

Product-semantics based form design of active wearable upper-limb exoskeletons

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Abstract. With the development of wearable exoskeletons, people's demand for wearable exoskeletons is no longer limited to functionality alone. The aesthetics and symbolic meanings of wearable exoskeletons have also become a focus of attention. This paper aims to propose a method for designing the form of active wearable upper-limb exoskeletons based on product semantics, in order to enhance their form design to meet workshop scenarios and satisfy the physical and mental needs of users. Firstly, it analyzes product symbols and uncovers the appearance semantics, function semantics, symbolic semantics, and market semantics of wearable exoskeletons based on the product semantics. Then, the design process for the form design of active wearable upper-limb exoskeletons based on product semantics is proposed. Finally, design verification is implemented through design proposals of active wearable upper-limb exoskeletons used in logistics handling, fully considering the intrinsic connection between exoskeletons and their product semantics without interfering with the key technical structure of the exoskeleton and effectively integrating refined product semantic symbols into design practice. This can improve the functional utility of exoskeletons, enhance user experience, endow them with rich sociocultural and emotional connotations, and increase market competitiveness.

Keywords: Active wearable upper-limb exoskeleton / the product semantics / the form design

1 Introduction

The wearable exoskeletons was widely used in industrial manufacturing process, which can perform tasks requiring large forces [1]. Studies on wearable exoskeletons have focused on function and enhancement, with limited work on design aesthetics. The current research on the aesthetic design of exoskeleton products is in a scarce state. For example, Irawan et al. [2] designed the Chairless chair to help workers who have to stand for long periods by using inexpensive and readily available local components. Wang et al. [3] proposed a user requirement-oriented fusion model to provide guidance for the design of lower limb exoskeleton products. Meanwhile, the market exoskeletons feature a basic design, lackluster materials, and need enhancement in comfort and cultural resonance. The product semantics is the study of the symbolic qualities of man-made forms in the context of their use and the application of this knowledge to industrial design [4]. Introducing the product semantics into wearable exoskeletons design can address the current lack of research and literature. And wearable exoskeletons require designs that are more humanized and

emotionally resonant for better human-machine interaction. Starting from the perspective of product semantics, it is expected to find solutions to this problem. So, this paper aims to develop a design method for active wearable upper-limb exoskeletons used in logistics handling, utilizing product semantics to enhance their form for workshop use and to meet users' physical and mental requirements. Pictured below in Figure 1 is the outline of this paper.

The research hypothesis was that the combination of the product semantics and the form design of active wearable upper-limb exoskeletons not only enables the exoskeletons to match the working environment correctly, convey the functions accurately and reduce work fatigue to improve work efficiency, but also enhance the attractiveness of the product through the deep integration between the product and the sociocultural context. And the aesthetic design is what we focused on in this research.

2 The product semantics

The product semantics' theoretical framework began in 1950 with the "study of the use of symbols" at the University of Ulm in Germany, and it is a discipline that has held significant transformative power in the field of

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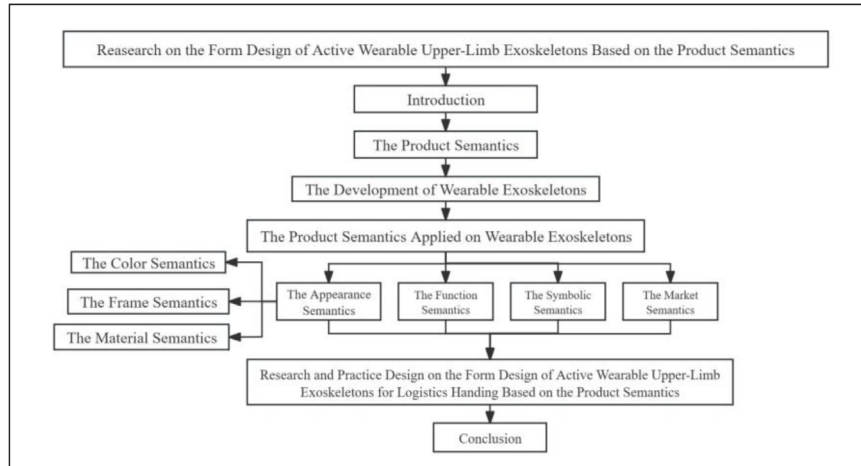


Fig. 1. The outline of this paper.

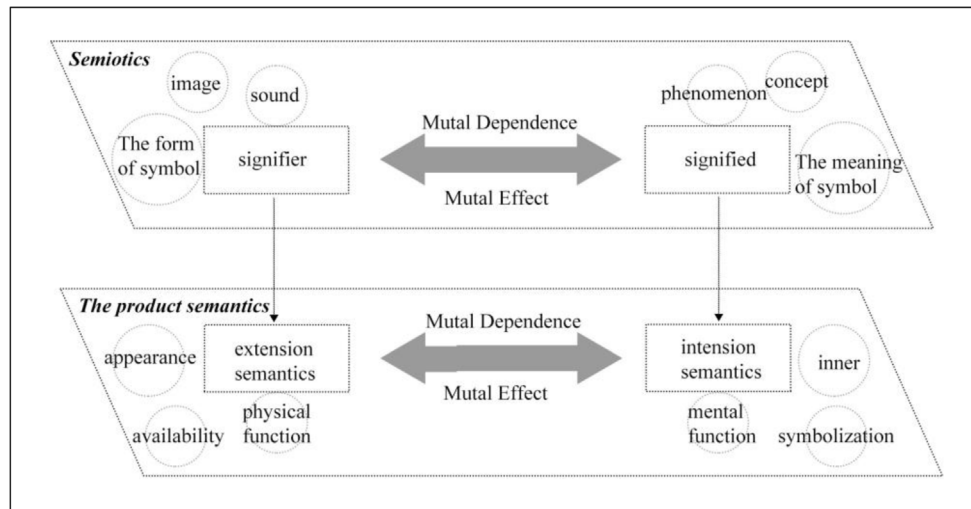


Fig. 2. The relationship between semiotics and the product semantics.

industrial design since the 1980s. In 1984, it was defined by the Industrial Designers Society of America (IDSA) as follows: The product semantics is the study of the symbolic characteristics of the form of artificial objects in use situations, and how to apply this understanding to industrial design [4].

