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Research article

Determinants of wearer satisfaction factors for harnesses in upper-limb assistive wearable robots

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ABSTRACT

Wearable robots are increasingly being deployed for use in industrial fields. However, only a few studies have focused on the usability of wearable robots. The present study evaluated the factors affecting the usability of a harness in securing a wearable robot to the body because the harness directly affects the work efficiency, and thus its design and use require careful consideration. A comparative evaluation of the arrangement of the Vest Exoskeleton before and after improvements was conducted, in which participants performed a benchmark assembly task while wearing the robot. Results showed that wearability decreased after the improvements due to the additional straps and buckles used, but the overall wearing satisfaction improved as a result of increased stability. Stability and convenience were the main factors affecting the overall wearing satisfaction, while sub-indicators included wearing comfort and tactile sensation. Therefore, improvements in stability, such as those related to fixation strength and tactile sensation, had a direct positive impact on the overall wearing satisfaction.

1. Introduction

Driven by recent technological developments, an increasing number of workplaces have been implementing processes involving the use of wearable robots [1,2]. Wearable robots are broadly categorized into devices that either assist or enhance human muscle strength [3]. Active wearable robots are powered by actuators, batteries, and controllers, where force is applied through the actuators [4]. However, although these robots can provide greater strength and durability to the user, they can be substantially heavy and bulky, limiting their practicality in certain applications. In contrast, passive wearable robots may lack the ability to provide as much assistance as that provided by active robots, but they do not require an external power source and simply rely on their mechanical structure to provide assistance to the user. These passive wearable robots are typically lighter and more compact than active robots, rendering them more practical for daily use [5–7].

Wearable robots are mechatronic systems designed for the purpose of assisting with human motion or substituting human motor functions via human–robot interactions [8]. These systems interact with the human musculoskeletal system and have been employed

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Table 1
Critical aspects and characteristics of prior research.

Title	Author	Crucial Aspects and Characteristics	Remarks
Usability of fall arrest harness	Angles, J.	1. Analyzed harness design by considering both user perception and physical characteristics 2. Developed a system to measure harness strap pressure to perform a quantitative assessment of harness fit 3. Performed a comparison between three different harness types, taking into account EMA reports, strap pressures, and survey responses	These features can contribute to the development of more accurate and reliable harness designs.
The wearing sensation of men and women in sports wear with water vapor permeable fabrics	Cho, J. H., Ryu, D. H.	1. The sportswear tested was made from four different vapor-permeable materials, allowing us to analyze differences in comfort and functionality between materials. 2. The test subjects consisted of 8 (female) and 4 (male) healthy adults with similar gender, age, and body type to minimize individual differences and increase the reliability of the experimental results. 3. The experimental method is conducted by the Ganzfeld method, including skin temperature measurement and subjective sensory evaluation by area, and both quantitative and qualitative data can be collected. 4. The experimental results provide a variety of information, including information on the comfort and functionality of each material, as well as a comparative analysis of the change in comfort and subjective sensation due to changes in body weight.	Sportswear manufacturers and researchers may find the information useful.
Parachuting harnesses comparative evaluation on energy distribution grids	Hembecker, P. K., Poletto, Â. R., Gontijo, L. A.	1. Conducted a comparative analysis of three types of parachute harnesses used to ensure safety when working in the electrical industry, collecting specific information on the daily use of the products from the user's perspective, based on which weaknesses and opportunities for improvement are identified 2. Tested the parachute harness prototypes with subjects under actual use conditions, and present them as recommendations, with analysis based on feedback provided by users and quantitative measurements of physical workloads	Innovative in evaluating safety equipment, with results that can be used in other industries as well.
On-orbit evaluation of a new treadmill harness for improve crewmember comfort and load distribution	Perusek, G. P., Sheehan, C. C., Savina, M. C., Owings, T. M., Davis, B. L., Ryder, J. W.	1. Evaluated a new harness design, the Glenn Harness, with non-invasively measured dynamic loads, improving fit and load distribution for six crewmembers while addressing issues found in previous studies. 2. Quantitatively measured actual dynamic loads during exercise in space for the first time using load-sensing instrumentation, providing details unknown in previous studies	Expected to provide a foundation systems and training protocols that can positively impact the health and safety of crewmembers during spaceflight.
Effectiveness of undershirt fabric on harness comfort in upper extremity prosthetic users; a pilot study	Harris, M. S., Esparza, W. O.	1. To improve harness fit for upper extremity amputees using a new textile material 2. Previous studies have used cotton undershirts to improve fit, but this study seeks to improve fit (comfort, moisture wicking ability, friction reduction, and temperature regulation) by using performance wear materials provided by a performance wear apparel manufacturer 3. Analyzed the results through subjective evaluations of the participants	No specific mention of harness type or application was made.
Wearing comfort evaluation of a summer flight suit to improve ventilation	Jeon, E.-J., Park, S.-K., You, H.-C., Kim, H.-E.	1. Evaluated the comfort of the summer raincoat in terms of objective and subjective aspects, and identify the effect of the breathability of the summer raincoat on the wearer's comfort. 2. By investigating the appropriate areas for the application of ventilation holes in the upper and lower integrated flight suit, ventilation holes were applied to four areas such as shoulders, armpits, and knees, and a design was made to efficiently	Credited with playing a key role in evaluating comfort and improving ventilation

(*continued on next page*)

Table 1 (*continued*)

Title	Author	Crucial Aspects and Characteristics	Remarks
		discharge heat and moisture of the summer raincoat to minimize discomfort when wearing it. 3. Conducted anthropophysiological measurements of the subjects to accurately identify the fit and ventilation performance of the summer raincoat. 4. 10 healthy men were tested in an artificial climate chamber, which allows us to control environmental factors from the outside and obtain relatively accurate results.	
A harness for enhanced comfort and loading during treadmill exercise in space	Novotny, S. C., Perusek, G. P., Rice, A. J., Comstock, B. A., Bansal, A., Cavanagh, P. R.	1. Proposed improvements to the harness worn during treadmill exercises aboard the International Space Station (ISS) 2. Mimicked a more realistic situation than previous studies by having subjects perform 12 treadmill workouts in space over a three-week period to evaluate their discomfort and fatigue levels while wearing the harness 3. Used methods developed in previous studies to optimize the experimental harness to provide a personalized fit, helping users exercise more comfortably 4. Used a Visual Analog Scale (VAS) to assess the level of discomfort and fatigue experienced by the wearer, allowing for objective data collection 5. Provided a 15-min training session to help subjects adapt to running in the ZLS, increasing the reliability of the results	The harness design that fixes the body during treadmill exercise in the microgravity environment significantly reduces discomfort and fatigue, enhancing the effectiveness of the exercise for maintaining musculoskeletal (bone density) strength
Usability issues concerning child restraint system harness design	Rudin-Brown, C. M., Kumagai, J. K., Angel, H. A., Iwasa-Madge, K. M., Noy, Y. I.	1. Evaluated usability issues related to child restraint system (CRS) harness design using four convertible infant car seats with varying design characteristics 2. Previous research suggests that evaluation of specific CRS models can provide useful information to consumers, but it would be more helpful if all CRS were designed to meet basic usability criteria	Makes sense as a first step in assessing usability issues in CRS harness designs and finding practical ways to improve them.

in industrial, medical, and military applications as well as in construction sites and disaster relief efforts [9]. Research on wearable robots in industrial fields has been mainly conducted for preventing the development of musculoskeletal disorders and increasing job efficiency in industrial workers [10].

