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Evaluation of the Effects of Passive Lower-Limb Exoskeletons on Muscle Activities According to Working Heights

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Abstract: Introduction: Research and development efforts regarding passive lower-limb exoskeletons are actively ongoing to reduce work-related musculoskeletal disorders (WMDSs) from improper and prolonged posture. The aims of this study were to evaluate the effects of passive lower-limb exoskeletons and working heights on muscle activity and subjective comfort ratings. Methods: In this study, 20 males performed a 10-min drilling task for three levels of working height (60, 85, and 110 cm), and three levels of intervention (WO: without exoskeleton, W_{CEX}, and W_{CC}) were used as independent variables. The EMG data of eight muscles and subjective discomfort ratings in each of the six body parts were analyzed in this study. Results: The results of this study confirm that the effect of wearing a lower-limb exoskeleton device may vary depending on the muscle type and working height. Overall, the positive effects of wearing were generally observed in the lower-limb muscles, whereas the muscle activity of the upper limbs showed an increasing trend when wearing the device at a height of 85 cm or more. Conclusions: Therefore, to obtain positive effects in both the upper- and lower-limb muscles, using the lower-limb exoskeletons at a working height of 85 cm or less is recommended.

Keywords: passive lower-limb exoskeleton; leg assist device; work-related musculoskeletal disorders (WMSDs); ergonomic intervention

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1. Introduction

Working in a static standing position for a long time frequently occurs in many industrial sites, including automobile assembly lines. In automobile manufacturing plants, more than 80% of workers perform standing or walking tasks for more than 50% of their daily working hours [1]. Waters and Dick (2015) [2] reported that prolonged standing tasks cause back pain; if they last more than 30 min, they cause fatigue and discomfort. Yazuli et al. (2019) [3] also confirmed that maintaining continuous standing work without sufficient rest caused muscle fatigue in the worker's back and lower limbs. Accordingly, the International Labor Organization (ILO, 2010) [4] issued guidelines that workers should have chairs for prolonged standing tasks and sit for a certain period. However, applying these guidelines in workplaces may not be feasible as it is difficult to use chairs depending on the working environment, and it is even more difficult to use them when workers frequently move.

Many researchers, including government agencies, have proposed solutions to problems related to prolonged standing work or poor lower-limb posture during tasks. As a result, the passive lower-limb exoskeleton device, which can be used for both standing and sitting postures, has recently received much attention [5,6]. A passive exoskeleton device is a mechanical device to assist human joints or movements without an external power source or battery. Although it is true that there are still several barriers to applying the exoskeletons directly to the workplace, the passive exoskeleton is relatively easier to apply to the field without significant changes in the work environment than the active exoskeleton. Thus, the passive exoskeleton is being considered in various fields to reduce physical fatigue by reducing muscle activity [7,8]. Among the passive exoskeletons, the lower-limb exoskeleton is an auxiliary device that allows the user to maintain a sitting position without a chair. The passive lower-limb exoskeleton, as an alternative to an active exoskeleton, does not require an external power source or battery and also has the advantage of being relatively lightweight and easy to wear using a belt or buckle [9].

Several studies have evaluated the effects of passive lower-limb exoskeleton devices. For example, Pillai et al. (2020) [10] tested the squatting posture while working before and after wearing a passive leg assist device and reported that the activity of the rectus femoris (RF) muscle significantly decreased when wearing the device, while that of the tibialis anterior (TA) muscle increased slightly. Hasegawa and Muramatsu (2013) [11] showed that wearing a lower-limb assistive device reduced the floor reaction force when caregivers assisted in transferring elderly or physically challenged patients. Luger et al. (2019) [12] reported that studies on the stress applied to other joints were necessary, although lower-limb devices effectively reduced lower-limb muscle activity. As such, wearing lower- and upper-limb exoskeleton devices can have both positive [13–15] and negative [16–19] effects, and, in particular, the effect of wearing an exoskeleton device may vary depending on the working environment, so further research is needed.

Although there are several studies on lower-limb exoskeleton devices, there are limitations in that more studies are needed on the differences in effectiveness when applying them to various working heights and muscles. Therefore, this study aimed to (1) quantify the effect of wearing a lower-limb exoskeleton by evaluating the muscle activity of eight muscles and the subjective discomfort ratings of six body parts and (2) examine how the effect varies when applied at three working heights.

