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DESIGN AND EVALUATION OF SINGLE-STAND CHAIRLESS EXOSKELETON FOR STANDING AND SITTING TASKS

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Abstract

With the advancement of assistive technology, numerous chairless exoskeletons have emerged in the market, enabling users to perform tasks in standing and sitting postures. However, design information of the chairless exoskeletons, particularly on the structural strength, user's muscle contraction, contact pressure and usability, are scarce, which influences the user acceptance of the devices. This study aimed to determine the user's requirements and develop a single-stand chairless prototype exoskeleton. The prototype was compared to a double-stand chairless commercial exoskeleton to evaluate its mechanical compression strength, muscle contraction, contact stress, and system usability scale (SUS). A questionnaire survey was performed among 103 operators of manufacturing industries to determine the user's requirements for a chairless exoskeleton. Ten subjects participated in muscle contraction, contact pressure, and SUS studies. A chairless exoskeleton's most required design feature was 'ease of use.' Muscle assessment quantified a significant reduction of contraction in the lower limb muscles (P-value < 0.05) when wearing the single-stand chairless prototype exoskeleton. Furthermore, the contact pressure under the thighs was eliminated when sitting on the single-stand chairless prototype exoskeleton. The usability study revealed an average SUS of 79.5, defining a better usability of the single-stand chairless prototype exoskeleton, compared to a SUS of 67.3 for the double-stand chairless commercial exoskeleton. The authors concluded that the single-stand chairless prototype exoskeleton effectively minimises muscle fatigue and contact stress as well as improves usability for sitting and standing tasks. This comprehensive design information is undoubtedly helpful for designers to improve user acceptance of the devices in industrial applications.

Keywords: Ergonomics, Exoskeleton technology, Manufacturing industry, Usability, Wearable assistive device.

1. Introduction

Most tasks in the manufacturing and service sectors require workers to perform them in standing or sitting postures. For example, electronics and automotive assembly operators must stand throughout working hours. In service sectors, professionals like cashiers and nurse practitioners spend most of their working hours standing. According to the U.S. Bureau of Labor Statistics, on average, nurse practitioners must stand 61 percent of the workday [1]. Sitting posture requires less muscle effort, but that does not exclude sedentary workers from the health risks. Occupations such as clerks and telemarketers spend much of their time sitting. On average, accountants and auditors must sit for 91 percent of the workday [1]. Static posture combined with prolonged standing or prolonged sitting increases the risk for musculoskeletal disorders (MSDs). The Health and Safety Executive (2021) recorded 370,000 cases of self-reported MSDs in Great Britain. In 2018, there were 272,780 MSDs cases in the U.S. private sector [2].

In recognition of the adverse health caused by prolonged standing and prolonged sitting, one of the good practices to minimise the risk of MSDs is to alternate the sit, stand positions, and move the body to prevent static posture during working hours. A study found that intervention of sitting, standing and walking significantly reduced body discomfort compared to continuously sitting and standing throughout working hours [3]. In the advancement of assistive technology, inventors developed a device known as a chairless exoskeleton to enable workers to perform tasks in standing, sitting and moving at the workplace. An exoskeleton is a mechanical device worn by human to augment strength, enhance body motion, supports posture, or assist physical activity.

Abundant published studies highlighted that ergonomics interventions using a chairless exoskeleton is helpful in minimising muscle fatigue associated with prolonged standing [4-7]. Lately, many chairless exoskeletons emerged in the market and have been deployed by manufacturing industries to enable their workers to perform tasks in standing and sitting postures. The high-end chairless exoskeletons include Archelis, ExoChair, and Noonee Chairless Chair [8]. Notably, there are non-branded and low-cost chairless exoskeletons sold in the market with the price range of USD 80 to USD 150. Due to affordable prices, industrial users might be interested in buying and using the chairless exoskeletons. Even though the chairless exoskeletons are helpful to actively switch sit to stand or vice versa, information on the user’s requirements and the rigidity of the device, particularly on the structural strength, is not comprehensively reported, which influences the perception of the users towards safety and acceptance of the said device.

While there have been some substantiations regarding the effects of chairless exoskeleton on the muscle contraction of the biceps femoris, rectus femoris, vastus lateralis, and vastus medialis [9], very minimal studies investigate the gastrocnemius and tibialis anterior muscles. In different contexts, previous researchers have frequently designed and developed chairless exoskeletons with double-stand support [8, 10]. However, there appear to be no studies on single-stand chairless exoskeletons. Recently, Chae et al. [10] studied the usability of a double-stand Hyundai chairless exoskeleton. However, the effects of a single-stand chairless exoskeleton on the muscle contraction of the user and the contact pressure while wearing the device remain unclear. Negligence of these critical factors in the study of the chairless exoskeleton is a potential threat to the ergonomics principles of human-machine interaction, thus affecting user acceptance. Therefore, this paper aims to determine the user's requirements for designing a chairless exoskeleton. Additionally, this paper compared the mechanical compression strength, muscle contraction, contact stress, and usability of a newly designed single-stand chairless prototype exoskeleton versus a double-stand chairless commercial exoskeleton. This information would assist designers and manufacturers of chairless exoskeletons to improve user acceptance and adoption of the devices in daily living activities and industrial applications.

