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Mapping of Human Contact Areas for Application Field of Wearable Robots

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Abstract This study investigated the current state of various wearable robot technology companies to collect basic data to develop clothing suitable for wearable robots. The companies were examined country-wise and classified by their field of application. Furthermore, body mapping was performed on the human contact areas of the wearable robots according to the field of application. The results showed that most wearable robot technology companies are situated in Europe, Asia, and North America. Classifying wearable robots by the field of application yielded that 50.0%(N=39) were applicable for rehabilitation/healthcare, 37.2% (N=29) for industrial use, 10.3% (N=8) for military, and 2.6%(N=2) for sports. The body mapping showed that the contact areas of the rehabilitation/healthcare products could be classified as hand, arm, upper body, lower body, foot, and whole body. These types of products have the most diverse categories of contact areas among all the product categories. Industrial products were classified into waist, upper body, lower body, and whole body; their distinctive feature is that the corresponding wearable robots assist only the waist area. Military products were designed to cover the whole body for protection. Sports products were produced for the lower body only.

Keywords Wearable robot, Exoskeleton robot, Market condition, Body mapping, Contact area

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Introduction

Recently, brain-controlled and muscle-supporting exoskeleton robots have become accepted as body replacement clothing under the category of biotechnology clothing (Bae & Ha, 2017). Kim et al. (2019) discussed the problems of wearable robots from clothing aspects through a professional clothing journal. Many researchers have highlighted the importance of functional clothing that can be worn with wearable robots (Chung, Park, Shin, Koshiba & Tamura, 2006; Kim, Song, Lee, & Kwon, 2018), suggesting the necessity to approach wearable robots from the perspective of apparel study.

Wearable robots are most primarily affected by the clothing environment, and those who utilize wearable robots wear everyday clothing. However, everyday clothing lays emphasis on aesthetic fit, instead of functionality (Kang, 2012), and therefore, the characteristics of wearable robots are not considered, which may reduce wearing comfort. Moreover, wearable robots are formed using solid alloys, and the issues arising from robot parts may be resolved by wearing functional clothing considering the physical contact between the wearable robots and the body.

The locations of accessories affect clothing wearing satisfaction (Lee & Suh, 2010), and wearing effects are related to the contact area of the clothing with the skin (Park

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& Kim, 2007). Moreover, Bang et al. (2014) showed that differentiating wearing characteristics by body parts is important for functional clothing that perform particular operations and require complex functions. Therefore, obtaining fundamental data about the locations and areas for wearable robots prior to designing clothing for wearable robots is considered crucial.

This study, with regard to the wearing characteristics of wearable robots, investigated the locations and areas for wearing wearable robots to suggest an appropriate functional clothing system that can be worn with them. Particularly, the current status of the wearable robot industry was analyzed, and the distribution of body parts where robot parts are worn was examined and visualized by classifying robot products into "utilized fields by enterprise." Development directions, such as clothing for wearable robots, placement of appropriate materials according to the body parts, and designing of functional patterns, were considered in the analysis.

Background

Development of Wearable Robots

Research cases show that wearable robots are worn on various body parts. Jang et al. (2009) designed robots to be worn on knees to support walking muscles and minimize the wearing area. Lenzi et al. (2011) developed an elbow-active orthosis capable of repetitive remedial exercise. Mengüç et al. (2014) developed a soft sensing suit by placing wearable soft sensors on the rear, knee, and ankle to monitor joint angles. While developing an exoskeleton to assist users who cannot move, Totaro et al. (2017) suggested wearable modules that can only be worn on knees and ankles. Concurrently, according to a study on exoskeleton robots that support waists (Yoon, 2018), such robots can be worn on the waist, whole body, or hip joint based on the developer. The development directions of wearable robots in previous studies and of those currently being developed vary in the locations and areas of the robots depending on their purpose.

Wearability of Wearable Robots

Wearable robots are devices that enhance muscle strength and stamina and are worn on specific body parts, such as arms or legs (Kim, 2018). Although the current wearable robots offer various mechanical and physical functions, they lack in providing comfort to the wearer (Novak & Riener, 2015). For example, body parts surrounded by wearable devices attached to a wearable robot may perspire depending on the body motion or the external environment, and inadequate pressure level may lead to skin discomfort or damage (Nimawat & Jailiya, 2015).