More specifically, wearable robots have been used to reduce the strain on a worker's body, tools, and related equipment [11]. These wearable devices are divided into two types, namely passive or active robots, according to the presence of actuators respectively. Of them, passive-type robots are predominantly used in conventional industry fields as they do not require recharging of batteries and can be applied in a wider range of environmental conditions than active-type robotic systems [12,13].

To date, there is limited literature on the usability of wearable robots. For instance, Bae et al. [14] presented certain guidelines for devising an assessment strategy that could be applied to product development and usability assessments. However, compared with the number of studies on the performance of wearable robotic systems, limited research has been conducted on usability assessments of wearable robots by actual users. Consequently, it has become critical to assess the usability of harness systems used in wearable robots, including their wearability, stability, and convenience [15].

Typical materials used for the harness include Velcro and textile straps. Factors such as the location where the harness is fixed, the materials used, and the width of the strap or Velcro can affect the contact points between the harness and the user's skin. As such, the harness can have a significant impact on the reported satisfaction of users of wearable robots [16]. Additionally, using an ill-fitting harness can have negative physical impacts on workers, including injury [17,18], as well as psychological impacts, with anxiety being a prevalent example, while using the robotic system [19]. For these reasons, the harness directly affects work efficiency, and thus its design and use require careful consideration.

Some representative examples of existing works on the usability assessment of harnesses or garments are presented in the following lines. Angles [20] and Rudin-Brown et al. [16] performed a usability evaluation on the design of a harness for the purposes of fall arrest and child protection. To assess the sensation of wearing such a system, Cho and Ryu [21] placed the wearer on a treadmill for a period of 20 min and quantified the changes in skin temperature of various body parts as well as clothing microclimates before and after the experimental process. Subjective sensations, including thermal, wetness, tactile, and comfort, were measured at 5-minute intervals, and data on subjective evaluations were collected. Jeon et al. [22] performed subjective and objective evaluations on the comfort of users while wearing a summer flight suit. The objective measurements included skin temperature, the microclimate inside the flight suit, sweat rate, and thermography of the flight suit, while the subjective measurements included temperature and fatigue sensation,

sensation of wetness/moisture, and thermal comfort. Certain previous studies evaluated the usability of harnesses and garments analogous to flight suits via in-depth interviews and survey data [16,23–26], while others have performed usability evaluations regarding harnesses used in specific fields, such as functional clothing, medical care, and sports, as summarized in Table 1. However, to our knowledge, there is a limited number of usability evaluation studies on harnesses used for wearable robots designed for use in industrial applications, which is the novelty of the present study.

In this paper, the usability of the initial and modified harness models of the Vest Exoskeleton (VEX), manufactured by the Hyundai Motor Company, was evaluated via user surveys and interviews. The VEX was designed to support workers who have to lift their arms for extended periods to perform overhead tasks in industrial environments; this support is implemented by reducing the mechanical force required from the shoulder and arm muscles and thus their levels of fatigue. Via these aids, this device also prevents musculoskeletal disorders. The robot can be worn as a vest and provides lifting assistance according to the angle of the arm, providing an adequate support for workers raising their arms during work activities.

In this study, the usability rather than the mechanical function of the robots was evaluated. The modified harness, which was developed by using users' feedback on the original one, was comparatively evaluated against the original design. The usability was analyzed with an emphasis on wearability, stability, and convenience. In addition, the comprehensive effects of wearability, stability, and convenience on the satisfaction of the wearer were investigated, and measures aimed at improving the usability were derived.

2. Methods

2.1. Harness design

The VEX has the structure of an exoskeleton designed as a vest, and it provides lifting assistance to the shoulders for workers who perform tasks with their arms raised for extended periods. The vest consists of compensators featuring a polycentric axis and a structure of multi-link assistance mechanisms that mimic the movements of the human shoulder joint. In addition, because the VEX is capable of offering up to 5.5 kgf of support and has a mass of 2.5 kg, which is lighter than comparable wearable robots, it has the potential to increase the efficiency of workers performing repeated motions of raising their arms while looking up for long periods of time in industrial settings.

Two types of VEX harnesses were used in our experiments, namely former and latter harnesses, where the latter harness was designed as an improvement on the former harness. More specifically, the former harness was the first harness developed by Hyundai Motor Company, while the latter harness improved the performance of the former one by supplementing the parts that users found

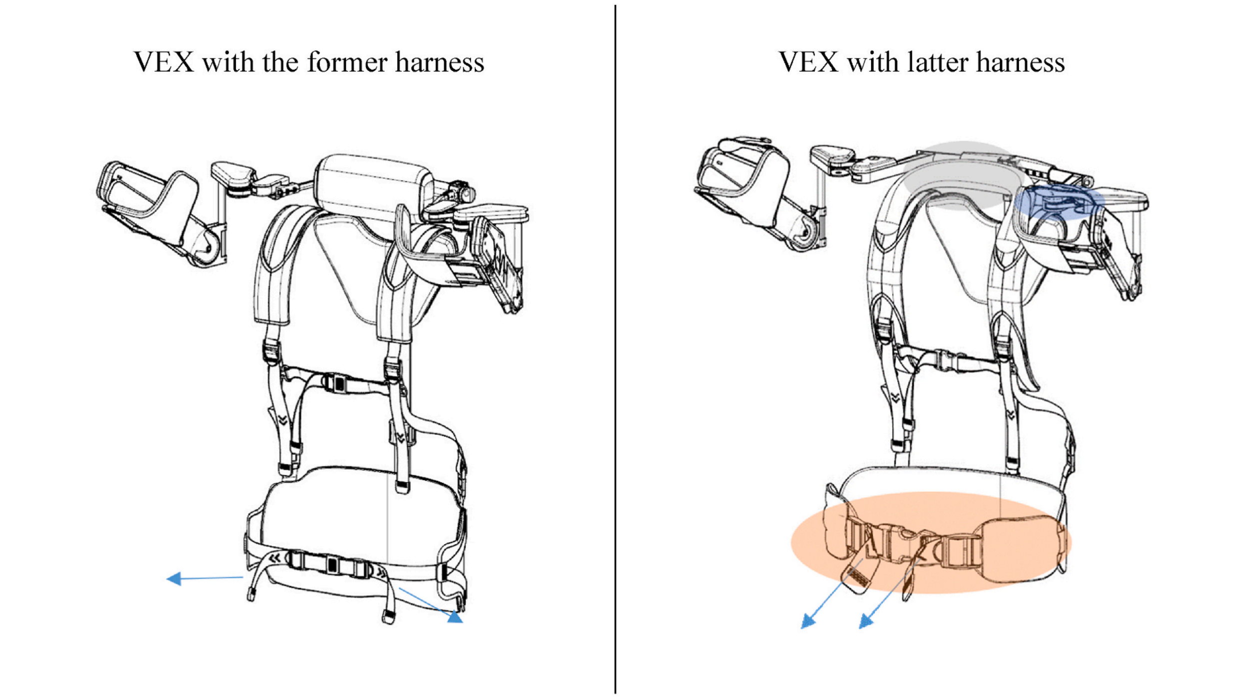

Fig. 1. Comparison of harness design before and after improvements. *Note.* Left panel: The former harness features a neck rest (Neoprene); two arm cuffs (1.5t Neoprene); back pad (3t Nylex); two shoulder straps (Taffeta); pelvic pad (Taffeta) and pelvic band (Nylex). Right panel: The latter harness features a neck rest (Neoprene); two arm cuffs (3t Neoprene); back pad (10t Nylex); two shoulder straps (Taffeta); pelvic pad (Taffeta) and pelvic band (Nylex). Detailed illustration of the latter harness featuring the added arm cuff with buckle and improved materials for neck rest, pelvic pad and pelvic band. The illustrations were provided by Hyundai Motor Company.

inconvenient through the user experience evaluation. However, a limitation of the previous user experience evaluation was that it was not possible to clearly identify the most important factors affecting the usability of the harness. The neck rest of the former harness is incorporated into the robot, which was found to be inconvenient by the users, whereas, the hardware and the neck rest were separated from the robot in the latter harness, and the neck rest was made in the shape of a neck pillow to increase the wearability. A separate aperture was also added for an improved fixation to the neck. The safety strap used a general purpose 20-mm-wide webbing that could be secured using a buckle. In addition, the thickness of the material was increased to provide additional tactile (cushioning) for comfort.