2. Methods

2.1. Survey of user's requirements

This study identified that the chairless exoskeletons' target users would be manufacturing industry operators. The purpose of the survey of users' requirements was to determine the design features of the chairless exoskeletons needed by the operators. A questionnaire survey was developed using Google Forms and distributed randomly to operators working in manufacturing industries in Malaysia. The inclusion criteria of the survey respondents were performing jobs in standing, being full-time workers, and having working experience of more than one year. The survey form was written in English and Bahasa Malaysia to ensure that the respondents understood the information required in the questionnaire. The cover page of the questionnaire survey form provided the following information: the background of the researchers, the purpose of the survey, the explanation and pictures of the chairless exoskeletons, and the confidentiality of the information. The questionnaire survey captured information about the operators, such as gender, age, body mass, height, and workplace standing duration. In addition, the survey form asked for respondents' feedback on the chairless exoskeleton design features they preferred. The design features included stability, safety, movement flexibility while wearing the exoskeleton, ease of use (usability), the weight of the exoskeleton, adjustability features, portability, comfort, purchase cost, and appearance or aesthetics. These design features were consistent with the recently published survey by Riccò et al. [11]. The survey form listed the design features together with the level of agreement and the scores: "Strongly disagree" (score = 1), "Disagree" (score = 2), "Neutral" (score = 3), "Agree" (score = 4), and "Strongly agree" (score = 5) to ease them to rate the feedback. Moreover, the survey form allowed the respondents to write other design features from their insights. The survey form was distributed to the operators through their human resources officers and supervisors.

2.2. Single-stand prototype exoskeleton vs. double-stand commercial exoskeleton

In this study, single-stand chairless prototype exoskeleton and double-stand chairless commercial exoskeleton were evaluated to determine the effects of their design on the mechanical compression force, muscle contraction of the user, contact pressure, and usability. Input from the user requirements survey was considered to design and fabricate a single-stand chairless exoskeleton. In the design, relevant anthropometric dimensions such as popliteal height, buttock popliteal length, and knee height were referred to Malaysian anthropometry data published by Hassan et al. [2] and Karuppiah et al. [13]. The single-stand chairless exoskeleton consists of:

(1) Safety body harness - made of nylon with elastic straps and buckles to attach the user to the exoskeleton seat,
(2) Saddle - made of polyurethane foam to support the buttock of the user,
(3) Vertical adjustable stand made of aluminium to support the body weight of the user,
(4) Pin lock mechanism - made of hardened steel to adjust the height of the vertical stand,
(5) Aluminium handle or lever for stand height adjustability,
(6) Base support - made of aluminium to prevent the user from turning backwards,
(7) Hinge - made of hardened steel to attach the base support to the stand. The hinge allows the base support to flip up and down to minimise the exoskeleton's bulkiness.
(8) Bolts and nuts - to tighten the hinge to the stand and base support.

Details of the single-stand chairless prototype exoskeleton and the double-stand chairless commercial exoskeleton tested in this study are shown in Table 1.

Table 1. Single-stand chairless prototype exoskeleton vs. double-stand chairless commercial exoskeleton.

	Single-stand prototype exoskeleton	**Double-stand commercial exoskeleton**
		
Construction materials	Aluminium alloy for the stand. Polyurethane foam for the seat pan.	The stands are made of ABS plastic.
Shock absorber mechanism	Ventilated nylon with elastic band and buckle.	Nylon velcro strap.
Shock absorber mechanism	Coil spring made of hardened steel.	Not available.
Height adjustment mechanism	Telescopic aluminium rod. Stainless steel pin lock with lever-actuated.	Plastic rod stopper with spring actuation.
Height range	40 - 70 cm.	60 - 71 cm.
Range of thigh-body angle (degree)	90º to 180º.	90º to 180º.
Saddle tilt (degree)	60º to 100º.	Not adjustable.
Mass (kg)	3	1.5

2.3. Participants

Ten male undergraduate students from a local university participated as experimental subjects in the muscle contraction assessment, contact pressure measurement, and usability test. The mean ± SD for age and body mass was 23.5 ± 2.4 years and 62.3 ± 4.2 kg, respectively. The Universiti Teknikal Malaysia Melaka Research Ethics Committee examined and approved the experimental protocols (Reference no.: UTeM.11.02/500-25/1/4(Jilid 2)(33). Participants were screened through a self-reporting interview and were qualified if they had no history of low back pain, shoulder and arm pain, neurological disorders, or physical injury. The research details were provided to the participants, including the experiment's benefits and risks, confidentiality, voluntary participation, and experiment procedures. A consent form was given to each participant before starting the experiment. The participants were informed that their participation in the experiment is voluntary and that they might withdraw at any time.

2.4. Experiment task

This study created a simulated product assembly process as the experimental task to represent actual standing tasks in the industry. The purpose of the experiment task was to give activity to participants involved in the experiments of muscle contraction, contact pressure measurement, and usability study. The experimental task was an assembly process of electric plugs, as shown in Fig. 1. A manual screwdriver was provided to assemble the plugs. The sequence of the assembly process was: (1) Place the lower cover of the plug on the table; (2) Insert the earth pin into the top centre hole of the lower cover; (3) Insert the neutral pin into the bottom hole on the left lower cover; (4) Insert the live pin into the bottom hole on the right lower cover; (5) Insert the fuse holder in the lower cover; (6) Insert the fuse into fuse holder; (7) Attach the upper cover to lower cover of the plug. These two covers are pressed together to ensure they are rigidly fixed; (8) Insert the screw into the centre round hole of the lower cover; (9) Tighten the screw in the clockwise direction using a screwdriver.