2. Methods

2.1. Participants

Twenty healthy adult males (mean ± SD: age: 24.4 ± 2.4 years; height: 176.0 ± 3.1 cm, weight: 78.0 ± 9.0 kg) without a history of musculoskeletal disorders were recruited for this experiment. All participants were males because most workers in automobile assembly lines who needed to wear the lower-limb exoskeletons were males. Seventeen participants were right-handed, the remaining three were left-handed, and all participants performed the test using their dominant hand.

2.2. Lower-Limb Exoskeletons

The test used two types of passive lower-limb exoskeleton, the CEX and Chairless Chair (Figure 1), and both devices were wearable chairs that could be used for both standing and sitting tasks.

- The CEX (Hyundai Motor Group, Seoul, Republic of Korea) can be adjusted at three angles (55, 70, and 85°) by pressing the adjustment button step by step, and the length of the frame can be adjusted appropriately according to the user and working environment (Figure 1, left). It consists of thigh supporters and calf supporters. Additional bars, the knee angle adjustment parts, are configured to support the body weight and balance from the floor. It weighs about 1.8 kg and can be adjusted to suit the user's body, using buckles and Velcro on the thighs and calves. The CEX can support up to 200 kg body weight.
- The Chairless Chair 2.0 (CC) (Noonee, Wendlingen, Germany) can also be adjusted to the angles of the body frame using buttons located in the upper part (thigh) of the

frame. While the CEX can accommodate three angles, the Chairless Chair can adjust the angle (100 to 156°) by pressing the adjustment button to release it at the desired angle. However, it cannot be adjusted at angles lower than 100° or less (Figure 1, right). It consists of thigh supports and frames attached to shoes to support the floor. The 3.0 kg Chairless Chair is designed to withstand up to 120 kg.

Figure 1. CEX (**left**) and Chairless Chair (**right**).

2.3. Experimental Procedures

The experimental procedures were approved by the Institutional Review Board of Sungkyunkwan University and were performed following the Declaration of Helsinki (IRB #SKKU-20210107). Before the test, the participants were provided with detailed information about the purpose and procedure of the experiment and then gave their written informed consent. After disinfecting the participant's skin with alcohol cotton, electromyography bipolar electrodes (Ag/AgCl, with a 2.5 cm inter-electrode distance) were attached to the muscles to collect electromyography (EMG) signals. The EMG data were collected using the wireless system of the Noraxon Telemyo 2400 DTS (Noraxon, Scottdale, AZ, USA). The electrode locations were identified according to SENIAM guidelines [20]. The maximum voluntary contraction (MVC) and resting EMG were measured two times with a 60-s rest between trials for each muscle, and the mean of the two measurements was used as the MVC in this study. The EMG was sampled at a rate of 2000 Hz. Only data in the 20–400 Hz range were collected using bandpass filtering for the EMG signals, and all EMG signals were normalized based on the MVC. The methods for measuring the MVC of each muscle were as follows: (1) upper trapezius—lifting a shoulder in a sitting posture; (2) middle deltoid–raising arm laterally in a sitting posture; (3) biceps brachii—bending elbow while sitting with the elbow at 120° of extension; (4) triceps brachii—stretching elbow while sitting with the elbow at 120° of extension; (5) erector spinae—raising back and legs in a prone position; (6) rectus femoris—stretching knee while in sitting position with feet in the air; (7) biceps femoris—bending a knee in a prone position with the knee at 90° of flexion; (8) tibialis anterior—bending ankle while in sitting position at 90° of flexion with feet on the floor.

Each participant performed a warm-up exercise for about 10 min to get used to the drilling task and exoskeleton devices. After the warm-up exercise, participants rested for about 10 min. Then, the participant performed a 10-min drilling task every 60 s (drilling task for 40 s and resting for 20 s, respectively) on the experimental frame, which was custom-made for this study (Figure 2). Three working heights (60, 85, and 110 cm) of the experimental frame were set up based on the 50th percentile of knee, hip, and back heights for adult males aged 20 to 59 in South Korea [21]. The drill used in the test was an electric drill (JAYA, Seoul, Republic of Korea) that weighed about 1.5 kg and is typically found in manufacturing sites. This test did not limit the speed of the drilling task, and participants were instructed to perform the task in their preferred style and speed for all working heights.

