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Firefighter Hose Rolling Method: Low Back Pain Risks Analysis with Full-Factorial Approach

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Firefighters frequently face the risk of Low back pain (LBP) due to the strenuous nature of their duties, especially during hose rolling tasks. Prioritizing their safety and health is vital. This study aimed to evaluate and compare various hose rolling techniques to lower the LBP risk in firefighters. A full-factorial approach was employed to exhaustively examine every possible combination of three key factors: the hose rolling method (conventional, mechanical, motorized), hose condition (dry, wet, dirty), and hose length (10, 20, 30 meters). Across 27 different trials, an Industrial Lumbar Motion Monitor (iLMM) was used to assess the LBP risk, which is lift rate, average twisting velocity, maximum moment, maximum sagittal flexion, and maximum lateral velocity. The study's results indicated that conventional method had the highest LBP risk at 58.22%, with mechanical rolling at 34.33%. In contrast, the motorized hose rolling method showed a significantly lower risk, averaging at 17.44%. This denotes a 40.78% reduction in LBP risk compared to conventional hose rolling method, positioning the motorized roller as the most effective and safest option among those tested. This method's efficacy underscores its potential as a viable solution for improving firefighter safety. These findings offer important insights into occupational health and safety in firefighting. The data suggests that adopting motorized hose rolling tools could significantly alleviate the physical burdens and associated health hazards firefighters face. This advancement is a critical step towards enhancing their overall safety and well-being in the field.

Keywords:
Engineering technology; low back disorders; firefighter; hose roller; ergonomics;

1. Introduction

Previously, the conventional hose rolling method has led to physical strain and hazardous situations, a concern highlighted by Gentzler *et al.*, [1]. The ergonomic hose rolling tools known as mechanical hose roller and motorized hose roller was designed to reduce the risks of lower back pain

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(LBP) among firefighters [2]. According to Katsavouni *et al*., [3], the innovation of ergonomic designed tools is to reduce physical exertion, enhance operational efficiency, and prolong fire hose lifespan. These parameters are crucial in assessing the ergonomic performance of the hose rolling tools and their impact on the safety and efficiency of firefighters. Shifting from conventional hose rolling method to ergonomically optimized tools is to enhance firefighter safety, wellbeing, and operational efficiency. This research's practical implications are highlighted through experiments conducted at Universiti Tun Hussein Onn Malaysia (UTHM), Pagoh, involving active firefighters. Their insights added valuable context to the academic findings. In summary, this study not only strives to develop specialized hose rolling tools but also provides a detailed analysis of their effectiveness in reducing LBP risks. By focusing on hose condition, length, and rolling method, it offers actionable insights that could significantly improve the well-being of firefighters, making a tangible difference in their everyday operations and long-term health. Previous study had been conducted by Karim *et al*., [4] focusing on survey among firefighter needs for hose rolling tool for reducing backpain during hose rolling activities.

The LBP risks analysis using the design of experiment (DOE) method is conducted to fill the gap in existing research. As outlined by Jankovic *et al.,* [5], DOE helps constructed structural experiment design where multiple factors and levels can be optimized. The study employs advanced tools like the industrial lumbar motion monitor (iLMM) and Ballet software, evaluating the LBP risks factors like lift rate, twisting velocity, and sagittal flexion.

A critical gap in previous research, identified by Fiodorenko-Dumas *et al*., [6], is the fatigue analysis of firefighter body posture in hose rolling operations. This research bridged the gap by examining the LBP risks analysis based on body posture of firefighters while handling the fire hose roller tools with various hose rolling methods using industrial lumbar motion monitor (iLMM) and Ballet software. This research also significantly contributes to the improvement of firefighters' long-term health by addressing potential risks of Lower Back Disorders (LBD) associated with conventional hose rolling. The application of hose rolling tools improves the firefighters body posture, reducing LBP risks during hose rolling operations. The development of hose rolling tools could also reduce the fire hose maintenance costs by minimizing friction between the fire hose and the ground surface, potentially extending the lifespan of hoses, and reducing replacement expenses. The main objective of this paper is to analyze the LBD risks of hose rolling tools methods using Design of Experiment DOE methods. The methods considered in this paper are conventional method of rolling hose, mechanical, and motorized hose rolling method.

