8–10].

Fabricating a tool for fire hose care requires the use of high-efficiency materials and tool systems; otherwise, it could lead to potentially dangerous circumstances for consumers. The adoption of specialised tools and equipment engineered to decrease the physical exertion required for heavy lifting and handling lowers the risk for firefighters during hose-rolling operations. The revised hose roller tool features an adjustable height of 920–1200 millimeters and a width of 450 mm, including the tires, marking an increase from the original design's fixed height of 840 mm. This prevents consumers from bending or adopting awkward postures while operating the tools. In addition, the diameter of the hose roller hook was too small to produce a tidier-rolled fire hose. The fabrication process of the hose roller included the shaping, fitting, and application of bolts and nuts, as shown in Figures 2.1–2.3.

Figure 2.1: The Result of an Aluminum Sheet After Being Shaped Using Grinder During Fabrication

Figure 2.2: The Fitting Task of Shaped Aluminum Sheet Using a Bracket and a Rivet

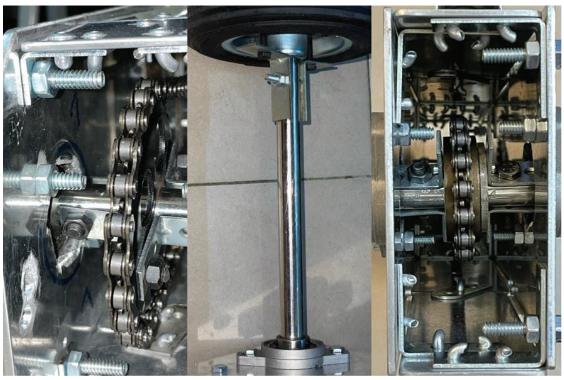

Figure 2.3: The Application of Bolts and Nuts Respectively During the Fabrication Process

2.1 Fabrication

The hose roller tool testing process was carried out to determine whether the tool was capable of rolling the fire hose smoothly and tidily in preparation for fatigue analysis. The hose roller tool was tested by firefighters at Pagoh Fire Station. The ability of the hose-rolling tool to accommodate the weight, size, and conditions (dry and wet) of the fire hose during hose-rolling was also tested. The fire hose utilised in the measuring process had a length of 30 m, a width of 10.5 centimeters, and a weight of 20 kg. The efficiencies of the tool were measured based on how well it could roll the fire hose compared to the manual method and its tidiness when rolled. The testing process for the hose roller at the Pagoh Fire Station is shown in Figure 2.4.

Figure 2.4: The Testing Process of Hose Roller at Pagoh Fire Station

2.3 Fatigue Analysis

Fatigue analysis was performed to determine the capabilities and durability of the hose roller and the probability of a firefighter being exposed to ergonomic risk while using the hose roller tool or manually handling hose rolling. Fatigue analysis is the study of a model or material's tendency to fracture. When the stress cycles are regular and lower than the normal strength, this can be achieved by applying constant-amplitude loadings [11]. Previous research has frequently used the i-LMM to assess various material-handling operations. One study focused on measuring lower back movements in different hotel room cleaning methods and established that the use of tools decreased the risk of LBD [16]. Body posture data were recorded using the i-LMM tools provided by the Ergonomic Excellence Centre, National Institute of Occupational Safety and Health (NIOSH). The i-LMM toolkit enables the evaluation of LBD risk in industrial settings by analysing body postures and the impact of dynamic movements. The i-LMM tool consists of a triaxial thoracolumbar goniometer that measures the lumbar spine motion [12] and includes the BALLET software and a set of harnesses with two attached motion sensors.

To conduct fatigue analysis, firefighters were randomly selected using i-LMM tools. This ensures the relevance of the target users, authenticity of the LBD data provided, and task-specific expertise. The study selected participants with no previous spinal trauma who conformed to standard anthropometric dimensions. Participants chosen for the study had an ideal physique, weighing 64 kg and standing 166 cm tall, with no history of medical conditions, particularly in the lumbar area, including spinal or cartilage injuries. This was done to avoid serious injuries caused by past injury experiences and to ensure that the respondents were fit for fatigue analysis.

The respondents were required to wear the harnesses with one sensor directly in line with the spine and the other on the same level as the pelvis. The iLMM tool and harness were applied to the respondents prior to the data collection process, as shown in Figure 2.5. The lift rate, average twisting velocity, maximum moment, maximum sagittal flexion, and maximum lateral velocity were measured using the motion sensors. The sensors capture position data at 60 Hz, which can be accessed via a desktop or notebook computer using the BALLET software [12]. The BALLET software was used to determine the average risk of LBD as a percentage. The collected data appeared on the BALLET program start-up screen, as shown in Figure 2.6.

