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Performance and Effectiveness of a Passive Back-support Exoskeleton in Manual Material Handling Tasks in the Construction Industry

Ali Golabchi[*,1], Niromand Jasimi Zindashti [2], Linda Miller[3], Hossein Rouhani[2], Mahdi Tavakoli[4]

[1]Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB, Canada

[2]Department of Mechanical Engineering, University of Alberta, Edmonton, AB, Canada

[3]EWI Works International Inc., Edmonton, AB, Canada

[4]Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB, Canada

Abstract

Work-related musculoskeletal disorders are a leading contributor to workplace injuries in the construction industry, with the low back being the most affected body part. Recent developments have led to the introduction of exoskeletons on industrial job sites as a means to mitigate the risk of work-related musculoskeletal disorders. Due to the newness of industrial exoskeletons, the successful application of this technology in the construction industry requires a thorough evaluation of different aspects of its adoption, especially user acceptance, to ensure a successful and effective uptake. As manual material handling tasks are the most common cause of low back injuries, this study aimed to evaluate the impact of using exoskeletons when adopting different postures during dynamic and static manual material handling tasks. An experiment was carried out and data reflecting Rate of Perceived Exertion, Level of Discomfort, overall fit and comfort, effectiveness, and interference levels were collected. Overall, the participants perceived the exoskeleton suit as effective, with discomfort being reduced in the low back and most other body parts. However, the results indicated the importance of considering the specific task at hand (e.g., dynamic vs static manual material handling) and the posture adopted (e.g., squatting vs stooping) when evaluating and selecting an exoskeleton for construction tasks. Also, the results show differences between male and female participants in most usability and effectiveness responses. In conclusion, passive exoskeletons have the potential to be adopted to reduce the rate of WMSDs in construction. However, proper training and supervision are required on the postures adopted by the workers, based on the specific characteristics of the task carried out. Also, different results from male and female responses show that different exoskeletons, or an exoskeleton with two different designs, may lead to higher efficiency than using one exoskeleton for both groups.

Keywords: Exoskeleton; Back-support; Manual Material Handling; Construction; Ergonomics; Wearable robot

1- Introduction

Work-related Musculoskeletal Disorders (WMSDs) are the most common and fastest increasing cause of work-related disabilities [1, 2]. If not treated properly, these disorders can impose substantial costs [1]. In Europe, WMSDs are the most common cause of disability, absence, and loss of productivity [3]. Work that involves heavy lifting, awkward postures, and repetitive movements are among the most common biomechanical factors associated with WMSDs [4]. In the construction industry, manual material handling (MMH) involving lifting, carrying, pushing, pulling, lowering, restraining, and holding is the most common cause of occupational fatigue, low back pain and injuries. Both dynamic (e.g. carrying) and static (e.g. holding) MMH tasks can lead to high rates of WMSDs, including 30% of all lost workday cases among construction trades in the US [5].

In addition to job and workplace ergonomics training, technical interventions are one of the most effective mitigation strategies when it comes to preventing WMSDs [6]. An easy-to-implement wearable assistive device called an exoskeleton, also known as exosuits or wearable robots, can reduce fatigue and strain, thereby preventing injuries to those parts of the body that are stressed the most during everyday workplace activities [7-10]. Recently, these wearable robots are adopted for different industrial applications to mitigate the ergonomic risks associated with physically demanding tasks, especially the ones involving MMH. The use of exoskeletons for such physically demanding tasks has shown to reduce fatigue and the frequency of injuries [11]. Considering the complex nature of construction tasks and the fact that WMSDs are disproportionately prevalent among construction workers [9], exoskeletons may be a particularly effective and novel control method to mitigate WMSDs in this industry.

In a recent study, Zhu et al. [12] investigated existing exoskeleton technologies and analyzed their potential for MMH tasks in construction. They generated a map to suggest the appropriate exoskeleton type for each trade while evaluating the benefits and challenges. In another study, Cho et al. [13] designed a wearable exoskeleton to habituate construction workers to safe postures and demonstrated that the developed exoskeleton can effectively assist workers when performing construction tasks. Ogunseiju et al. [14] evaluated a postural assist exoskeleton and its effectiveness for construction tasks involving MMH. They reported improvements in posture when using the exoskeleton over time, although higher perceived discomfort in the low back was reported due to the pressure applied to the users' back. In another study, Capitani et al. [15] described the development of a passive exoskeleton to assist construction workers in dealing with shotcrete projection tasks. They indicated that the designed exoskeleton preserved adaptability to different lower-limb tasks without reducing its comfort during utilization. Furthermore, Chen et al. [16] presented a bilateral knee exoskeleton to provide kneeling assistance for construction workers. The results showed reductions in knee pressure, potentially leading to decreased WMSD risk for workers when performing kneeling activities on level and sloped surfaces.

In previous studies, it is shown that the effectiveness of the exoskeletons depends heavily on user acceptance since exoskeletons use may present unexpected safety and usability challenges [9, 17]. Thus, more research is required to evaluate the different usability aspects of the adoption due to the recentness of using the exoskeleton technology for the construction industry. Also, most of the previous studies have focused on a limited types of MMH tasks in terms of their nature (static, dynamic) and body posture (e.g. squatting, bending), while there are various types of MMH tasks in the construction industry, and there is a lack of studies around these tasks, especially for the construction sector. Considering these points, this study aimed to evaluate the effect of a back-support exoskeleton on postures adopted when carrying out construction MMH tasks. The goal of this study was to compare different postures, squatting and bending, adopted during dynamic and static MMH tasks, with and without exoskeletons. The experiments were designed to provide feedback on the impact of using exoskeletons on comfort, fatigue, load distribution, worker' intention-to-use, and other usability factors. Both male and female subjects were considered since the effectiveness of exoskeletons was not well-studied in terms of gender differences in the previous studies.

2- Material and Methods

2-1- Experimental design

We used a passive exoskeleton for the experiment, since passive exoskeletons have shown to be more suitable for a number of industrial applications compared to active exoskeletons due to lighter weight, lower price and simpler maintenance [5]. Furthermore, we studied a back-support exoskeleton, since the back is the primary body part affected by WMSDs in construction. Back support exoskeletons are designed to reduce the load on the low back muscles during bending tasks by redistributing the weight to the legs [18]. We used a BackX exoskeleton which weighs 7.2 lbs and can reduce the strain on the user's low back. It consists of two leg straps and a vest coupled to each other by two torque generators at both hip joints. Also, it has two operation mode, instant and standard. In the instant mode, it is engaged in all postures, while in standard mode, support is provided when the users' trunk bends 30° to 45°. We selected this exoskeleton because it can be used for a variety of MMH tasks, such as bending, squatting, walking. It is shown that BackX can minimize the risk of back injuries among workers who repeatedly go through stooping, squatting, and bending postures for various tasks [18]. The experiment was designed to simulate dynamic and static MMH tasks. Participants were asked to carry out the tasks in different scenarios to cover different task types (i.e., dynamic and static), postures (i.e., freestyle, bending, squatting), and the impact of the exoskeleton (i.e., with and without wearing the exoskeleton).