The tactile sensation (namely, convenience) of the back pad was modified to increase the ventilation in the areas in close contact with the skin, and the length of the shoulder strap was increased for improved comfort. The overall height of the pelvic pad was reduced to enhance the operability and wearability of the harness in postures that involved bending at the waist, and a pad was attached in front of the anterior superior iliac spine to prevent pain when in contact with the webbing. Finally, the thickness of webbing was changed from 20 to 40 mm to prevent twisting when the device was being worn, and the direction of webbing adjustment was reversed for tighter attachment of the pelvic band to the body. Fig. 1 presents a comparison of the VEX harness before and after the listed improvements.

2.2. Participants

The working environment used in the experiment was based on the design of an automobile factory, a setting where such a device may find application, and the test subjects were adult males with experience in the automotive manufacturing sector, who never used a wearable robot before. Table 2 summarizes the participants' characteristics.

Among 28 participants, two of whom were in their twenties, 9 in their thirties, 16 in their forties, and 1 in his fifties. The size of the VEX used in the experiment was adjustable to fit workers with a height of 170–180 cm. Participants were recruited to represent the range of the average weight and height of South Koreans based on a database of standard human body information [27]. According to the assessment board of the project, which consisted of anonymous experts and was organized by the government – Ministry of Trade, Industry and Energy, approval of the institutional review board was not required. Since this experiment included confidential information from the Hyundai Motor Company, the institutional review board process could be exempted.

2.3. Instruments

Table 3 outlines the instruments used in the experiment. A thermal imaging camera was used to detect temperature differences (noise equivalent temperature differences < 40 mK). A 4-channel camera was also used, capable of simultaneously capturing photographs in four directions. Lastly, the study employed an electric drill, comparable in type to those frequently observed in front-end module (FEM) production environments.

2.4. Experimental environment

The experiment was conducted in the summer to keep temperature and humidity similar to those encountered in real production environments during the summer. During the experimental procedure, the ambient temperature was consistently held at approximately 26 °C, while relative humidity was stabilized at 46%. An aluminum structural framework was used as part of the experimental environment; this frame replicated an arrangement that is found in actual FEM assembly lines.

2.5. Research methodology

The evaluation method and survey were adapted from Cho and Ryu [21] and Jeon et al. [22]. The empirical assessment of the pair of VEX harnesses involved quantifying the wearers' core temperature, heat dissipation, and the harness's external temperature pre and post-utilization. In contrast, the perceptual appraisal examined aspects such as the harnesses' ergonomic fit, structural integrity, and ease of use. The investigative methodology adopted in this study is depicted in Fig. 2.

The study aimed to discern the relative wearability, stability, and convenience of both the former and latter harness iterations. Participants uniformly executed predefined tasks, alternating between the two harness versions, with the sequence randomized.

Owing to the variances in the donning procedures between the two harness versions, a comprehensive manual was disseminated to ensure participants' pre-experimental familiarity with the respective methodologies. During the study's inception, metrics such as the duration for harness application and participant-associated errors; like strap entanglements or neglecting the arm buckle fastening in the refined harness were meticulously recorded.

The primary task assigned necessitated participants to sequentially navigate between three designated markers, engaging with

Table 2
Composition of participants' characteristics.

	Age	Height (cm)	Weight (kg)
Mean	40.1	172(±3)	71.48(±3)

Table 3
Measurement instruments.

	Experimental equipment	Brand	Model
1	Thermometer	Braun	ThermoScan IRT-4520
2	Thermal imaging camera	Testo	890 basic (NETD <40 mK)
3	4-channel camera	JWC Networks	–
4	Anthropometric tools	FAS	TK-11242
5	Thermo-hygrometer	SATO	SK-150GT
6	Electric drill	KEYANG	DIW-1800L (4.0 Ah)

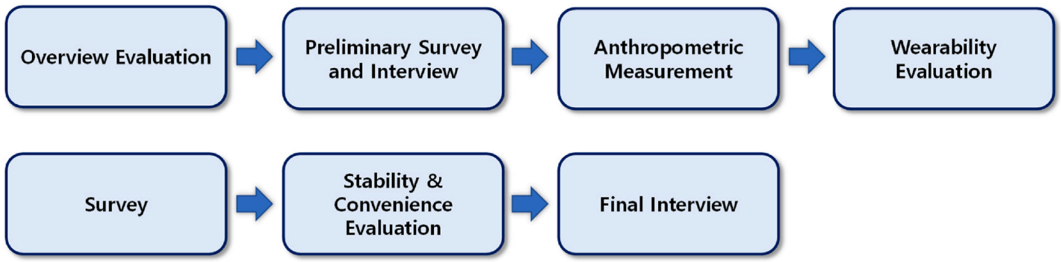

Fig. 2. VEX user satisfaction evaluation process flow.

overhead screws at each point, and subsequently reverting to the point of commencement. Fig. 3, with its left facet, elucidates the experimental methodology at the first locale, whereas its right facet delineates the participant-wise sequence of task execution, with numeric indicators elucidating the prescribed movement sequence. Within a constricted timeframe of 15 min, this activity was iteratively executed by participants. Although the session's temporal confines were strictly adhered to, there were no impositions regarding the frequency of task completion or the locomotion velocity of the participants. Post-experimental protocols mandated a cooling-off period, persisting until a normalization in participants' otic temperature; ascertained using a Braun TehrmoScan IRT-4520, Germany and localized temperature perturbations due to harness contact.

Precisely prior to and following each experimental iteration, thermal measurements of the regions of the participants' bodies impacted by the harness, as well as the temperature of the harness itself, were documented using a thermal imaging camera (Testo, 890 basic, Germany). To gauge facets such as wearability, stability, and functional convenience, alongside the overarching satisfaction derived from donning the harness, an evaluative instrument was delineated, detailed in Table 4. The domain of wearability comprised four indices assessed on a seven-point scale [22,28]. Both the stability and convenience dimensions encompass four evaluative parameters. Save for the wearing pressure metric, all were appraised on a seven-point scale, adhering to the guidelines promulgated by the International Organization for Standardization [29]. Culminating the evaluation, the overall satisfaction of the harness users was ascertained on a seven-point scale, anchored from 1 (completely dissatisfied) to 7 (highly satisfied).

