Article

Verification of Industrial Worker Walking Efficiency with Wearable Hip Exoskeleton

Yunhee Chang [1],*, Jungsun Kang [1], Bora Jeong [1], Gyoosuk Kim [1], Bokman Lim [2], Byungjune Choi [2] and Younbaek Lee [2]

1 Korea Compensation and Welfare, Rehabilitation Engineering Research Institute, Incheon 21417, Republic of Korea; js0670@comwel.or.kr (J.K.); jeongbora77@comwel.or.kr (B.J.); gskim7379@comwel.or.kr (G.K.)

2 Wirobotics Incorporation, Yongin 16942, Republic of Korea; bokman.lim@wirobotics.com (B.L.); bjchoi@wirobotics.com (B.C.); younbaek@wirobotics.com (Y.L.)

* Correspondence: yhchang2@comwel.or.kr; Tel.: +82-32-509-5249

Featured Application: This study can help prevent muscle fatigue and promote efficient energy consumption in industrial workers using a wearable hip-exoskeleton device.

Abstract: In highly mobile workplaces, wearable walking-assistant devices reduce muscle fatigue in workers' lower extremities and increase energy efficiency. In our study, we verify this following the development of an ultralight wearable hip exoskeleton for industrial workers. Ten healthy male adults participated in this study, and their muscle activity, muscle fatigue, and energy expenditure were compared with and without a device while walking on a treadmill and going up stairs. While walking on a treadmill with the assistive device, muscle fatigue in the gastrocnemius decreased by 79.5%, and oxygen uptake and energy expenditure per minute decreased by 7.9% and 7.4%, respectively. While climbing stairs with the assistive device, muscle fatigue of the tibialis anterior decreased by 83.5%, average muscle activity of the rectus femoris, semitendinosus, and gastrocnemius muscles decreased significantly, and oxygen uptake and energy expenditure decreased by 14% and 12.9% per minute, respectively. We confirm that an ultralight wearable hip exoskeleton helps the wearer reduce lower-limb muscle fatigue and use metabolic energy more efficiently. The results of this study are intended as basic data to expand the use of ultralight wearable hip exoskeletons at industrial sites and to improve device performance.

Keywords: hip exoskeleton; industrial workers; walking efficiency; muscle fatigue; energy expenditure

1. Introduction

Although walking assist exoskeletons have shown strong growth mainly in the medical rehabilitation of older adults and the disabled, the demand for exoskeletons on industrial sites has also increased significantly in recent years. In particular, interest is growing in wearable exoskeletons to prevent musculoskeletal disorders, to reduce fatigue, and to improve productivity. The scope of application is expanding across industries, for example, in logistics, manufacturing, construction, and services [1,2].

Industrial workers can perform physical labor more efficiently with the help of exoskeletons. For example, in lifting, transporting, and assembling [3], they can alleviate physical fatigue and improve work efficiency. Additionally, proper support can help prevent disease and injury associated with overstrain [4].

Robotic exoskeleton devices that support the work of industrial workers, depending on the field of application, are divided into upper limbs, lower limbs, and the waist. In particular, lower-extremity systems must aid the hip, knee, or ankle to enable the user to walk or climb stairs [5].

Lower-extremity assistors include multi-joint robotic systems that can control all lower-extremity joints or single-joint robotic systems that control each lower extremity joint separately. A multi-joint robotic system can effectively perform lower extremity movements through the coordinated output from each joint; however, the need to support multiple joints simultaneously can make the system complicated and heavy [5].

Given their advantage of being lighter than the multi-joint robotic systems, single-joint robotic systems are highly usable once their suitability for a purpose is established. Various hip-assistive robotic devices have been developed for physical enhancement using single-joint robotic systems for the lower extremities. The hip joint is a ball-and-socket joint that enables multi-axis movements such as flexion/extension, adduction/abduction, and internal and external rotation [5].

Some researchers have developed systems to assist the hip in the form of cable-driven modules that support multiple degrees of freedom of the hip joint [6], while many others have developed hip-assistive devices that support hip flexion movements. Various power transmission methods have been used to provide joint torque for hip joint flexion. Examples are spooled-webbing actuators [7], cable-driven modules [8–10], and passive actuators [11,12].

Lower-limb-assistive exoskeletons that assist walking are already widely used in medical rehabilitation [13–15]; however, wearable exoskeletons for industrial workers have many limitations, owing to their high price, heavy weight, and uncomfortable fit [5].

Despite incredible advances in exoskeleton technology, exoskeletons are still mostly limited to research labs or used for expensive clinical treatments.

The biggest reason for the limited accessibility may be that their complexities result in increased costs, weight, and size. This complexity comes from the requirement for robust exoskeletons that can accurately mimic the complex movements of human limbs and joints [16].

The misalignment between the exoskeleton and user joints causes uncontrolled interaction forces, negatively affecting the wearer's mobility and metabolism [17] and causing discomfort [18].