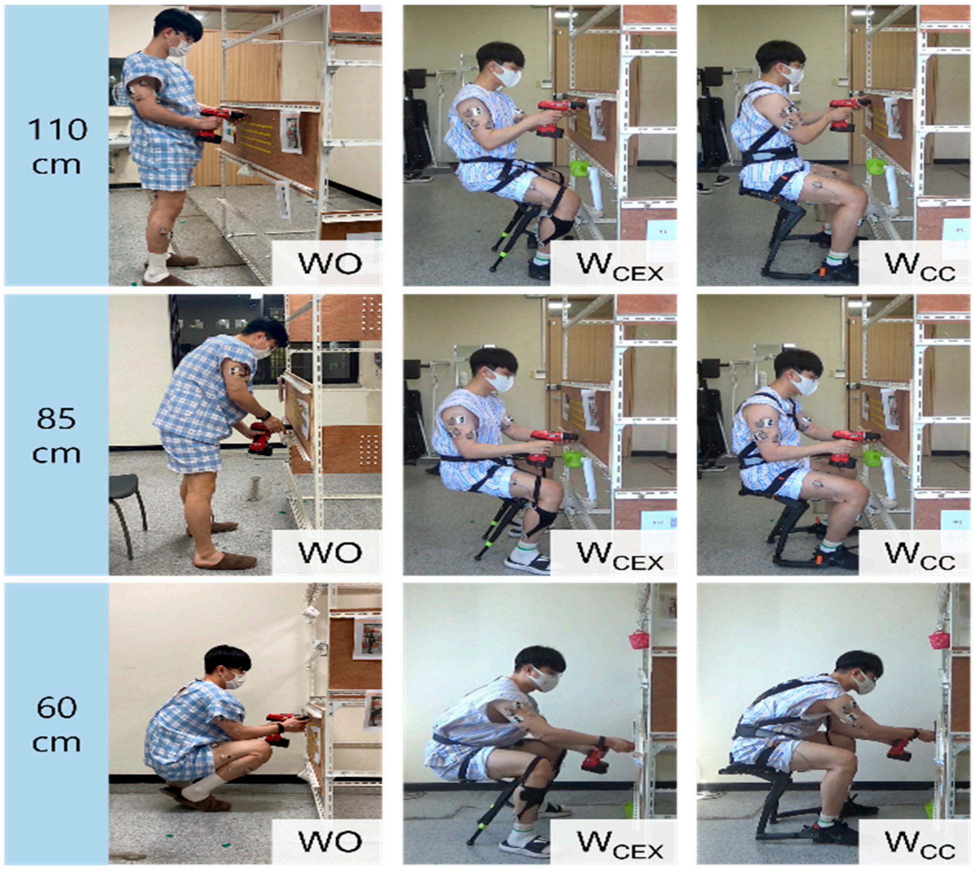

Figure 2. Drilling task without exoskeleton (WO, **left**), with CEX (W_{CEX}, **middle**), and with CC (W_{CC}, **right**) at the working heights of 110 cm (**top**), 85 cm (**middle**), and 60 cm (**bottom**).

Thus, all participants performed nine drilling tasks, including all combinations of three levels of intervention (WO, W_{CEX}, and W_{CC}) and three levels of working height. The tests were carried out over three days to prevent fatigue, and the tasks were randomly conducted based on the three levels of intervention.

2.4. Statistical Analysis

Three levels of intervention (without Exo—WO; with CEX—W_{CEX}; and with CC—W_{CC}) and three working heights (60, 85, and 110 cm) were selected as independent variables. Muscle activity and subjective discomfort ratings were selected as dependent variables.

The muscle activity of eight right muscles (four upper-limb muscles and a lower back muscle: upper trapezius, middle deltoid, biceps brachii, triceps brachii, and erector spinae; three lower-limb muscles: rectus femoris, biceps femoris, and tibialis anterior) was measured as dependent variables. Subjective ratings of body discomfort were measured using Borg's CR-10 scale for six body parts (neck, chest, back, shoulder, arm, and leg) after drilling task performance [22].

The normality of the dependent variables was examined using Shapiro–Wilk and Kolmogorov–Smirnov tests, and then a generalized linear mixed model (GLMM) was applied for analysis in this study. Then, a post-hoc analysis was performed using Tukey's HSD to compare the differences between interventions and working heights. Subsequently, the interaction effect was also included in this model. All statistical analyses were performed using SPSS 9.0 (SPSS Inc., Chicago, IL, USA). The level of statistical significance was set at $p < 0.05$.