Fig. 1. Simulated industry task of electric plug assembly process.

In the experiment task, the participants performed the electric plugs assembly process in five work conditions: standing without the exoskeleton, standing with the commercial double-stand chairless exoskeleton, sitting with the commercial double-stand chairless exoskeleton, standing with the single-stand chairless prototype exoskeleton, and sitting with the single-stand chairless prototype exoskeleton. In the sitting position with the exoskeletons, the hip and knees were at 90° flexion, and the feet were in full contact with the floor. Meanwhile, in standing, the participants wore the exoskeletons, but the stand did not touch the floor (the participants had no standing support).

The experiment was conducted at the Ergonomics Laboratory of the Fakulti Teknologi dan Kejuruteraan Industri dan Pembuatan, Universiti Teknikal Malaysia Melaka. The air conditioner temperature in the laboratory was set at 20 - 22 ºC to ensure the participants' thermal comfort and maintain skeletal muscle contractility in performing the experiment.

2.5. Mechanical compression test

The mechanical strength test (Fig. 2) aimed to quantify the maximum vertical compression force that the exoskeletons can maintain. A destructive compression force test was carried out over the stands of the single-stand chairless prototype exoskeleton and the double-stand chairless commercial exoskeleton. The test was performed using Universal Testing Machine (Autograph AG-IC, Shimadzu Scientific Instruments) at a 10 mm/min load speed.

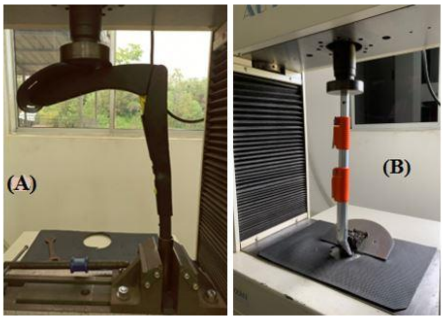

Fig. 2. Compression force test of commercial exoskeleton (A), and prototype exoskeleton (B).

2.6. Muscle contraction assessment

Muscle contraction of the participants without and wearing the exoskeletons was measured using the DELSYS Trigno wireless surface electromyography (EMG) measurement instrument (DELSYS, Boston, USA). The instrument was checked and calibrated to ensure the EMG signals were valid and reliable. The EMG experiment aimed to measure the maximal and submaximal contraction of the vastus lateralis, gastrocnemius, and tibialis anterior muscles (Fig. 3(A)). These muscles are commonly measured in the study of chairless exoskeletons [14]. The maximal contraction is also known as a maximum voluntary contraction (MVC), in which participants exert their maximum effort to contract the measured muscles. Meanwhile, submaximal contraction refers to the contraction of the measured muscles while performing the tasks with and without wearing the exoskeletons. The participants tested their maximal contraction or MVC in 30 seconds. As for the submaximal contraction test, all participants performed the EMG experiment in 30 minutes for each work condition mentioned in the experiment task.

Before the experiment began, participants were trained at a submaximal contraction for the required procedures. All participants were given a chance to do a light trial to familiarise themselves with the exoskeletons and the experimental procedures. The total duration for each participant to complete the experiment was 2 hours, 30 minutes, and 30 seconds. The EMG signals acquisition and processing were referred to study by Ricardo et al. [15]. The EMG data collection started with acquiring the raw EMG signals from each muscle. The EMG signals were measured at the sampling rate of 1000 Hz. Then, the EMG raw signals undergo a filtration process to eliminate noise. The following process was rectification, in which the EMG signals were turned to positive values, or the data were set above the baseline (zero mark). Subsequently, a smoothing process was carried out to remove outlier data. Finally, the EMG data were interpreted by the percentage of normalised root-mean-square (RMS amplitude, in microVolts). These EMG data acquisitions, and processing were performed by the DELSYS EMGworks software (DELSYS, Boston, USA). In this study, the RMS of the submaximal contraction amplitude value was divided by the RMS of the maximal contraction amplitude value and multiplied by 100. In mathematical equation, the percentage of normalised EMG is written by:

$$\text{RMS}=(\text{submaximal amplitude value} / \text{maximal amplitude value}) \times 100 \quad (1)$$

2.7. Contact pressure measurement

The purpose of the contact pressure measurement was to quantify the magnitude of the mechanical pressure (in kilo pascal, kPa) exerted in the area of contact between the user's body, the floor and exoskeleton's part. As shown in Fig. 3(B), this study applied Body Pressure Measurement System, CONFORMat (Tekscan, USA) to measure the contact pressure. The measurement areas were under the feet when standing with and without wearing the exoskeletons, under the buttock when sitting on the single-stand chairless prototype exoskeleton, and under the thigh when wearing the double-stand chairless commercial exoskeleton.

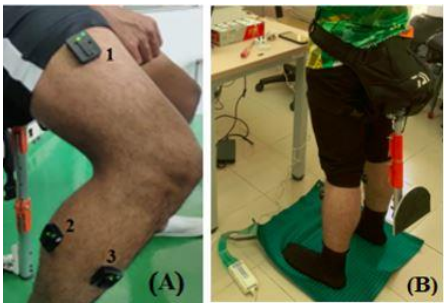

Fig. 3. (A) EMG sensors placement on vastus lateralis - 1, gastrocnemius - 2, tibialis anterior - 3. (B) Contact pressure measurement under feet.