Because most walking-assistance exoskeletons assist movement with power, they are heavy and rigid, which can interfere with the wearer's natural movement, and often become a burden, particularly when the power is cut off. Consequently, considerable fatigue occurs after wearing the robot, which limits its application to industrial sites or daily life fields that require active physical activity [5,19].

Therefore, exoskeleton devices that can be applied to industrial sites must be light, flexible, easy to wear, make little noise, and should not interfere with the wearer's movements even when power is cut off.

Recently, various lower-limb wearable devices have been developed that reflect these requirements. WIRobotics Co., Ltd. (Yongin, Korea) has also developed an ultralight wearable hip exoskeleton that can be worn all the time and that supports human movement by improving convenience and portability. Accordingly, this study aims to analyze the effectiveness of these ultralight wearable walking-assistive exoskeletons.

Most previous studies related to the efficiency of walking-assistive exoskeletons examined lower-limb muscle effort, energy efficiency [13,14], or muscle fatigue [8]. Lee et al. (2017) reported that a hip exoskeleton improves walking function and cardiopulmonary metabolic efficiency in the elderly [13], and Kim et al. (2018) reported that a hip exoskeleton reduces cardiorespiratory metabolic consumption when walking up stairs [14].

In our study, we analyze lower-limb muscle activity, fatigue, and energy expenditure during treadmill walking and stair climbing to verify the effectiveness of an ultralight wearable hip exoskeleton.

2. Materials and Methods

2.1. Participants

Ten young healthy male adults participated in this study. The average age of the subjects was 39.9 ± 9.1 years, height 178.9 ± 5.9 cm, weight 77.4 ± 8.6 kg, and body mass index 24.2 ± 2.5 kg/m^2.

The inclusion criteria were healthy men aged 20–55 years who could work in industrial fields, who had not experienced any musculoskeletal or neurological disease that may have affected their walking within the previous six months, and who had no problems with cognitive functioning so as to understand the experimental content.

2.2. Ultralight Wearable Hip Exoskeleton Device

The walking-assistive device used in this study was an ultralight wearable exoskeleton for hip joint assistance weighing 1.4 kg and developed to support the walking mobility of industrial workers.

A hip exoskeleton device called "We Innovate Mobility" (WIM) uses a single motor while walking to assist the movement of both hip joints simultaneously. When a rotational force is generated by the motor drive, torque is applied to both thigh supports (or adaptive frames). A flexion auxiliary torque is generated on the leg moving forward for the swing; conversely, an extension auxiliary torque is generated on the trailing leg. The drive strategy is based on human gait mechanics [20] and is a form-factor design in which the main body equipped with a single motor is in front of the pelvis, as shown in Figure 1.
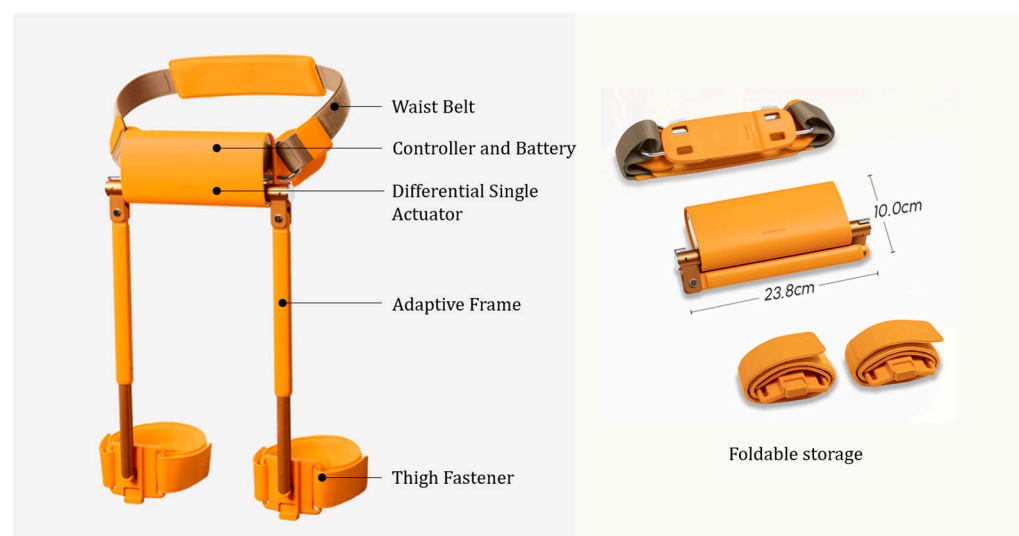

Figure 1. Wearable hip exoskeleton (WIM) used in the study.