1.1 Literature Review

This literature review aims to give an overview of earlier research and improvements in the design of ergonomic hose rolling tools, with a focus on fabricating process and LBP risks analysis regarding the ERF and LBP risks. This research had also discussed the use of software and DOE methods to be applied to optimize and evaluate the data of LBP risks.

There are five main types of LBP risk which are lift rate, average twisting velocity, maximum moment, maximum sagittal flexion, and maximum lateral velocity. Lifting process is one of the leading causes of LBP where lifting process can be considered as a common movement which worker have performed in most of industry working environment as highlighted by Fiodorenko-Dumas *et al*., [6]. Kim *et al*., [7] also inferred that lift rate activities, which are likely prevalent in roles such as emergency medical service and rescue, contribute to the increased prevalence of LBP among firefighters. Twisting in spinal area could contribute to LBP risks in numerous working field. The research conducted by Al Amer *et al*., [8], defines that he prevalence of LBP among health workers in Saudi Arabia is notably high which the key causes include work-related activities such as back twisting. Based on a study conducted by Halonen *et al*., [9] the highest cause associated to LBP risks were observed for working in twisted positions.

Sagittal flexion refers to the forward bending of the spine in the sagittal plane, which is the plane that divides the body into left and right halves. When someone bends forward, particularly at the lower back region, it involves sagittal flexion. According to Zawadka *et al*., [10] forward movement of the lower back and hip could be main factor of the low back pain risks. The study by Hira *et* al., [11] found that increased sagittal spine misalignment, specifically a larger sagittal vertical axis (SVA), was linked to higher rates of low back pain (LBP) and decreased physical performance. Lateral flexion refers to the bending of the spine sideways, towards either the left or right side of the body. This movement occurs primarily in the cervical and lumbar regions of the spine, allowing the torso to bend sideways while maintaining alignment, as stated by Edwards *et al*., [12]. A study carried out by Sadler *et al*., [13] outlined a decreased lateral flexion range, restricted hamstring flexibility, and reduced lumbar lordosis were linked to a higher likelihood of experiencing low back pain.

In LBP risk analysis conducted by Allread *et al*., [14], the iLMM is used for monitoring lumbar motion in industrial operations, providing wearable sensors to identify work conditions contributing to LBP risks. Prior to run the experiment, the iLMM tool was fitted to an experimental subject and the potentiometers were calibrated to zero as highlighted by Masharawi *et al*., [15]. The Ballet software is a tool used to analyzes LBP risks data from iLMM such as lift rate, average twisting velocity, maximum moment, maximum sagittal flexion, and maximum lateral velocity as stated by Schall Jr *et al*., [16]. SolidWorks aids in 3D modelling, allowing early identification of design issues and ergonomic concerns discussed by Mazani *et al*., [17] and Pei *et al*., [18]. These tools contribute to a holistic approach for managing and mitigating LBP risks.

DOE systematically identifies process factors and levels, reducing time and costs while optimizing outcomes. By exploring factor interactions, DOE uncovers unexpected relationships, enhancing process understanding, concerns by Durakovic *et al*., [19]. Study by Bouyahia et al., [20] using the DOE as a methodical approach highlighted that it effectively carries out the elements influencing a system's outcome to optimize procedures and experiments. The application of full-factorial method allows for the manipulation of all possible combinations of factor levels, providing a complete analysis of the experiment and precise estimation of main effects and interaction effects, stated by Antony et al., [21]. There are several types of DOEs which is response surface, fractional factorial, Taguchi, and full factorial. Compared to traditional methods, DOE minimizes tests, maximizing resource efficiency, described by. Its statistical basis ensures reliable decision-making through several types of data analysis. Across industries, DOE serves as a vital tool for improving process performance, emphasizing its indispensable role in modern research and industry, according to Jankovic *et al.,* [5].