Figure 2.5: The Application of i-LMM Tool

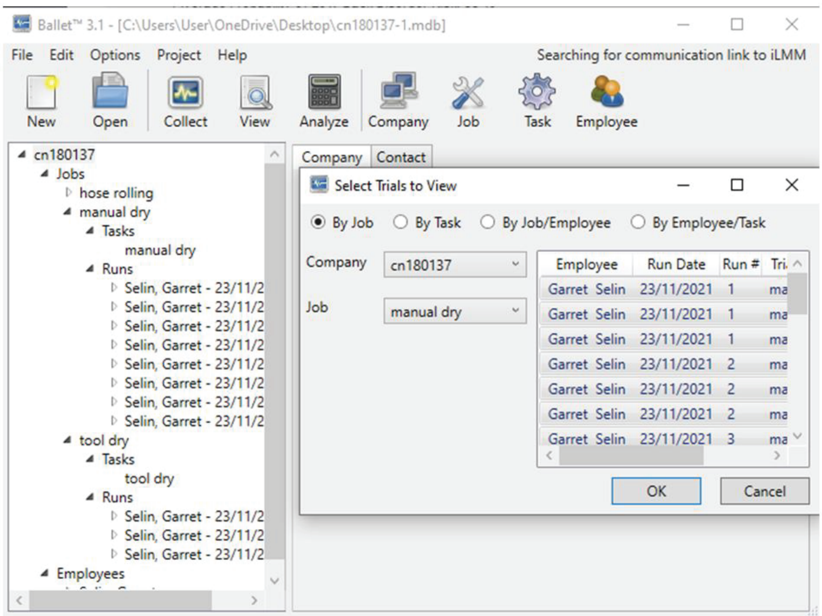

Figure 2.6: Graphical User Interface of Ballet Software Version 3.1.

2.4 Design of Experiment (DOE)

DOE provides a framework for researchers to explore how various input factors may influence the expected outcomes of their studies. When numerous factors are changed simultaneously, the DOE can discover crucial interactions that might have been overlooked if it had only tested one component at a time. Consider a three-factor, two-level, complete factorial design. Thus, eight runs were conducted. The condition of the hose, the way it was rolled, and the length of the hose are the three factors that were examined. To determine which component had the most impact on ERF uniformity, each was tested at "high" and "low" levels on the factorial. Three replicates were used for each setting to calculate the average percentage of LBD risk.

The hose length was chosen as the experimental factor because longer hoses require more effort to roll, which could increase the risk of fatigue and strain. The hose condition (wet vs. dry) was included to simulate real-situation challenges because wet hoses are heavier and more difficult to handle. The hose-rolling method was assessed to determine the effectiveness of the fabricated tool in reducing LBD risks compared with the manual method. Tool optimisation is enhanced through DOE results, which identify the key factors affecting ergonomic risk. If the hose length or technique is critical, the tool can be adjusted to accommodate different sizes or encourage safer rolling methods, thereby reducing strain and injury. The DOE factor analysis is presented in Table 1 and the DOE testing analysis in Table 2.

Table 1 Table of DOE Factor Analysis

Factors	Factors name	Level 1, Low (-1)	Level 1, High (+1)
1	Hose condition	Wet	Dry
2	Hose rolling method	Manual	Tool
3	Length of hose	Long	Short

Table 2 Table of DOE Testing Analysis

Run	Factors		
	1	2	3
1	+1	-1	-1
2	+1	+1	-1
3	+1	-1	+1
4	+1	+1	+1
5	-1	-1	-1
6	-1	+1	-1
7	-1	-1	+1
8	-1	+1	+1

3.0 RESULTS AND DISCUSSION

3.1 Fabrication

This research employs a fabrication approach that evolved from prior studies with improvements integrated into the original concept [13]. The dimensions of the produced hose roller tool differ slightly from those of the initial design. The testing process was also improved based on the fatigue analysis, which will be explained further in the next section. The dimensions of the hose roller tool were extended and made to appear larger on the hose roller hook to enable it to perform well during fatigue analysis. This also serves as a balancing mechanism for the movement of the hose-roller tool. The design of the fabricated hose roller tool was drafted using the SolidWorks software in both isometric and exploded views. The isometric and exploded views of the hose roller tool were extracted from SolidWorks software, as shown in Figure 3.1. The hose roller tool was fabricated according to the design shown in Figure 3.2.