3. Results

3.1. Muscle Activity (EMG)

3.1.1. Effect of Passive Exoskeleton on EMG

Wearing an exoskeleton led to a statistically significant decrease in muscle activity in the lower-limb muscles (rectus femoris: RF, biceps femoris: BF, and tibialis anterior: TA), while the effects on the back and upper-limb muscles were not statistically significant (Table 1). In the case of the RF, wearing the CEX (W_{CEX}) significantly reduced muscle activity by about 68.8~69.7% compared to the cases without exoskeletons (WO) and wearing the Chairless Chair (W_{CC}). There was no significant difference in RF muscle activity between WO and W_{CC}. In the case of the BF, there was a significant decrease in muscle activity when wearing the CC (W_{CC}) and CEX (W_{CEX}), by 78.5% and 71.5%, respectively, compared to WO. TA muscle activity was also decreased significantly by 67.1% and 57.9% when wearing the CC (W_{CC}) and CEX (W_{CEX}), respectively, compared to without exoskeletons (WO).

Table 1. Mean (standard error) values of muscle activity according to interventions.

Muscle	Intervention [Unit: %MVC]			*p*-Value
	WO	W_{CC}	W_{CEX}	
Upper trapezius (UT)	9.2 (1.8)	9.3 (1.3)	10.1 (1.4)	0.854
Middle deltoid (MD)	3.0 (0.2)	3.4 (0.4)	3.2 (0.3)	0.622
Triceps brachii (TB)	3.8 (0.6)	4.6 (1.2)	4.1 (1.1)	0.860
Biceps brachii (BB)	9.1 (1.0)	10.1 (1.2)	10.3 (1.2)	0.669
Erector spinae (ES)	12.8 (1.1)	11.6 (1.1)	14.1 (1.1)	0.226
Rectus femoris (RF)	6.4 (1.3) ^{A}	6.6 (1.4) ^{A}	2.0 (0.5) ^{B}	0.002 *
Biceps femoris (BF)	15.8 (1.9) ^{A}	3.4 (0.7) ^{B}	4.5 (0.6) ^{B}	<0.001 *
Tibialis anterior (TA)	7.6 (1.6) ^{A}	2.5 (0.6) ^{B}	3.2 (0.5) ^{B}	<0.001 *

Asterisks indicate the statistical significance of the main effect (i.e., intervention) evaluated in generalized linear mixed models ($p < 0.05$). Different letters indicate significant statistical differences among the three intervention conditions obtained from post-hoc follow up tests ($p < 0.05$, Tukey's test).

3.1.2. Effect of Working Height on EMG

The differences in muscle activity according to working height were significant for the upper trapezius (UT), biceps brachii (BB), biceps femoris (BF), and tibialis anterior (TA), as shown in Table 2. While the UT and TA showed significantly greater muscle activity at the lowest working height of 60 cm, the BB and BF showed the highest muscle activity at the 85 cm working height.

3.1.3. Interaction Effects between Working Height and Passive Exoskeleton on EMG

The interaction between working height and intervention was significant in five muscles, including two upper-limb muscles, the upper trapezius (UT) and middle deltoid (MD), and three lower-limb muscles, the rectus femoris (RF), biceps femoris (BF), and tibialis anterior (TA).

In the case of the shoulder muscle, the muscle activity of UT significantly decreased for W_{CEX} and W_{CC} (CEX: 58.1%, CC: 77.7%) compared to WO at the lowest working height of 60 cm, while the UT activity significantly increased when wearing the exoskeletons at 85 and 110 cm working heights (85 cm—CEX: 92.5% and CC: 110.0%; 110 cm—CEX: 513.6% and CC: 563.6%).

The MD also showed a similar trend to the UT. The muscle activity of MD significantly decreased when wearing the exoskeletons (W_{CEX} and W_{CC}) at the lowest working height of 60 cm (CEX: 32.5%, CC: 40.0%), and it significantly increased at heights above 85 cm (85 cm—CEX: 13.8%, CC: 27.6%; 110 cm—CEX: 68.2%, CC: 90.9%) (Figure 3).

Table 2. Mean (standard error) values of muscle activity according to working height.