A 3^3 full factorial DOE with 3 factors and parameters was employed by Nyabadza *et al.,* [22], resulting to each factor was tested at three levels, and all possible combinations of these levels were tested. By systematically varying these parameters, researchers could efficiently identify the most influential factors. However, its disadvantage lies in the exponential increase in experimental runs with additional factors or levels. To mitigate this, the fractional factorial designs or alternative optimization strategies was utilized, stated by Kaniapan *et al*., [23]. The Taguchi method, devised by Genichi Taguchi, optimizes system efficiency while reducing experimental trials, concerns by Hiwa *et al*., [24]. An experiment conducted by Freddi *et al*., [25], employed an L18 orthogonal array to investigate fibre parameter effects on tensile strength where it consists of system, parameter, and tolerance design phases, aiming to enhance quality and diminish variability.

2. Methodology

This section discusses the detailed process of LBP risks analysis through the evaluation of hose rolling methods which is the conventional handing, mechanical, and motorized hose rolling methods. This study was undertaken in collaboration with National Institute for Occupational Safety and Health (NIOSH) and Fire and Rescue Department of Malaysia (JBPM) in the Muar district. Therefore, the full-factorial method has been applied as design of experiment to identify the efficiencies of the hose rolling method on reducing the possibility of firefighter facing an LBP risk. The hose rolling methods was set as experimental factors with the levels to be evaluated are conventional method, mechanical and motorized hose rolling tool method. The experimental tools that were used during LBP risks analysis are the iLMM tools with Ballet software. The Ballet software is a tool used to automatically generate the percentage value of LBD risks from the iLMM tools as stated by Schall Jr *et al*. [16]. The data of body posture is collected while the firefighter equipped the iLMM tools during hose rolling operations as an experiment subject and can be assessed from the Ballet software. The LMM, or Lumbar Motion Monitor, is an exoskeleton designed to copy the movement of the T-sections in the lumbar spine, as outlined by Lee *et al*., [26].

By conducting the LBP analysis, the value of the LBP risks can be evaluated from different method of tasks. This approach played a vital role in investigating how hose rolling tools could effectively minimize the LBP risks faced by firefighters, particularly concerning the lift rate, average twisting, moment, sagittal flexion, and lateral velocity.

2.1 Design of Experiment

Compared to Taguchi method shows by Latiff *et al*., [27], in this research, each factor consists of three levels which is labelled as 1, 2, and 3. The general formula for determining the total number of experimental runs in a full factorial design is given by Eq. (1) and Eq. (2) which is the multiplication of number of levels for every factors.

$$Number\ of\ runs = (levels\ in\ factor\ 1)x\ (levels\ in\ factor\ 2)x\ (levels\ in\ factor\ 3) \tag{1}$$

$$Number\ of\ runs = 3x3x3 \tag{2}$$

There is a total of 27 experimental runs numbers conducted to cover all combinations of factor levels where each run represents a unique combination of factor levels for the three factors. The research focused on three factors, namely condition of the hose, the rolling method employed, and the length of the hose. Table 1 shows the factors involved in this research, while Table 2 presents the run numbers of DOE analysis.

Table 1
Table of DOE factorial testing

Factors		Levels		
		1	2	3
A	Hose Rolling Method	Conventional	Mechanical Tool	Motorized Tool
B	Fire Hose Condition	Dry	Wet	Dirty
C	Fire Hose Length	10-meter	20-meter	30-meter

Table 2
Table of DOE testing analysis

Trials	Factors		
	A	B	C
1	1	1	1
2	1	1	2
3	1	1	3
4	2	1	1
5	2	1	2
6	2	1	3
7	3	1	1
8	3	1	2
9	3	1	3
10	1	2	1
11	1	2	2
12	1	2	3
13	2	2	1
14	2	2	2
15	2	2	3
16	3	2	1
17	3	2	2
18	3	2	3
19	1	3	1
20	1	3	2
21	1	3	3
22	2	3	1
23	2	3	2
24	2	3	3
25	3	3	1
26	3	3	2
27	3	3	3