Table 1 presents the WIM dimensions and hardware specifications. The main body volume when the thigh frame is folded is $23.8 \times 10.0 \times 5$ cm^3. This space consists of a single electric motor, battery, and controller. The battery capacity is 3.35 Ah, and it can be used continuously for approximately 2 h with a peak-assist torque of 4 Nm. The main body comes in one size, whereas the waist belt and thigh attachments are available in small and medium sizes, and they can be worn with a waist circumference ranging from 26 to 36 inches (66.04–91.44 cm). The stroke length of the adaptive frame ranges from 160 to 350 mm. This ensures compatibility with various heights and leg lengths. Exoskeletons that are wearable on top of clothing have a structural difference between the rotational drive and joint rotation centers. If this mismatch is not addressed with an adjustable flexible mechanism, the device can be obstructive during walking.

Table 1. WIM size dimensions and hardware specifications.

Overall size	$23.8 \times 10.0 \times 5$ cm^3
Weight	1.4 kg (including battery, fastener)
Operating time per charge	Approximately 2 h (assist mode)
Battery	Lithium-ion battery, 14.4 Vd.c., 3.35 Ah
Applicable body size	Main body—one size
	Waist or thigh fastener—two sizes (waist $26'$~$36'$)
Adaptive thigh frame stroke	160~350 mm

This complements the shortcomings of existing wearable exoskeletons that place dual actuators on the sides of the hip joint and improves convenience in that users do not have difficulty moving, even in a narrow space. In addition, the WIM's compact size improves wearability by applying a soft waist belt, and the foldable storage reduces the device volume at least five times compared to that of existing rigid-type frame exoskeletons [15].

The hip exoskeleton WIM has 11 degrees of freedom (DoF) mechanically; these consist of 3 DoF in the hip, 2 DoF in the adaptive frame, and 6 DoF in the thigh connector. Only 1 DoF is an active joint at the hip. The thigh frames on the sagittal plane are driven in both the widening and narrowing directions. The assistance torque control is performed using current sensing without the torque sensor, and it is based on backdrivable actuators [21]. Backdrivable actuators are flexible drives with minimal drive friction and resistance, enabling them to move smoothly even when the device's torque is off. The generation of assistance torque is based on the difference in hip angles sensed in a sine waveform during walking. Using this information, a symmetrical torque in the form of gait assistance is generated for both hips.

2.3. Measurement

A wireless surface electromyography measurement system (Ultium EMG, Noraxon Corp., Scottsdale, AZ, USA) consisting of a wireless transmitter, electromyography (EMG) sensor, and Ag/AgCl electrode was used to measure the activity and fatigue of the lower limb muscles.

As representative muscles involved in flexion and extension of the lower-extremity joints, the rectus femoris (RF) and semitendinosus (ST), which are responsible for flexion and extension of the hip and knee joints, and the tibialis anterior (TA) and medial gastrocnemius (GCM), which are responsible for dorsiflexion and plantar flexion of the ankle joint, were selected [22]. The measured muscle activity (μV) used the normalized value for the individual's maximum voluntary contraction (MVC), and the unit of measure is % MVC.

Eight electromyography electrodes were attached to both lower extremities and the average muscle activity (% MVC) and median frequency (Hz) of the muscles were analyzed.

To analyze muscle fatigue, the median frequency, the frequency at which the EMG power spectrum is halved into equal power regions, was analyzed.

Because muscle fatigue causes the EMG frequency spectrum to shift downward over time, analysis of median frequency is one of the most effective methods for processing EMG signals during fatigue analysis [23].

In this study, the slope of a second-order polynomial curve, which can predict the expected attenuation pattern of the central frequency spectrum, was analyzed. This means that the greater the slope in the negative direction, the more severe the muscle fatigue.

To analyze the energy expenditure, we used a human spirometry system (K4b2, Cosmed Corp., Rome, Italy) consisting of a portable O_2/CO_2 gas analyzer, flow meter, data transceiver, mask, and heart rate monitor. Oxygen uptake (VO_2/kg), heart rate (beats per minute), energy expenditure per minute (kcal/min), total energy expenditure (kcal), and net energy expenditure per minute (kcal/min) were analyzed.

Oxygen uptake measures an individual's ability to absorb oxygen and deliver it to working tissues and the ability of working tissues to utilize oxygen. Cardiorespiratory capacity is defined as maximum oxygen uptake [24].

The total energy expenditure (total EE) is calculated from the gas exchange of oxygen and carbon dioxide, measured through indirect calorimetry, and refers to the body's total energy expenditure for heat production and work output [25]. The energy expenditure per minute (EEM) is the total energy expenditure divided by minutes, and the net energy expenditure per min (net EEM) was the EEM while walking minus the EEM at rest [13].

2.4. Experimental Procedure

This experiment was conducted at the Rehabilitation Engineering Research Institute in Incheon, South Korea. Participants had electromyography and metabolic energy expenditure measured while walking on a treadmill for 6 min and climbing five flights of stairs (Figure 2).

Figure 2. Examples of walking up stairs (**left**) and walking on a treadmill (**right**).