In addition to the survey data, further insights were gathered through semi-structured interviews with participants. These interviews were designed to elaborate on the questionnaire responses, asking participants to clarify the specific rationale behind their

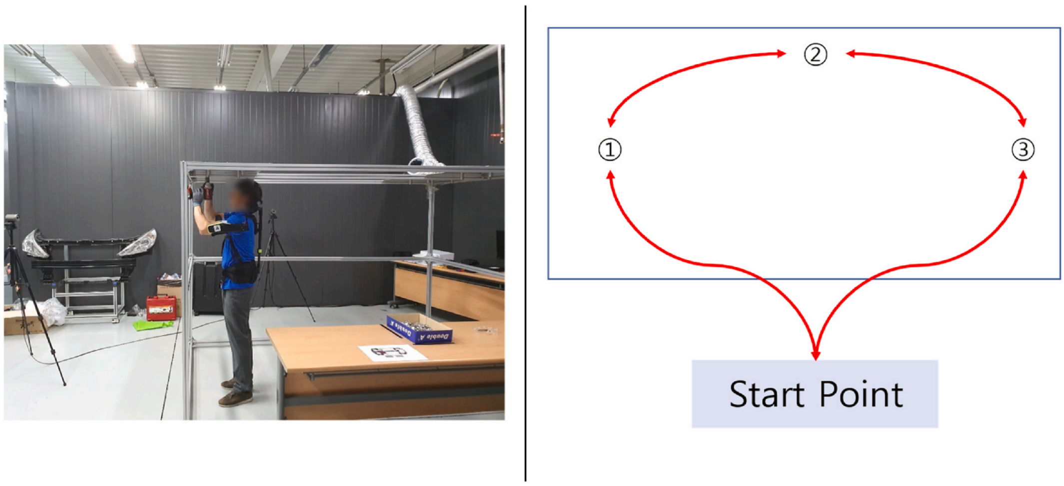

Fig. 3. Experimental task process. *Note.* Left panel shows experimental setting and process. Right panel shows flow of the experimental process.

Table 4
Survey items, categories, and measurement scales.

Evaluation item	Categories	Measurement scales
Wearability	Easy to remember	1 (*very difficult to remember*) to 7 (*very easy to remember*)
	Easy to fasten	1 (*very difficult to fasten*) to 7 (*very easy to fasten*)
	Easy to adjust	1 (*very difficult to adjust*) to 7 (*very easy to adjust*)
	Overall wearability	1 (*not satisfied at all*) to 7 (*strongly satisfied*)
Stability	Wearing pressure	1 (*no pressure at all*) to 6 (*extreme pressure*)
	Fixation strength	1 (*very loose*) to 7 (*very secure*)
	Wearing comfort (safety)	1 (*very uncomfortable*) to 7 (*very comfortable*)
	Overall wearing stability	1 (*not satisfied at all*) to 7 (*strongly satisfied*)
Convenience	Thermal sensation	1 (*feel cold*) to 7 (*feel hot*)
	Wetness sensation	1 (*very dry*) to 7 (*very wet*)
	Tactile sensation	1 (*very bad*) to 7 (*very good*)
	Overall convenience	1 (*not satisfied at all*) to 7 (*strongly satisfied*)
Overall wearing satisfaction	N/A	1 (*not satisfied at all*) to 7 (*strongly satisfied*)

Note. N/A = not applicable.

selections. This step aimed to illuminate any potential variances in the participants' interpretation or perception of the survey categories. For instance, some participants might have found higher levels of applied pressure from the harness to be comfortable ('wearing pressure'), while others might have been uncomfortable even with minimal pressure. During these interviews, queries were also made regarding participants' preferences for the materials used in the pads and straps, as well as any recommendations they might have for enhancing these components.

Within the survey's wearability section, the participants were prompted to gauge the intuitiveness of the harness' donning procedure, the simplicity of securing its fastenings, the ease with which adjustments could be made to ensure an optimal fit, and their cumulative judgment on the harness' wearability. Semi-structured interviews delved deeper into challenges or discomforts encountered by participants during their interaction with the harness. Notably, since participants had been previously endowed with a comprehensive manual detailing the harness' application methodology, they were instructed to proceed grounded in their recollection of this guide, independent of any intervention from the research team.

In relation to stability, questions were posed to participants about their ability to sustain a steady posture while engaged in the assigned tasks wearing the harnesses. Inquiries also delved into sensations of pressure, the efficacy of fixation, comfort levels, and their holistic assessment of stability while outfitted in the system. Interviews offered additional insights into whether the pressure experienced while wearing the harness was considered acceptable or problematic. Concerning convenience, the survey delved into the participants' perceptions of thermal comfort, wetness levels, and tactile experiences, as well as their overall ease and comfort during the tasks executed in the experiment. The category of thermal sensation pertained to the participants' perceptions of heat, whereas wetness sensation focused on their assessment of moisture levels. Tactile sensation questions were concerned with the pad's thickness and satisfaction regarding the strap material.

Objective metrics were also collected for analysis. Wearability evaluation encompassed the duration needed for participants to don the harness, the incidence of errors made during the donning and wearing processes, and scores from the survey. Stability during wear was quantified through a four-channel observation camera, which recorded the number of completed tasks as well as the rate of errors occurring during the testing phases. Convenience assessments utilized a thermal imaging camera to log temperature readings of the harness as well as the temperatures of those areas of participants' bodies most directly influenced by the harness, both before and after each testing session.

2.6. Data analysis

Table 5 provides a synopsis of the diverse data types gathered through experimental trials, questionnaires, and semi-structured interviews. To determine the appropriateness of performing parametric tests, the data were first subjected to Shapiro–Wilk tests for normality. Given that the normality assumptions were met, paired t-tests were subsequently employed for the statistical analysis. The

Table 5
Collected data and data-gathering process.

Evaluation items	Collected data (Data gathering process)
Wearability	Survey categories: easy to remember, easy to fasten, easy to adjust, and overall wearability
	Experiment measurements: time taken to don the harness and wearing error frequency
	Semi-structured interviews
Stability	Survey categories: wearing pressure, fixation strength, wearing comfort (safety), and overall wearing stability
	Experiment measurements: the number of tasks completed
	Semi-structured interviews
Convenience	Survey categories: thermal sensation, wetness sensation, tactile sensation, and overall convenience
	Experiment measurements: heat before and after the experimental session completion, body temperature, and thermal graphic image
	Semi-structured interviews

SPSS Statistics 21.0 program was used for the data analysis.

3. Results

3.1. Wearability

The results obtained here indicated the time taken to put on the latter harness was longer, but the frequency of wearing errors was reduced when using the latter design compared with the former. In particular, various types of errors occurred, such as not properly understanding the method of putting on the harness, not recognizing the length adjustment strap of the neck pad, or wearing the chest and shoulder straps with the straps twisted. After the participants had put on the VEX, the experimental moderator was informed. The moderator then examined how the participants had put on the VEX and checked for any incorrectness (e.g., wearing the chest straps with the straps twisted) to determine the number of errors (Fig. 4).

As shown in Fig. 5, the mean value of the number of errors in putting on the harness decreased by 13.43% for the latter harness compared with the former harness, but the mean value of time taken to put on the harness increased by more than 50.56%. Many positive opinions regarding the former harness in terms of wearability were reported. The average scores for the latter harness in categories related to wearability were lower than those given to the former harness (Fig. 6).