The product semantics is a discipline that has developed based on semiotic theory. It posits that products themselves constitute a complete system of symbols and serve as carriers for conveying messages and expressing meaning [5]. In the early 20th century, Ferdinand de Saussure delineated the pivotal concepts of “signifier” and “signified”, marking a significant milestone in the evolution of linguistic studies to semiotics [6]. The “signifier” refers to the manifestational form and cognitive structure encoded in the symbol, while the “signified” encapsulates the profound significance inherent within the symbol. Individuals apprehend the information encoded by the “signifier” through their sensory encounters, and then elucidate the underlying “signified” beneath the symbol, using their

existential experiences and conventional practices. In this way, they will attain a profound comprehension of the symbol’s significance. Many scholars and designers integrate semiotics into their exploration of product semantics, contending that the form of products ought to encapsulate both the extensional and intensional semantics during the process of information dissemination [7]. The extensional semantics emphasizes the material functions and practicality of a product, representing a rational cognition, while the intensional semantics focuses on the spiritual functions and symbolic value of a product, representing a perceptual cognition. They complement each other and jointly influence the design, use, and value of the product. Based on the theory of product semantics, this paper further divides the extensional semantics and intensional semantics of the active wearable upper limb exoskeleton into four aspects: the appearance semantics, The function semantics, The symbolic semantics, and The market semantics for in-depth analysis and research. Pictured below in Figure 2 is the relationship between semiotics and the product semantics.

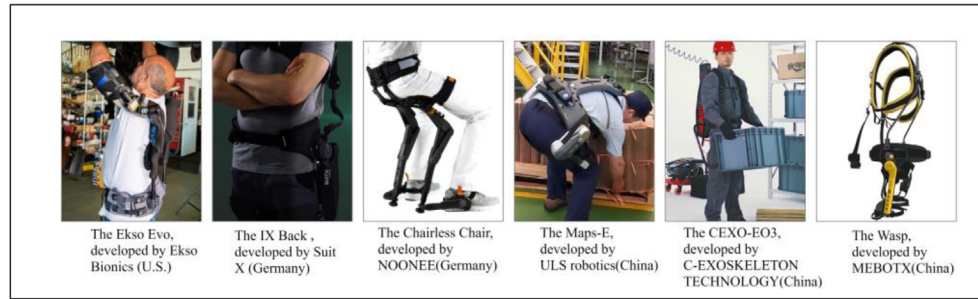


Fig. 3. Typical wearable exoskeleton products.

3 The development of wearable exoskeletons

3.1 Background

The wearable exoskeleton is a human-machine integrated device that can assist or actively assist to meet the human body's movement needs [8]. Presently, significant advancements and applications of wearable exoskeletons have been observed in various domains, including but not limited to the medical and military domain [9]. In the medical domain, wearable exoskeletons serve to facilitate the ambulation recovery of patients afflicted with paralysis or partial disabilities, augment rehabilitation processes, and effectively mitigate challenges associated with the aging demographic. In the domain of military operations, the wearable exoskeletons can substantially augment the combat proficiency, enhance the efficiency of special operations, bolster battlefield rescue and medical support capabilities, as well as improve the productivity of logistics support and engineering construction for servicemen. Due to the exceptional assistive abilities of wearable exoskeletons, they can effectively mitigate the risk of occupational injury and enhance workforce productivity, leading to their gradual integration into industry domain including the logistics industry [10], industrial assembly [11], and the construction industry [12], etc.

3.2 Typical wearable exoskeleton products

The Ekso Evo [13], developed by Ekso Bionics (U.S.), is an upper-body exoskeleton that features a lightweight design, fewer points of body contact, enhanced comfort, and optimized breathability. The IX Back waist and back assisted exoskeleton, developed by Suit X (Germany), not only effectively alleviate back fatigue, but also enforce proper posture during lifting operations. Its innovative design guides users to bend their knees in an ergonomically correct manner when lifting and bending, instead of falling into a hollow back. The Chairless Chair [14], developed by NOONEE (Germany), is a lower-body exoskeleton that doesn't impede walking, but that also supports the wearer when they go into a sitting position. The MAPS-E, developed by ULS robotics (China), is an upper-body exoskeleton that provides intelligent electric assistance to the user's shoulders and arms, providing effective protection for reducing workers' labor burden and improving production efficiency. It consists of three parts: upper-limb

control system, shoulder control system, and central control integrated system. The CEXO-EO3, developed by C-EXOSKELETON TECHNOLOGY (China), is a waist exoskeleton that can augment the waist muscles of laborers to enhance productivity levels. The Wasp, developed by MEBOTX (China), is a passive waist assisted exoskeleton that can store the gravitational potential energy of the human body in the process of bending, intelligently judges the physical information of human body through sensors, and performs accurate energy release during the process of getting up release, realize power assistance. Pictured below in Figure 3 is six of the wearable exoskeleton products from different companies.

Researching the typical wearable exoskeleton products in the market, analyzing their appearance, functions, symbolism, and market semantics. The design could benefit from a bit more vibrancy, perhaps with a wider array of colors and materials. It might not be the most comfortable or intuitive, and it could really use some elements that add cultural richness and emotional connection. It's just not quite there in terms of marketability and winning over consumers' hearts.

4 The product semantics applied on wearabale exoskeletons

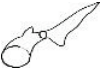
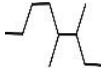
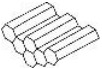
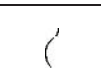
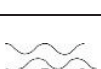
4.1 The appearance semantics

The appearance semantics serves as a bridge between designers and users. The appearance semantics can be further divided into the frame semantics, the color semantics, and the material semantics. These three elements are what users can directly perceive through their senses and serve as the most direct language for conveying the core values, brand image, and usage methods of a product [15]. At the same time, the appearance semantics is also an important means of product emotional design, which conveys metaphorical symbolic product semantics through product appearance and can evoke emotional resonance from users, thus improving their experience.

4.1.1 The frame semantics

The frame semantics not only directly express the main idea of its design, determining its functionality and practicality, but also convey specific emotions and symbolic meanings through lines, surfaces, shapes, and structural elements.

Table 1. The frame semantics of wearable exoskeletons.

Name	Natural object	Line symbols	Surface symbols	Volume symbols	The frame semantics of wearable exoskeletons
Shark					Mighty, Power, Fluency
Honeycomb					Structure, Stable, Lightness
Scallop					Lightness, Uniform, Stable
Human body					Fluency, Reliability, Muscle
Bamboo					Efficiency, Stable, Uprightness
Leaf					Roundness, Naturalness, Conciseness
Spine					Efficiency, Structure, Flexible
Wave					Fluency, Lightness, Conciseness

For wearable exoskeletons design, it is most important to ensure the normal operation of the exoskeleton's key structures while providing coverage and protection. Additionally, the design should stimulate the user's emotional resonance and sensory experience through the frame semantics design.

The process of acquiring and expressing the semantic features of product frame is a process of abstracting design concepts and transforming them into visual forms. This process involves a deep understanding of the product's characteristics and creatively transforming them into specific shapes with meaning. By combining the frame semantics with the bionics design, dissecting natural objects and extracting line, surface, and volume symbols, we can compose basic product shapes through modification and combination. Consequently, Table 1 delineates the refined sensory image vocabularies pertinent to wearable exoskeletons.