2-2- Participants

For this study, 12 able-bodied individuals, including 6 male and 6 female, were asked to participate in the experiment. The mean and standard deviation for the age, body weight, and body height of the participants were 28 ± 6.28 years old, 64.8 ± 15.4 kg, and 1.7 ± 0.1 m, respectively. None of the participants reported any current or previous musculoskeletal disorders or illnesses. The detailed process including the objectives, instructions and possible risks were explained to each participant through written and verbal instructions and on-site discussions. Ethics approval was received for the study from the University of Alberta Research Ethics Board.

2-3- Testing Procedure

The variables of the experiment included freestyle, bending, and squatting lifting postures, existence of the exoskeleton, and the static and dynamic nature of the task. Dynamic MMH involved lifting a 20 lb. box, carrying it during a 32-foot walking , and placing it and the floor for five times, while each time lifting and placing on a surface with a different height (i.e., on the floor and on a table). Static MMH tasks involved moving items, with weight less than 0.5 kg, from a box and placing them on a table through a static posture.

Prior to the experiment, participants were introduced to the procedure and equipment. Participants were given enough time between every two experimental trials to recover from any fatigue associated with performing the task. After completing each trial, the participants were asked a series of questions including the Rate of Perceived Exertion (RPE), Level of Discomfort (LOD), overall fit and comfort of using the exoskeleton, the extent to which the exoskeleton limited movements and interferes with movements, effectiveness of the exoskeleton, and other general feedback. In total, seven scenarios reflecting different postures and the exoskeleton's use were tested. Fig. 1 also shows the experiment setup for some of the scenarios as a sample.

2-4- Participant Response

The participants were asked to rate the level of their perceived discomfort (i.e., LOD) on a Borg CR 10 scale, where 0 indicates no discomfort and 10 shows maximum discomfort [19]. The intensity of perceived discomfort was measured and quantified after conducting each experimental trial. Furthermore, the participants provided the discomfort ratings separately for each body part including shoulder, chest, low back, thighs, feet, etc. on a scale of 0 to 10. Also, RPE was rated from 1 (very light activity) to 10 (maximum effort), fit/comfort of the exoskeleton suit was rated from 1 (not satisfactory) to 10 (very satisfactory), limitation/interference was rated from 1 (limits a lot) to 10 (does not limit at all), and effectives was rated from 1 (not effective at all) to 10 (very effective). Collected data was explored through descriptive statistical analysis.

3- Results

3-1- Dynamic tasks

According to Fig. 2, the average RPEs for the different posture scenarios during the dynamic MMH were fairly close. Overall, it can be concluded that the exoskeleton's use and the posture used does not impact the average RPE in dynamic MMH. It is also worth noting that in cases where the exoskeleton was used, a maximum RPE of 6 was reported by users.

The results indicate that the participants felt similar effectiveness in all postures, while they experienced more comfort during squatting compared to bending (Fig. 3). Overall, the participants felt that the exoskeleton moderately limits their movements and interfered with other tasks.

As shown in Fig. 4, most of the perceived discomfort was detected in the low back and legs. While using the exoskeleton substantially reduced the discomfort in the low back during bending and squatting, using the exoskeleton with a freestyle posture did not have considerable impact in improving the discomfort in the low back. It is also observed that the perceived discomfort in legs and arms was much higher when squatting compared to bending. The reason for this observation could be mainly due to the moment tolerated by the legs and knee joints because of the weight of the upper body and its considerable moment arm in squatting. Also, because of the difference postures of arms during bending and squatting, the users experienced more discomfort in this part of body in the squatting than bending. Fig. 4 shows an increased level of discomfort in the upper leg and knee since the exoskeleton transferred load from the chest and upper body to upper legs.

3-2- Static tasks

While minimum and maximum reported RPEs were similar for all scenarios, the average RPE was reported as slightly higher for squatting, which indicates the difficulty of performing the static task in a squatting posture due to the pressure applied to the legs and the need to maintain balance (Fig. 5).

As shown in Fig. 6, the overall effectiveness, interference, and comfort levels were higher in bending compared to squatting both when an exoskeleton was worn.

Since the body was positioned in an awkward position for a prolonged period of time during the static task, the discomfort levels were generally high during static MMH tasks without the exoskeleton (Fig. 7). Similar to the dynamic tasks, most of the reported discomforts were in the low back and legs. The use of the exoskeleton caused higher discomfort levels on the chest during bending, which was due to the chest pad. While the use of the exoskeleton reduced the discomfort on the legs in bending compared to squatting, the discomfort in the low back was much less in squatting. The moment arm and the weight of the upper body could be the main reasons for these different observations in bending and squatting. Also, similar to the dynamic tasks, the upper leg was negatively affected by using the exoskeleton in both bending and squatting postures.

3-3- Dynamic MMH tasks vs. Static MMH tasks

While other factors remained the same, a higher level of limitation was reported during static tasks (Fig. 8). Overall, it can be concluded that the exoskeleton's performance for bending is similar for both static and dynamic tasks.

According to Fig. 9, the overall effectiveness, limitation and comfort levels were higher for dynamic squatting task, compared to static squatting tasks. Since dynamic tasks involve more movements, such as walking during carrying the load, it seems that the exoskeleton needs modifications to not restrict other movements than the lifting.

3-4- Male vs. Female Users

As shown in Fig. 10, male participants reported higher RPE levels in the dynamic scenarios compared to female participants. Also, the perceived exertion was similar for bending and squatting postures among both groups.

While both male and female participants reported a slightly higher RPE in squatting compared to bending, male participants reported higher RPEs for all scenarios of static MMH (Fig. 11). Using the exoskeleton did not improve the exertion levels when adopting the bending posture.

Table 1 shows a comparison of the average responses for the usability factors for male and female participants. As shown in Table 1, female participants found the exoskeleton more effective in all MMH scenarios, while both groups rated the fit and comfort level similar. On the other hand, female participants rated the limitation factor of the exoskeleton higher than male participants.

Male participants reported higher discomfort when carrying out the dynamic task without the exoskeleton, with the highest discomfort in the low back (Table 2). When using the exoskeleton with a freestyle posture, both male and female groups reported discomfort in the chest area, with male participants reporting substantially higher LOD. During dynamic bending, male participants reported the highest discomfort on the chest, low back, and knees, while female participants reported the highest LOD on the upper leg and knees. The highest reported LOD during dynamic squatting was felt on the chest, low back, and knees for male participants and upper leg, knees, and arms for female participants. While male participants reported discomfort on the shoulder in all dynamic scenarios, there was no reported LOD for shoulders by female participants. Overall, male participants reported higher LOD for all body parts except arms. Also, when carrying out the static task without the exoskeleton, male participants reported the highest discomfort in the low back, shoulder, and knees, while female participants reported the highest LOD on the arms and knees. The exoskeleton's use for the static bending task resulted in higher discomfort in both groups, with male participants reporting the highest LOD on the chest, low back, and knees, and female participants reporting the highest LOD on the upper leg, knees, and arms. For static squatting, male participants reported higher LOD in all body parts compared to female participants. The highest LOD was reported in the chest, low back, and knees for male participants, while the highest LOD was reported in the upper leg, knees, and arms for female participants. Both groups reported similar LOD in the upper legs. Overall, similar to the dynamic MMH scenarios, male participants reported higher LOD compared to female participants for all body parts except arms for static MMH scenarios.