Moreover, Li et al. (2018) stated that an exoskeleton decreases the load but increases the stress for the wearer. Yoon (2018) examined the possibility of using an exoskeleton robot to support the waist of a soldier and found that no exoskeleton robot can fulfill the requirements of the army. Recently, the International Electrotechnical Commission, an international standards organization, established a specific standard for robots. Authorization and evaluation guidelines are also being developed for robots domestically (Bae et al., 2018), thus, increasing the demand for studies that focus on the improvement of the wearability of wearable robots. Therefore, currently, wearable robots need to be developed with focus on wearability as well as enhancement in the mechanical functions.

Method

Data Acquisition

In this study, data on manufacturers were searched and collected from internet sites to investigate the technology status of wearable robot businesses. Website addresses and information of each business were collected from an Exoskeleton Report (n.d.) containing information on wearable robot businesses from March to July 2019. To acquire information on companies from various countries, search words "wearable robot company" and "exoskeleton company" were searched on Google (www.google.com) and Naver (www.naver.com). A total of 64 wearable robot companies were collected, and information on wearable robot products was obtained from the website each company. Each company developed and manufactured at least one product, and information on a total of 78 types of products was acquired. Products that varied only in color were not differentiated.

Analysis Method

This study categorized the information on the wearable robots according to country and the application field. None of the manufactured products of the subject companies were for disaster rescue purposes, such as the ones mentioned by Kim et al. (2019). Lee and Han (2014) analyzed the technology trend of wearable robots by categorizing them into military industrial, medical rehabilitation, and social welfare fields, which referenced the study of Jang and Song (2016) in which application fields were categorized more specifically. Moreover, wearable robot companies that produce products for sports were included in this study. Therefore, a category of sports was added. Specifically, the selected categories were military, industrial, rehabilitation/medical, and sports application fields. The sorted data were analyzed using SPSS 24.0 statistical program, from which frequency and percentage were calculated. Body mapping was conducted after categorizing, to identify the overall worn body parts of a robot according to the application field. The body mapping converted the results of the frequency analysis into a diagram, in which a higher frequency was depicted with a darker color.

Data acquisition and categorization were conducted in this study with two experts each on apparel study and wearable robot technology to confirm the reliability of the data. First, the data on the locations for the robot products to be worn were collected from the websites of all the robot companies. Thus, wearable robots were classified according to their wearing body parts. However, where information was insufficient on the websites, the wearing images on the website and the product information were collected to select a wearing body part by expert group discussion to enhance the data reliability. Moreover, products with overlapping application fields were categorized into the application field of their primary purpose.

Results

Current Status of Wearable Robot Industry

The distribution of the domestic and international wearable robot companies researched in this study by country is provided in Table 1. The names of the wearable robot companies are listed in Table 2. Among the wearable robot companies, 35.9% were in Europe, 28.1% in Asia, 26.6% in North America, 6.3% in the Middle East, and 1.6 % in South America and Oceania. This shows that wearable robot companies were mostly located in Europe, followed by Asia. As exoskeleton robot clothing is mentioned in the trend analysis of future Korean clothing (Bae, 2016), the number of companies developing or selling wearable robots is expected to increase in Korea. Following Asia, North America had the highest number of wearable robot companies, and the United States had many wearable robot companies, as it is one of the most prominent countries in robot technology (Kim, 2019).

Table 1. Distribution of wearable robot companies by country

World	Count	%
Asia	18	28.1
N. America	17	26.6
S. America	1	1.6
Europe	23	35.9
Oceania	1	1.6
Middle East	4	6.3
Total	64	100.0

Wearable companies organized by the application field are listed in Table 3. The rehabilitation/ medical field accounted for 50.0 %, industrial 37.5 %, military 10.0 %, and sports 2.5 % of the total, revealing that most wearable robot companies manufactured products for rehabilitation purposes. There are sufficient preceding studies supporting the present study result that most wearable robots are developed for rehabilitation/medical purposes. Some examples are the development of a wearable robot to support the elbow movement of elderly (Jang, Han, Kim, Jang, & Han, 2008), building of a robot for leg rehabilitation (Kim & Kim, 2017), and development of an exoskeleton robot system to enable independent ambulation or assist walking rehabilitation (Lee