Muscle	Working Height [Unit: %MVC]			*p*-Value
	60 cm	**85 cm**	**110 cm**	
Upper trapezius (UT)	11.8 (1.9) ^{A}	6.7 (1.1) ^{B}	10.1 (1.4) ^{AB}	0.009 *
Middle deltoid (MD)	3.0 (0.3)	3.3 (0.3)	3.3 (0.4)	0.710
Triceps brachii (TB)	3.9 (1.2)	4.4 (1.0)	4.3 (0.8)	0.930
Biceps brachii (BB)	7.4 (0.9) ^{B}	11.5 (1.2) ^{A}	10.6 (1.2) ^{AB}	0.016 *
Erector spinae (ES)	11.6 (1.2)	14.0 (1.3)	12.9 (0.8)	0.212
Rectus femoris (RF)	6.1 (1.4)	4.3 (1.2)	4.6 (1.0)	0.390
Biceps femoris (BF)	5.6 (0.7) ^{B}	12.3 (2.0) ^{A}	5.8 (1.0) ^{B}	<0.001 *
Tibialis anterior (TA)	7.8 (1.6) ^{A}	3.2 (0.6) ^{B}	2.4 (0.5) ^{B}	<0.001 *

Asterisks indicate the statistical significance of the main effect (i.e., intervention) evaluated in generalized linear mixed models ($p < 0.05$). Different letters indicate significant statistical differences among the three intervention conditions obtained from post-hoc follow up tests ($p < 0.05$, Tukey's test).

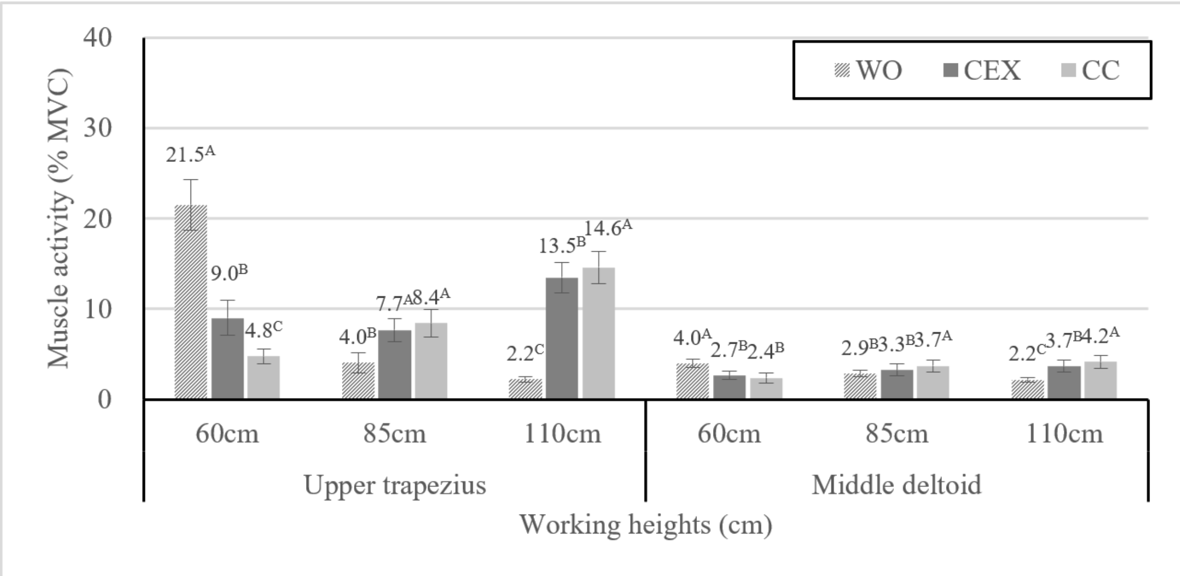

Figure 3. Interaction effect between working height and exoskeleton on upper-limb muscles. Different letters indicate significant statistical differences ($p < 0.05$, Tukey's test).

The RF muscle activity showed a significantly decreasing trend for W_{CEX} and W_{CC} at the working height of 60 cm (CEX: 92.6%, CC: 83.7%), but the muscle activity of RF was significantly increased in the case of W_{CEX} at 85 and 110 cm working heights (85 cm: 229.6%; 110 cm: 141.9%).

In the case of the BF, the muscle activity decreased when wearing the exoskeletons (W_{CEX} and W_{CC}) at all working heights, and this tendency was particularly pronounced at the 85 cm working height (CEX: 82.9%; CC: 85.0%). In the case of the TA, there were no significant differences in muscle activity regardless of whether the exoskeletons were worn at 85 and 110 cm, but there was a significant decrease when the device was worn (W_{CEX} and W_{CC}) at the 60 cm (CEX: 74.4%; CC: 92.6%) working height (Figure 4).