3-5- User Feedback

Participants were also asked for feedback on different usability metrics of the exoskeleton in an open-ended format. According to Table 3, their opinion about the exoskeleton is moderate, based on their overall feeling. Based on their explanations, the exoskeleton helped with distributing the loads, but it also limited their movement and caused discomfort in body parts, such as the chest and thigh. The level of heat/humidity that the exoskeleton caused was considered ignorable by the participants. Most participants preferred to use the exoskeletons if they had to do a lot of MMH tasks because although it restricted their movement, its help during lifting and carrying the loads was considerable. In terms of the preferred posture, most participants preferred squatting during dynamic MMH and bending during static MMH.

3-6- Combined Scenarios and Postures

Construction workers are typically involved in a variety of tasks involving both dynamic and static MMH as well as various postures (e.g., squatting and bending) during their daily activities. Thus, the combined results for different scenarios of MMH tasks can help further evaluate the performance of exoskeletons for tasks involving a variety of MMH tasks and postures. According to Table 4, the average RPE did not improve when using the exoskeleton, and the RPE was higher during squatting MMH tasks compared with bending MMH tasks. Also, the exoskeleton decreased the LOD in the knee and low back. However, squatting and bending postures resulted in different LODs with exoskeleton; the LOD in the knee, arm, and shoulder parts decreased during bending MMH tasks, while the LOD in the shoulder and low back areas decreased during squatting MMH tasks.

4- Discussion

WMSDs are leading cause of loss of productivity in the construction industry, and recently exoskeletons have been proposed and used to reduce the load on workers' body parts. In this study, a passive exoskeleton (BackX) was used while doing MMH tasks. Both dynamic and static tasks as well as male and female paticipants were considered for the experiments. The results showed improvements in reducing the loads of users' body parts, especially low back, and therefore they could be adopted in the construction industry, alghouth improvements should be considered for the future designs.

4-1- Static MMH Tasks

In static MMH tasks, participants reported different and contradictory results in bending and squatting scenarios. In terms of effectiveness and overall LOD, their opinion is more positive about the bending MMH tasks, while they felt less discomfort in low back and chest in squatting MMH tasks (Fig. 6). Also, in squatting, the knee was adversely affected by using the exoskeleton more than other body parts, while its LOD in bending was lower than when the exoskeleton was not used (Fig. 7). The reason may rely on the mechanism of each task; in the bending tasks, the knee did not bear much joint moment, while in squatting, there was large joint moment due to the weight of upper body and upper leg. This should be taken into consideration for future modification of the exoskeletons.

4-2- Dynamic MMH Tasks

Participant's opinion about wearing the exoskeleton in dynamic MMH tasks was moderate. Although the exoskeleton helps them for lifting, its use led to moderate discomfort as well. The reason may rely on the fact that dynamic MMH tasks involved other movements, e.g., walking, as well, and the exoskeletons may not be properly designed for those movements. Similar to static MMH tasks, knee and upper leg were adversely affected by using the exoskeleton in squatting (Fig. 4), highlighting the necessity of exoskeleton modification if squatting is involved. Also, using the exoskeleton with freestyle movement is not as effective as squatting and bending, especially in the low back.

4-3- Perceived Discomfort

Based on the users' perceived discomfort, the exoskeleton reduced the load, in the low back, especially in squatting tasks (Table 4), and increased it in other body parts, especially the chest. Also, the female participants felt less discomfort in the low back (and many other body parts) than the male ones (Table 2). Kazerooni et al. [18] evaluated the BackX exoskeleton using objective metrics. While their study showed that the average muscle activities of thoracic and lumbar erector spinae muscles reduced 75% and 56% respectively, no significant difference between male and female was found. Also, another study [20] showed that using BackX exoskeletons resulted in the reduction of the peak muscle activity of lumbar erector spinae by 21.8% in a dynamic lifting task. These different, and in some cases contradictory, results reveal two important points: (1) anthropometric differences can result in different outcomes; (2) conditions of different tasks in the literature may differ and cause deviations. Thus, there is a need for comprehensive studies comparing the the effect of different factors for the same study participants and tasks to better understand the effect of each factor.

4-4- Users' Movement

Wearing exoskeleton reduced the participants' movement and resulted in feeling discomfort in body parts, especially legs and chest. The results from previous studies also showed that the range of motion reduced while using the exoskeletons [14, 21]. However, there was a perception of benefits and willingness for users to use exoskeletons in their long-term activities (Table 3). The perceived discomfort in chest and legs was expected since the torso weight was mainly supported by the chest pad and straps connected to it, and also the exoskelton transferred a portion of chest load to the upper-legs. However, in the future designs, it would be worth to modify the exoskeleton to reduce the discomfort as it could impact the long-term user compliance.

4-5- Static MMH Tasks vs Dynamic MMH Tasks

Comparing static and dynamic MMH tasks, the difference was not high, and in most evaluations, their results were similar. Nevertheless, the results from other studies indicated differences between dynamic and static MMH tasks [17, 22]. Their results showed significantly higher discomfort in dynamic MMH tasks compared to static tasks. Independent of exoskeleton design and test conditions, dynamic MMH tasks involve more movements, e.g. walking, than static ones. Therefore, movement restriction and discomfort in dynamic MMH tasks would be higher than, or at least at the level of, static MMH tasks.

4-6- Squatting MMH Tasks vs Bending MMH Tasks

The combined (e.g. considering bending from both dynamic and static tasks together) results, Table 4, showed that squatting and bending tasks had different effects on participants' discomfort. For example, the LOD of the low back for bending tasks (the average of its mixed result) was higher than squatting tasks. Similarly, Baltrusch et al. [23] have found that the LOD was higher when the task required hip flexion. Their results showed that using different exoskeletons specifically adjusted for bending and squatting could result in higher effectiveness. This idea was also suggested in [24], where the effect of two exoskeletons were evaluated on lifting tasks.

4-7- Body parts

Using the exoskeleton increased the LOD on the chest and upper legs in all conditions. The LOD increased in chest area because of the exoskeleton's chest pad; also, since load transferring frames of the exoskeleton connect upper body to the thigh parts, the LOD in these parts is higher in all conditions of using the exoskeleton. Also, the knee and arm experienced higher LOD in squatting compared to bending, while the LOD of the low back was higher in bending. The reason, as explained in the previous sections, was due to the different postures and the moment arm of the participants' upper body weight.