Table 2. Wearable robot companies by country

World	Country	Country and company name
Asia	Korea	· Daewoo Shipbuilding & Marine Engineering, · Hyundai Motor Company, · P&S Mechanics Co. Ltd., · Exoatletasia, · Angel Robotics, · NT Robot
	China	· Fourier Intelligence
	Hong Kong	· Medexo Robotics, · Rehab-robotics
	Japan	· Cyberdyne, · DaiyaIndustry Co., Ltd., · Honda, · Innophys, · Mitsubishi Heavy Industries, · Panasonic – Activelink, · Archelis, · Walk-mate Lab, · Toyoflex
N. America	U.S.	· AlterG, · Ekso Bionics Holdings, Inc., · Lockheed Martin, · Myomo Inc., · Parker Hannifin, · Rewalk Robotics, · Sarcos LC, · Spring Active, · SRI International – Super flex, · Strongarmtech, · US Bionics / SuitX, · Raytheon, · Darpa, · Wyss Institute
	Canada	· B-temia, · Bionic Power, · Bionik Laboratories
S. America	Mexico	· Roki Robotics
Europe	France	· Exhauss, · Gobio Robot, · Japet, · Rb2d
	Russia	· Exoatlet, · Rostec
	U.K.	· 20KTS+(20 Knots Plus Ltd), · Kinetic Innovations Ltd
	Netherlands	· Focal Meditech BV, · Laevo, · Intespring
	Spain	· GOGOA Mobility Robots, · Marsi-bionics
	Switzerland	· Hocoma, · Noonee AG, · Reha Technology
	Italy	· Kinetek Wearable Robotics
	Sweden	· Bioservo Technologies AB, · PhaseX AB
	Latvia	· Againer
	Rumania	· Axosuits
	Germany	· Ottobock
	Austria	· Tyromotion GmbH
Oceania	New Zealand	· Rex Bionics
Middle East	Israel	· Meditouch, · Motorika Medical, · Rotbot Systems
	Turkey	· Bama Teknoloji

& Han, 2014). Examples of the development of industrial wearable robots include a wearable robot that assists conveyance of heavy loads, assembly, and lifting operations (Ha, Lee, Back, Kim & Lee, 2012) and a robot that supports the muscular strength of workers that require aid for the elbow muscle (Lee, Lee & Kim, 2015). The present study also showed that many wearable robots are being produced for laborers. However, although it is extensively believed that military wearable robots are intensively studied, there were not many such companies. Moreover, although wearable robots developed for sports were found, studies on them were scarce. Overall, the wearable robots were primarily for rehabilitation and medical uses as well as industrial purposes. However, their applied fields are gradually expanding.

Table 3. Wearable robot distribution by application field

Application field	No. of companies	%
Rehab/medical	39	50.0
Industrial	29	37.2
Military	8	10.3
Sports	2	2.6
Total	78	100.0

Equipped Body Parts of Wearable Robots

The equipped body parts were body mapped by classifying the products of the wearable robot companies according to the application field, and these are comprehensively depicted in Figure 1. The results of the analysis performed for each application field are shown in Figures 2, 3, 4, and 5, and representative images of the wearable robot products for each body map are organized in Tables 4-7.

Equipped body parts of rehabilitation/medical wearable robots. The body mapping results of the equipped body parts of the rehabilitation/medical wearable robots are presented in Figure 2, and the representative products are provided in Table 4. The rehabilitation/medical robots were worn on the hand (N = 4), arm (N = 8), upper body (N = 1), lower body (N = 16), foot (N = 1), and whole body (N = 9). The case of rehabilitation/medical wearable robots worn on the hand included robots equipped on the hand and the upper elbow. As for the arm, many products excluded the hand. Products intended to enhance motor abilities were not equipped on the hand, whereas devices developed for rehabilitation games or motion support for grabbing and lifting included the hand. In addition, the rehabilitation/medical robots were mostly worn at the lower body, with many products made to equip at both the waist and the legs with a control apparatus at the upper body. Furthermore, there were products for assisting patients with Parkinson's disease, which could only be worn at the feet. In addition, products that assist carrying heavy loads or assist the strength of the body as well as the arms were developed to be worn on the whole body.

The body mapping results showed that the rehabilitation/medical wearable robots were most commonly worn on the legs. Therefore, when designing clothing to be worn with a wearable robot, the development of the bottoms must be prioritized. Moreover, when designing the tops, comfort at the sleeves is crucial as many robots were worn on the arms and the hands. In this case, it must be considered that robots only partially cover the joint.