4.1.2 The color semantics

There is a general consensus among humans regarding their perception of color [16]. Different colors can evoke a series of unique feelings and emotional responses [17]. For example,

red is often associated with passion, energy, and motivation, and it can inspire people's emotions and actions. In contrast, blue symbolizes calm, peace, and wisdom, providing people with a sense of tranquility and relaxation. Therefore, colors can influence people's emotions in the workplace and impact work efficiency. Proper use of colors can improve work efficiency and job satisfaction, while improper use can lead to poor performance.

The choice of colors for wearable exoskeletons in industrial settings like factories and warehouses significantly impacts both workplace safety and the emotional health of employees. The design of these exoskeletons' colors should be customized to suit the specific working environment, job content, and the occupational crowd. The aim is to select hues that promote operator happiness and reduce fatigue, thereby effectively communicating the core objective of the product's design to its users, as shown in Table 2.

4.1.3 The material semantics

In the product semantics, the material elicits multi-dimensional feelings, including physiological attributes that directly affect the senses, and emotional attributes

Table 2. The color semantics of wearable exoskeletons.

Color	Sample	Color code	Color emotion	Normal semantics	The Color semantics of wearable exoskeleton
Cadmium red		#D22B2B	Warm color	Hotness, Vitality, initiative	Prohibition, Danger Warning, Powerful
Bright yellow		#FFEA00	Warm color	Happiness, Glory, Warmth	Caution, Safety, Warning signs
Sapphirine		#0096FF	Cool color	Coolness, Apathy, Sense	Technology, future, Indication
Cadmium green		#097969	Cool color	Life, Youth, Comfort	Safety, Fatigue relief, Adjust
French grey		#D3D3D3	Neutral color	Fineness, Softness, Simplicity	Background, Elegance, Dirt-resistant
Black matte		#28282B	Neutral color	Dignity, Moodiness, Seriousness	Secret technology, Honor, Powerful
Ivory white		#FFFFFF0	Neutral color	Purity, Brightness, Innocent	Brightness, Freshness, Cleanness

that are triggered by them. For example, metal initially gives people a direct physical impression of its hardness and coldness, which then evolves into modern, industrial, and powerful emotional attributes. In contrast, textile materials first touch people's hearts with their soft and warm physiological characteristics, thereby evoking a primitive and rustic emotional experience.

Depending on the materials used, wearable exoskeletons can be divided into two types: rigid exoskeletons and flexible exoskeletons. Rigid exoskeletons provide strong support and power, but they face challenges in terms of comfort, flexibility, weight, cost, and adaptability [18]. On the other hand, flexible exoskeletons have significant advantages in comfort, adaptability, and movement freedom, yet they also confront challenges related to energy conversion efficiency, stability, and force transmission [19]. As research in materials science continues to advance, a variety of new materials are being applied to wearable exoskeletons, including titanium alloys, aluminum alloys, carbon-fiber materials, liquid metal, textile materials, pneumatic artificial muscles, polymer artificial muscles [20] and magneto-rheological fluids [21] et al. Table 3 indicates that these materials offer different advantages and also endow wearable exoskeletons with distinct material semantics.

4.2 The function semantics

The importance of the function semantics in product design is self-evident. Users derive further deep-level inferences and associations from the features of product components, which enable the product to convey the functional connotation vividly and imaginatively. For example, a multifunctional tool knife exhibits its uses, like a blade and screwdriver, intuitively through design, eliminating the

need for a manual. This intuitive expression of functionalities not only enhances the user experience but also reduces the risk of mis-operation, highlighting the core value of the function semantics in product design.

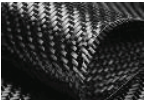
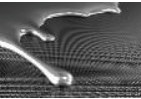
The structure of wearable exoskeletons varies depending on the application field. However, the basic components generally include a binding system, an energy supply unit, joint structures, and supportive linkages. Table 4 provides the function semantics analysis of wearable exoskeletons using the BES-PRO lower-limb exoskeleton developed by ULSrobotics as an example.

4.3 The symbolic semantics

The symbolic semantics of a product plays a crucial but implicit role in design. It not only enhances the cultural connotations and emotional values of the product, but also increases its appeal and recognizability. Products' symbolic semantics go beyond surface features like shape, color, and material. They communicate through abstract, intangible means, relying on emotional experiences, social contexts, and cultural traditions to convey profound message.

The symbolic semantics of wearable exoskeletons can be specifically divided into the aesthetic symbols and the social symbols. The aesthetic symbolic primarily expresses itself through the appearance and function semantics of products, namely through their shapes, colors, materials, and functions that users can directly perceive, which can bring them immediate aesthetic experiences or insights. The social symbolic pertain to the sense of belonging that a product cultivates within its broader societal context. Designers enhance the cultural implications and emotional value of products by integrating their design aesthetics with the social milieu and cultural traditions in which the

Table 3. The material semantics of wearable exoskeletons.

Material	Samples	The material semantics of wearable exoskeleton
Titanium alloy		High strength, high rigidity, lightweight-----Safety, strong support, lightness Anti-corrosion-----Long working life Heat intensity, low temperature performance-----Coping with various work environments
Aluminum alloy		High strength, high rigidity, lightweight-----Safety, strong support, lightness Anti-corrosion-----Long working life Weldability-----Strong plasticity
Carbon-fiber		High strength, high rigidity, lightweight-----Safety, strong support, lightness Fibroid-----Fluffiness, high fit, Strong plasticity Anti-friction, anti-corrosion-----Long working life
Liquid metal		High strength-----Safety Freedom of movement-----High degree of freedom Non-rigid structure-----High fit
Textile material		Fibroid-----Fluffiness, high fit, Strong plasticity Lightweight-----Lightness
Pneumatic artificial muscles		Lightweight-----Lightness Simple structure-----Low cost, easy to clean
Polymer artificial muscles		Muscle-like-----High deformation, strong stretching force The deformation ability is not limited by the environment-----Coping with various work environments
Magnetorheological fluids		Fast response-----Safety High reversibility-----Strong plasticity

products are immersed. This amalgamation heightens the appeal and uniqueness of the products, endowing each item with a distinct societal identifier.