4-8- Male Users and Female Users

The male and female participants reported different RPE and LOD of body parts. The female participants experienced lower RPE and LODs for most of their body parts and scenarios (Table

2). Alemi et al. [24] studied the effect of two exoskeletons, namely BackX and Laevo. Their results for BackX exoskeleton showed that the RPE of different body parts of female participants was slightly higher or equal to male participants'. Also, the normalized peak values of EMG signal amplitudes for female participants were slightly higher than male participants' for all studied muscles. Additionally, their results indicated that Laevo and BackX exoskeletons could be the most helpful for female and male users, respectively. Therefore, it seems that both anthropometric differences and exoskeleton designs can led to different outcomes between male and female users, and further studies are required to evaluate the effect of each factor on the exoskeleton effectiveness.

4-9- Future Improvements

Considering all these factors and results, the examined exoskeletons should be modified in some tasks to have higher effectiveness. Since the real-world users of the exoskeletons usually perform movements other than those the exoskeleton is designed for, if the exoskeleton has negative effects on those tasks, its usability will diminish by the time. In future designs and modifications, it should be considered that using the exoskeleton should not impair the users' movements, other than the targeted ones, such as walking during dynamic tasks, or body rotations during static ones. In addition, exoskeletons should be adjusted to different anthropometric factors, especially gender. It may result in higher performance and effectiveness if more than one different sizes of exoskeleton be used with male and female users (or other anthropometric-based classifications).

5- Evaluation Framework

There are many exoskeletons for different MMH tasks conducted in the construction industry, but there is a lack of a standard evaluation framework for finding most appropriate exoskeleton(s) for specific task and joints. Based on the results obtained in this study together with other relevant studies in the literature, the following steps should be taken as a framework for the evaluation of the exoskeletons:

- Identifying existing, commercially available exoskeletons for the targeted tasks and body parts.

- Conducting preliminary studies to find the more appropriate exoskeletons based on subjective evaluations. Such metrics as the fitness, effectiveness, restriction, comfortability, and perceived exertion can be used in this step. The exoskeletons would be worn by a number of users for some days during performing their tasks. In this step, the inclusion of all anthropometric ranges (gender, body shape, etc) is highly valuable.
- Filling out a questionnaire at the end of each trial (collecting subjective evaluations)
- Conducting a comprehensive analysis on subjective evaluations to find the most appropriate, comfortable, and effective exoskeleton(s) for each gender, task, and body part. In one study [24], it was shown that male and females users preferred different exoskeletons for lifting tasks. Also, in this study, the results indicated that the effectiveness of BackX exoskeleton was different for male and female participants.
- Evaluation of selected exoskeletons using objective metrics. In addition to subjective evaluations, quantitative analysis is required to confirm the performance of the selected exoskeletons. Muscle activation, joint angles, and tissue loads can be studied in this step.
- Using the selected exoskeletons in the real field for a limited number of users and evaluating the performance of the exoskeletons based on feedback from the users .
- Using the finalized exoskeletons in long-term trials.

6- Conclusion

Emerging technologies, such as exoskeletons, have the potential to reduce the high rate of WMSDs in the construction industry. However, their adoption has to be evaluated from different aspects before introducing them to job sites, to ensure a successful and effective uptake. As MMH tasks are among the top contributors to WMSDs in construction, this study aimed to evaluate the impact of a passive back-support exoskeleton on different MMH task and postures. The results indicate that (1) the impact of using the exoskeleton is similar for dynamic and static MMH tasks, while it is slightly less effective for squatting during static tasks, (2) using the exoskeleton reduces the load on the low back overall, but might cause discomfort on chest and legs based on posture, (3) male participants experience higher discomfort on almost all body parts when wearing the exoskeleton compared to female participants, and (4) a majority of the participants rated the exoskeleton as providing acceptable usability, while female participants found the suit more effective. According to the reported LOD, the low back, knees, upper legs, and chest are the most affected body parts by the exoskeleton. Meanwhile, the use of exoskeleton reduced discomfort in the mentioned body parts except the chest. Based on the results, it can be concluded that passive exoskeletons have the potential to be adopted to reduce the rate of WMSDs in construction. However, proper training and supervision is required on the postures adopted by the workers, based on the specific characteristics of the task carried out. It is important that exoskeletons are properly selected for the task at hand and are solely used for the identified task. This study was limited to the experiments carried out for a short period of time. Long-term trials are required to reflect on the impact of using exoskeletons over time. Furthermore, while subjective metrics can be useful for evaluation of exoskeletons from a usability perspective, the lack of objective measures limits the generalization of the analysis. Future studies should also include objective evaluation features [25] for a more comprehensive analysis. Furthermore, the findings of studies such as this one can be used in future studies to assist with improving the design of exoskeletons.

Declarations

Competing interests

The authors declare no competing interests.

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethics Approval

This study was approved by the research ethics board of the authors' current institution (Pro00109264), and all methods were performed in accordance with the relevant guidelines and regulations. All participants were informed of the experimental procedures and gave informed written consent before the test.

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7- Tables

Table 1 Comparison of usability responses between male and female participants

Metric	Category	Trial type	Female (ave)	Female (sum)	Male (ave)	Male (sum)
Fit/Comfort	Dynamic MMH	Exoskeleton + Freestyle	6	36	6.83	41
		Exoskeleton + Bending	5.5	33	5.83	35
		Exoskeleton + Squatting	6.17	37	6	36
	Static MMH	Exoskeleton + Bending	5.83	35	5.83	35
		Exoskeleton + Squatting	5.5	33	5.67	34
Limit/Interference	Dynamic MMH	Exoskeleton + Freestyle	6.33	38	5.33	32
		Exoskeleton + Bending	5.17	31	5.17	31
		Exoskeleton + Squatting	6	36	5	32
	Static MMH	Exoskeleton + Bending	6.83	41	5.33	32
		Exoskeleton + Squatting	4.83	29	5	30
Effectiveness	Dynamic MMH	Exoskeleton + Freestyle	6.83	41	5.67	34
		Exoskeleton + Bending	6.67	40	6.17	37
		Exoskeleton + Squatting	7.17	43	5.33	32
	Static MMH	Exoskeleton + Bending	7.17	43	5.83	35
		Exoskeleton + Squatting	5.83	35	4.67	28

Metric	Category	Trial type	Female (ave)	Female (sum)	Male (ave)	Male (sum)
Fit/Comfort	Dynamic MMH	Exoskeleton + Freestyle	6	36	6.83	41
		Exoskeleton + Bending	5.5	33	5.83	35
		Exoskeleton + Squatting	6.17	37	6	36
	Static MMH	Exoskeleton + Bending	5.83	35	5.83	35
		Exoskeleton + Squatting	5.5	33	5.67	34
Limit/Interference	Dynamic MMH	Exoskeleton + Freestyle	6.33	38	5.33	32
		Exoskeleton + Bending	5.17	31	5.17	31
		Exoskeleton + Squatting	6	36	5	32
	Static MMH	Exoskeleton + Bending	6.83	41	5.33	32
		Exoskeleton + Squatting	4.83	29	5	30
Effectiveness	Dynamic MMH	Exoskeleton + Freestyle	6.83	41	5.67	34
		Exoskeleton + Bending	6.67	40	6.17	37
		Exoskeleton + Squatting	7.17	43	5.33	32
	Static MMH	Exoskeleton + Bending	7.17	43	5.83	35
		Exoskeleton + Squatting	5.83	35	4.67	28