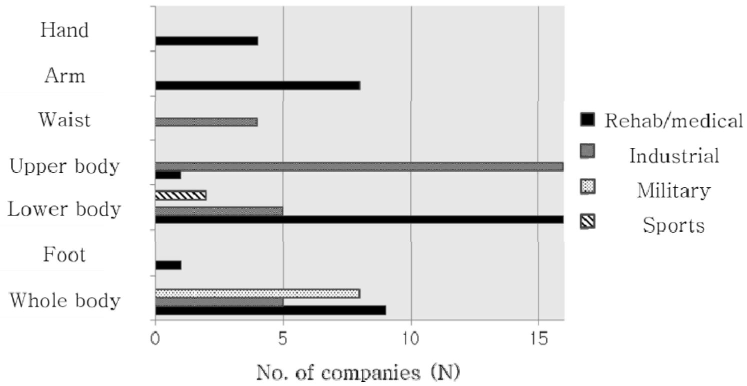


Figure 1. Equipped body parts by application field

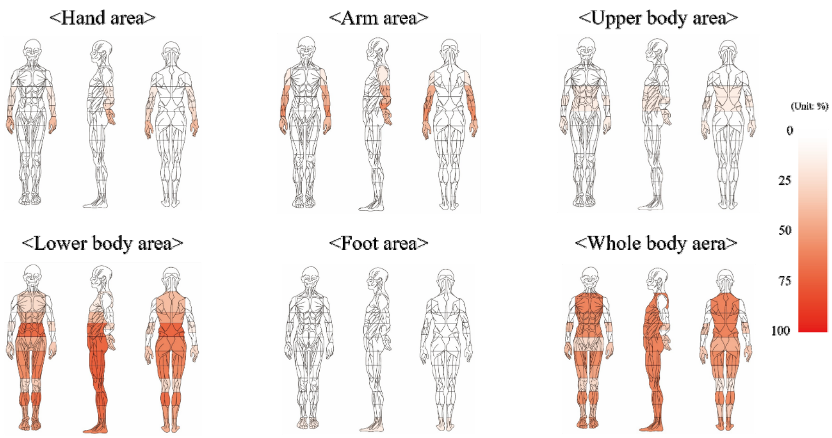


Figure 2. Mapping of equipped body parts for rehabilitation/medical wearable robots

Table 4. Rehabilitation/medical wearable robot products by equipped body part

Equipped body part	Image of wearable robot product	
Hand	 Hand of hope (Rehab-robotics, n.d.)	 Fourier M2 (Fourier Intelligence, n.d-a.)
Arm	 Myopro Orthosis (Myomo, n.d.)	 Arm tutor (Medi touch, n.d.)
Upper body	 Alex (Kinetek, n.d.)	
Foot	 Walkaid (Medexo robotics, n.d.)	
Lower body	 Exo legs (PhaseX A, n.d.)	 EAM (Exoatlet, n.d.)
Whole body	 Fourier X1 (Fourier Intelligence, n.d.-b)	 Super flex exosuit SRI International, n.d.)

Equipped body parts of industrial wearable robots. The body mapping results of the equipped body parts of the industrial wearable robots are depicted in Figure 3, and the representative products of each body mapping are provided in Table 5. The industrial robots were worn on the waist (N = 4), upper body (N = 16), lower body (N = 5), and whole body (N = 5). The products produced to alleviate the stress on the waist in laborious works, such as lifting heavy objects, or to augment the motions of a worker, were classified as waist mapping. The products that required arm motions were classified in the upper body category. The products classified as lower body were worn on only the legs or on the shoulders, back, and legs. The products manufactured to carry cargo or perform prolonged operations were for wearing only on the legs, whereas the products that realign posture when sitting or, undergoing repetitive or prolonged sitting operations, were partially equipped on the upper body. Examining the body mapping results of the whole body showed that the entire body was covered unlike in the case of the rehabilitation/medical wearable robots. The products worn on the entire body were for extensively enhancing the productivity of workers or to be worn on hazardous sites. They also served the purpose of supporting strenuous operations, such as carrying cargo or conducting repetitive operations, simultaneously preventing injuries.