ULSrobotics is a Chinese company specializing in exoskeleton robot technology. The exoskeleton product family of ULSrobotics covers upper-limb, waist, lower-limb, and whole body, among others. At the aesthetic symbolic level, the product family boasts curves that flow seamlessly and an ergonomic design that conforms to the contours of the human body, seamlessly integrating the principles of human engineering to afford users a more comfortable experience. In terms of color coordination, the neutral hues of white and charcoal gray not only convey

a sense of fatigue prevention and stability, but also accentuate the futuristic vibe of technology. The primary components are constructed from advanced materials such as engineering plastics, aerospace aluminum alloy, and carbon fiber, which not only make the product lightweight but also enhance the perception of technological robustness and modernity. At the social symbolic level, the series of products from ULSrobotics are clearly mapped to their respective application fields through their distinct functional designs, reflecting a high degree of professionalism and targeted approach. The consistency in style of these products together convey the core psychological concept of the brand. The information conveyed by the product series

Table 4. The function semantics of wearable exoskeletons.

The BES-PRO developed by ULSrobotics	Components	The function semantics of wearable exoskeletons
	Energy supply unit	Geometric units-----Easy to install and dismantle Hollowed-out structures-----Lightweight and heat dissipation Bending shape-----Ergonomics, easy body fit
	Joint structure	Bending shape-----Ergonomics, easy body fit Smooth appearance lines-----Light and comfortable Multiple structure----- High flexibility to prevent limited bending at the joints
	Supportive linkages	Bending shape-----Ergonomics, easy body fit Smooth appearance lines-----Light and comfortable Multiple structure-----High flexibility to prevent limited bending at the joints
	Blinding system	Hollowed-out structures-----Lightweight and heat dissipation Hollow shape-----Ergonomics, easy body fit

resonates with the company slogan “Empowering Humans, Unlimited Power”, which complements the company’s futuristic and tech-oriented corporate image, as shown in Figure 4.

4.4 The market semantics

Wearable exoskeletons are a commercial product. A product is not just a material vessel to meet people’s needs, but also a complex entity that can evoke emotional resonance, convey functional values, and embody cultural symbols. In the market context, products are endowed with deep-level semantic meanings, including the appearance semantics, the function semantics, and the symbolic semantics. The appearance semantics establish emotional connections between products and users through their appearance; function semantics ensure that the functional characteristics of products can be clearly and accurately conveyed to users; while symbolic semantics evoke emotions and associations in users’ minds, building a deep level of identification. When these three semantic levels are effectively integrated, products can demonstrate their unique market semantics in the market and win widespread recognition from users.

C-EXOSKELETON TECHNOLOGY, a exoskeleton technology company in china, takes its name from the inherent impression people have of robots. The name not only immediately associates people with the image of the company’s product but also imbues the product with an indestructible and powerful sense. During the “618” event in 2018, C-EXOSKELETON TECHNOLOGY collaborated with JD Logistics to equip front-line workers with advanced exoskeleton robots (Fig. 5), effectively reducing their labor burden. This move not only attracted

widespread attention from the general market, but also deeply conveyed the functional semantics of providing additional assistance and protection. After that, the “Iron Man Armor” company pledged to continuously innovate and expand its products in terms of function, material, and design to better serve humanity in a wider range of markets in the future. As exoskeleton technology continues to advance and commercialize, exoskeletons are gradually becoming a new favorite in the market, winning widespread recognition.

5 Design practice

5.1 Wearable exoskeletons market analysis

Despite the growing trend towards industrial automation and mechanization, more than 40% of workers in Europe still suffer from Work-related Musculoskeletal Disorders due to material handling, repetitive movements and awkward postures, according to EU surveys [22,23]. This condition not only impairs the physiological well-being of employees but also constitutes a latent hazard to the productivity of corporate operations and the consistency of the workforce. Therefore, within the domain of industrial manufacturing, the integration of active wearable upper-limb exoskeletons assumes paramount importance. This innovation markedly augments the functional capabilities of laborers and mitigates the physiological strain associated with the lifting of cumbersome objects or the engagement in repetitive activities. Consequently, it effectively safeguards the well-being of the workforce, embodying the Human-centric of secure production. It is anticipated that this technology will witness a substantial enhancement in operational efficiency. The next section of the article will

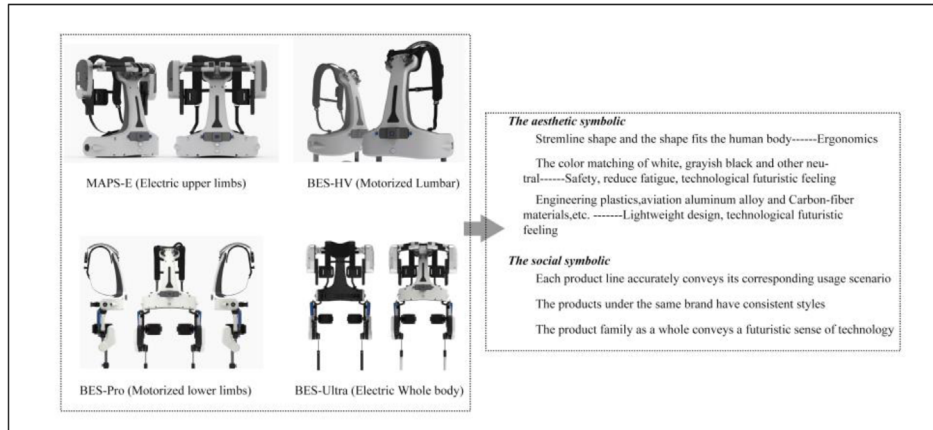


Fig. 4. The symbolic semantics of ULS Robotics' product family.

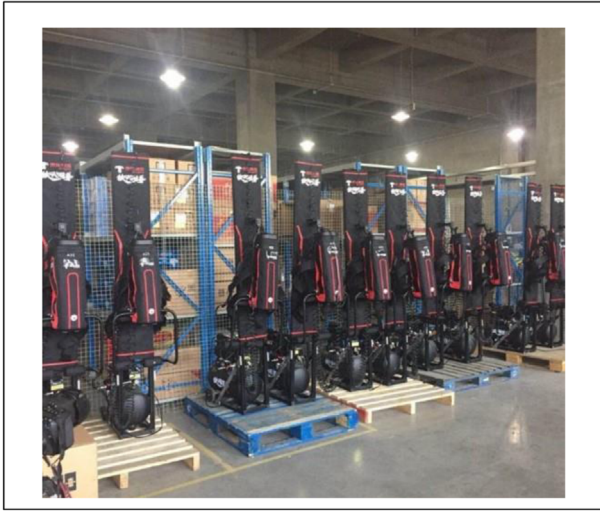


Fig. 5. 'C-EXOSKELETON TECHNOLOGY' wearable exoskeletons for JD logistics.

focus on the form design of active wearable upper-limb exoskeletons for logistics handling workers in the field of industry, based on the product semantics.