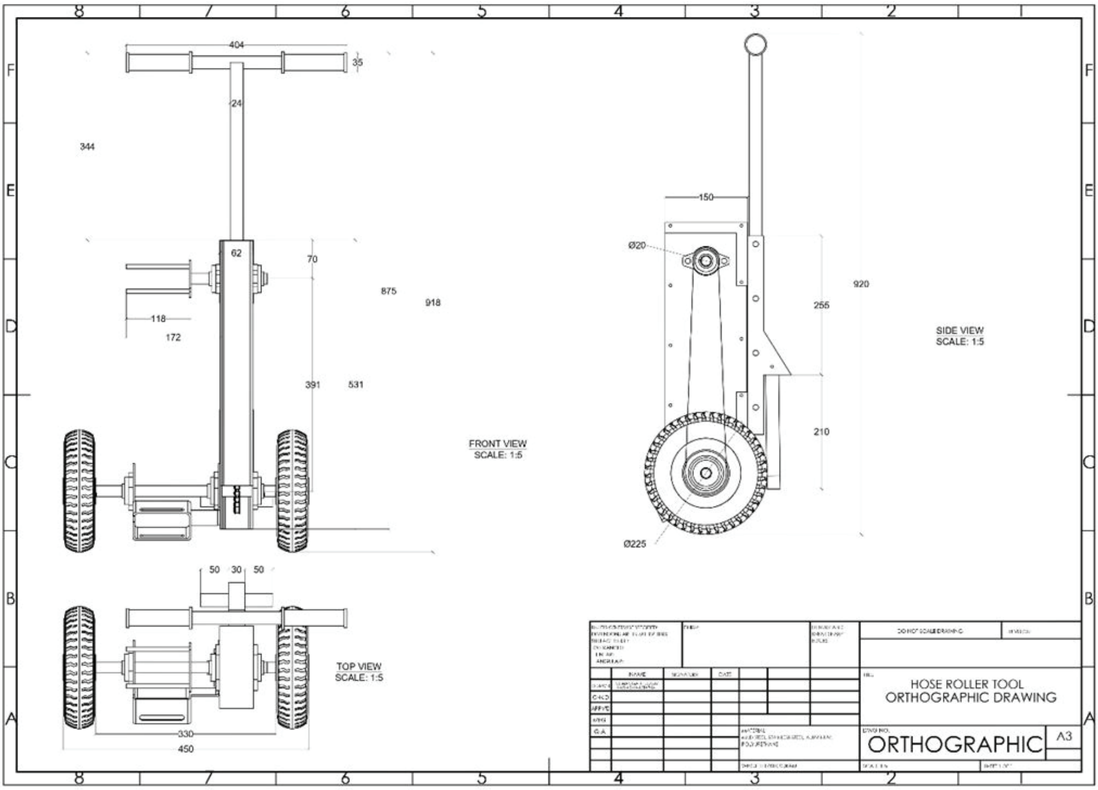

Figure 3.1: Exploded View and Isometric View of Hose Roller Tool

Figure 3.2: A Complete Fabricated Hose Roller Tool

3.2 Data Analysis

For the fatigue analysis, data were collected as two participants performed the hose-rolling task, with a third individual monitoring the process using BALLET software. Manual handling and the use of a hose-rolling tool were the two methods analysed to collect data. Each method was repeated three times, and three average probabilities of LBD risk were generated as percentages. Values such as the specifications of the hose-rolling tools and the distance between the tools and respondent must be inserted earlier to perform data collection on the BALLET program, as shown in Figure 3.3. This information was then used by the BALLET program to accurately compute the average risk of LBD.