Table 2 Comparison of LODs between male and female participants

Metric	Category	Trial type	Female (ave)	Female (sum)	Male (ave)	Male (sum)
Fit/Comfort	Dynamic MMH	Exoskeleton + Freestyle	6	36	6.83	41
		Exoskeleton + Bending	5.5	33	5.83	35
		Exoskeleton + Squatting	6.17	37	6	36
	Static MMH	Exoskeleton + Bending	5.83	35	5.83	35
		Exoskeleton + Squatting	5.5	33	5.67	34
Limit/Interference	Dynamic MMH	Exoskeleton + Freestyle	6.33	38	5.33	32
		Exoskeleton + Bending	5.17	31	5.17	31
		Exoskeleton + Squatting	6	36	5	32
	Static MMH	Exoskeleton + Bending	6.83	41	5.33	32
		Exoskeleton + Squatting	4.83	29	5	30
Effectiveness	Dynamic MMH	Exoskeleton + Freestyle	6.83	41	5.67	34
		Exoskeleton + Bending	6.67	40	6.17	37
		Exoskeleton + Squatting	7.17	43	5.33	32
	Static MMH	Exoskeleton + Bending	7.17	43	5.83	35
		Exoskeleton + Squatting	5.83	35	4.67	28

Table 3 Participants' responses to usability questions

Category	Trial type	Question	Average response (%)
Dynamic MMH	Exoskeleton + Freestyle	Overall feeling	moderate
		Level of heat or humidity	17 (hot/humidity)
		Suitability for long-term use	83 (yes)
		Did Exo make you use different posture?	75 (yes)
		Your typical posture for lifting (Bending or Squatting)	86 (Squatting)
		Which posture do you think will work better with the exoskeleton?	59 (Squatting)
	Exoskeleton + Bending	Overall feeling	Low-to-moderate
	Exoskeleton + Squatting	Overall feeling	Moderate
	Overall dynamic	Preferred posture for Dynamic MMH tasks (Bending or Squatting)	79 (Squatting)
		Would you use the exoskeleton for dynamic MMH in overall?	71 (yes)
Static MMH	Exoskeleton + Bending	Overall feeling	Low-to-moderate
	Exoskeleton + Squatting	Overall feeling	Low-to-moderate
	Overall static	Your preferred posture for static MMH tasks (Bending or Squatting)	33 (Squatting)

Table 4 The results of all MMH scenarios

Response type	Metric	Combined bending	Combined squatting	Combined all MMH	Combined (No-Exo)
Usability responses	RPE	3.33	3.67	3.43	3.13
	Fit/comfort	5.75	5.83	5.92	-
	Limit/Interference	5.63	5.21	5.5	-
	Effectiveness	6.46	5.75	6.13	-
LODs of body parts	Knee	2.3	4	3.12	3.29
	Upper leg	2.9	3.53	3.11	2.5
	Arm	0	2	1.1	1
	Shoulder	1.16	1	1.47	1.25
	Lower back	2.81	2	2.61	2.71
	Chest	3.25	3	3.23	0

8- Figures

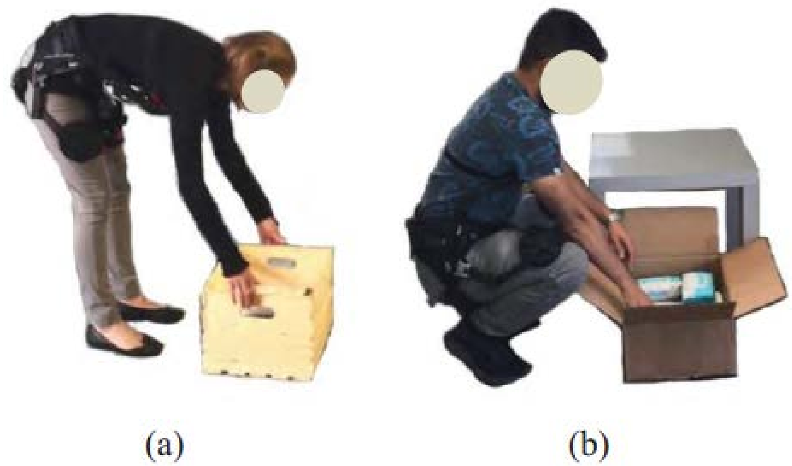

Fig. 1 Experiment Setup: (a) dynamic MMH, bending with exoskeleton, (b) static MMH, squatting with exoskelton

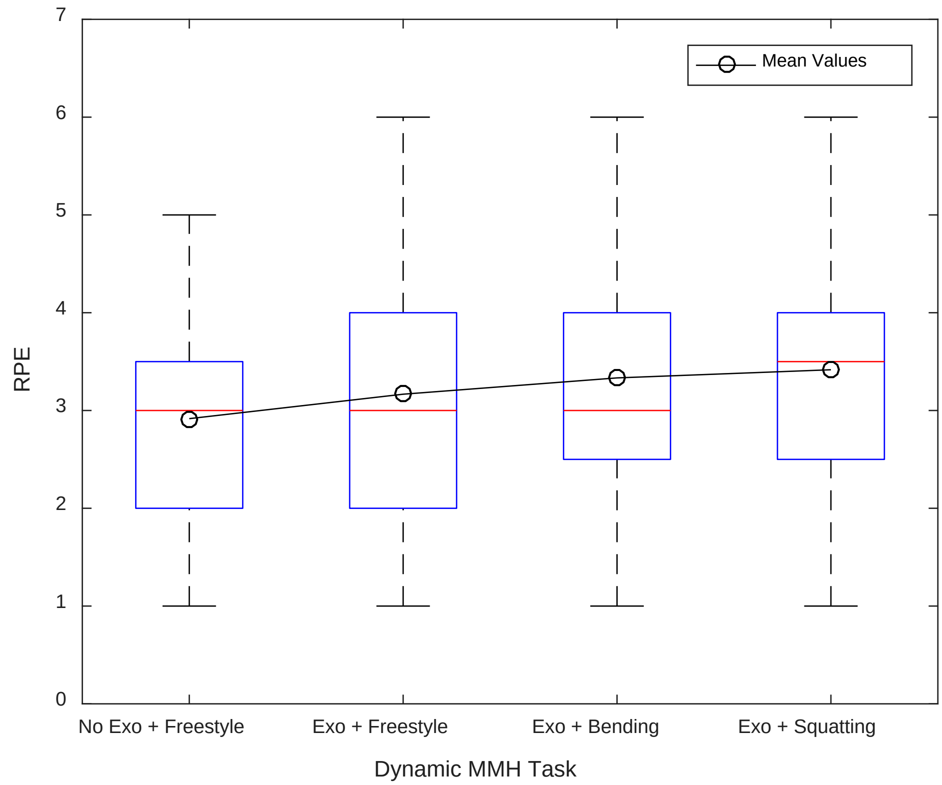

Fig. 2 Reported RPE for dynamic MMH**.** Results are presented for different postures, with or without wearing the exoskeleton.