5.2 Target population analysis

The job of a logistics handler involves loading, unloading, moving, and storing goods. The problems faced by logistics workers during their work: Firstly, workers need to bend frequently during loading and unloading, which puts continuous pressure on their waists. Secondly, the upper limbs bear a heavy load during the handling of heavy goods, leading to prolonged high-pressure conditions. If the incorrect loading and unloading posture is maintained for a long time, especially when handling goods beyond the physiological load, it may lead to muscle strain. Over time, this not only may cause musculoskeletal diseases but also may cause physical discomfort and long-term fatigue,

which may affect the safety and efficiency of work. When conducting design practices, it is essential to fully consider the physiological and psychological needs of logistics handling workers during the work process and ensure that the design is human-centric.

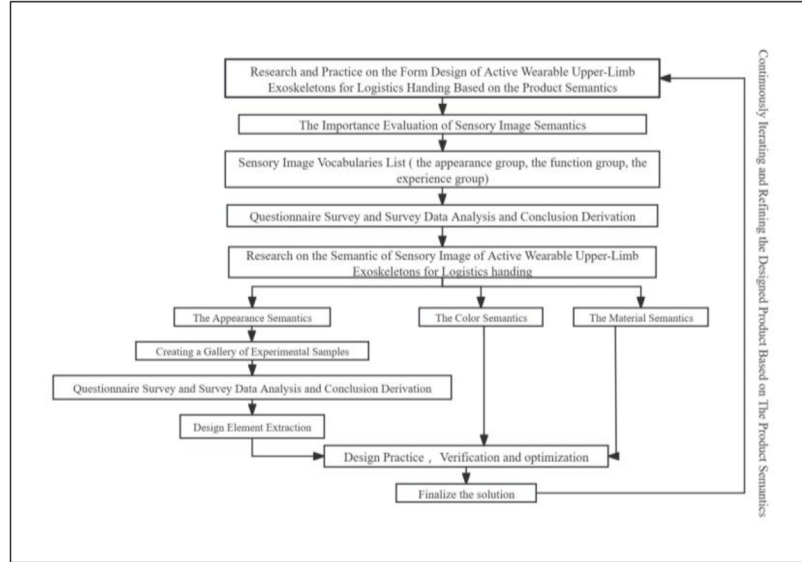
5.3 The key technology of active wearable upper-limb exoskeleton used for logistics handling

The active wearable upper-limb exoskeleton for logistics handling primarily serves to provide the user with assisted torque, thereby amplifying the user's strength, distinct from the rehabilitation exoskeleton. Presently, active wearable upper-limb exoskeletons predominantly feature a rigid construction that encapsulates the shoulder, elbow, and wrist joints. They are being engineered to achieve enhanced lightness, flexibility, and miniaturization. The pivotal technologies and core functionalities encompass the drive system, transmission mechanism, training modes, active control strategies, and the degree of freedom.

Based on the current advancements in active wearable upper-limb exoskeleton technology, as well as the extensive experiments and tests carried out by relevant technical engineers, the device has been configured with dimensions of 750 mm × 500 mm × 310 mm (L*W*H) and a cumulative weight of 6 kg, thereby accommodating the majority of workers. In terms of the driving system, an electric motor is used, which has a simple structure and is easy to disassemble [24]. It also has high movement precision. The transmission mechanism is optically installed at the joint in a direct drive configuration, thereby minimizing losses and maximizing motor efficiency and precision [25]. The training mode is set to active mode, which enhances the user's active movements and frees them from the limitations of pre-set movements, greatly improving the interaction between humans and machines [26]. In terms of degrees of freedom, the assist joints are located at the shoulder and elbow, with two active degrees of freedom and two passive degrees of freedom. The device is powered by a 36-volt lithium-ion battery, which sustains approximately 5 to 7 hours of uninterrupted functionality, as shown in Table 5.

Table 5. Comprehensive parameters.

Device size	750 mm × 500 mm × 310 mm (L * W * H)
Device weight	6 kg
The driving system	Electric motor
The transmission mechanism	Direct drive configuration
The training mode	Active mode
Degree of freedom	4 items
Power source	36-volt lithium-ion battery

**Fig. 6.** Design flow.

5.4 Research and practice on the form design of active wearable upper-limb exoskeletons for logistics handling based on the product semantics

5.4.1 The design flow of active wearable upper-limb exoskeleton used for logistics handling

Based on the aforementioned discussion, this article will embark on a practical design endeavor focusing on logistics handling, utilizing an active wearable upper-limb exoskeleton based on the product semantics. The aim is to explore new directions in the design of exoskeleton products. Pictured below in Figure 6 is the design flow.

5.4.2 The importance evaluation of sensory image semantics

The first step is to collect a wide range of sensory imagery words related to exoskeletons in recent academic papers, news reports, websites, etc., and then conduct a selection and sorting process. The refined sensory imagery words are then categorized into three layers [15]: the appearance group (the appearance semantics), the function group (the function semantics), and the experience group (the symbolic semantics and the market semantics), and compiled into a sensory image vocabularies list (Tab. 6).

The second step is to further clarify the user's needs for exoskeletons by identifying the most fitting sensual image vocabularies, and conducting a survey using an online questionnaire made from a list of sensory image vocabularies (Taking Likert scale as the main part to measure the degree of fit between the sensory image vocabularies and the exoskeleton design.), The average value and standard deviation, as in (1) and (2), can then be calculated and used to evaluate the importance of the sensory image vocabulary, resulting in the collection of 70 questionnaires, 51 valid questionnaires, and statistical and analytical results of the experiment.

$$\frac{\sum_{i=1}^n x_i}{n} = \mu \quad (1)$$

$$\sqrt{\frac{\sum_{i=1}^n (x_i - \mu)^2}{n}} = \sigma. \quad (2)$$

In terms of the design evaluation, Sensory image semantic importance evaluation radar chart was chosen because it is uniquely suitable for analyzing and visualizing the emotional, perceptual, and aesthetic attributes that are critical to the product semantics of active wearable

Table 6. Sensory image vocabularies list.