2.8. Usability test

The usability test involved fifteen participants. After they used the devices, these participants were asked to rate the usability of the single-stand chairless prototype exoskeleton and the double-stand chairless commercial exoskeleton. The usability test was based on the ten questions of the system usability scale (SUS) developed by Brooke [16]. The SUS questions were formatted using Google Forms to facilitate participants in providing usability feedback. The SUS scores range from strongly disagree (score of 1) to strongly agree (score of 5). This method is frequently used when testing a product's usability [17].

2.9. Statistical analysis

Statistical analysis associated with the analysis of variance (ANOVA) was performed using Microsoft Excel 2016 to find any significant difference in terms of users' muscle contraction when wearing the single-stand chairless prototype exoskeleton and the double-stand chairless commercial exoskeleton. The significance level was set at $\alpha = 0.05$ for the statistical test.

3. Results

3.1. User's requirements

This study produced a list of users' requirements for a chairless exoskeleton's design features based on a questionnaire survey among 103 industrial operators in Malaysian manufacturing industries. The priority or rank of the user's requirements was classified through the priority score. For example, the calculation of the priority score for the user's requirements "Stability" is: (1 x 0) + (2 x 0) (3 x 22) + (4 x 31) + (5 x 50) = 440/ 103 = 4.27. The priority scores for all design features are tabulated in Table 2. In general, the priority scores for all user's requirements are greater than 4, indicating that the respondents agreed with the design features of the chairless exoskeleton. It was found that "ease of use" obtained the highest priority score (4.56), meaning users prefer a chairless exoskeleton that is easy to use.

Table 2. User's requirements, number of rating of agreement, and priority score.

User's requirements	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly agree (5)	Priority score
Stability	0	0	22	31	50	4.27
Safety	0	0	10	39	54	4.42
Movement flexibility	0	0	9	42	52	4.41
Ease of use	0	0	7	31	65	4.56
Light	0	0	13	28	62	4.47
Adjustability	0	0	3	42	58	4.54
Portability	0	0	9	55	39	4.29
Comfort	0	0	17	32	54	4.36
Low-cost	0	0	18	36	49	4.30
Appearance/ aesthetic	0	0	27	29	47	4.19

3.2. Mechanical compression force

Based on the mechanical compression test (Fig. 4), the stand of the single-stand chairless prototype exoskeleton could withstand a maximum compression force of 10.7 kN (~1090 kg). Furthermore, the test recorded that the break force of the single-stand chairless prototype was 5 kN (~509 kg). On the other hand, the stand of the double-stand chairless commercial exoskeleton could hold a maximum compression force of 1.14 kN (~116 kg). Moreover, its stand recorded a deformation at force of 0.525 kN (~53.5 kg).

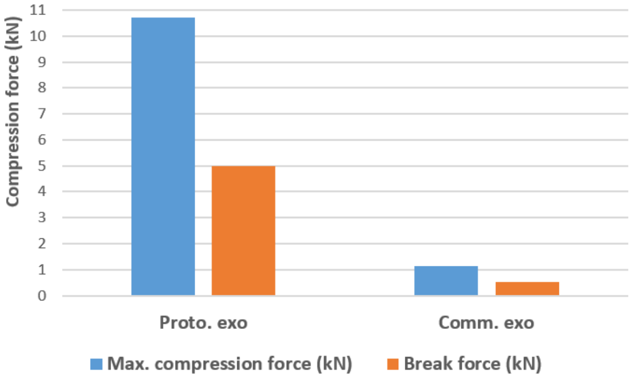

Fig. 4. Comparison of mechanical compression force between the single-stand chairless prototype exoskeleton (Proto. exo) and double-stand chairless commercial exoskeleton (Comm. exo).

3.3. Muscle contraction

Results of muscle contraction while wearing and not wearing the exoskeletons are interpreted by comparing the root-mean-square (RMS) of the electromyography (EMG) signals to the maximum voluntary contraction (MVC). The RMS represented the actual contraction of the measured muscles when the participants were wearing or not wearing the exoskeleton. The MVC is always at 100% as it represents the maximum effort of the muscles. It is indicated by a bold horizontal line, as illustrated in Figs. 5 and 6. A low percentage of actual muscle contraction as compared to MVC is seen favourably because it demonstrates minimal user effort.

Figure 5 exhibits muscle contraction results in all measured muscles (gastrocnemius, vastus lateralis, and tibialis anterior) during sitting. With the assistance of the single-stand chairless prototype exoskeleton (denoted as Proto. exo), a notable reduction of RMS was shown compared to the double-stand chairless commercial exoskeleton (denoted as Comm. exo). Apparently, the results indicate that the single-stand chairless prototype exoskeletons helped achieve a lower muscle contraction compared to the double-stand chairless commercial exoskeleton.

Further statistical analysis associated with the analysis of variance (ANOVA) was performed to determine any significant difference in the muscle contraction indicator, RMS, when wearing the single-stand chairless prototype exoskeleton and the double-stand commercial chairless exoskeleton during a sitting position. Based on the ANOVA results in Table 3, while in a sitting position, this study found a significant difference in the contraction of the left and right gastrocnemius, vastus lateralis, and tibialis anterior muscles, as indicated by P-value < 0.05.