There were 166 expressions containing complaints about wearability; these complaints accounted for 41.71% of total opinions expressed. Specifically, the participants complained that it was "difficult to wear on the arms and to fasten with one hand" and "difficult due to unclear information regarding the positioning of the buckles and straps," and some participants pointed out that the strap was complicated and difficult to handle (Table 6).

The time taken to put on and difficulty of putting on the harness perceived by the participants were slightly increased in the latter harness due to the changes in the method of fastening the neck support of the latter harness, the change in the chest strap position, and the addition of the arm cuff buckles. However, the number of errors in the wearing of the harness decreased; thus, it can be concluded that the modified wearing method was more intuitive. Because the ease of putting on the latter harness was low, it is concluded here that it is necessary to improve the attachment method of the latter harness. The improvement plan, developed by using the semi-

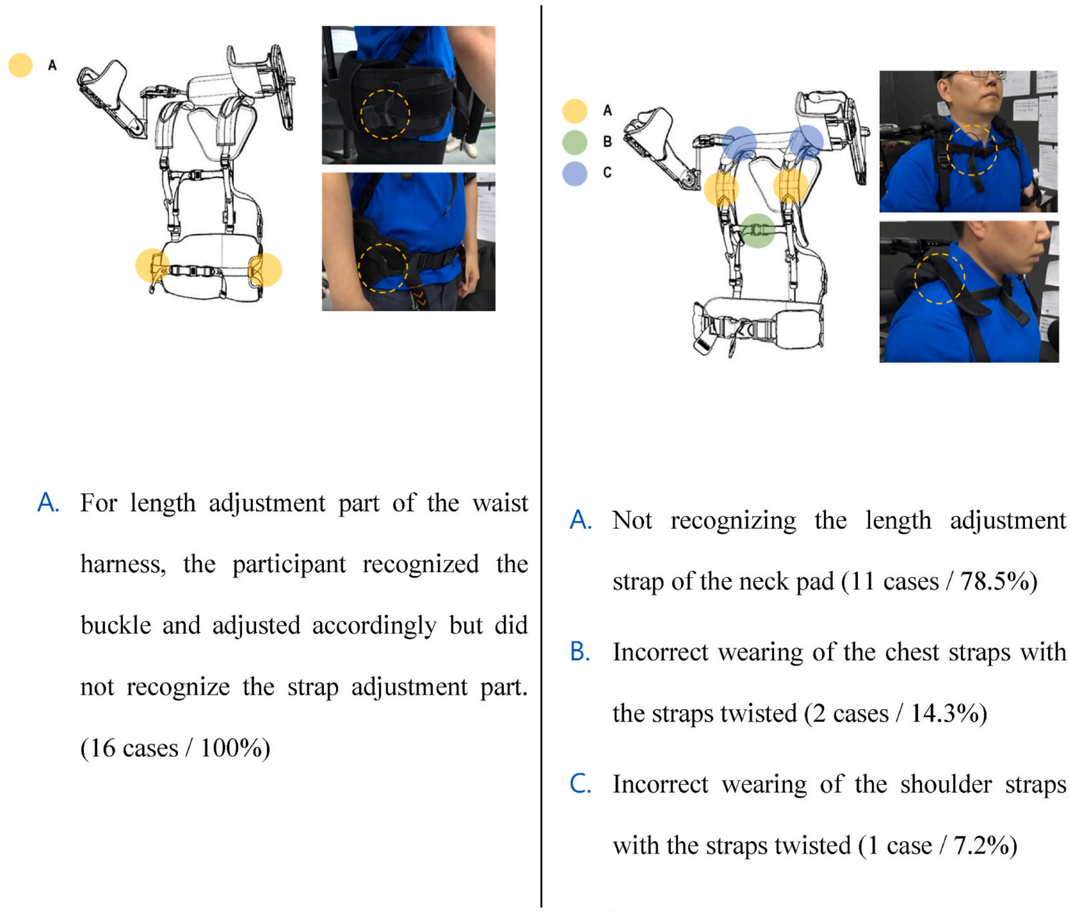

Fig. 4. Major wearing errors.

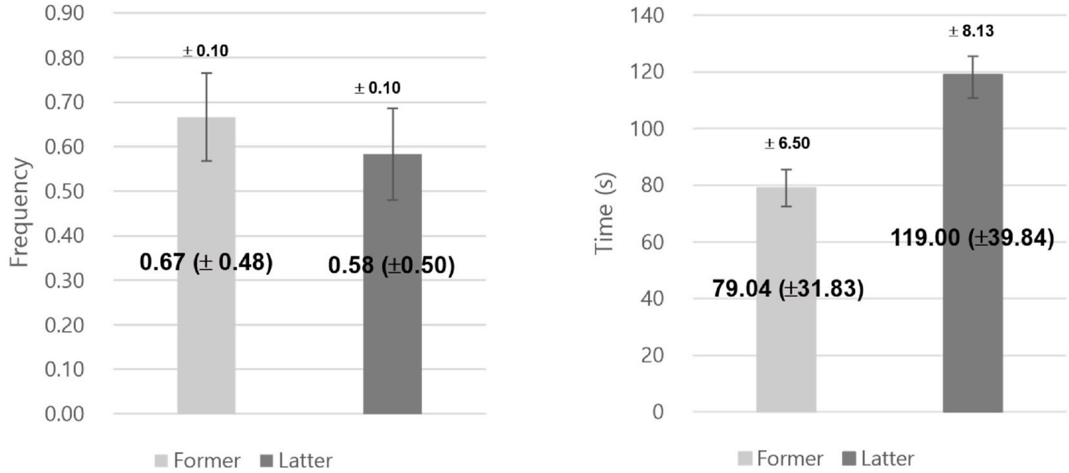

Fig. 5. Wearing errors (number of incorrectly worn harnesses) and time taken to put on harnesses. *Note.* Error bars show standard errors. Numbers in parentheses indicate standard deviation.

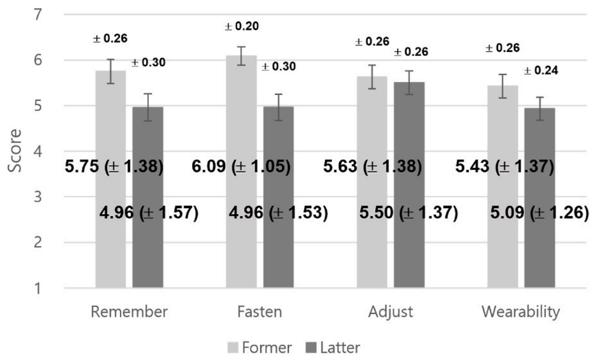

Fig. 6. Wearability evaluation based on survey data. *Note.* Error bars show standard errors. Numbers in parentheses indicate standard deviation.

Table 6
Results based on wearability interview data for the latter harness.

	Negative perception of wearability	Mention frequency
1	Difficult to wear on the arms and difficult to fasten with one hand	39
2	Difficult due to unclear information on the positions such as the buckles and straps	30
3	Complicated and difficult process of tightening the harness	20
4	Difficult to handle the adjusting strap	14
5	Poor sense of adjustment in adjusting the strap	13

structured interview results, proposes methods to simplify the fastening of the neck support (neck pad height adjustment) of the latter harness and the upper arm cuff buckle fastening.