Sensory image vocabularies							
The Appearance Group							
Conciseness	Structure	Smoothness	Roughness	Aesthetics	Standard	Luxuriousness	Vitality
Fashion	Antiquity	Peculiarity	Sharp	Science and technology	Safety	Classicism	Integration
The Function Group							
Conciseness	Firmness	Lightness	Complexity	Richness	Variability	Modularization	Safety
Science and Technology	Comfort	Constraint	Standard	Effort-saving	Advancement		
The Experience Group							
Safety	Tenderness	Implication	Synergy	Science and Technology	Relaxation	Advancement	
Vitality	Fashion	Generalization	Classicism	Newness	Practicality		

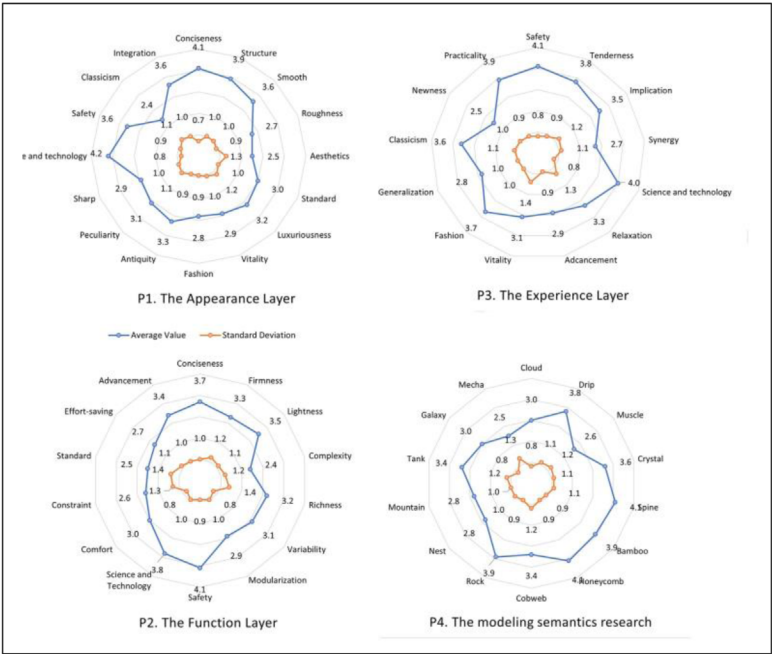


Fig. 7. Sensory image semantic importance evaluation radar chart.

exoskeletons. This method supports the study’s objectives of enhancing user experience and embedding sociocultural meaning in this design. In the appearance form, the average values of “Science and Technology”, “Conciseness”, “Structure”, and “Safety” are higher (Fig. 7 P1). In the logistics handling process, due to the complexity of the working environment and the work content, people are more inclined to hope that the upper-limb exoskeleton they wear is lightweight and simple, so as to avoid danger during operation. And with the development of science and technology, people’s expectations for exoskeletons are filled with technological fantasies. In the function group, the average values of “Safety”, “Science and Technology”,

“Conciseness” and “Lightness” are higher (Fig. 7 P2). The logistics handling of active wearable upper-limb exoskeletons is essentially a loading and unloading equipment, with the primary goal of improving logistics handling efficiency. Therefore, in terms of function, it needs to be simple and intuitive, accurately conveying its functional semantics, which can effectively improve work efficiency and also convey a safety semantic of protecting the workers. In the experience group, the average values of “Safety”, “Science and Technology”, “Conciseness” and “Lightness” are higher (Fig. 7 P3). For most people, the concept of exoskeletons is still confined to the mass media and literature, so in the level of experience, the survey

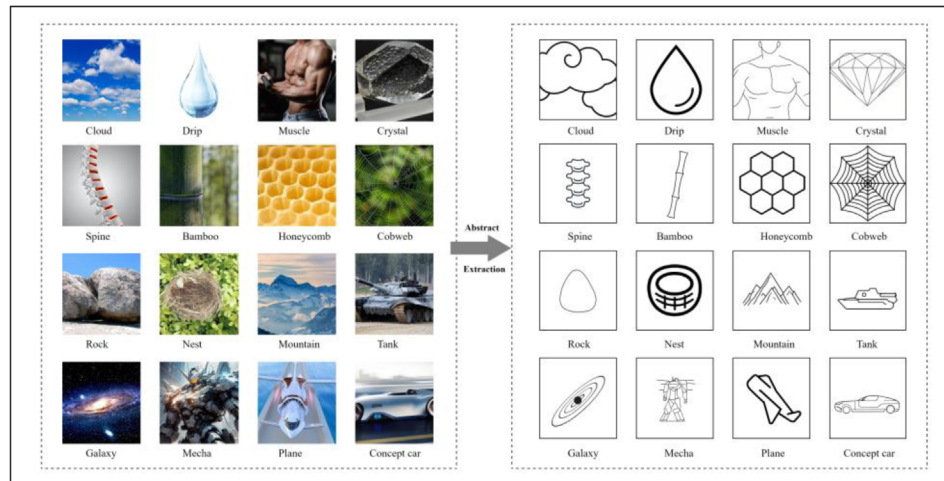


Fig. 8. Gallery of experimental samples.

participants mainly focus on whether the exoskeleton equipment is safe and whether accidents may occur during use, causing injuries to personnel. After analyzing the results of the questionnaire survey, calculating and comparing the average value and standard deviation of each sample, the semantic importance evaluation of the form design of active wearable upper-limb exoskeletons for logistics handling based on the product semantics can be obtained. “Conciseness”, “Structure”, “Safety” and “Science and Technology” are the important sensory image semantics to be expressed in this design practice.

5.4.3 Research on the semantic of sensory image of the form design of active wearable upper-limb exoskeleton based on the product semantics

The first step is to gather elements that directly or indirectly convey the important sensory image semantics “Conciseness”, “Structure”, “Safety” and “Science and Technology” from recent papers, articles, websites, etc. on exoskeletons, and then select and organize them. These elements are then abstracted and extracted to create a gallery of experimental samples (Fig. 8).

The second step is to conduct a survey through questionnaire form, based on the experimental sample images created in the first step, asking the respondents to select the image that best conveys the concepts of the important sensory image semantics “Conciseness”, “Structure”, “Safety” and “Science and Technology” to them. and conducting a survey using an online questionnaire made from a list of sensory image vocabularies (Taking Likert scale as the main part to assess the level of fit between the sensory vocabulary and the exoskeleton design among surveyed participants), The average value and standard deviation, as in (1) and (2), can then be calculated and used to evaluate the importance of the sensory image vocabulary, resulting in the collection of 70 questionnaires, 51 valid questionnaires, and statistical and analytical results of the experiment.

The same design evaluation method as above. After calculating the average value and standard deviation of the sample scores, the scores of the honeycomb structure and

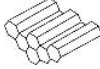
the spine structure were higher (Fig. 7 P4). Honeycomb structures, characterized by their regular hexagonal arrangement and clean lines, not only possess aesthetic appeal but also showcase functional excellence. They epitomize the design philosophy of simplicity without compromising utility. The honeycomb’s robust and durable nature instills a sense of stability and reliability. Similarly, the spinal structure, a vital component of organisms, offers strong support and protection, with its intricate and orderly arrangement serving as an ideal representation of “structural integrity”. Honeycomb structures, due to their unique geometric shapes and efficient space utilization, have found widespread application in fields such as architecture and aviation, reflecting the advancement and innovation of modern technology. Conversely, the complexity of the spinal structure and its precise regulatory functions have piqued human interest in the realm of technology.