Figure 6 shows the muscle contraction results in the left and right gastrocnemius, vastus lateralis, and tibialis anterior while in a standing position. The condition for not wearing the exoskeleton (denoted as No exo) recorded lower muscle contraction than wearing the single-stand chairless prototype exoskeleton and the double-stand chairless commercial exoskeleton. Also, the results indicate that the single-stand chairless prototype exoskeleton generated a slightly higher muscle contraction than the double-stand chairless commercial exoskeleton. However, all measured muscles showed a non-significant difference (P-value > 0.05) as evidenced by ANOVA results in Table 3. In other words, the muscle exertion while wearing and without wearing exoskeletons are essentially the same.

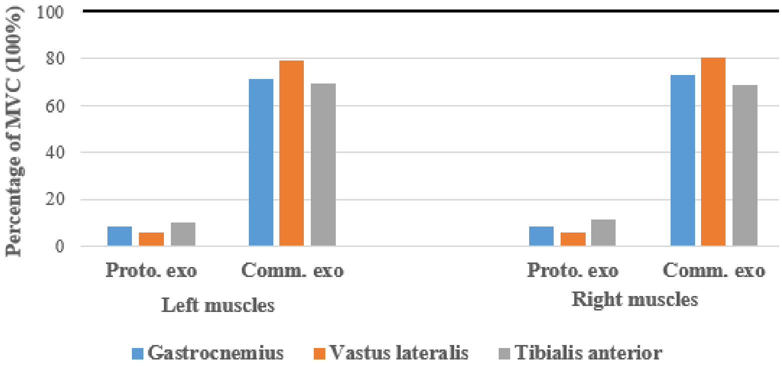

Fig. 5. Actual muscle contraction vs. MVC during sitting.

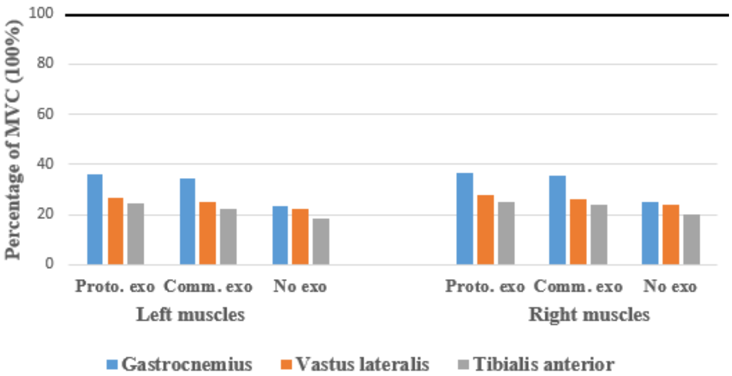

Fig. 6. Actual muscle contraction vs. MVC during standing.

Table 3. ANOVA of muscle contraction when wearing single-stand chairless exoskeleton vs. double-stand chairless commercial exoskeleton.

Body positions	Muscles	P-value
Sitting	Left gastrocnemius	9.6×10^{-9}
	Right gastrocnemius	2.3×10^{-10}
	Left vastus lateralis	1.16×10^{-10}
	Right vastus lateralis	4.01×10^{-12}
	Left tibialis anterior	9.76×10^{-9}
	Right tibialis anterior	2.3×10^{-8}
Standing	Left gastrocnemius	0.096
	Right gastrocnemius	0.071
	Left vastus lateralis	0.116
	Right vastus lateralis	0.139
	Left tibialis anterior	0.138
	Right tibialis anterior	0.074

3.4. Contact pressure

Table 4 and Fig. 7 show the results of peak pressure (kPa) under the feet, the thigh, and the buttocks while wearing and not wearing the exoskeletons. In the standing position and wearing the single-stand chairless prototype exoskeleton, contact pressure under the thigh and buttocks can be ignored. Furthermore, in the sitting position, the single-stand chairless prototype exoskeleton created no pressure under the thigh. However, it generated a contact pressure of 9.5 kPa under the buttock. In contrast, the participants received a peak pressure of 33.2 kPa under the thigh when wearing the double-stand chairless commercial exoskeleton in the sitting position. In other words, the single-stand chairless prototype exoskeleton minimised the contact pressure by 71% compared to the double-stand chairless commercial exoskeleton. Interestingly, in a standing position, the peak pressures under the feet are almost the same while wearing and not wearing the exoskeletons.

Table 4. Contact pressure (kPa) on different positions and areas. Standard deviation, SD in bracket.

Exoskeletons	Positions	Under feet	Under thigh	Under buttocks
Single-stand prototype	Standing	137.7 (3.8)	0	0
	Sitting	Not measured	0	9.5 (0.4)
Double-stand commercial	Standing	135.9 (3.2)	0	0
	Sitting	Not measured	33.2 (1.4)	0
No exoskeleton	Standing	135.2 (3.3)	0	0

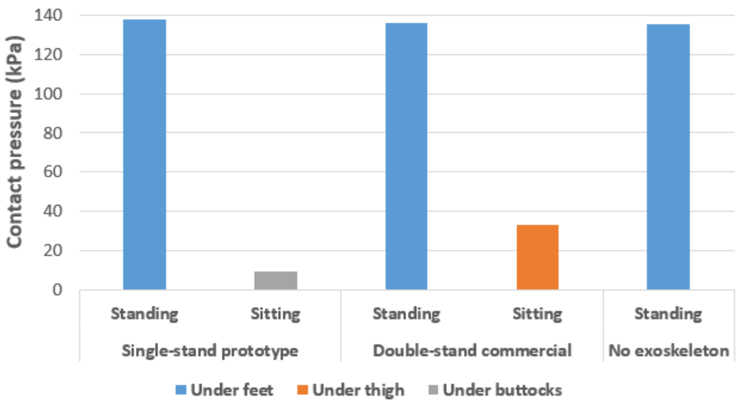

Fig. 7. Comparison of contact pressure between the single-stand chairless prototype exoskeleton, double-stand chairless commercial exoskeleton, and without wearing exoskeleton.