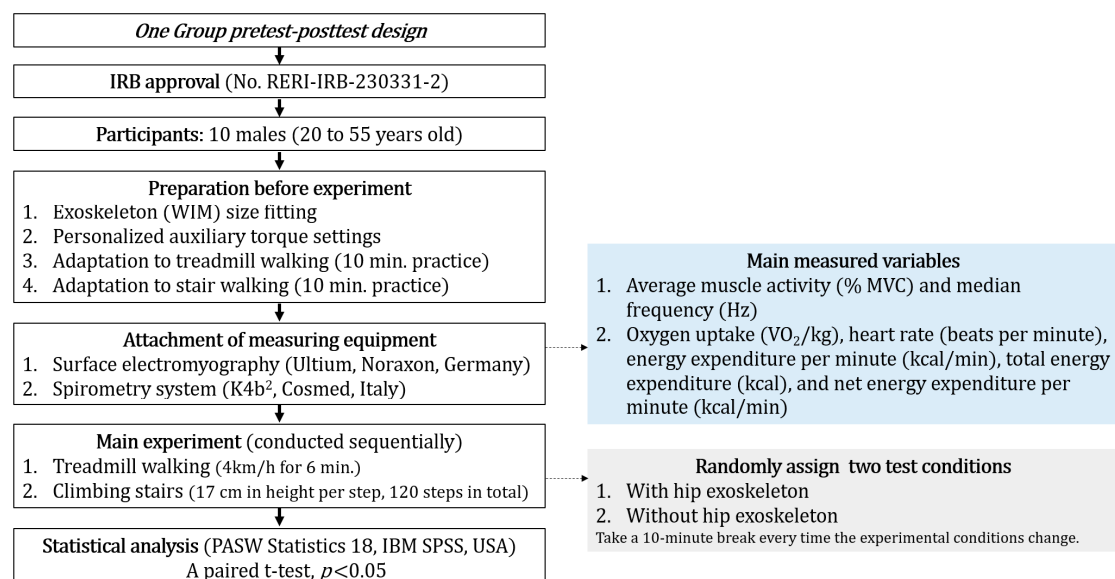The experimental flow chart of this study is shown in Figure 3.

Figure 3. Experimental flow chart of this study.

Before starting the clinical trial, the researchers adjusted the size of the exoskeleton such that participants could wear the WIM comfortably; then, they conducted adaptation training for 10 min each on a treadmill and on a six-step custom staircase in the laboratory while wearing the device.

In the adaptation training phase, the individual's preferred and most comfortable assistance torque of the WIM was determined.

After the adaptation training, each subject had surface electromyography electrodes attached to their lower extremities, a heart rate monitor attached to their chest, and a face mask placed over their nose and mouth. Participants were instructed not to speak during the experiment.

In this experiment, treadmill walking was conducted first, followed by stair walking after sufficient rest time (approximately 10 min) to stabilize breathing.

The treadmill experiment was conducted by walking for 6 min at a speed of 4 km/h; the 6 min walking test is a functional test method used in clinical practice to measure cardiopulmonary capacity.

Treadmill walking was conducted under two conditions: wearing and not wearing the WIM, and the conditions were provided randomly. After each condition, participants rested for 10 min to restore the metabolic rate to baseline.

The stair-climbing experiment, similar to the treadmill walking, was performed in a random order under two conditions: wearing and not wearing the WIM.

Participants were asked to climb five flights of stairs without stopping, at their chosen walking speed, with a 10 min break between the two conditions.

To evaluate the speed difference between the two conditions while climbing stairs, the performance time was recorded with a stopwatch.

2.5. Data Analysis

Descriptive statistics were presented as means and standard deviations.

Surface electromyography data were processed using software (MR 3.18, Ultium EMG, Noraxon, Scottsdale, AZ, USA) provided by Ultium equipment.

Data were sampled at 1000 Hz; they were first passed through a 10–350 Hz sixth-order Butterworth bandpass filter, followed by full-wave rectification. Additionally, the root mean square (RMS) of the signal was calculated using a sliding 100 ms window [26].

sEMG signals were normalized to the individual's maximal voluntary contraction (MVC) data.

To analyze muscle fatigue, the median frequency value was analyzed using Ultium software (MR 3.18).

After analyzing the frequency characteristics by performing a Fourier transform on the contraction section of the surface EMG raw signal, the change in the median frequency was expressed as a slope using a linear regression algorithm. The larger the slope, the higher the rate at which muscle fatigue accumulated [27].

The electromyography data were analyzed for average muscle activity and muscle fatigue values obtained during the entire time of treadmill and stair walking.

To calculate metabolic energy expenditure, we applied a net oxygen consumption (mL/min/kg), net metabolic rate (W/kg), and respiratory exchange ratio (RER) calculated from VO_2 (ℓ/min). This is because the net value is a more accurate representation of metabolic efficiency than the gross value [28]. To compare the amount of metabolic energy consumed during that time, VO_2 and RER were calculated as the average values for the last moment of each condition, and the energy cost (kcal/min) for each condition was calculated using the regression equation reported by Zuntz [29]. Next, the resting metabolic rate was subtracted from each total metabolic rate to obtain the net metabolic rate for each condition [30]. The net metabolic rate for each condition was standardized by dividing it by the body weight (W/kg), and then it was compared with the average value.