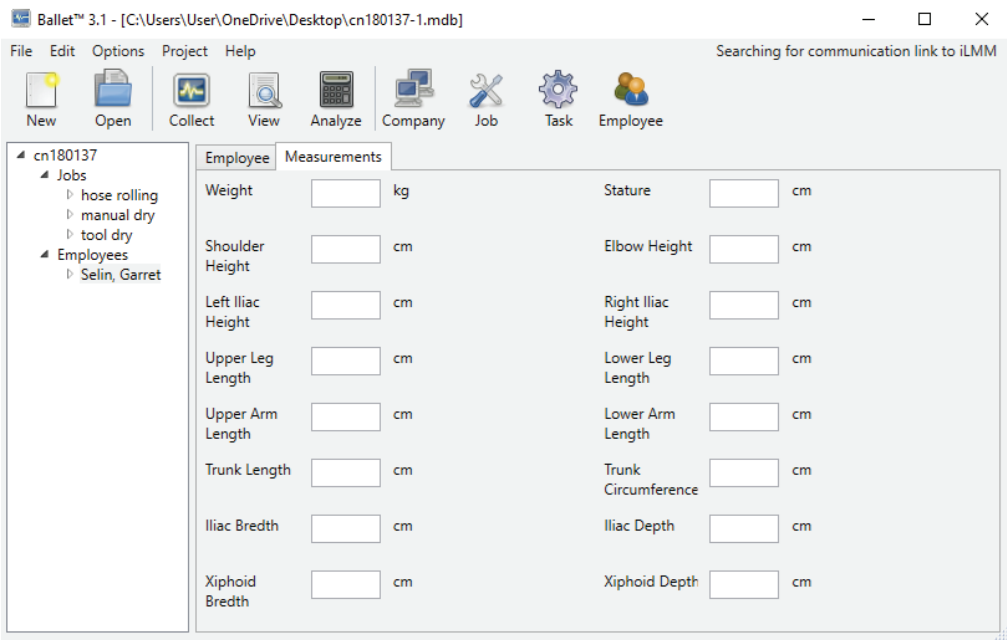

Figure 3.3: The Value Required for Hose Rolling Tool Specification in BALLET Software

Three distinct runs were performed using both methods. Three independent datasets with an average probability of LBD risk from the manual handling approach are shown in Figures 3.4–3.6. The average probabilities, expressed as percentages at the top left of each figure, were high for the manual handling method. A slight increase from 55% to 59% was observed, indicating the risk of LBD that participants encountered during the manual hose rolling procedures. Figures 3.4–3.6 feature bar charts that highlight twisting velocity, sagittal flexion, and lateral velocity as the key movement areas affecting respondent posture. This area of body posture increases LBD risk value due to actions such as repetitive motion and poor posture, especially when respondents must squat forward while manually rolling a fire hose.

Data for the hose-roller tool approach were recorded for three distinct runs. According to the statistics from the hose-rolling tool method, its average likelihood is lower than that of the manual handling approach, which ranges from 18% to 32%. The data obtained using the hose-roller tool method are shown in Figures 3.7–3.9. Based on these figures, the movement areas that affect the respondent's posture include twisting velocity, sagittal flexion, and lateral velocity. The value of sagittal flexion showed the highest increase, as the respondent's footwork was the only rapid movement among other body movements during the hose rolling activities.

Based on both hose rolling methods, the value of the LBD risk showed significant differences when the manual handling method had a higher value of LBD risk than the hose rolling tool method. In conclusion, there was a positive correlation between the duration of repetitive tasks in particular body positions and increased LBD risk values.

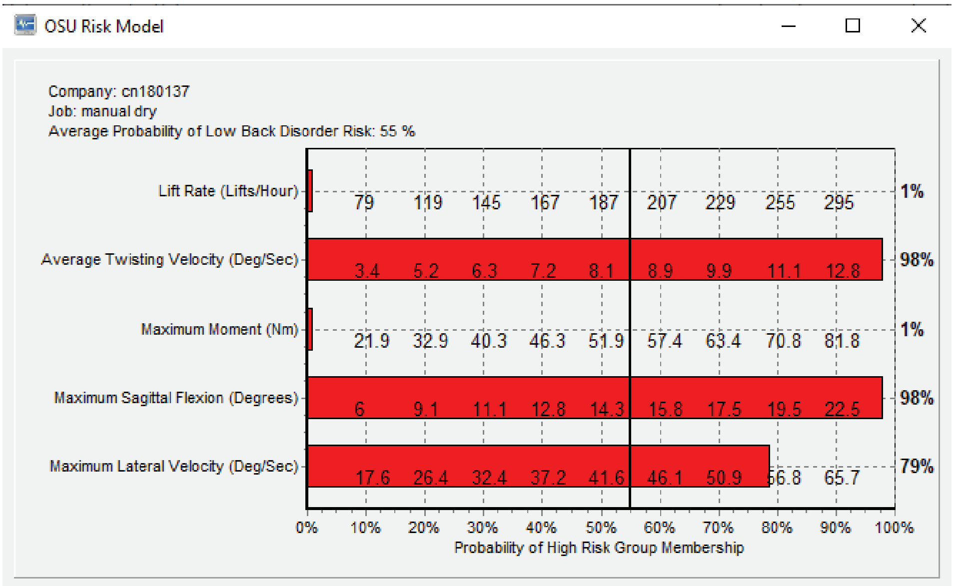

Figure 3.4: Data of Average Probability of LBD Risk on First Run for Manual Handling Method