2.2 Industrial Lumbar Motion Monitor (Ilmm) and Ballet Software

The iLMM is a wearable device to track spinal movement, including position, speed, and acceleration where it has a built-in electrogoniometer to measure spine movement, as mentioned by Duncan *et al*., [28]. Also highlighted by Lee *et al*., [24], the device acts as a spine exoskeleton and can be worn by attaching it to the chest and waist with harnesses. The iLMM is selected as an experimental tool because it has the capacity that able to track the motion of the lumbar spine. The firefighters have been chosen as experiment subject to use the iLMM tools harnesses while performing multiple hose rolling tool method. The complete set of iLMM tool consist of two motion sensors for upper body and lower spinal, body harness and connecting cable. The positioning of motion sensors are shown in Figure 1. These motion sensors detect the LBP risk through the frequency of spinal movement and body posture. Position data are recorded at 60Hz from the sensors and can be accessed through desktop or notebook computer onto a Ballet software.

(a) (b)

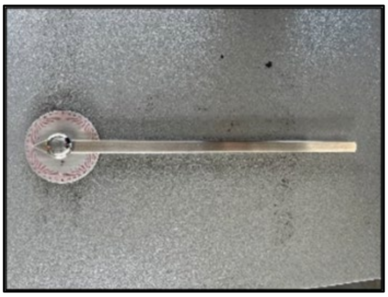
Fig. 1. The (a) iLMM tool set and (b) position of motion sensors

2.3 Initial Value for Body Position

To enable the Ballet software to generate the data on the average likelihood of lower back pain (LBP) risk, initial data on body position must be entered before the experiment begins. Figure 2 depicts the starting values for body position at the start of the experiment runs, which were recorded earlier in the experiment. Beginning values include vertical hand height, moment arm, load weight, coupling, asymmetry, duration, initial force, and activity type. A variety of measurement equipment can be used to get the appropriate results. Table 3 shows the measurement method for the first values that must be entered.

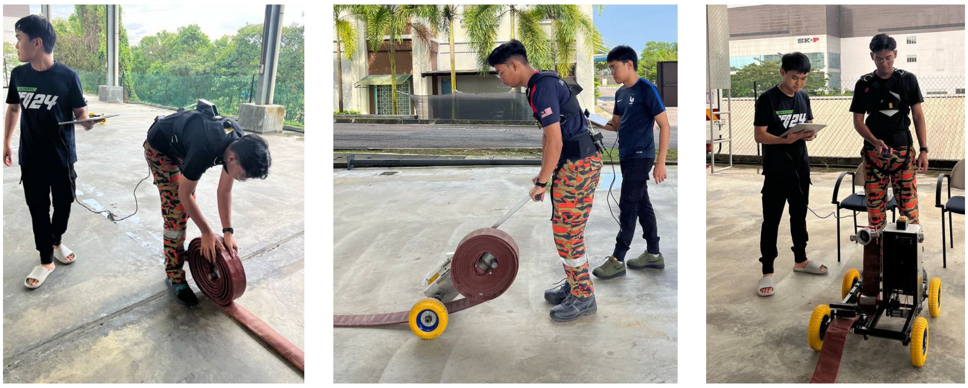
Fig. 2. Recording initials value of body posture

Table 3
The measuring process for initial value for body position

Equipment	Initial value	Application
	Vertical start	The tool was positioned at handling area and are pointed vertically downward to obtain the distance of the handling area to the ground.
	Moment arm	The tool was positioned at waist area and are pointed horizontally to the handling are to obtain the distance of the handling area to experiment subject's body.
	Asymmetry angle	The protractor was placed on either side of the waist to obtain the angle of the spinal area.
	Initial force	The force gauge was placed directionally to the load by using pushing tip. The value of force was recorded in newton (N) once the load can be pushed.

2.4 Low Back Pain (LBP) risks analysis

Data collection of this research was done by performing three types of hose rolling approaches for 27 experiment runs. Each run is then varied with different fire hose length (10, 20, 30 – meter) and hose rolling conditions (dry, wet, and dirty). Data collections are performed by two persons as depicted in Figure 3. The firefighter as experimental subjects wore the iLMM tools while performing the hose rolling operations while the other person managing the recorded data through the Ballet Software connected to the iLMM tools.