3.5. Usability score

The usability of the single-stand chairless prototype exoskeleton and the double-stand chairless commercial exoskeleton was assessed by the system usability scale (SUS). Figure 8 shows a comparison of the SUS score for each SUS question for both exoskeletons. The single-stand chairless prototype exoskeleton obtained an average SUS score of 79.5, reflecting good usability [18]. This is shown by the SUS score for Q3 (*I thought the exoskeleton was easy to use*), reflecting the device was good in terms of usability. Consequently, the participants liked to wear the single-stand chairless prototype exoskeleton, as evidenced by high score for Q1 (*I think that I would like to use this exoskeleton frequently*). On the other hand, the average SUS score of the double-stand chairless commercial exoskeleton was 67.3, which was perceived as marginally acceptable [18].

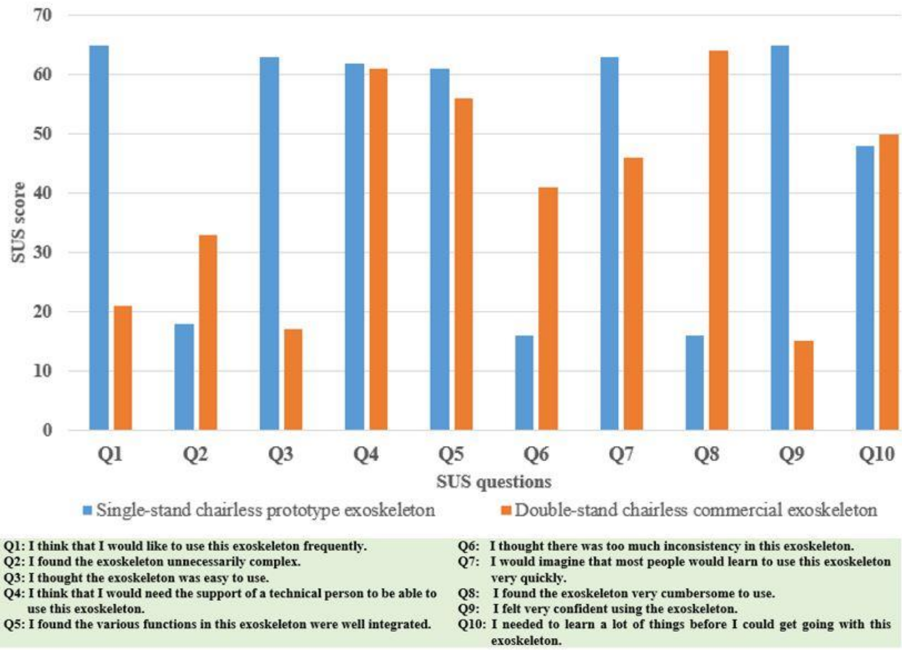

Fig. 8. Usability score of the single-stand chairless prototype exoskeleton and the double-stand chairless commercial exoskeleton.

4. Discussion

4.1. User's requirements

The survey findings shed light on critical user's requirements for chairless exoskeletons, offering valuable insights into operators' preferences and priorities in Malaysia's manufacturing industries. These findings have significant implications for aligning user requirements with existing exoskeleton designs and the potential impact on future industrial applications. The identified user's requirements, particularly the emphasis on ease of use, adjustability, lightness, and safety, align closely with the features that users prioritise in chairless exoskeleton design. The recognition of these key aspects echoes the findings of past studies, as referenced by Wolff et al. [19] and Jung and Ludden [20]. This consistency across studies suggests a robust set of user preferences that designers and manufacturers should consider when developing chairless exoskeletons.

The paramount importance given to ease of use in the survey findings highlights the significance of user experience in the adoption and utilisation of chairless exoskeletons in industrial settings. The usability of the device becomes a crucial factor in ensuring its effective integration into daily work routines. This underscores the notion that, beyond structural strength, functionality, and technological specifications, the human-machine interaction element plays a pivotal role in successfully implementing chairless exoskeletons.

In addition to the mechanical design requirements such as lightness, safety, and adjustability, the survey underscores the equal importance of elements related to the human-machine interaction. The ease of donning and comfort of wearing the chairless exoskeleton emerge as critical factors that directly impact user satisfaction and, consequently, the overall success of exoskeleton adoption in industrial contexts. This insight emphasises the holistic nature of user requirements, encompassing both technical and ergonomic considerations.

The findings suggest that future chairless exoskeleton designs should prioritize and integrate features that enhance ease of use, adjustability, lightness, safety, and overall user comfort. Manufacturers and designers can leverage these insights to develop more user-centric and ergonomic exoskeleton solutions. Moreover, the emphasis on these user requirements indicates a potential for increased acceptance and adoption of chairless exoskeletons in various industrial applications, contributing to improved worker well-being and productivity.