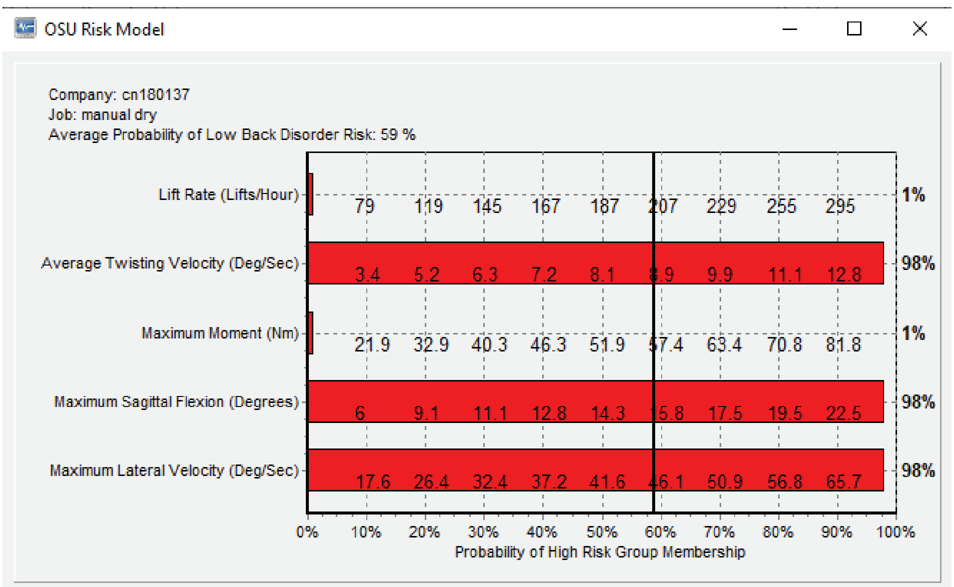

Figure 3.5: Data of Average Probability of LBD Risk on Second Run for Manual Handling

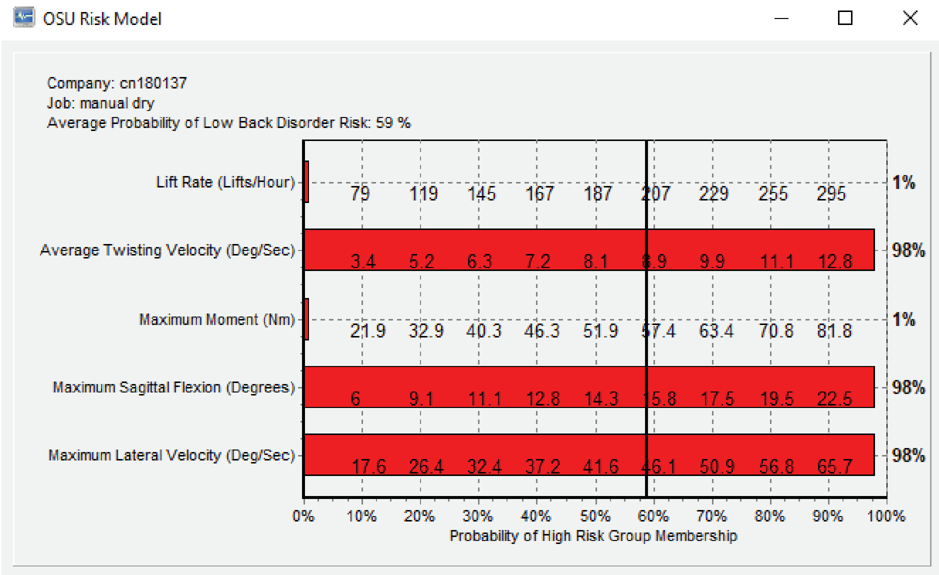

Figure 3.6: Data of Average Probability of LBD Risk on Third Run for Manual Handling