(a) (b) (c)

Fig. 3. LBP risks data collection for (a) conventional, (b) mechanical, and (c) motorized hose rolling approach

For the condition of the fire hose, the wet and dirty fire hose are set up manually as depicted in Figure 4. For the wet fire hose condition, water was filled into the fire hose and spilled onto the fire hose surface. For the dirty fire hose condition, the sand was used and spilled on the fire hose surfaces.

(a) (b)

Fig. 4. Fire hose conditions set up for (a) wet and (b) dirty

3. Result

This section presents the results of analysis and discussion related to design and fabrication of the hose roller tool, and fatigue analysis among firefighters. Reviews of existing hose roller design from previous studies provided originality and several improvements for the fabricated hose roller tool. The improvement made to the hose roller tool functionality was evaluated through testing prior to fatigue analysis. Full factorial design via DOE method was employed to conduct the fatigue analysis. This study intends to provide valuable insights into the impact of hose rolling methods on body positions and movements of firefighters during hose rolling activities.

3.1 Conventional Method

In the conventional approach, the risk of lower back pain (LBP) was generally high, with line charts showing risks between 54% and 59% as shown in Figure 5. The Ballet software maximum value of secure from LBP risks are 30% while it could record up to 60% LBD risks value [13]. By referring to Table 2, the experiment runs for the conventional approach are constructed at number 1,2,3, 10, 11, 12, 19, 20, and 21. The risk levels for handling both dry and wet hoses were identical, as indicated by overlapping lines on the chart, both consistently at 59%. This similarity suggests that this method is risky for hose rolling tasks. The risk was slightly lower for dirty hoses, ranging from 54% to 59%, possibly due to the different surface friction when the hose interacts with itself and the ground. Dirty hoses seemed to have less grip compared to dry and wet ones.

This method involved the participants arranging the hoses by hand, pressing them down to roll them up neatly. This required actions like squatting and kneeling, leading to bending and twisting of the spine, which increased the LBP risk. The findings from previous research by Mustapha *et al.*, [2] suggest that a rougher hose surface contributes to a higher LBP risk in hose rolling operations.

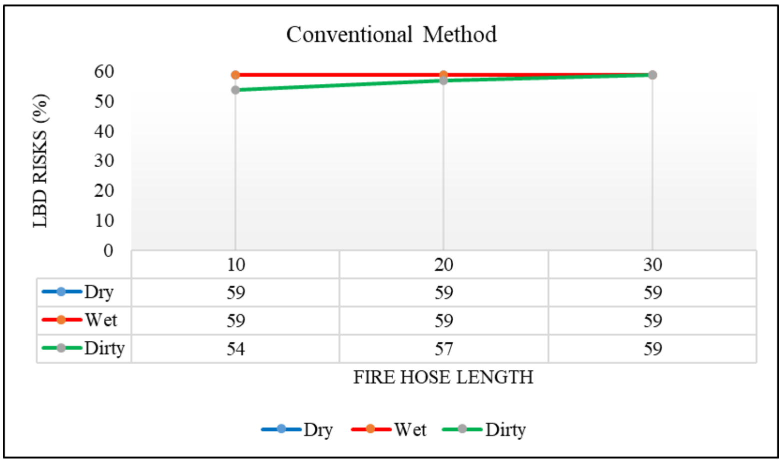


Fig. 5. Line chart of LBP risk value for conventional method

3.2 Mechanical Hose Rolling Method

Using the mechanical hose roller tool, the LBP risk values ranged from 26% to 48%, suggesting this method was still not safe for hose rolling where the maximum value of LBD risks (30%) lied between the ranged value of this approach as shown in Figure 6. By referring to Table 2, the experiment runs for the mechanical hose rolling approach are constructed at number 4, 5, 6, 13, 14, 15, 22, 23, and 24. The highest risk was with dry hoses, showing a range of 39% to 48%, followed by wet hoses with a lower risk between 28% to 38%. Dirty hoses had the lowest risk, varying from 26% to 32%. These differences may be due to how the hose surfaces interact with both the mechanical tool and the floor.