In summary, the honeycomb structure and the spine structure have significant advantages in expressing the important sensory image semantics “Conciseness”, “Structure”, “Safety” and “Science and Technology”, which is worthy of subsequent experimental exploration.

The third step is to extract the frame design elements of the important sensory image semantics “Conciseness”, “Structure”, “Safety” and “Science and Technology”. Through the second step of the questionnaire survey, it was decided to extract line symbols, surface symbols and surface symbols from the two natural images of honeycomb structure and spine structure to express the important sensory image semantics “Conciseness”, “Structure”, “Safety” and “Science and Technology” (Tab. 7). These three symbols are arranged and combined to apply to the design of the appearance of the exoskeleton.

In terms of the color semantics, the active wearable upper-limb exoskeletons used in the logistics handling field is mainly used in logistics handling sites and is regarded as an important industrial equipment. In order to enhance the mood of the user, improve the safety of operation, alleviate fatigue, and ultimately achieve the precision and efficiency of operation, the color design should prioritize the selection

Table 7. Design elements extraction.

Natural object	Name	Line symbols	Surface symbols	Volume symbols	Available parts of the exoskeleton
	Spine				Integral shape Hollow designation Joint structure Supportive linkage
	Honeycomb				Heat dissipation site Hollow designation

of low saturation black, gray, and white series as the main tone. In terms of the material semantics, in addition to using engineering plastics for the main structure, other parts can be made of aerospace aluminum alloy and carbon fiber, which not only helps achieve lightweight design, but also effectively conveys the product's science and technology feeling.

5.4.4 Practice of designing active wearable upper-limb exoskeleton based on the product semiotics for logistics handling

The first step is to convert the above semantic symbols into specific products. The form design of the active wearable upper-limb exoskeleton for logistics handling is essentially a "Package design", which refers to the determination of the shape of the mechanical parts such as the engine wrapped inside and not exposed. Therefore, for this design, the designer's adjustments to the shape are limited and must be based on existing key structural components to conduct the exterior design work. In the design stage, the first step should be to clarify the intrinsic relationships between the various exterior components. Then, using the product semantics symbols derived from the above analysis, the designer should carry out detailed design implementation for each component while ensuring that the design style of the exterior components remains consistent. Finally, starting from the visual effects of the overall shape, the designer should verify whether the design elements of the various components can achieve mutual coordination and resonance. In conclusion, three design schemes were successfully derived utilizing three-dimensional modeling software, as depicted in Figure 9.

The second step, design verification. The semantic difference method is used to verify whether the above three schemes conform to the important sensory image semantics "Conciseness", "Structure", "Safety" and "Science and Technology". The definition of semantic difference method is based on the hypothesis that perceptual thinking can be measured. Through the empirical subject's understanding of the object, several levels of typical semantic description of product design are carried out.

In the form of a questionnaire survey of experts, Taking Likert scale as the main part to judge the importance of the important sensory image semantics "Conciseness",

"Structure", "Safety" and "Science and technology" expressed by the above three schemes, resulting in the collection of 15 questionnaires, 15 valid questionnaires, and Table 8 presents the statistical and analytical results of the experiment. According to the average values, as in (1), the third scheme is most in line with the important sensory image semantics "Conciseness", "Structure", "Safety" and "Science and Technology". Combined with the structural evaluation of relevant engineers and other opinions, the final selection scheme 3 is determined, and the scheme 3 is optimized in detail.

The third step is design optimization. Through the above elaboration and conclusion, the research extracts the design elements by using the product semantics method, combines the emotion, enterprise spirit, sociality and culture expressed by the product, and focuses on the important sensory image semantics "Conciseness", "Structure", "Safety" and "Science and Technology". The form design of the active wearable upper-limb exoskeletons for logistics handling is carried out.

Firstly, the structure and key technologies of the active wearable upper-limb exoskeleton for logistics handling are analyzed in depth to clarify the layout of the main structural components and their interrelationships. Based on this, we should focus on ensuring the stability and suitability of the exoskeleton's appearance, while preventing spatial conflicts between components and reserving sufficient design space for form design. We should also carefully plan the layout of signal lines and wires to achieve an orderly arrangement and precise reserved holes, ensuring coordination and unity with the appearance design of the components. Based on this, we can proceed with the design of appearance components, thereby comprehensively enhancing the functionality and aesthetics of the product.

After in-depth analysis, we can divide the active wearable upper-limb exoskeleton for logistics handling into three main parts: the first is the back-mounted main structure with motors and batteries (Fig. 10 P1&P2), which is not only the largest part of the entire exoskeleton system but also the visual focus. It also plays an important role in supporting the back and needs to be perforated to improve the heat dissipation efficiency of the motors and batteries. Therefore, we modeled the driving system enclosure after the shape of the human spine to not only

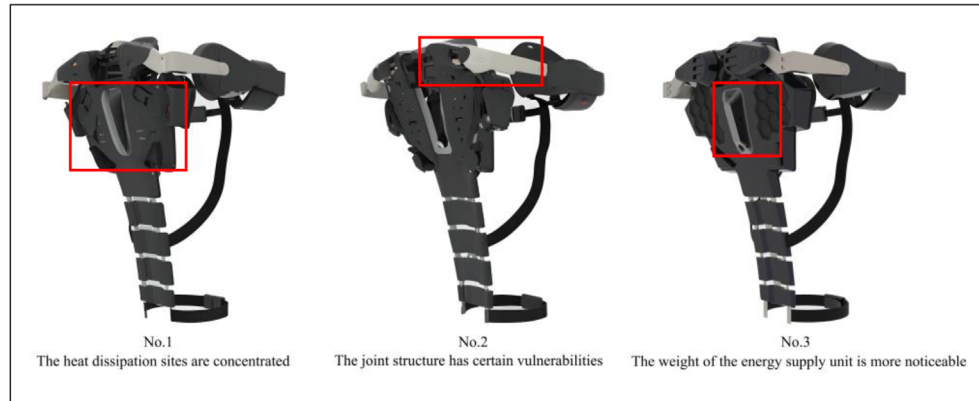


Fig. 9. Design schemes of active wearable upper-limb exoskeletons for logistics handling.

Table 8. The result of design verification.