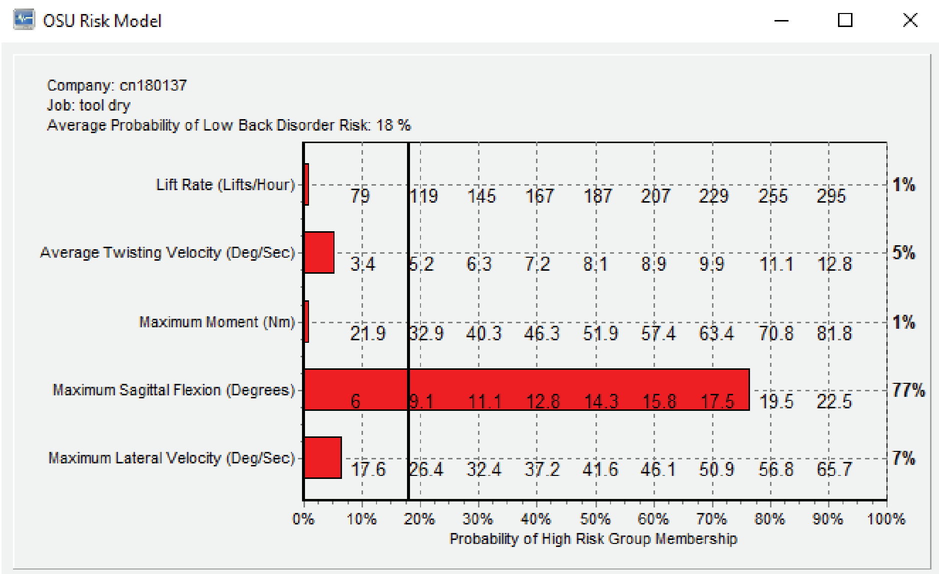

Figure 3.7: Data of Average Probability of LBD Risk on First Run for Hose Rolling Tool Method

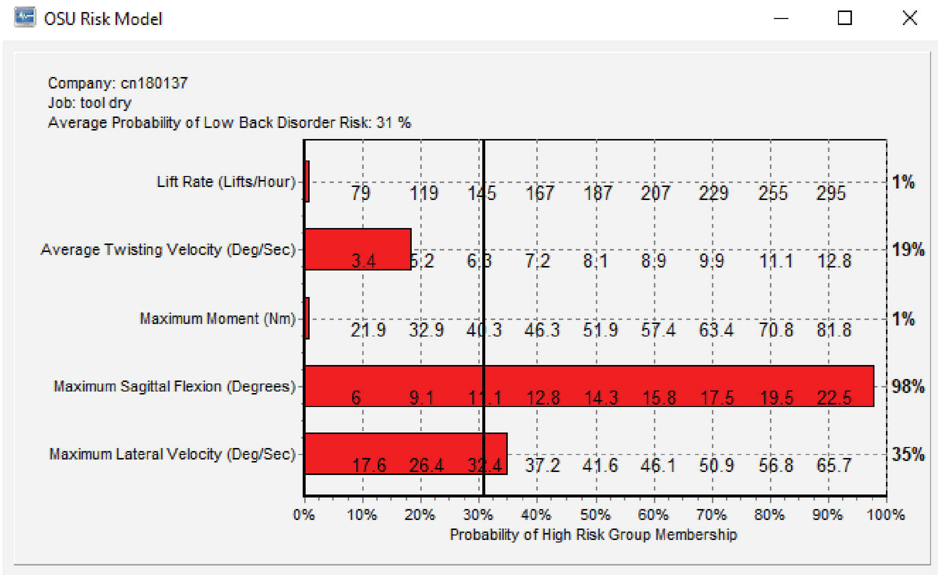

Figure 3.8: Data of Average Probability of LBD Risk on Second Run for Hose Rolling Tool Method