Statistical analysis was performed with SPSS software version 18 (PASW Statistics 18, IBM SPSS, Armonk, NY, USA) to verify the difference between the conditions with and without the device (WIM and no WIM).

First, the normality of the data was confirmed using the Kolmogorov–Smirnov test, and since normality was satisfied, a paired *t*-test was performed to test the difference. The level of statistical significance was set at $p < 0.05$.

3. Results

3.1. Treadmill Walking

3.1.1. Muscle Activity and Fatigue

Table 2 shows the results of the analysis of the average muscle activity and muscle fatigue of the lower-limb muscles during the six-minute treadmill walking.

Table 2. Results of average muscle activity and muscle fatigue of lower-extremity muscles during six-minute treadmill walking.

		No WIM	WIM	% Difference	t-Value
RF	Muscle activity (%MVC)	18.42 ± 9.34 [§]	16.91 ± 8.95	−8.20%	0.591
	Muscle fatigue (Hz)	-0.005 ± 0.020	-0.001 ± 0.020	−84.62%	−0.838
ST	Muscle activity (%MVC)	30.60 ± 12.06	29.02 ± 15.16	−5.16%	0.334
	Muscle fatigue (Hz)	-0.037 ± 0.053	-0.009 ± 0.018	−76.82%	−1.654
TA	Muscle activity (%MVC)	11.05 ± 2.82	11.58 ± 3.12	4.80%	−0.708
	Muscle fatigue (Hz)	-0.007 ± 0.008	-0.008 ± 0.008	18.31%	0.407
GCM	Muscle activity (%MVC)	17.29 ± 2.64	17.42 ± 4.83	0.74%	−0.106
	Muscle fatigue (Hz)	-0.015 ± 0.013	-0.003 ± 0.013	−79.45%	−4.244 **

RF, rectus femoris; ST, semitendinosus; TA, tibialis anterior; GCM, gastrocnemius; [§] mean ± standard deviation; ** $p < 0.01$.

When wearing a WIM compared to no WIM, the average muscle activity of the RF and ST decreased by 8.20% and 5.16%, respectively, and those of the TA and GCM increased by 4.80% and 0.74%, respectively, but the difference was not statistically significant.

Muscle fatigue analysis showed that, compared to no WIM, the RF and ST with WIM use decreased by 94.62% and 76.82%, respectively, while TA increased by 18.31%; however, the difference was not statistically significant.

However, when wearing a WIM, muscle fatigue of the GCM decreased by 79.45%, showing a statistically significant difference ($p < 0.01$).

3.1.2. Energy Expenditure

The results of energy consumption measured during six-minute treadmill walking are shown in Table 3.

When wearing a WIM compared with no WIM, oxygen uptake, EEM, total EE, and net EEM were significantly reduced by 7.93%, 7.39%, 7.26%, and 10.59%, respectively (all $p < 0.001$). However, there was no significant difference in the heart rate between the conditions.

Table 3. Results of energy expenditure during 6 min treadmill walking.

	No WIM	WIM	% Difference	t-Value
Oxygen uptake (VO$_2$/Kg)	9.28 ± 1.22 [§]	8.55 ± 1.55	−7.93%	5.447 ***
Heart rate (bpm)	88.93 ± 12.05	86.78 ± 14.74	−2.42%	1.647
EEM (kcal/min)	3.47 ± 0.40	3.21 ± 0.48	−7.39%	5.102 ***
Total EE (kcal)	10.41 ± 1.22	9.66 ± 1.43	−7.26%	5.636 ***
Net EEM	2.42 ± 0.33	2.16 ± 0.42	−10.59%	5.102 ***

EE, energy expenditure; EEM, energy expenditure per min; [§] mean ± standard deviation; *** $p < 0.001$.

3.2. Climbing Stairs

3.2.1. Muscle Activity and Fatigue

Table 4 presents the results of the analysis of muscle activity and fatigue when climbing stairs up to the fifth floor.

Table 4. Results of average muscle activity and muscle fatigue of lower-extremity muscles during walking up stairs.

		No WIM	WIM	% Difference	t-Value
RF	Muscle activity (%MVC)	19.90 ± 11.63 [§]	16.56 ± 9.87	−16.78%	3.404 **
	Muscle fatigue (Hz)	0.005 ± 0.050	−0.040 ± 0.057	−873.08%	1.923
ST	Muscle activity (%MVC)	14.06 ± 7.99	12.47 ± 7.69	−11.32%	3.234 **
	Muscle fatigue (Hz)	−0.024 ± 0.074	0.026 ± 0.069	−206.15%	−2.014
TA	Muscle activity (%MVC)	15.73 ± 5.05	14.75 ± 4.90	−6.23%	1.382
	Muscle fatigue (Hz)	−0.113 ± 0.082	−0.019 ± 0.024	−83.51%	−2.754 *
GCM	Muscle activity (%MVC)	22.95 ± 9.00	19.85 ± 8.23	−13.49%	2.529 *
	Muscle fatigue (Hz)	−0.105 ± 0.084	−0.025 ± 0.119	−76.08%	−2.197

RF, rectus femoris; ST, semitendinosus; TA, tibialis anterior; GCM, gastrocnemius; MA, muscle activity (%MVC); MF, muscle fatigue (Hz); [§] mean ± standard deviation; * $p < 0.05$; ** $p < 0.01$.