The industrial personal protective gears were mainly developed to protect the body from external physical and chemical factors. However, because it is currently possible to develop wearable personal protective gears that detect hazards (Kim, Kim, Chae, Kim & Kim, 2017), an increase in industrial wearable robots is expected. Therefore, it is necessary to deduce the most effective locations for wearing them according to the location, working clothes, and purpose of the workers. Moreover, physiological responses may vary by the body part depending on the working environment, even for wearable robots worn on the entire body, which must be thoroughly considered when developing related clothing.

Tops must be prioritized when developing the clothing to be worn with industrial wearable robots utilizing body mapping data. Robots worn on the upper body are generally vests that partially cover the arm, excluding the joints. Appropriate coverall or bottom working clothes need to be developed as many industrial robots are worn on the whole body and the lower body, and clothing need to be developed considering wearable robots being equipped on the waist.

Equipped body parts of military wearable robots. The body mapping results of the military wearable robots by the equipped body part are depicted in Figure 4, and representative products are provided in Table 6. All the military robots covered the entire body (N = 8). Exoskeleton robots in the military field decisively differ from industrial ones because they require environmental resistance to operate in severe environments, such as storms, blizzards, and dust (Yoon, 2018). Military wearable robots are equipped with mechanical devices on the entire body, unlike other application fields, and are produced for protective purposes. When designing clothing to be used with military wearable robots based on the body mapping results, the focus must be on covering the entire clothing and enhancement in the wearing comfort for each item, considering that soldiers also bear various accessories.

Equipped body parts of sports wearable robots. The body mapping results of the sports wearable robots by the body part are depicted in Figure 5, and the representative products are summarized in Table 7. Sports wearable robots have not been extensively developed yet; therefore, there were all worn on the lower body (N = 2), and the company that produced sports wearable robots targeted skiers as the consumers. The two products supported the leg muscles and alleviated the pain in the knees. “Againer” was worn over and under the knees, and “Ski mojo” was worn beneath the

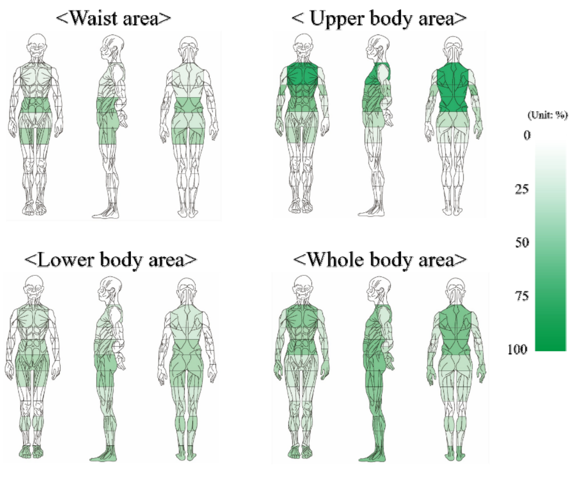


Figure 3. Mapping of equipped body part for industrial wearable robots

Table 5. Industrial wearable robot products by equipped body part

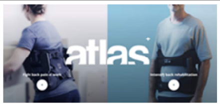
Equipped body part	Image of wearable robot product	
Waist	 HAL lumbar type for labor support (Cyberdyne, n.d.)	 Atlas (Atlas, n.d.)
Upper body	 Paexo (Ottobock, n.d.)	 IP12 (Europe Technologies, n.d.-b)
Lower body	 Archelis (Archelis, n.d.)	 IP14 (Europe Technologies, n.d.-c.)
Whole body	 Power assist suit (Mitsubishi Heavy Industries, n.d.)	 Guardian XO (Europe Technologies, n.d.-a)

Table 6. Military wearable robot products by equipped body part

Equipped body part	Image of wearable robot product	
Whole	 Exobuddy (Intespring, n.d.)	 XOS 2 (Raytheon, n.d.)

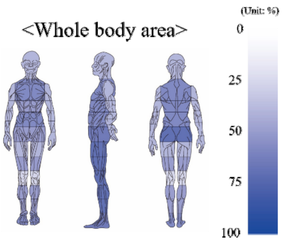


Figure 4. Mapping of equipped body part for military wearable robots

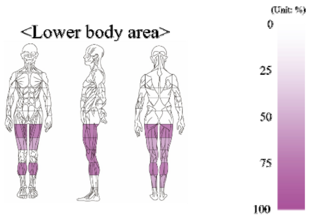


Figure 5. Mapping of equipped body part for sports wearable robots

Table 7. Sports wearable robot products by equipped body part

Equipped body part	Image of wearable robot product	
Lower body	 Againer (Againer, n.d.)	 Ski mojo (Ski~mojo, n.d.)

hips as well as the knees. Even robots with the same purposes are expected to exhibit different effects according to where they are equipped. The body mapping results of the sports wearable robots showed that the items worn on the lower body must be prioritized when designing related clothing.