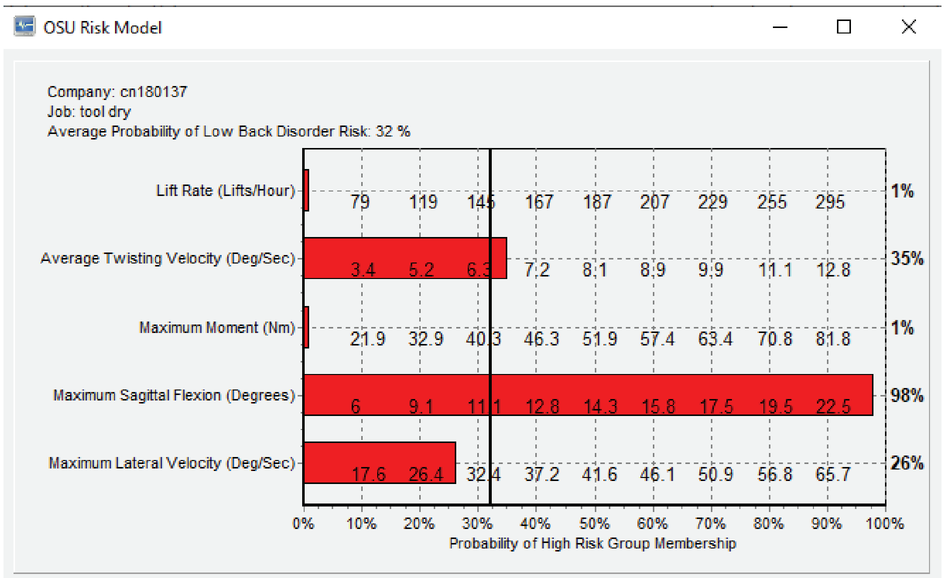

Figure 3.9: Data of Average Probability of LBD Risk on Third Run for Hose Rolling Tool Method

3.3 Data Comparisons between Manual Handling and Hose Rolling Method

A data comparison was used to evaluate the efficiency of the fabricated hose-rolling tool. Two types of hose-rolling methods were compared: manual handling and hose roller tool. A data comparison approach is used to determine the efficiency of the hose-roller tool. A comparison of the average LBD risk for each approach is presented in Table 3

Table 3 Data Comparison of Total Average LBD Risk

Method	LBD Risks (%)	Run	Total Average
Hose Roller Tool	18	1	27%
	31	2	
	32	3	
Manual Handling	55	1	57.67%
	59	2	
	59	3	

The outcomes of the LBD risk analysis using the BALLET software highlight a significant difference in exposure to LBD risks between manual handling and the use of the hose-rolling tool. Firefighters were considered at risk of LBD when the average risk value exceeded 30% [12]. Manual hose rolling showed a substantially higher LBD risk, with an average of 55–59% and an overall average of 57.67%, far exceeding the 30% risk threshold. In contrast, while the hose roller tool showed a slight increase in the LBD risk from 18% to 32%, its overall average risk remained at 27%, which was below the critical 30% limit. The increased LBD risk in manual handling can be attributed to more frequent and intense body movements such as flexing, twisting, and awkward postures, which are known contributors to musculoskeletal fatigue and injury. The data strongly suggest that manual rolling exposes firefighters to a substantially higher risk of LBD, with an overall risk percentage nearly twice the limit defined by the BALLET software.

In comparison, the hose-rolling tool proved to be a more ergonomic solution. This minimises the need for repetitive and awkward body postures such as bending and twisting and reduces the biomechanical strain on the firefighter's lower back. This was reflected in a reduced average LBD risk value of 27%, indicating that the tool could effectively mitigate the risk of injury. However, the LBD risk exceeding 30% in some instances suggests that further refinement of the tool design may be necessary. For example, enhancing the ergonomics of the tool to further reduce the need for twisting or bending could help bring all LBD risk values below the critical threshold. Additionally, user training to ensure correct posture and tool usage could further reduce exposure to LBD hazards. Overall, while the hose roller tool is effective in reducing the LBD risk compared to manual handling, ongoing improvements are needed to ensure that it consistently keeps firefighters within a safe ergonomic range during hose-rolling tasks.

4.0 CONCLUSION

The hose roller tool developed in this study successfully reduced ERF and LBD risk among firefighters when performing hose-rolling tasks. Fatigue analysis using i-LMM tools revealed that the hose roller tool significantly lowered the average LBD risk to 27% compared with the 57.67% average risk for manual handling. This demonstrates that the tool mitigates key risk factors, such as awkward postures, forceful exertions, and static positions, reducing the possibility of MSDs. The current design of the tool has proven effective in minimising physical strain and improving ergonomic safety during hose rolling activities.

However, some areas require further improvement and exploration. Future research should assess the performance of the tool under different conditions, such as wet and dry hoses, to reflect actual firefighting scenarios. Enhancements in fabrication, such as replacing rivets with bolt-and-nut fittings, are recommended to increase durability. In addition, applying the DOE method can optimise the design of the tool by testing the relevant factors at various levels. Future designs could incorporate ergonomic features such as better handle grips or motorisation to further reduce forceful exertions. A comprehensive ergonomic risk assessment using standardised techniques should also be conducted to fully evaluate and compare the effectiveness of the tool with manual methods.

ACKNOWLEDGEMENT

The authors wish to thank the Universiti Tun Hussein Onn Malaysia for their involvement in this study. This research was supported by the Ministry of Human Resources, National Institute of Occupational Safety and Health (NIOSH), under *Geran Kontrak Kementerian* Vot K447, and Universiti Tun Hussein Onn Malaysia (UTHM) through GPPS Vot Q213.