From of the average muscle activity analysis, the RF, ST, TA, and GCM with the WIM all decreased compared to no WIM, and there was a statistically significant difference in all the muscles except the TA ($p < 0.01$, $p < 0.05$).

Compared with no WIM, muscle fatigue with WIM use was reduced by 873.08%, 206.15%, and 76.08% in the RF, ST, and GCM, respectively, but the difference was not statistically significant. In contrast, the TA's fatigue decreased by 83.51%, showing a statistically significant difference ($p < 0.05$).

3.2.2. Energy Expenditure

Table 5 shows the results of the energy expenditure analysis for climbing the stairs to the fifth floor.

Table 5. Results of energy expenditure during walking up stairs.

	No WIM	WIM	% Difference	t-Value
Performance time (sec)	98.00 ± 16.21 [§]	109.10 ± 19.43	11.33%	−1.941
Oxygen uptake (VO_2/Kg)	15.73 ± 2.74	13.53 ± 1.86	−13.99%	3.116 *
Heart rate (bpm)	114.62 ± 15.01	105.60 ± 12.98	−7.87%	3.329 **
Energy expenditure per minute (kcal/min)	5.94 ± 0.89	5.17 ± 0.89	−12.91%	3.369 **
Total energy expenditure (kcal)	9.59 ± 1.50	9.43 ± 2.09	−1.59%	0.320
Net EEM	4.89 ± 0.88	4.12 ± 0.87	−15.65%	3.369 **

EE, energy expenditure; [§] mean $\pm$ standard deviation; * $p < 0.05$; ** $p < 0.01$.

There was no significant difference in the stair-walking performance time for WIM use between the two conditions, excluding total EE, oxygen uptake ($p < 0.05$), heart rate ($p < 0.01$), EEM ($p < 0.05$), and the net EEMs ($p < 0.01$) all decreased.

4. Discussion

Our study analyzed muscle activity, muscle fatigue, and energy expenditure during treadmill walking and stair climbing to verify the walking efficiency of an ultralight wearable hip-assistive device (WIM) for industrial workers.

4.1. Treadmill Walking

There was no significant difference in the average muscle activity between the WIM and no WIM groups of treadmill walking. When wearing a WIM, the average muscle activity of the thigh (RF and ST) decreased, and the average muscle activity of the shank (TA and GCM) slightly increased, but the difference was not statistically significant. In addition, there was no significant difference in RF, ST, and TA muscle fatigue between the two conditions; however, when wearing a WIM, muscle fatigue in the activity of the GCM decreased by 79.5%, which was confirmed to be a statistically significant decrease.

The muscle fatigue value presented in this study was an analysis of the slope of the frequency that occurred in the entire measurement section; if the measured value was negative, it was interpreted that muscle fatigue had occurred. Fatigue was found to occur in all muscles when walking on a treadmill, regardless of whether a WIM was worn. Fatigue in the RF, ST, and GCM muscles, but not the TA, was found to be reduced when wearing WIM.

Meanwhile, in this study, TA muscle fatigue was found to increase by 18.3%, although this increase was not statistically significant.

The WIM assists the flexion of the hip joint at the front of the pelvis, thereby assisting the forward movement of the leg. These features can increase the range of flexion of the lower-extremity joints, especially the hip joint. Jin et al. (2017) reported that, when wearing a soft robot suit that provided hip flexion assistance by wrapping a belt, the maximum hip flexion angle increased by an average of 5.4%, and the maximum vertical positions of the knee and ankle joints also increased [7].

Although the lower-extremity angles were not directly measured in this study, considering previous studies, it is expected that the hip, knee, and ankle joint angles would have increased even if a WIM with a similar control method had been used. In the case of assistive exoskeletons that assist in bending the legs, the overall angle of the lower-extremity joints may increase if too strong torque is applied. Excessive deviation of the lower-extremity joint angles from the normal range can result in inappropriate muscle activity patterns, ultimately leading to increased muscle fatigue.

Therefore, it is necessary to supplement the control mechanism to assist the legs through appropriate torque control, while preventing excessive leg elevation.

Additionally, the main outcome related to gait efficiency in this study was a reduction in muscle fatigue in the GCM. In the case of the GCM, there was no difference in muscle activity between the WIM and no-WIM groups, but muscle fatigue was significantly reduced.