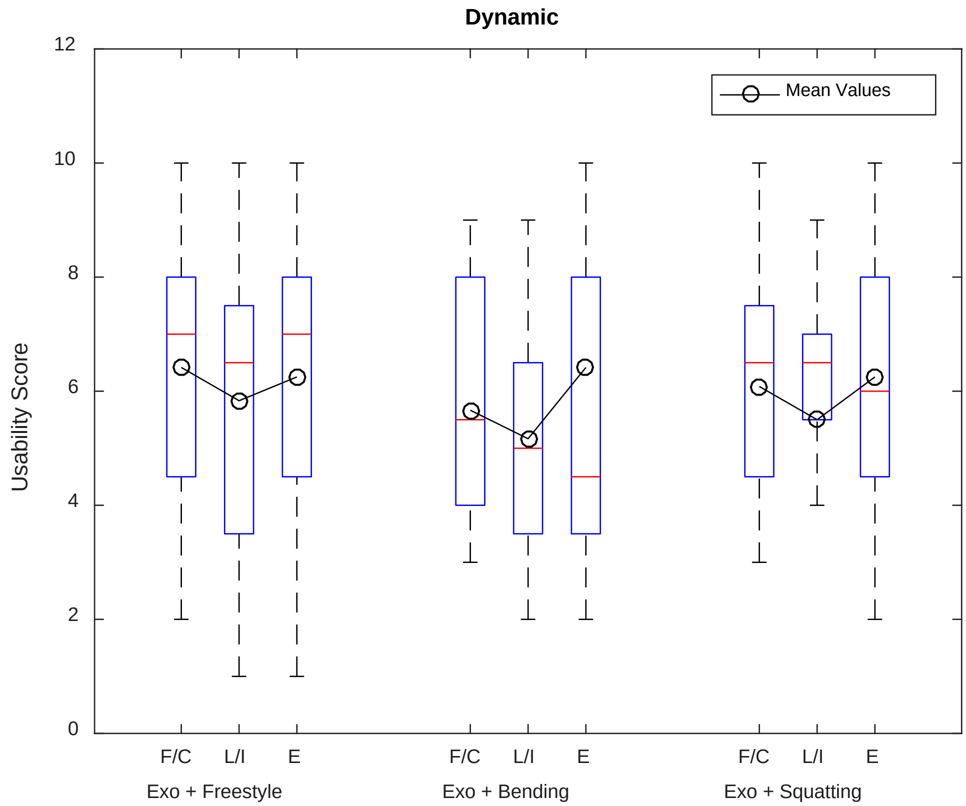

Fig. 3 Reported usability (F/C: Fit/Comfort, L/I: Limit/Interference, E: Effectiveness) of Exoskeletons for dynamic MMH. Results are presented for different postures, with or without wearing the exoskeleton.

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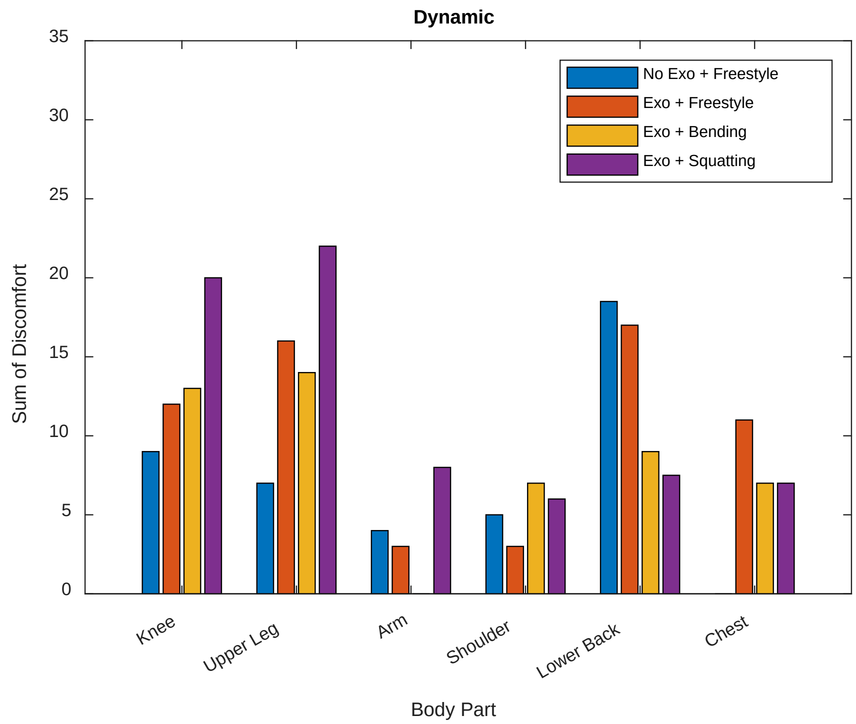

Fig. 4 Perceived discomfort of body parts for dynamic MMH. Results are presented for different postures, with or without wearing the exoskeleton.

490

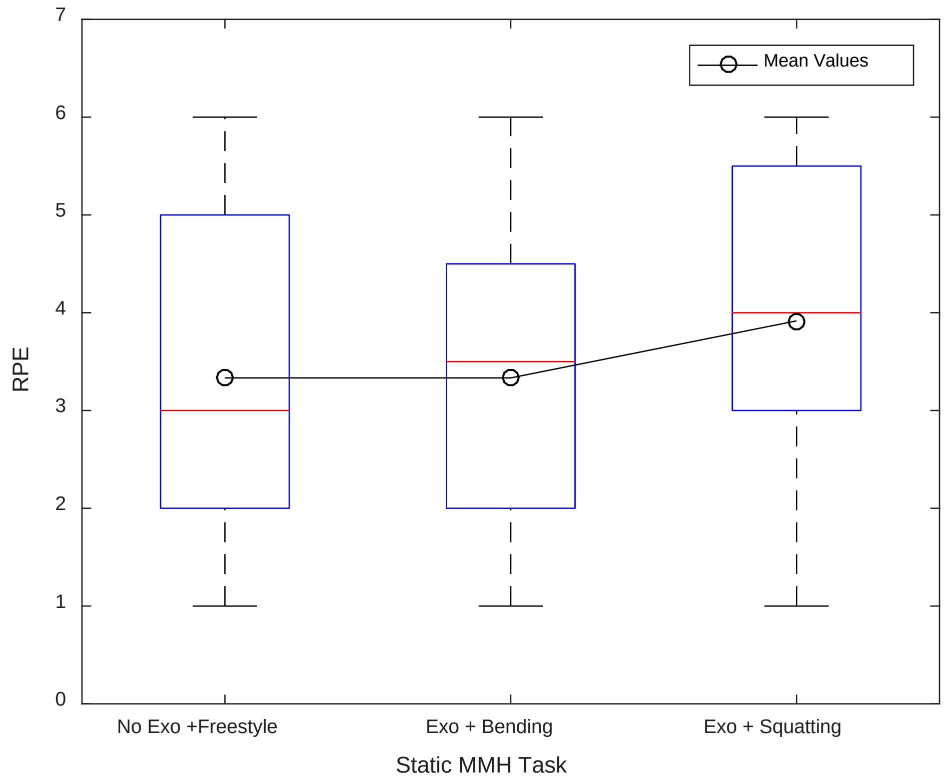

Fig. 5 Reported RPE for static MMH. Results are presented for different postures, with or without wearing the exoskeleton.