In summary, rehabilitation/medical wearable robots were diversely classified into hand, arms, and feet. As patients and the elderly are the main consumers of rehabiliation/medical wearable clothing, clothing design that considers physiological response on wearing a robot is required. Although industrial wearable robots may support muscles, they do not enhance their strength (Kim, 2013). Therefore, industrial wearable robots must not hinder movement while reinforcing a muscle to have a beneficial effect. Military wearable robots are worn on the entire body similar to protective gear; however, the latter are difficult to move in because of the heavy weight (Bae & Kim, 2012). Accordingly, comfort must be prioritized when designing military clothing to be used with wearable robots. Although sports wearable robots have not been extensively developed, they are being actively studied, such as studies on sensor attachment guidelines to develop motion sensing smart sportswear with motion sensors (Han et al., 2017), outdoor clothing design (Kim, 2016), and outdoor design for trail running (Kim, 2015). Therefore, the development of wearable robots to be worn during exercise is considered significant.

Conclusion

In this study, wearable robot companies were investigated country-wise and their products were classified to the application field. Subsequently, the equipped body parts were body mapped by the application field, and further direction for clothing design in each field was considered.

The considered wearable robots were mostly developed in Europe, Asia, and North America, with 50.0%, 37.2%, 10.3%, and 2.6% of them for rehabilitation/medical, industrial, military, and sports purposes, respectively. Body mapping of the equipped body parts of the wearable robots by the application field showed that the rehabilitation/ medical products were classified into hand, arm, upper body, lower body, and foot, with more equipped parts than any other application field. The industrial products were categorized into waist, upper body, lower body, and whole body, and their distinct feature was that they were supported only the waist. The military products were designed to cover the entire body for protective purposes. There was only one wearable sports robot, which was worn on the legs for a specific sport. In conclusion, the robots were equipped on various body parts according to their application field, and when suggesting the clothing system of a wearable robot or designing clothing to be combined with a robot, it is crucial to differentiate based on the application field. Rehabilitation/medical wearable robots are worn on various body parts and are typically used by the elderly; therefore, skin sensation and body type should be preferentially analyzed, supported by studies that verify physiological responses to remove factors that hinder rehabilitation therapy. When developing clothing to be worn with industrial wearable robots, clothing design that does not hinder the movement of the robot according to the wearing purpose is required. Moreover, wearable robots that deliver force may assist operational works at industrial sites; however, they may not enhance muscular power. Therefore, methods to solve this problem must be continuously sought.

In particular, the working environment is extremely diverse; thus, extra caution is required when selecting functional fabrics. Military wearable robots cover the whole body, and therefore, clothing worn with them should be developed to be comfortable considering the physiological responses variation with the body part. Above all, clothing that does not hinder movement must be designed. When developing clothing to be worn with sports wearable robots, it is vital to support or protect a certain body part while not impeding movement by minimizing the equipped area to the said certain body part. Furthermore, various sportswear items have been developed; therefore, it is possible to propose a guideline for wearing clothes with sports wearable robots.

In this study, wearable robot companies and products were researched and organized to provide a guideline for their application in the clothing industry, and the suggested directions of clothing design hold academic significance. Wearable robots are designed to be worn on various body parts according to the wearer and its purposes; therefore, the body mapping conducted in this study is expected to be applicable when constructing product strategies for wearable robot clothing. Moreover, the establishment of a functional clothing system to be used with wearable robots in this study will expand the wearable robot clothing market as a companion product of wearable robots.

A limitation of this study is that mainly companies that developed exoskeleton robots were researched because despite the intensive studies on soft-type robots, they are not at the stage of commercialization. Soft-type robots are being continuously studied, and therefore, further research on them is required in the future. Additionally, objective body responses when wearing wearable robots and the subjective feelings of the wearer according to the equipped body part must be analyzed to provide diverse fundamental data for designing clothing to be used with wearable robots.

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