When muscle contraction increases, muscle activity also tends to increase; however, increased muscle activity does not necessarily increase muscle fatigue. The patterns of muscle activity and fatigue may vary depending on the action and type of muscle [31]. Muscle fatigue refers to a decrease in the ability of a muscle to generate maximum force. The degree of muscle fatigue can be estimated from changes in the frequency range (spectrum) of electromyography [32].

Therefore, while increased muscle activity implies increased strength, increased muscle fatigue implies a shift from high to low frequencies. Sometimes, to maintain a certain level of muscle strength, muscle contractions that cause muscle fatigue may occur, leading to a further increase in the recruitment of motor units [33].

The GCM's reduction in muscle fatigue when walking on level ground is expected to increase work efficiency by reducing fatigue in the calf muscle while wearing a WIM for long periods of time in industrial fields with extensive movement.

In a similar previous study, Lee et al. (2017) reported a decrease in RF muscle activity when wearing a walking-assistive exoskeleton and found that the walking-assistive exoskeleton under study (GEMS) not only directly reduced the walking strategy of the hip joint but also reduced muscle use by reducing knee and ankle maneuvering [13].

Although the driving mechanism of the exoskeleton used by Lee et al. in 2017 was different from the one used in this study, the reduction in muscle effort from the use of the wearable exoskeleton was interpreted as a similar result for the walking efficiency of both products [13].

In addition, our results showed that energy expenditure, oxygen uptake, EEM, total EE, and net EEM decreased significantly during treadmill walking (all $p < 0.001$). Oxygen uptake decreased by 7.9% and total EE decreased by 7.3%.

These results are similar to Lee et al.'s study in 2017. He reported that oxygen consumption decreased by 7% and total EE decreased by 6.6% when wearing the GEMS exoskeleton and that GEMS induced efficient walking in older adults by reducing cardiopulmonary metabolic costs [13].

A recent study, using a hip-assistive soft exoskeleton receiver, reported a 17.4% reduction in net metabolic energy expenditure during treadmill walking in young adults [34]. In addition, Ding et al. [35] and Young et al. [36] reported that the metabolic power decreased by 4.6% and 9.7%, respectively, when walking using a hip-assistive robot. In our study, the net metabolic power decreased by 10.6%, which was lower than the 17.4% obtained by Zhang et al. [34] but higher than the results of Young et al. [36] and Ding et al., which demonstrated that the WIM device could reduce calf muscle fatigue and provide significant benefits with respect to cardiopulmonary metabolic efficiency.

4.2. Ascending Stairways

The walking efficiency of a wearable hip exoskeleton was verified through a stairway ascension experiment.

The results showed that the average muscle activity of the RF, ST, TA, and GCM decreased when wearing the WIM, and that a statistically significant difference was observed in all the muscles except the TA. Additionally, when wearing the WIM, fatigue in the ST, TA, and GCM, but excluding the RF, tended to decrease; however, only the TA showed statistical significance.

Treadmill walking significantly reduced GCM fatigue, whereas ascending stairs significantly reduced TA muscle fatigue.

During stair ascension, the plantar flexors (gastrocnemius) and vastus medialis lateralis primarily exert vertical propulsion during the stance phase, whereas the gluteus maximus

and hamstrings act as the driving force for forward propulsion. Additionally, during the swing phase, the antagonist muscles across the hip, knee, and ankle joints control the leg by distributing the force from the leg to the rest of the body [37].

This study did not measure the muscle activity of all prime movers used in ascending stairs. However, the fatigue of the GCM, which is the driving force of vertical propulsion, decreased by 76.1%, and the muscle fatigue of the ST, which is involved in forward propulsion, was also reduced by 206.2%, indicating that the assistive power of the WIM was effective.

Meanwhile, RF muscle fatigue significantly increased during stair walking, whereas the average muscle activity decreased by 16.8%. As mentioned, it has been confirmed that the patterns of muscle activity and fatigue are different [31].

In addition, muscle fatigue increased despite a decrease in the RF muscle activity when climbing stairs. This suggests that a factor causing muscle fatigue was acting on the muscles, even with the WIM device assisting.

In fact, the participants in this study reported that although the WIM made it easier to walk up stairs, they complained of discomfort owing to the mismatch between leg movements and the thigh support frame when climbing stairs. This is believed to not provide optimal control because unlike walking on level ground, the range of the hip flexion angle increases when climbing stairs.

It is presumed that these factors may have caused muscle fatigue by interfering with the normal muscle activity of the RF involved in hip joint movement. Improvements in this regard should be addressed going forward.

Previous studies related to verifying the efficiency of walking-assistive exoskeletons have mainly analyzed muscle activity.

Lee et al. (2017) interpreted the decrease in muscle activity of the RF as being because of a decrease in muscle activity and an increase in walking efficiency from wearing the exoskeleton [13]. In addition, Lee et al. (2020) reported that the muscle activity of the RF decreased by up to 47% when walking up stairs using the soft exosuit system [38].