491

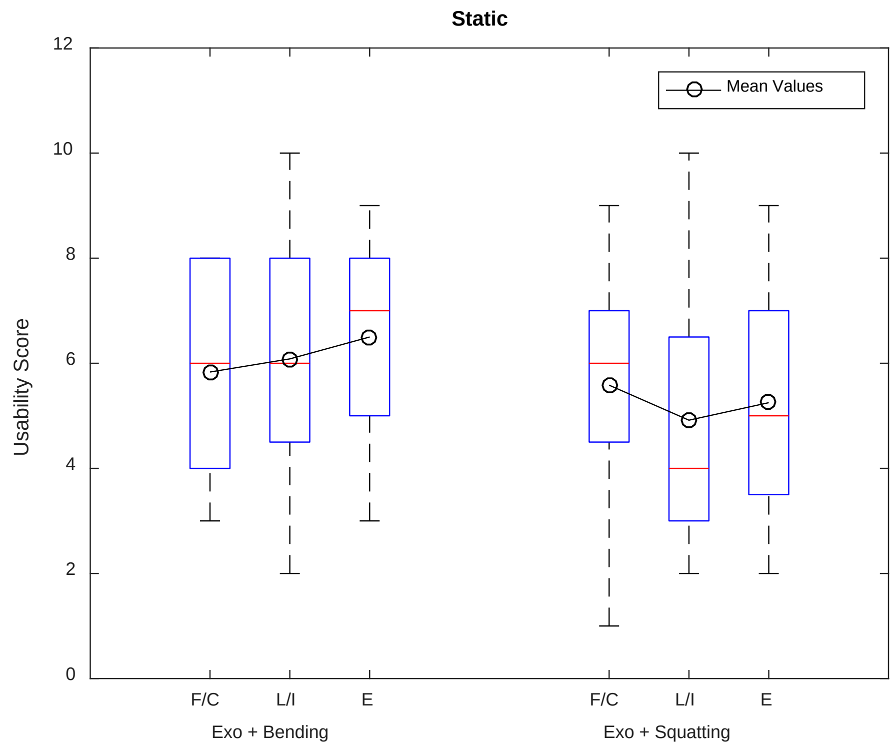

Fig. 6 Reported usability (F/C: Fit/Comfort, L/I: Limit/Interference, E: Effectiveness) of exoskeletons for static MMH in different postures.

492

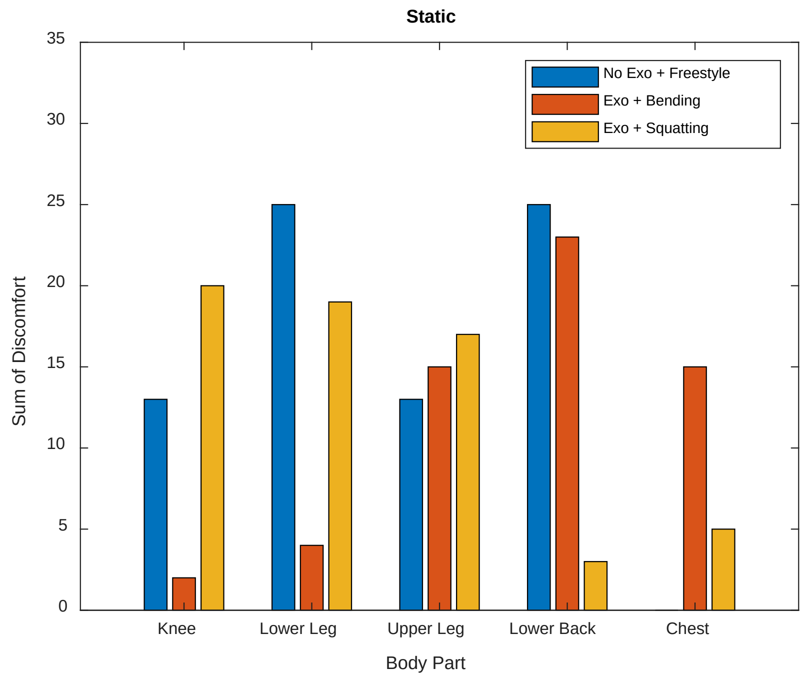

Fig. 7 Perceived discomfort of body parts for static MMH in different postures.

493

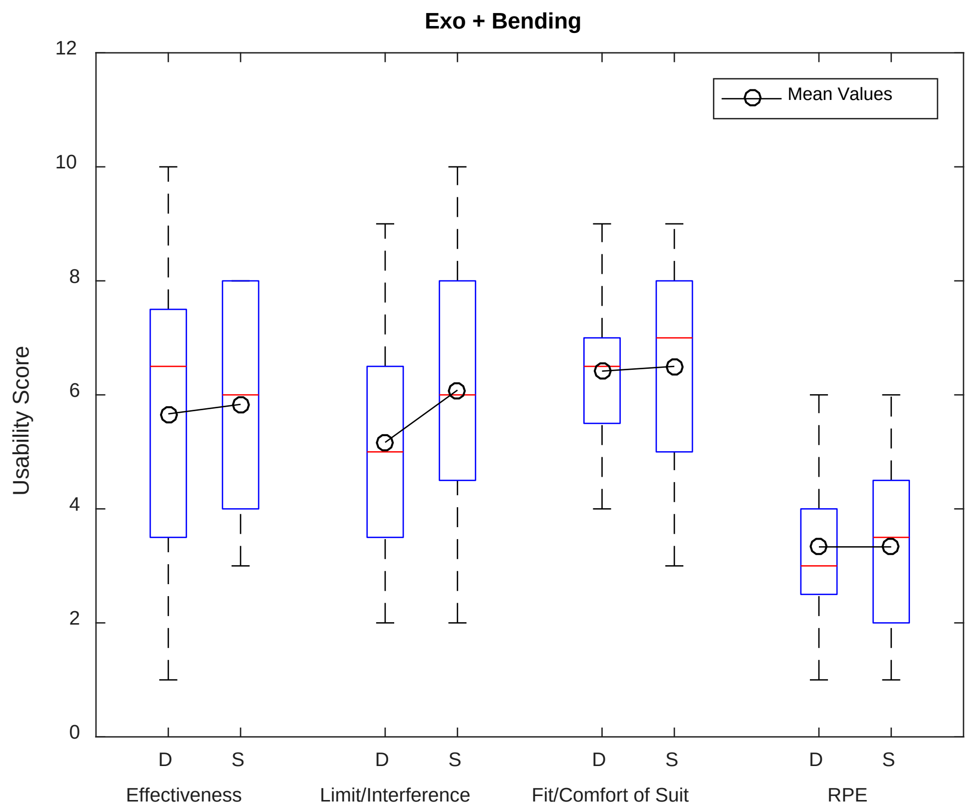

Fig. 8 Comparison of exoskeleton's usability between static (S) and dynamic (D) task scenarios for bending posture.