Design schemes	Conciseness	Structure	Safety	Science and Technology	The average values
No. 1	4.5	4.1	4.3	4.3	4.3
No. 2	4.0	4.2	4.0	3.8	4.0
No. 3	4.8	4.7	4.4	4.5	4.6

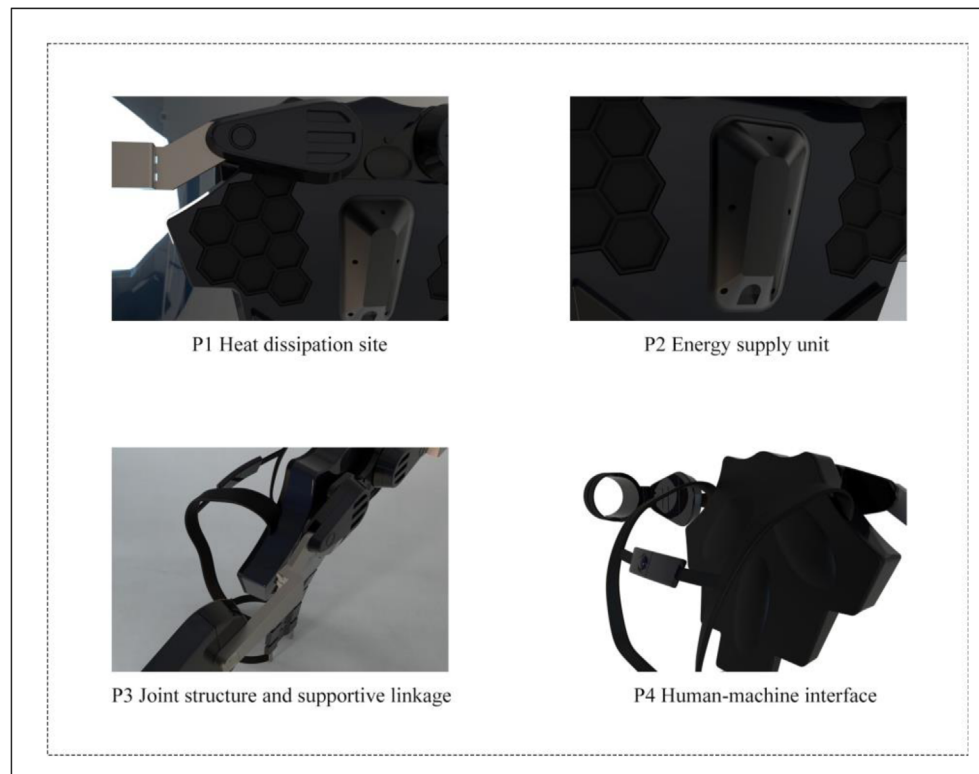


Fig. 10. Design details show.

reflect the design philosophy of “Safety” and “Conciseness” but also further enhance the “Structure” aspect of the product by designing the heat dissipation area using biomimetic honeycomb structures. Secondly, there is the joint structure and supportive linkages (Fig. 10 P3), which

constitutes the movement unit of the wearable exoskeleton. By modularizing the biomimetic muscles and achieving coordinated operation of the assistive joints through linkage mechanisms, the product effectively conveys its “Structure” and “Safety”. The final section is the binding

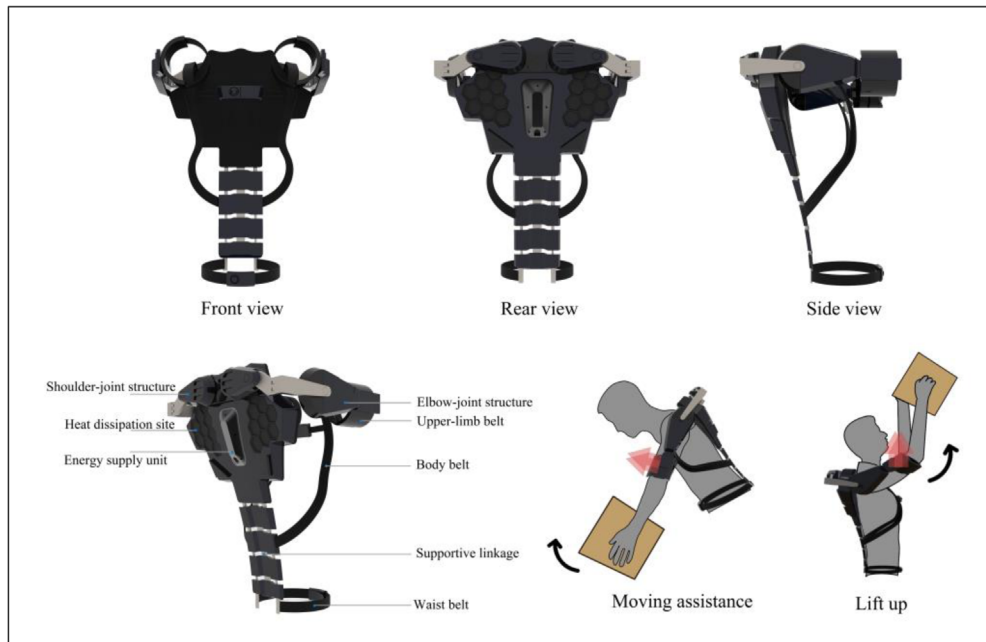


Fig. 11. Design renderings.

system (Fig. 10 P4), which has been rationally simplified in its layout to achieve a design that is both stable and minimalistic, thus conveying the semantic of “conciseness” for the product.

In the final confirmation stage, the focus is on verifying whether the individual parts of the exoskeleton accurately convey the product semantics, and evaluating the overall effect of these parts after assembly to ensure coordination between the parts and an accurate expression of the intended semantics. This process is aimed at ensuring that the final product achieves consistency and harmony in terms of semantic conveyance and style expression. The final product rendering is shown in Figure 11.

6 Conclusion

This paper conducted a comprehensive analysis of active wearable upper-limb exoskeletons based on the product semantics, examining four aspects: the appearance semantics, the functional semantics, the symbolic semantics, and the market semantics. It uncovered the unique product semantic symbols of active wearable upper-limb exoskeletons. Based on this, a set of form design flow of active wearable exoskeletons for logistics handling based on the product semantics was constructed, supplemented by a questionnaire survey of the target population. According to the results, the design elements of active wearable exoskeletons used for logistics handling were clarified, and the final product design was guided. The fusion of the product semantics and the form design in upper-limb exoskeletons enhances both functionality and product appeal.

This paper opens up new ideas for the form design of active wearable exoskeletons suitable for various fields, and promotes the research and development innovation

of the form design of active wearable exoskeletons in various fields. However, the study also has limitations, such as: given that the application cases of active wearable exoskeletons are relatively few, and the population that has actually come into contact with exoskeletons is not widespread, the data collected has certain limitations; additionally, due to the complex key structural technology of active wearable exoskeletons, the design practice section at the end of the paper still needs further research.

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Conflicts of 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.

Data availability statement

Not applicable.

Author contribution statement

Jiawei Huang: investigation, Methodology, data curation and writing - paper draft, Hao Wu: Methodology, supervision and writing improvement, Zhiyuan Yu: Methodology.

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