3.2. *Stability*

Maintaining a stable posture while wearing the VEX was extremely important for consistently performing the task of overhead screw fastening during the 15 min long experimental sessions. Therefore, this study compared the number of tasks (number of times the screw was tightened) performed while wearing each harness. The survey data indicated a high level of satisfaction for the latter harness, with an average increase regarding tasks performed of 2.17% compared with the results of experiments performed using the former harness (Fig. 7).

Fig. 8 shows the average values for fixation strength, wearing comfort, and overall wearing stability. The responses on wearing pressure were divided into positive and negative based on the basis of the subjective sensations of the respondents. The interview data indicated that some participants felt discomfort due to the pressure of the VEX, felt pain, or felt that the harness was not fixed properly while they performed the task; some participants stated that they preferred working without the harness. In the case of the latter

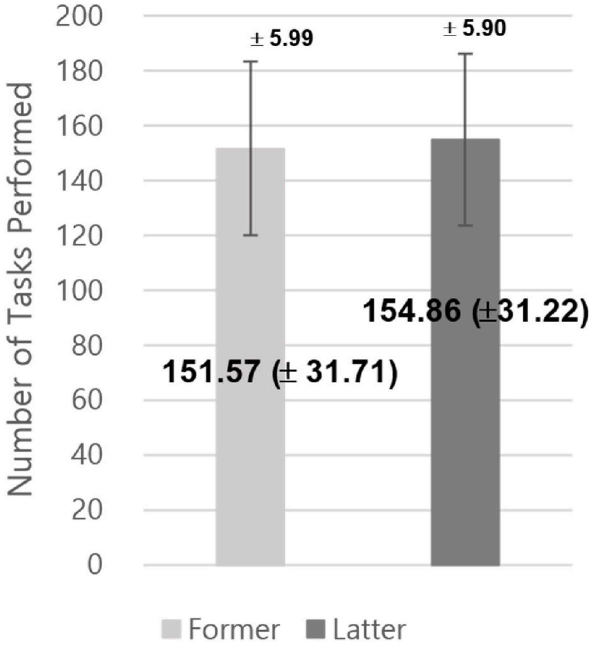

Fig. 7. Number of tasks performed. *Note.* Error bars show standard errors. Numbers in parentheses indicate standard deviation.

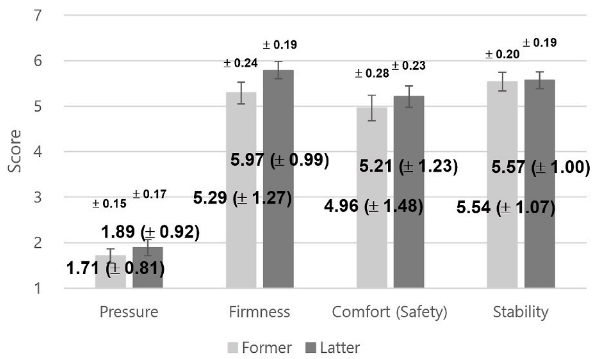

Fig. 8. Stability evaluation based on survey data. *Note.* Pressure = wearing pressure; Firmness = fixation strength; Comfort (Safety) = wearing comfort; Stability = overall wearing stability. Error bars show standard errors. Numbers in parentheses indicate standard deviation.

harness, the wearing stability was improved by the addition of the arm cuff buckle and optimization of the harness in the area of the waist belt. We note that the fixation strength was improved even though the waist belt area was decreased, and it can therefore be judged that the slight improvement in the job efficiency was due to the better fixation system.

However, due to the firm fixation of the latter harness, 125 out of 398 (31.41%) expressions of opinion in the semi-structured interview data indicated a limitation in respondents' posture (mobility restriction). Most of the participants pointed out that the harness was not properly fixed to the body or that the free movement of the arms was difficult due to the mechanical structure of the harness (Table 7).

Table 7
Stability interview results for latter harness.

	Negative perception of stability	Mention frequency
1	Feeling discomfort or pain due to pressure	15
2	Feeling of the harness not properly fixed	13
3	Harness not functioning properly (more comfortable without the harness)	12
4	More strength was required to move to the desired position due to the fixing of the arm	8
5	Discomfort due to excessive fixation (limited mobility)	6

3.3. Convenience

In this investigation, the convenience of the harnesses was assessed considering the participants' body parts with which the harness was in contact (neck, arms, back, and lower back). For both the former and latter harnesses, the responses were close to one (no feeling of thermal sensations related to the harness) (Fig. 9), but the average score related to thermal discomfort for the latter harness was slightly higher than that obtained by the former harness. The responses related to sensations of wetness ranged from four (*neutral*) to five (*somewhat wet*), showing a slight difference between the former and the latter harnesses (Fig. 10).

The questions addressed to the participants, which were used to assess the tactile sensations experienced while wearing the harnesses, intended to identify their subjective perception of how the material felt through contact with the harness when the VEX was worn. The tactile sensation could assist users in maintaining a stable posture [30]. The latter harness scored a higher rating for the neck area, indicating that the participants felt more comfortable when the material used in the neck area changed (Fig. 11). In terms of the detailed convenience with respect to the former and latter harnesses, the satisfaction level of the latter harness was relatively low, but the overall wearing convenience was similar to former one. Consequently, it can be concluded that the overall wearing convenience was relatively improved (despite the difference in thermal and wetness between the former and latter harnesses) due to the change in the fixation method of the neck area and the addition of arm cuff buckles, which rendered the fixation more stable and increased the thermal and wetness sensation in the neck and arm areas.

To obtain an objective evaluation of convenience, the subject's body temperature, body heat, and surface temperature of the harness were measured before the experiment, immediately after the experiment, and 10 min after the experiment (Table 8). The body temperature dropped immediately after performing the task both while wearing the former and the latter harnesses, but the overall average temperature of the neck, arms, back, and lower back rose by 0.31 °C (from 28.53 °C to 28.84 °C) while wearing the former harness, and by 0.15 °C from 28.71 °C to 28.86 °C while wearing the latter harness. Thus, the former harness showed a greater increase in body temperature.

From the semi-structured interview data, 107 (26.88%) of 398 expressed opinions were identified as being related to the wearing convenience of the latter harness. In the survey, the participants mentioned that they hardly felt any specific thermal discomfort related to wearing the harness. However, in the semi-structured interview, while the participants were wearing the latter harness, there were 59 comments related to the feeling of thermal discomfort or wetness from the pad and 27 comments related to the discomfort or inconvenience due to friction or tight sensations; these comments accounted for the majority of the comments related to the convenience of the harnesses (Table 9). It is likely that the participants expressed negative opinions about thermal discomfort because they compared the situation with when they worked without the wearable robot.

The material of the latter harness increased the wearing comfort in the neck area and resolved problems related to increases in the body temperature. However, the change in the fastening method in the neck area and the addition of the arm buckle caused an increase in the thermal discomfort, leading to a decrease in the overall convenience of the latter harness compared with the former version.

3.4. Overall wearing satisfaction

The overall wearing satisfaction increased with the improvement made to the fixation strength and the improved tactile sensation in the low back area for the latter harness compared with the former harness (see Figs. 8 and 12, and Table 10). The result from the user evaluations showed that the overall fixation strength and tactile sensation in the lower back area were improved, and despite the increase in time required to put on the harness (due to the increase in the fastening area and the change of the attachment method), the overall wearing satisfaction was improved. It can therefore be concluded that the wearing satisfaction of the harness can be further improved through the improvement to the fixation strength.