As mentioned in previous studies, the results of muscle activity and fatigue do not necessarily match, because fatigue can increase even if muscle activity is low. Therefore, discussions on walking efficiency based on decreased muscle activity should be viewed with caution, as fatigue can be caused by prolonged use despite reduced muscle activity. Studies of wearable exoskeleton walking efficiency should verify muscle activity and muscle fatigue.

In analyzing the energy expense of stairway ascension, it was found that there was no significant difference in the performance time with and without a WIM. However, while this was not true for the total EE, the oxygen uptake, heart rate, EEM, and net EEM showed statistically significant decreases. Wearing a WIM significantly reduced the oxygen uptake by approximately 14%, the heart rate was significantly reduced by 7.9%, the EEM by 12.9%, and the net EEM by 15.7%.

Unlike treadmill walking, the significant decrease in heart rate during the more difficult stair walking was interpreted as a significant benefit of the assistive power of the WIM during stair walking.

In this study, when wearing a WIM, EEM was reduced by 7.4% when walking on a treadmill, but the energy efficiency was higher at 12.9% when climbing stairs. The net EEM showed that treadmill walking and ascending stairs had higher energy efficiencies of 10.6% and 15.7%, respectively.

The results of this study were similar to those of Kim et al. (2018) [14], although there were differences in the reduction rates of energy consumption. Kim et al. [14] reported that when climbing stairs, an exoskeleton (GEMS) significantly reduced net oxygen consumption and net metabolism by 8.6% and 10.2%, respectively. In addition, it was reported that the net metabolic power with a walking-assistive exoskeleton (GEMS) was significantly reduced even though it was 2 kg heavier than a general soft robot, which is a very meaningful result [14].

Stair walking is a difficult activity that requires approximately 30–40% more cardiopulmonary metabolic energy than walking on level ground [39,40]. The results of this study are encouraging because the EEM and net EEM decreased more when climbing stairs than when walking on level ground. It is believed that metabolic energy can be used more efficiently if workers wear WIMs while climbing stairs at industrial sites.

Although many products cannot be compared because the types, driving methods, and hardware types of exoskeletons are diverse, we compared the energy efficiency of our product with that of a hip joint exoskeleton with similar design and weight (Table 6).

Table 6. Comparison of energy metabolism reduction rates between products with similar performance.

	Type	Weight	Test Environment	Metabolic Reduction
Kim et al. (2022) [9]	Soft	2.31 kg	Level ground	7.2%
Lee et al. (2017) [13]	Rigid	2.8 kg	Level ground	6.6%
Kim et al. (2018) [14]	Rigid	2.8 kg	Up stairs	10.16%
WIM in this study	Soft and rigid	1.4 kg	Level ground	7.4%
WIM in this study	Soft and rigid	1.4 kg	Up stairs	12.9%

Use of a lightweight (2.31 kg), portable hip-flexion-assistive exosuit with a similar form-factor location as our device showed a metabolic reduction of $7.2 \pm 2.9\%$ when walking on level ground compared to walking without the exosuit [9]. In addition, in the rigid-type GEMS, weighing 2.8 kg, the net metabolic rate decreased by 6.6% when walking on level ground and by 10.16% when walking up stairs [13,14]. In the case of our product (WIM), energy metabolism decreased by 7.4% when walking on level ground (treadmill), and by 12.9% when walking up stairs.

Both GEMS and our product showed a greater decrease in energy metabolism when walking up stairs than when walking on level ground.

Our product uses a single actuator, which can be compared to the existing product, further reducing the weight compared to the existing product. Nevertheless, it is noteworthy that metabolic energy decreased by 12.9% during stair assistance.

Reducing the weight of assistive devices worn on the human body at industrial sites is a very important issue, and our product is expected to be useful at industrial sites because it is the lightest and has the greatest energy consumption reduction effect.

5. Conclusions

In this study, we verified the walking efficiency of an ultralight wearable hip exoskeleton. Treadmill walking and stairway ascension were tested in 10 healthy adult men, and the lower-limb muscle activity, fatigue, and energy expenditure were analyzed.

The results showed that muscle fatigue of the GCM, oxygen uptake, EEM, total EEM, and net EEM were significantly reduced during treadmill walking while wearing the exoskeleton. In addition, when climbing stairs, the average muscle activities of the RF, ST, and GCM and muscle fatigue of the TA were significantly reduced, and a significant decrease in metabolic energy, including oxygen uptake, EEM, net EEM, and heart rate, was confirmed. This confirmed the efficiency of the hip exoskeleton device.

The hip exoskeleton is expected to be effective in reducing lower-limb muscle fatigue and to lead to efficient energy metabolism in healthy male adults in an industrial setting.

Although the average values of some results in this study differed greatly, that statistical significance could not be confirmed because of the large differences between individuals is a limitation of this study. In the future, we plan to supplement our study by expanding the number of subjects, verifying gender differences, and evaluating usability in terms of performance, portability, and convenience.

We hope that the results of this study will be used as basic data to improve the performance of hip-assistive devices, and they can also be presented as validation data to expand the use of wearable exoskeletons to industrial applications.

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