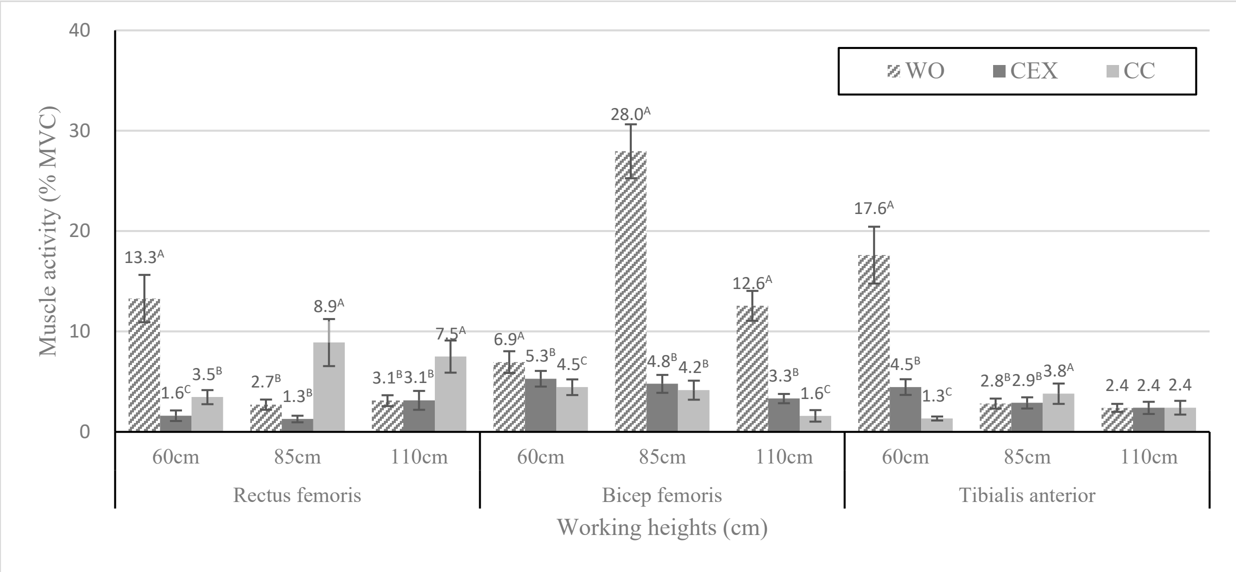

Figure 4. Interaction effect between working height and exoskeleton on lower-limb muscles. Different letters indicate significant statistical differences ($p < 0.05$, Tukey's test).

3.2. Subjective Discomfort Rating

The effects of the intervention and working height on the subjective discomfort ratings were not statistically significant in this study. Although the subjective discomfort ratings for the intervention were not significant, overall subjective discomfort in the neck, shoulders, chest, arms, and lower back, excluding the legs, tended to decrease for W_{CC} and W_{CEX}. Regarding leg discomfort, the lowest working height of 60 cm led to relatively higher subjective discomfort ratings than the other working heights of 85 and 110 cm, as shown in Table 3.

Table 3. Mean values of subjective discomfort rating according to intervention and working height.

Body Part	Interventions				Working Height			
	WO	W_{CC}	W_{CEX}	*p*-Value	60 cm	85 cm	110 cm	*p*-Value
Neck	2.1	1.6	1.5	0.677	1.7	1.8	1.7	0.053
Shoulder	2.1	1.7	1.6	0.541	1.7	1.8	1.9	0.152
Chest	1.5	1.5	1.2	0.265	1.4	1.4	1.4	0.057
Arm	2.3	1.8	1.8	0.476	1.8	1.9	2.1	0.189
Back	2.7	2.3	2.3	0.327	2.5	2.6	2.2	0.258
Leg	2.3	2.8	2.5	0.474	3.0	2.4	2.3	0.823

4. Discussion

This study was performed to identify the effects of not wearing exoskeletons and wearing lower-limb exoskeletons (CEX and Chairless Chair) on muscle activity and subjective discomfort ratings in the drilling task. Participants recruited for this study also performed a 10-min drilling task at three working heights (60, 85, and 110 cm) to determine the effect of the exoskeleton device at different working heights.

The effect of wearing a lower-limb exoskeleton on the lower-limb muscles was statistically significant in this study. The activity of the rectus femoris, biceps femoris, and tibialis anterior muscles was reduced by 68.8~69.7%, 78.5~71.5%, and 57.9~97.1%, respectively, compared to without an exoskeleton for all working heights. Similar findings were found in previous research. Many previous studies have reported the effect of reducing the activity of lower-limb muscles when performing tasks while wearing lower-limb exoskeletons.