Factors affecting the harness usability (including wearability, stability, and convenience) were analyzed to determine the effect that these factors had on the overall wearing satisfaction. Table 11 outlines the results of the correlation analysis with normality tests for each variable and the overall wearing satisfaction. Stability and convenience were identified to be the most important factors in

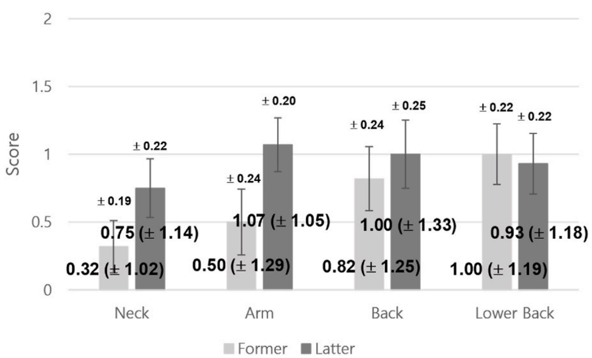

Fig. 9. Convenience evaluation based on survey data (thermal sensation). *Note.* Error bars show standard errors. Numbers in parentheses indicate standard deviation.

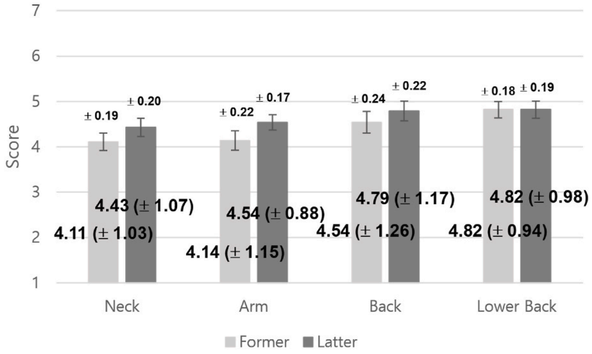

Fig. 10. Convenience evaluation based on survey data (wetness sensation). *Note.* Error bars show standard errors. Numbers in parentheses indicate standard deviation.

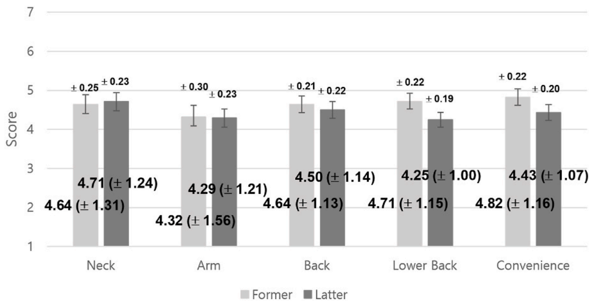

Fig. 11. Convenience evaluation based on survey data (tactile sensation and overall convenience). *Note.* Error bars show standard errors. Numbers in parentheses indicate standard deviation.

determining the overall wearing satisfaction of the latter harness. The factors that determine the wearing stability of the latter harness can then be ranked; we find that the reported wearing comfort ($r = 0.542$, $p = 0.003$) is more important than the tactile sensations reported (arm $r = 0.406$, $p = 0.032$; neck $r = 0.395$, $p = 0.037$).

Table 12 presents the results of a regression analysis undertaken to identify factors influencing the overall wearing satisfaction based on the survey data. Wearability and stability were found to not be significant factors; convenience ($B = 0.376$, $p = 0.029$) was judged to have a significant effect on the overall wearing satisfaction. That is, it can be concluded that in order to increase the overall wearing satisfaction, improvements should focus on the convenience of the harness rather than wearability or stability.

4. Discussion

Studies on exoskeletons have mainly focused on the design and performance of robots rather than on usability or user satisfaction. In addition, studies on exoskeleton harnesses have predominantly evaluated motor functions for medical purposes or body posture correction. Unlike previous literature, the present study aimed to assess the effects of harnesses on the operators' satisfaction by considering the distinct characteristics of industrial exoskeletons, which are meant to undergo repetitive tasks for a significant amount of time, especially when it comes to upper limb exoskeletons where it is of utmost importance to support the joints of the worker's neck, shoulders, and elbows, as well as anchoring the skeleton itself. Current exoskeleton products include the Levitate, developed by Levitate with a mass of approximately 3.2 kg and force assistance of 5.5 Nm, and the Ekso Vest which was developed by Ekso Bionics with a mass of approximately 4.3 kg and force assistance of 4.0–5.4 Nm. In contrast, the VEX, which has been developed by Hyundai and it is the subject of the present study, has a mass of approximately 2.5 kg and force assistance of 6.5 Nm. Considering that most of the wearable robots listed above are designed for workers performing tasks with raised arms, the weight of the wearable robot itself is critical since it needs to support the joints of the neck, shoulders, and elbows.

The majority of current literature has focused on the design and performance of wearable robots rather than on harness usability [31–33] or their impact on the human body [34]. Studies considering the harnesses used in such systems have largely focused on functional evaluations for medical use or for exercises intended to correct body posture [16,18,26,35,36]. Thus, the evaluation of the usability of harnesses used in wearable robots designed for use in industrial settings presented in this study could serve as essential reference data for further research on wearable robots for various industrial uses.

The results of our experimental study revealed that the stronger the fixation firmness, the more improved the wearing stability, and thus the better the overall satisfaction. We also determined that the change in the material of the waist pad had a compounding effect on users' sensation by improving the contact feeling.

Table 8
Body temperature (ear), body heat, and harness surface temperature before and after experiment.

	Before the experimental session										
	Body temperature (°C)	Body heat (°C)					Harness temp. (°C)				
		Left arm	Right arm	Back	Lower back	Neck	Left arm	Right arm	Back	Lower back	Neck
Former harness	36.75	28.61	28.62	28.70	26.69	30.05	23.73	23.98	23.61	24.00	23.77
SD (former)	0.29	0.82	0.96	0.99	1.00	1.46	1.07	0.89	1.11	1.17	1.11
SE (former)	0.05	0.15	0.18	0.19	0.19	0.28	0.20	0.17	0.21	0.22	0.21
Latter harness	36.72	28.71	28.88	28.91	27.00	30.03	24.15	24.41	24.04	24.49	24.09
SD (latter)	0.30	0.89	1.05	1.13	1.07	1.56	0.66	0.59	0.79	0.58	0.76
SE (latter)	0.06	0.17	0.20	0.21	0.20	0.29	0.12	0.11	0.15	0.11	0.14
	Immediately after the experimental session										
	Body temperature (°C)	Body heat (°C)					Harness temp. (°C)				
		Left arm	Right arm	Back	Lower back	Neck	Left arm	Right arm	Back	Lower back	Neck
Former harness	36.62	28.72	29.10	29.10	27.21	30.08	26.49	26.67	27.10	26.34	26.11
SD (former)	0.32	0.63	0.73	0.85	0.67	1.25	0.59	0.54	1.00	0.51	0.66
SE (former)	0.06	0.12	0.14	0.16	0.13	0.24	0.11	0.10	0.19	0.10	0.12
Latter harness	36.66	28.94	29.20	29.01	26.90	30.26	26.03	26.04	27.75	25.53	27.92
SD (latter)	0.25	0.84	0.81	0.78	0.66	1.17	0.75	0.67	1.11	0.60	1.01
SE (latter)	0.05	0.16	0.15	0.15	0.13	0.22	0.14	0.13	0.21	0.11	0.19
10 min after the experimental session											
	Body temp. (°C)	Body heat (°C)					Harness temp. (°C)				
		Left arm	Right arm	Back	Lower back	Neck	Left arm	Right arm	Back	Lower back	Neck
Former harness	36.70	28.66	28.84	28.80	26.81	30.16	25.00	25.16	24.74	25.14	25.07
SD (former)	0.24	0.80	0.90	0.90	0.90	1.58	0.57	0.51	0.59	0.51	0.50
SE (former)	0.05	0.15	0.17	0.17	0.17	0.30	0.11	0.10	0.11	0.10	0.10
Latter harness	36.71	28.63	28.76	28.50	26.64	29.74	24.65	24.84	24.70	24.85	25.45
SD (latter)	0.27	0.77	0.80	0.98	0.79	1.45	0.41	0.43	0.51	0.34	0.61
SE (latter)	0.05	0.14	0.15	0.18	0.15	0.27	0.08	0.08	0.10	0.06	0.12
Total Average (Before, Immediate, and 10 min after the experiment											
Former harness	36.69	28.66	28.85	28.87	26.90	30.10	25.07	25.27	25.15	25.16	24.98
Latter harness	36.70	28.76	28.95	28.81	26.85	30.01	24.94	25.10	25.50	24.96	25.82