494

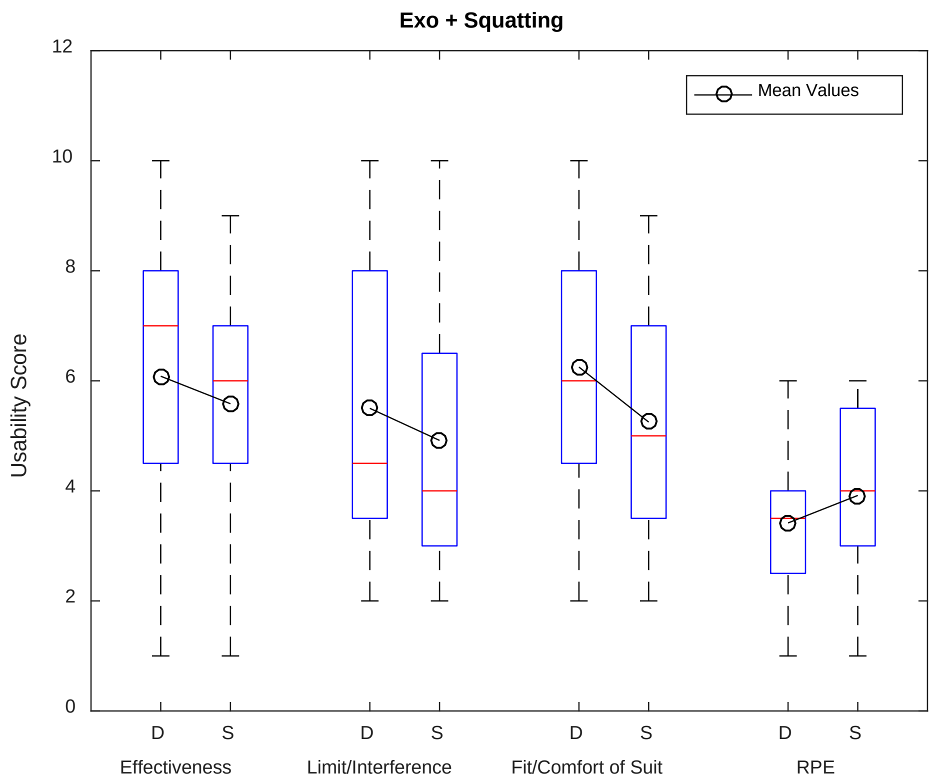

Fig. 9 Comparison of exoskeleton's usability between static (S) and dynamic (D) scenarios for squatting posture.

495

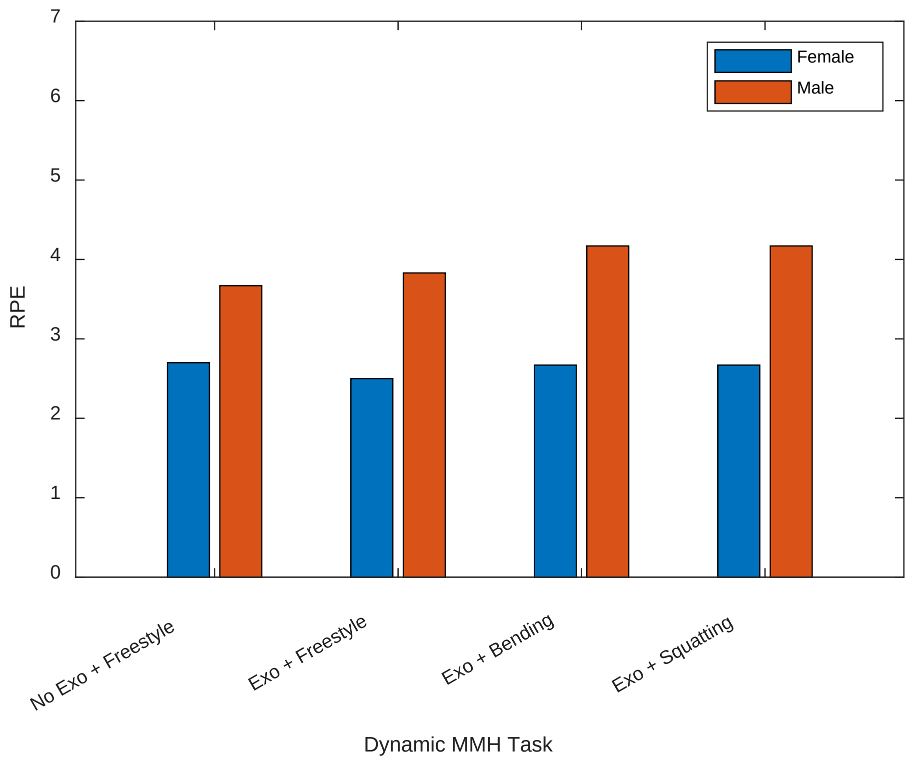

Fig. 10 RPE comparison between male and female participants for dynamic scenarios

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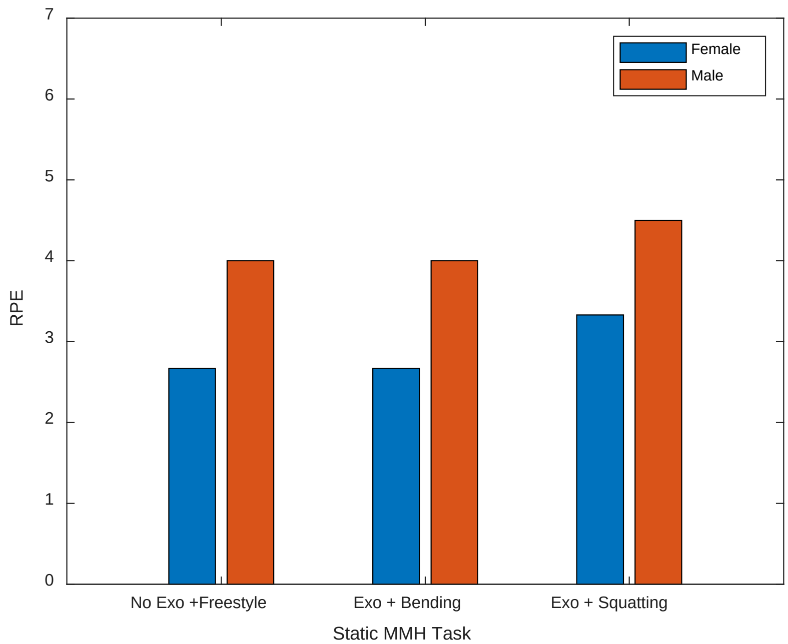

Fig. 11 RPE comparison between male and female participants for static scenarios