4.2. Mechanical compression force

The structural strength of the exoskeleton plays a critical role in ensuring the device can withstand or prevent any physical deformation caused by the load of users. Poor structural design of the exoskeleton can result in premature fracture under submaximal loads that can compromise user safety (e.g., fall risk). The structural strength depends on the construction materials of the exoskeleton. In this study, the single-stand chairless prototype exoskeleton can accommodate a heavy load of up to 509 kg. Its stand is made of aluminium alloy, known to be lightweight and stronger than ABS plastic. The weakest point was detected at the bottom of the stand. The stand is a hollow section with an outer diameter and wall thickness of 30 mm and 1 mm, respectively.

Meanwhile, the double-stand commercial chairless exoskeleton tested by this study has two stands supporting each user’s leg. The stands are made of ABS plastic. Based on the mechanical compression test, the double-stand commercial chairless exoskeleton can accommodate a user with a body mass of up to 107 kg before its stands deform. The weakest section of the commercial chairless exoskeleton was identified in the area of the locking mechanism for low and high stand adjustment. This section is isosceles trapezium-shaped with a dimension of 70 mm length × 41 mm width × 25 mm thickness. Besides, there are three square holes with dimensions of 13.2 mm × 12.8 mm each for pin locking. The hole inter-distance is 16.8 mm. This area is spotted as the weakest because it is a hollow section with a wall thickness of 3 mm. Moreover, the three holes reduced the total area, weakening the particular section.

4.3. Muscle contraction

This study analysed the muscle contraction in the left and right gastrocnemius, vastus lateralis, and tibialis anterior of the experiment participants. In a sitting position, this study revealed that the participants exerted the least muscle contraction when wearing the single-stand chairless prototype exoskeleton. This prototype enables a user to sit in a relaxed posture, leading to lesser muscle contraction. The results were consistent with the previous studies [9, 21, 22], where muscle contraction reduced significantly when wearing a proper design of a chairless exoskeleton. On the contrary, this study found that the contraction of the muscles was higher when wearing the double-stand chairless commercial exoskeleton in the sitting position. The vastus lateralis muscle recorded the highest contraction. This phenomenon can be explained by the effort of the participants to control their posture for body stability while sitting on the double-stand chairless commercial exoskeleton. They exerted higher muscle effort, particularly in thigh muscles, as the exoskeleton stands bent to the side during use. The double-stand, which was built of ABS plastic as was mentioned in the previous discussion, can only support the user's body weight of 107 kg, which is insufficient, especially for prolonged use. Therefore, high muscle effort/ contraction in the vastus lateralis is required to counteract the gravitational force when the body is unbalanced. A more significant muscle contraction causes a higher metabolic cost to be consumed. Also, prolonged use of the commercial exoskeleton may trigger muscular fatigue.

In a standing position and without wearing the exoskeleton, it was observed that the contraction of the muscles was relatively smaller than wearing the single-stand chairless prototype exoskeleton and the double-stand chairless commercial exoskeleton. This is due to additional weight from the exoskeletons causing the muscles to contract more for maintaining the body in an upright posture. As informed in Table 1, the mass of the single-stand chairless prototype exoskeleton and the double-stand commercial chairless exoskeleton are 3 kg and 1.5 kg, respectively. Due to its heavier weight than the commercial double-stand chairless exoskeleton, wearing the single-stand chairless prototype exoskeleton in a standing position induced more muscle contraction. However, the ANOVA test revealed that there was no statistically significant difference (P-value > 0.05) between any of the examined muscles. In other words, muscle exertion while wearing and without wearing the exoskeletons are essentially the same.

4.4. Contact pressure

Contact pressure is always present in the workplace. For instance, contact pressure occurred between the feet and the floor during standing, and the buttocks and the chair in sitting. It is almost impossible to avoid contact pressure. However, it should be minimised to alleviate potential adverse effects such as blisters and bruises. Prolonged exposure to high pressure at the area of contact between the user's body parts and the chairless exoskeleton is likely to cause restricted blow flow or compressed tissue, which can lead to bruises [23]. In addition, the strap used to attach the exoskeleton frame to the user's body can potentially cause shear stress to the surrounding soft tissues. The thigh straps create contact pressure ranging from 80-120mmHg, which may lead to skin and soft tissue injuries [24]. Contact pressure caused by force exerted on the user's body parts leads to undesired effects such as body discomfort and skin and soft tissues injuries, which can affect user satisfaction and acceptance to use the exoskeletons [25, 26].

Based on the results of contact pressure measurement, the highest contact pressure was identified under the feet when standing on the floor with and without wearing the chairless exoskeletons. This is due to the weights of the user's body and the exoskeletons concentrated to a contact area between the feet and the floor. The single-stand chairless prototype exoskeleton contributed relatively minor contact pressure under the buttocks. Its seat pan was designed with a sufficient area (24 cm width by 24 cm length) to support the buttocks. Additionally, the seat pan is cushioned by a 10 cm thickness of high-density foam and a coil spring. These design interventions are helpful to minimise the effect of contact pressure and shocks on the buttocks. On the other hand, the double-stand chairless commercial exoskeleton apparently caused the greatest contact pressure under the thigh while sitting. The user's thighs come in contact directly with the plastic-made thigh support, designed without any cushioning medium. Moreover, the support area is small (12.4 cm width by 16.8 cm length), which creates high contact stress under the thigh. Table 5 compares the seat pan of the single-stand chairless prototype exoskeleton and the thigh support of the double-stand chairless commercial exoskeleton, where the contact pressure mainly occurs.