Table 9
Convenience interview results for the latter harness.

	Negative perceptions related to convenience	Mention frequency
1	Feeling thermal sensation or wetness from the pad	59
2	Discomfort or inconvenience due to friction or tight sensation	27
3	Poor ventilation	10
4	Discomfort or inconvenience due to the material	7

5. Conclusions

This study performed a comparative evaluation of the usability of the former and latter harness designs of the VEX, and we proposed measures for the further improvement of the design. The overall wearing satisfaction was found to be affected by the material used and fixation strength of the harness, highlighting the importance of usability evaluation. Participants were recruited for usability evaluation experiments of the former and latter harness models, and the wearability, stability, convenience, and the overall wearing satisfaction were assessed.

The user evaluation results showed an overall improvement in relation to the fixation strength in the latter harness compared with the former design. This improvement increased task stability and, consequently, performance. The correlation analysis showed that the wearing comfort had the greatest effect on the overall wearing satisfaction, followed by the reported tactile sensations. The overall satisfaction derived from wearing the latter harness was greater than that derived from wearing the former harness despite the increase in the contact area of the VEX due to the new wearing method and increased time to put on the harness. In addition, to reduce the reported thermal effect of the harness, we propose that the pad should be made of a material with improved air ventilation characteristics.

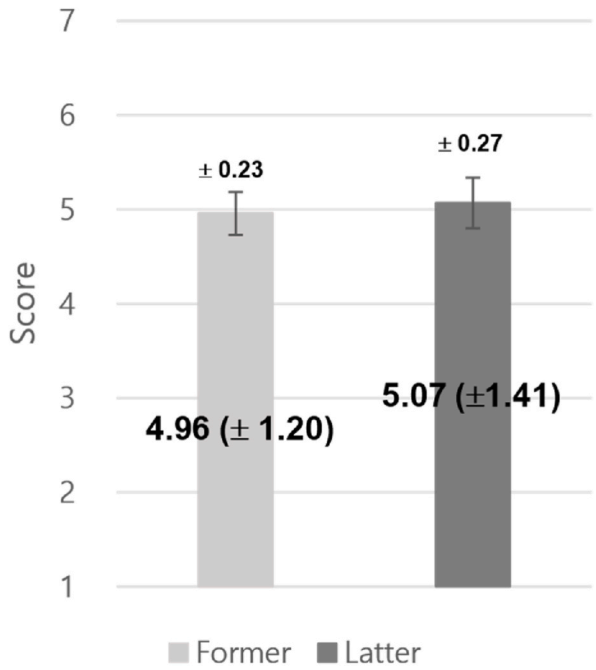

Fig. 12. Overall wearing satisfaction survey results. *Note.* Error bars show standard errors. Numbers in parentheses indicate standard deviation.

Table 10
Overall Wearing Satisfaction *t*-test Results.

Overall wearing satisfaction	Former harness *M* ±*SD*	Latter harness *M* ±*SD*	*M* ±*SD*	*t*	*df*	*P*
	4.96 ± 1.20	5.07 ± 1.41	−0.11 ± 1.34	−0.422	27	0.676

Note. *p < 0.001.

Table 11
Correlation analysis of the overall wearing satisfaction for latter harness.

Evaluation items	Categories		*r*	*P*
Wearability (r = 0.124, P = 0.529)	Easy to remember		0.239	0.220
	Easy to fasten		0.130	0.511
	Easy to adjust		0.130	0.510
Stability (r = 0.657, P = 0.000)	Wearing pressure		−0.223	0.255
	Fixation strength		0.334	0.073
	Wearing comfort		0.542**	0.003
Convenience. (r = 0.545, P = 0.003)	Thermal sensation	Neck	−0.043	0.830
		Arm	−0.102	0.606
		Back	−0.240	0.220
		Lower Back	−0.050	0.800
	Wetness sensation	Neck	−0.017	0.931
		Arm	0.026	0.89
		Back	−0.250	0.200
		Lower Back	−0.257	0.188
	Tactile sensation	Neck	0.395*	0.037
		Arm	0.406*	0.032
		Back	0.337	0.080
		Lower Back	0.169	0.391

Note. The total number of participants (N) = 28. *$p < 0.05$. **$p < 0.01$.

The limitations of this study are summarized as follows: The experimental environment was limited to the laboratory; thus, only a simple bolt assembly task could be evaluated. In addition, the experimental environment was similar to the actual work environment of industrial workers, but the work was not undertaken in an actual workplace setting. To verify the results of this study and obtain practical data, future studies should focus on the evaluation of the harness in actual workplaces. In addition, because wearable robots

Table 12
Regression analysis results for overall wearing satisfaction.

		df	Adj *SS*	Adj *MS*	*F*	*p*	B	β	*t*	VIF
Regression		3	26.767	8.9223	7.01	0.000				
Overall wearing satisfaction	Wearability	1	2.152	2.1523	1.69	0.199	0.148	0.114	1.30	1.05
	Stability	1	4.167	4.1667	3.27	0.076	0.330	0.183	1.81	1.51
	Convenience	1	6.424	6.4242	5.05	0.029	0.376	0.167	2.25	1.52

Note. VIF = variance inflation factor. Values of 10 or below indicate that the correlation (multicollinearity) between the independent variables is low and the regression results are reliable.

cannot provide the same degrees of freedom as actual human joints [37], the participants reported not only the discomfort related to the harness but also mechanical discomfort; this affected the evaluation of usability. In future research, mechanical discomfort needs to be minimized, and a more objective evaluation should be undertaken.

The findings of this study can be used as reference data for research related to various occupations and for usability evaluations of harnesses for wearable robots for lower limbs, as well as the functional evaluation of such items. The results of this study can contribute to the development and improvement of industrial-robot and general-purpose harnesses.

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Author contribution statement

U Ri Chae: Performed the experiments; Analyzed and interpreted the data; Wrote the paper. Gi Hyun Lee: Performed the experiments; Analyzed and interpreted the data. Hongbum Kim: Analyzed and interpreted the data; Wrote the paper. Kyujung Kim: Jongkyu Choi: Dong Jin Hyun: Conceived and designed the experiments. Jungmin Yun: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

The data that has been used is confidential.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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