REFERENCES

Afzal, M., Kiar, M., Nazri, M., Sabar, A., Fitri, M., Halim, A., & Daruis, D. (2019). Initial Ergon Risk Assessment on Unrolling And Rolling Fire Hose Act Among Firefighter At Putrajaya Fire And Rescue Station. *Hum Factor Ergon J, 4(2)*, 53–56. Retrieved from: https://doi.org/https://hfej.hfem.org/wp-content/uploads/2019/12/Paper-9-Dian-revised-.pdf

Allread, W. G., & Vossenas, P. (2022). Comparisons of Trunk Motions and Low Back Injury Risk between Alternative Hotel Room Cleaning Methods. *International Journal of Environmental Research and Public Health, 19(22)*, 14907. Retrieved from: https://doi.org/10.3390/ijerph192214907

Benfer ME, Forssell E, Scheffey J, Hughes J (2017) "Determination of Fire Hose Friction Loss Characteristics" in Fire Technology. The Fire Prot Research Prot Res Found. Vol. 53 pp. 1059-1075.

Biodynamic Solution I (2011) Operator's Manual for Acupath Lumbar Motion Monitor with BALLET Software. 1–72

Cyprien R (2017) Guid to Fatigue Anal. Fea for all. Retrieved from: http://feaforall.com/wp-content/uploads/2017/07/Fatigue-analysis-Guide.pdf.

Examiner P, Jillions JM (2004) "Reeling Device for Fire Hoses". U. S. Pat. Retrieved from: https://patentimages.storage.googleapis.com/ae/eb/66/079721e3c7d0cd/US6811110.pdf

Gentzler, M., & Stader, S. (2010). Posture stress on firefighters and emergency medical technicians (EMTs) associated with repetitive reaching, bending, lifting, and pulling tasks. *Work (Read, Mass.), 37(3)*, 227–239. Retrieved from: https://doi.org/10.3233/WOR-2010-1075

Isamudin A, Mahmood S (2021) "Design of An Ergonomic Portable Fire Hose Roller: A Simulation Study" in Prog Eng Appl and Technol Vol 2, pp. 1016–1025 Retrieved from: http://penerbit.uthm.edu.my/periodicals/index.php/peat

Kajaks, T., Ziebart, C., Galea, V., Vrkljan, B., & MacDermid, J. C. (2023). Posture Evaluation of Firefighters During Simulated Fire Suppression Tasks. *Workplace Health & Safety, 71(12)*, 606-616. Retrieved from: https://doi.org/10.1177/21650799231214275

Kodom-Wiredu JK (2019) "The Relationship between Firefighters' Work Demand and Work-related Musculoskeletal Disorders: The Moderating Role of Task Characteristics in Safety and Health Work. Retrieved from:https://doi.org/10.1016/j.shaw.2018.05.004

Luo C, Jin J (2012) Design Feature Analysis and Pilot Ergonomic Evaluation For Protective Fire Gear. *Procedia Eng. Vol. 43 pp.* 374–378. Retrieved from:https://doi.org/10.1016/j.proeng.2012.08.065

Manap M, Amat H, Sharif S, et al (2017) Guideline on Ergon Risk Assessment at Workplace. Dep Occup Saf Health. Ministry of Human Resources of Malaysia. Retrieved from :https://www.dosh.gov.my/index.php/legislation/guidelines/ergonomic/2621-01guidelines on-ergonomics-risk-assessment-at-workplace-2017/file

Manap M, Amat H, Sharif S, et al (2018). Guidelines for Manual Handling at Workplace. Dep Occup Saf Health. Ministry of Human Resources of Malaysia. Retrieved from: https://www.dosh.gov.my/index.php

NL., I., & McCauley, P. (2012). Work-Related Musculoskeletal Disorders Assessment and Prevention. Ergon - System Approach. doi: 10.5772/37229.

Sharifah, O., Ismail, B., Kadir, A., & Wan Mohd Nor, H. I. (2012). Accident Risk Indices Of Malaysia's Firefighters Working in 12 And 24 Hours Shift Works. J Occup. Saf. Health 9, 25–30. Retrieved from https://ir.unimas.my/id/eprint/119/

Stojanovic, B., & Epler, I. (2018). Application of aluminum and aluminum alloys in engineering. Appl Eng Lett. Retrieved from: https://scidar.kg.ac.rs/handle/123456789/17545