The dry hose, having the roughest surface, created more friction as it moved across the floor and through the roller tool. In contrast, the dirty hose, which became sandy over time, had less friction compared to the sticky wet hose. This method still required the research participant to bend slightly, especially when pushing the dry hose through the roller, leading to more spinal bending. From this, we can infer that a rougher hose surface increases the LBP risk during this task.

The inconsistent LBP risks value between variation of fire hose length shows the length of the fire hose barely affecting the operations of hose rolling. This can be relating with the similar amount of spinal movement and workloads for experiment runs of each fire hose length. This can also be concluded as regardless of the length of the fire hose, the LBP risks value are more likely affected by the method of hose rolling and the fire hose conditions compared to the fire hose length.

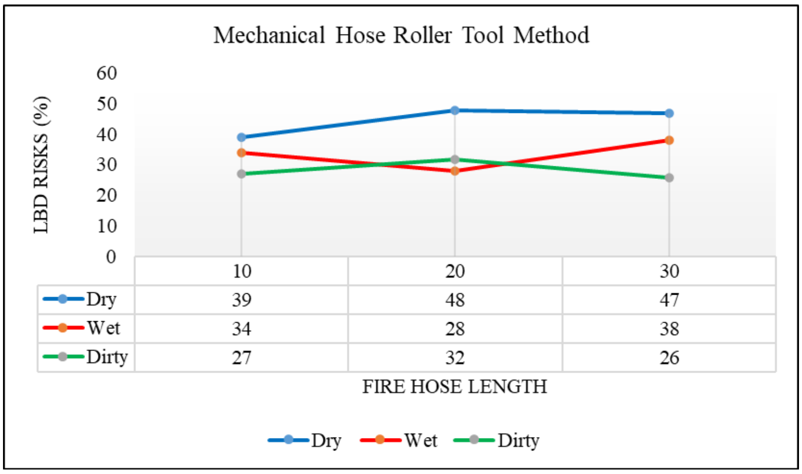


Fig. 6. Line chart of LBP risk value for mechanical hose roller tool

3.3 Motorized Hose Rolling Method

For the motorized hose roller tool method, each line chart was below 30% of LBP risks probability scale. Thus, this method was considered free from LBP risks and suitable for hose rolling operation. By referring to Table 2, the experiment runs for the motorized hose rolling approach are constructed at number 7, 8, 9, 16, 17, 18, 25, 26, and 27. Wet hose conditions showed the highest LBP risk value ranging from 24% to 28%, followed by dry hose condition with lower LBP risk value ranging from 10% to 20% as shown in Figure 7. The LBP risks value for dirty fire hose condition remained the lowest in the experimental runs, varying from 9% to 17%. These results were attributed to the friction between the surfaces and weight of the fire hose. Wet fire hose was the heaviest when rolled as the water trapped inside the fire hose also needed to be removed during rolling.

The line chart for wet fire hose also decreased throughout the experiment, indicating the amount of water removed from it. Research subject may struggle to hang and select the fire hose on the motorized hose roller tool before and after hose rolling activity. The dry fire hose appeared to be lighter than the dirty and wet hoses, but it still had higher LBP risk value compared to that of the dirty hose. This could be because the dirty hose turned sandy and slicker after a few seconds, causing the motorized hose roller tool to travel shorter distance. This method only required the research subject to walk certain distances to retrieve the fire hose from the motorized hose roller tool. Based on the observed line chart, it can be concluded that the less friction generated by the motorized hose roller tool causes shorter time taken to complete the rolling regardless of the weight of the fire hose.