Pillai et al. (2020) [10] evaluated the activity of six muscles (lumbar erector spinae, thoracic erector spinae, tibialis anterior, rectus femoris, semitendinosus, and lateral gastrocnemius) when performing bolting tasks while wearing the Leg X exoskeleton, and they reported that the rectus femoris muscle's activity decreased significantly when wearing the exoskeleton. Yan et al. (2021) [23] reported that the lower-limb muscle activity (vastus lateralis, biceps femoris, rectus femoris, and vastus medialis) decreased by 44.8 to 71.5%, and the plantar pressure also decreased by 58.5 to 64.2%, when performing an assembly task with lower-limb exoskeletons in a squatting posture. Luger et al. (2019) [12] also reported an approximately 25% reduction in gastrocnemius muscle activity when wearing an exoskeleton compared to working in a standing posture without the exoskeleton. Huysamen et al. (2018) [13] showed that the muscle activity of the erector spine and the biceps femoris was decreased by 12~15%% and 5% in tasks involving lifting a box of 7.5 kg and 15.0 kg, respectively, when wearing an industrial exoskeleton. Bosch et al. (2016) [24] also showed that the muscle activity of the lower back muscles and the biceps femoris muscle decreased by 35~44% and 20% during an assembly task, respectively, when wearing the exoskeleton. They also reported a 37~50% reduction in lower back muscle activity and a 24% reduction in biceps femoris muscle activity when wearing the exoskeleton in a static holding task.

The effect of wearing a lower-limb exoskeleton showed different aspects depending on the upper-limb muscles and working height in this study. The muscle activity of the upper trapezius (UT) and the middle deltoid (MD), which were the upper limbs, when wearing the lower-limb exoskeletons decreased by about 32.5~40.0% and 58.1~77.7%, respectively, compared to without the exoskeletons at a working height of 60 cm. On the other hand, at the height of 85 and 110 cm, the muscle activity of these muscles significantly increased when wearing the lower-limb exoskeletons, and this trend was more pronounced in the upper trapezius than in the middle deltoid. The results of increasing the muscle activity of the upper trapezius and the middle deltoid at high working heights might be explained by changes in working posture when wearing the exoskeleton device. When wearing the lower-limb exoskeletons at heights of 85 and 110 cm, the worker's sitting height was relatively lowered, so the worker had to lift his shoulders and arms more to compensate for this. Thus, this suggests that wearing the lower-limb exoskeletons at a working height of 85 cm or more negatively increases the workload on the upper-limb muscles. Similar to this study's findings, Kong et al. (2021) [25] compared the muscle activity of the whole body when wearing lower-limb exoskeletons at working heights of 40 to 140 cm. They also reported that the upper-limb muscle activity increased at the working height of 100 cm or more, and wearing the lower-limb exoskeletons was not recommended if the working position was higher than 100 cm.

Overall, the lower-limb muscles (rectus femoris, biceps femoris, and tibialis anterior) showed lower muscle activity when wearing the exoskeletons for all three working heights. The lower-limb muscles represented different patterns depending on the working height. There was no significant difference for the rectus femoris and tibialis anterior muscles depending on the wearing of the exoskeletons at working heights of 85 and 110 cm. However, these muscles' activity (RF and TA) significantly decreased by 83.7~92.6% when wearing the device at a height of 60 cm, which is a squatting body posture. Generally, the tibialis anterior muscle is extensively activated in the squatting posture, playing the role of body balance to prevent the body from falling backward [26–28]. In the case of the rectus femoris muscle, as an antagonist muscle in the squatting posture, the muscle activity was also higher than in the sitting posture. Since wearing the exoskeletons helped to balance the squatting posture, muscle activity was believed to decrease significantly. The biceps femoris (BF) muscle showed that muscle activity decreased significantly when wearing an exoskeleton device at all heights. This decline was more pronounced at the height of 85 cm. When the center of gravity was directed forward, the biceps femoris muscle was activated to maintain body balance [29]. When working without the exoskeletons at 85 cm, the body was flexed while performing the task, which means that the body's center of gravity was directed forward. Thus, the biceps femoris muscle was extensively activated. However, since the back flexion is significantly reduced if one wears an exoskeleton, the biceps femoris muscle activity is believed to decrease significantly at the 85 cm working height.