Table 5. Comparison of seat design between the single-stand chairless prototype exoskeleton and the double-stand chairless commercial exoskeleton.

	Single-stand exoskeleton prototype	Double-stand chairless commercial
Contact area between the buttock or thigh and exoskeleton support	Seat pan area for buttock support: 24 cm width x 24 cm length. The seat is pear-shaped with cushioned back support.	exoskeleton Thigh support area: 12.4 cm width × 16.8 cm length.
Material of seat pan	High-density foam with thickness of 10 cm.	ABS plastic without cushioning pad.
Shock absorption	 Coil spring	 None

4.5. Usability

Although mechanical properties are important in structural strength, usability is essential for achieving user satisfaction in exoskeleton applications. In their recent study, Li and Gan [14] pointed out that an exoskeleton might perform excellently in some respects, but it does not mean that it also has good usability. Usability refers to "usefulness" and "ease of use" that drive users' satisfaction and frequency of use of a product [27]. It is not only about the physical aspect but also the mental state; for example, less cognitive effort in donning and doffing the exoskeleton, and a feeling of secure and comfort while wearing the exoskeleton.

The usability of the single-stand chairless prototype exoskeleton was rated comparatively higher than the double-stand chairless commercial exoskeleton. The single-stand chairless prototype did not require the user to attach any exoskeleton's component to the shoes. The user just need to simply snap on buckles (marked by green circles in Fig. 9 (top) attached to the body harness's elastic bands for attaching the exoskeleton to the waist, buttock, and thighs. This study observed that the application of buckle-type bands eased the user in the wearing process of the body harness. This observation is in line with the study by Chae et al. [10], in which users preferred buckle-type straps to simplify the fastening process of the body harness.

On the other hand, the double-stand chairless commercial exoskeleton obtained a low score of SUS for Q3 (*I thought the exoskeleton was easy to use*). This reflects that the device was not very good in terms of usability. Consequently, the participants rated low scores for Q1 (*I think that I would like to use this exoskeleton frequently*) and Q9 (*I felt very confident using the exoskeleton*). This feedback pertains to the design of the body harness. Body harness is one of the critical components in exoskeleton construction as it is a medium to connect the user and the exoskeleton. The double-stand chairless commercial exoskeleton has two extended components that need to attach to the left and right user's shoes by using rubber bands. A critical usability issue was observed while the user attached the rubber bands to the shoes. This process must be done in standing, which affects the users' postural balance, as shown in Fig. 9 (bottom). This is due to the design of the double-stand chairless commercial exoskeleton restricted the natural movement of the user's body as it has limited number of degrees of freedom plus with the inflexible structure.

Fig. 9. Donning the single-stand chairless prototype exoskeleton (top) and double-stand chairless commercial exoskeleton (bottom).

4.6. Practical implications

The practical implications of this study have far-reaching effects on both the design choices made by manufacturers in the development of chairless exoskeletons and the informed application of ergonomic principles in workplace settings. The identified user requirements, such as ease of use, adjustability, lightness, safety, low cost, comfort, and stability, provide manufacturers with clear guidance on the critical design features that users prioritise in a chairless exoskeleton. This information can significantly influence the design choices made by manufacturers, ensuring that future iterations of chairless exoskeletons are tailored to meet user needs effectively. The functional prototype of the single-stand chairless exoskeleton, designed to alternate between sitting and standing postures during assembly tasks, presents a practical solution to mitigate body fatigue. Manufacturers and workplace designers can leverage these findings to incorporate ergonomic solutions that enhance worker well-being, particularly in tasks involving alternating postures.

5. Conclusion

Standing and sitting tasks are common in the manufacturing and service sectors. Workers may feel discomfort and fatigue if exposed to prolonged standing and sitting, particularly in the lower back, calves and feet. In this study, the authors performed a questionnaire survey to determine users' requirements for designing a chairless exoskeleton to prevent body fatigue associated with prolonged standing and sitting. The authors identified that a chairless exoskeleton's most required design features were ease of use, adjustability, light, safety, low cost, comfort, and stability. Based on the survey results, this study designed and fabricated a functional prototype of a single-stand chairless exoskeleton for the purpose of alternating sitting and standing postures in executing plugs assembly tasks. Subsequently, the single-stand chairless exoskeleton was compared to a double-stand commercial chairless exoskeleton to evaluate its efficacy on mechanical compression strength, muscle contraction, contact stress, and usability.

This study concluded that the single-stand chairless exoskeleton has high mechanical strength and usability, with low muscle contraction, and contact pressure. With these evidences, the single-stand chairless prototype exoskeleton was proven sturdy, easy to use, and effective in minimising muscle fatigue and contact stress, especially for sitting tasks. Although the double-stand commercial chairless exoskeleton is lightweight, this device is notably low in mechanical strength and usability, and greater in muscle contraction and contact pressure. Based on these findings, the double-stand commercial chairless exoskeleton might be practical for standing and mobility, but not to use it for sitting.

Design optimisation relating to materials, cost, reliability, and safety factors is suggested for future studies. Comprehensive information would assist designers and manufacturers of chairless exoskeletons in improving user acceptance and adoption of the devices in daily living activities and industrial applications.

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Abbreviations	
EMG	Electromyography
MSDs	Musculoskeletal Disorders
MVC	Maximum Voluntary Contraction
RMS	Root-Mean-Square
SUS	System Usability Scale

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