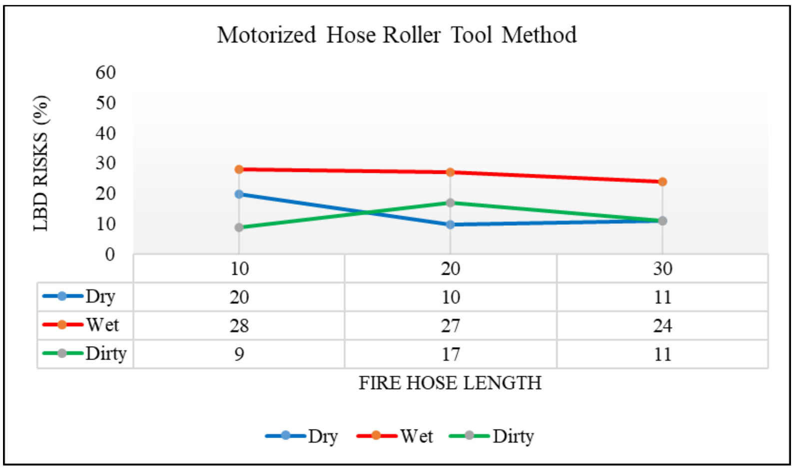


Fig. 7 Line chart of LBP risk value for motorized hose roller tool

3.4 Data Comparison

This data from LBP risks analysis was collected using the Ballet software. The total average probability of LBP risk for each hose rolling method was calculated by adding the probabilities for all three conditions (total of dry, wet, and dirty) and divided by the number of conditions (3). Eq. (3) shows the calculation of LBP risks for 10-m hose length for conventional hose rolling.

$$LBD\ risks\ = \frac{59\%\ (Dry) + 59\%\ (Wet) + 54\%\ (Dirty)}{3} = 57.33\% \tag{3}$$

The overall average probability of LBP risk for the three methods was also calculated by adding the average probability values for each hose length and divided by the number of hose lengths. The calculation for conventional hose rolling method is shown in Eq. (4).

$$LBD\ risks\ = \frac{57.33\%(10-meter) + 58.33\%(20-meter) + 59\%(30-meter)}{3} = 58.22\% \tag{4}$$

Based on the gathered data, it is evident that the conventional method of hose rolling presents a significantly higher risk of LBP compared to the alternative methods tested. Specifically, the conventional method showed an average probability of LBP risk at 58.22%. In contrast, the mechanical hose roller tool method demonstrated a lower, yet still considerable, LBP risk of 34.33%. This percentage is notable as it surpasses the 30% threshold, which is identified as the critical point for LBP risk in this context.

However, the most compelling results were observed with the motorized hose roller tool. This method consistently showed the lowest average probability of LBP risk across all nine experimental runs, registering at only 17.44%. This figure not only falls well below the critical risk but also indicates that the motorized hose roller tool is significantly effective in reducing LBP risk, reduced it by 40.78% compared to conventional methods.

These findings, including a detailed comparison of the LBP risk associated with each hose rolling method, are systematically presented in Table 4 of the research document. The data underscore the effectiveness of the motorized hose roller tool in minimizing the risk of LBP among firefighters, highlighting its potential as an ergonomic and safety-enhancing tool in firefighting operations.

Table 4
Data comparison of LBP risk for all hose rolling methods

Method	Fire hose length (meter)	Fire hose conditions Dry (%)	Wet (%)	Dirty (%)	Total average probability of LBP risks
Conventional method	10	59	59	54	58.22 %
	20	59	59	57	
	30	59	59	59	
Mechanical Hose Roller Tool	10	39	34	27	34.33 %
	20	48	28	32	
	30	37	38	26	
Motorized Hose Roller Tool	10	20	28	9	17.44 %
	20	10	27	17	
	30	11	24	11	

4. Conclusion

In conclusion, this research has advanced the understanding of LBP risks among firefighters by employing a full-factorial DOE method. Through systematic analysis of various factors affecting hose rolling, such as hose condition, length, and rolling method, valuable insights into ergonomic challenges have been gained. The DOE method allowed for a thorough examination of these variables and their interactions, leading to data-driven conclusions on reducing lower back strain during hose rolling. These findings are not only theoretically robust but also applicable in real operation situation, aiding in the development of firefighting equipment prioritizing firefighter health and safety.

The research establishes a clear link between specific operational activities and LBP risk, paving the way for broader ergonomic innovations in firefighting. It highlights the importance of a scientific approach to occupational safety, setting a precedent for future studies in high-risk professions. Based on the experiment conducted, the conclusion regarding which method imposes the highest risk to firefighters is the conventional method. The experiment identified the conventional method posing the highest risk to firefighters due to the value of LBP risks recorded which is 58.22%. This method also demonstrated a significant risk gained of 40.78% compared to the safest methods, motorized hose rolling approach.

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