He et al. (2007) [30] showed that the muscle activity of the rectus femoris increased during squatting motion without the exoskeleton, similar to working at a 60 cm height. In addition, the muscle activity of the biceps femoris was the lowest while sitting down as a condition of wearing an exoskeleton among squatting, sitting, and standing postures. Therefore, it could be explained that the loads of the rectus femoris were mainly reduced when working at 60 cm and wearing the exoskeletons, and those of the biceps femoris also decreased working in the WO state at 85 and 110 cm as a result of standing, according to wearing an exoskeleton.

It was observed that the subjective physical load of the lower limbs tended to increase slightly to 2.8 and 2.5 when wearing the Chairless Chair and CEX, respectively, compared to without exoskeletons (2.3). Luger et al. (2019) [31] also reported that wearing an exoskeleton device resulted in higher subjective discomfort ratings. Although the subjective discomfort was not significant in this study, it should be considered important because it is one of the key factors determining whether to wear exoskeleton devices in industrial sites [32]. When wearing lower-limb exoskeletons, the user cannot move freely and has a high level of discomfort due to the large, heavy, and rigid frames and pressure from the Velcro. Therefore, the developers of exoskeletons should pursue designs that consider not only the physical workload but also subjective discomfort.

In summary, it was found that the effects of applying the exoskeletons varied depending on the type of muscle and working height. Overall, the positive effects of wearing were generally observed in the lower-limb muscles, whereas the muscle activity of the upper limbs showed an increasing trend when wearing the device at a height of 85 cm or more. Therefore, to obtain positive effects in both the upper- and lower-limb muscles, using the lower-limb exoskeletons at a working height of 85 cm or less is recommended.

There are a few limitations in this study. The first limitation of this study is that the task was performed in a relatively short time (10 min). Although this study demonstrated some positive effects of the passive lower-limb exoskeletons, this study does not provide any implications for the longer-term use of the exoskeletons. Thus, future studies should consider longer task durations and realistic tasks. The second limitation is that the current study was conducted with only inexperienced young men in the student group. Further study is required for various user groups to verify the effects of exoskeletons and to minimize the effects of the skill level, gender, and age. The third limitation is that this study was conducted with only 20 participants. This sample size might cause statistical problems such as low statistical power. Thus, additional participants may need to be included for future research. Lastly, this study targeted relatively static tasks with shorter moving distances. Since mobility convenience is also one of the most important factors in determining whether to use a wearable exoskeleton device for the lower limbs, studies of more dynamic and active tasks using exoskeletons are needed in the future.

5. Conclusions

This study evaluated the effect of wearing exoskeleton devices on the lower limbs by measuring EMGs and subjective discomfort ratings. The CEX and Chairless Chair are wearable devices that the participant can use to stand or sit while performing a task. Results showed that the muscle activity of the lower limbs (rectus femoris, biceps femoris, and tibialis anterior) decreased significantly when the participant wore the exoskeleton device at different working heights. However, wearing the exoskeletons had different effects on the upper limbs (upper trapezius and middle deltoid) depending on the working height. When the participant used the exoskeleton device, the upper-limb muscle activity significantly decreased at the lowest working height (60 cm), increasing at 85 and 110 cm. Therefore, when considering the physical workloads of the upper and lower limbs, the exoskeleton device is most effective when applied to a height of 85 cm or less.

The most important implication of this study is that the effects and side effects of wearing an exoskeleton device vary depending on the working height and muscle type. Lower-limb muscles showed positive effects when worn at all three working heights, while upper-limb muscles showed different effects depending on the working height. This implies that the upper and lower limbs should be fully considered to introduce the exoskeleton. In addition, the task's characteristics, such as the working height and working type, should also be considered when introducing exoskeleton devices in the industrial field.

The recommendation of wearing a lower-limb exoskeleton at a working height of 85 cm or less may apply to manufacturing workers who perform assembly tasks that burden the knees and legs, such as automobile assembly lines with repeated and improper body postures due to low working heights. In addition, as mentioned in the Introduction, the risk of WMSDs in the agricultural sector is higher than in other sectors due to the use of squatting and knee-bending working postures during the harvesting of peppers, eggplants, and watermelon at a low working height. This study suggests that wearable lower-limb exoskeletons in agriculture sites can reduce the workload on farmers' lower and upper limbs and reduce the incidence of musculoskeletal disorders.

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