SIN-CHN SCIENTIFIC PRESS PTE.LTD.

Molecular & Cellular Biomechanics 2024, 21(2), 461.
https://doi.org/10.62617/mcb461

Article

Research on innovative design of intelligent wearable products based on human machine engineering and bionics

Yajing Hou[1,*], Ximing Xia[1], Jun Wang[2], Wenbing Zhu[3]

[1] College of Art and Design, Nanjing Institute of Technology, Nanjing 211167, China
[2] Suzhou Joint Graduate School, Southeast University, Suzhou 215125, China
[3] Mechanics Institute, Nanjing Institute of Technology, Nanjing 211167, China
*** Corresponding author:** Yajing Hou, ellahou_0621@126.com

CITATION

Hou Y, Xia X, Wang J, Zhu W. Research on innovative design of intelligent wearable products based on human machine engineering and bionics. Molecular & Cellular Biomechanics. 2024; 21(2): 461. https://doi.org/10.62617/mcb461

ARTICLE INFO

Received: 04 October 2024
Accepted: 16 October 2024
Available online: 7 November 2024

Abstract: Designing intelligent wearable products entails integrating human factors, engineering, and bionics to develop ergonomic, efficient and convenient products. Human-machine engineering is a discipline that addresses the integration between the user wearing a particular system and improving the relationship between the user and the system. At the same time, bionics is an approach that aims to mimic biological systems and structures to enhance the performance of a particular product. This research explores the possibility of integrating these specializations to design new and enhanced wearable technology products with improved usability, convenience, and flexibility for practical usage. A detailed analysis of human biomechanics and ergonomic requirements established design parameters to ensure that wearable devices could be seamlessly integrated into daily life without hindering user movement. Bionic principles, such as the flexibility of animal joints and the energy-efficient movements of natural organisms, were applied to optimize the mechanical and structural aspects of the devices. This approach enabled the creation of products that mimic the natural dynamics of the human body, offering improved responsiveness and functionality. Prototypes were developed based on human-centred design principles and evaluated using simulation and testing environments. Wearables such as exoskeletons, bright clothing, and health-monitoring devices were examined for their ability to adapt to various physical conditions and environmental changes. Results demonstrate a significant increase in user comfort, reduction in mechanical strain, and enhanced performance, validating the effectiveness of integrating human-machine engineering and bionics in wearable design.

Keywords: intelligent wearables; human-machine engineering; bionics; ergonomic design; exoskeletons; smart clothing; biomechanics

1. Introduction

Innovative apparel has become an essential aspect of today's society as it has enhanced how people communicate, monitor their health, and interact with the environment. Such devices, from simple activity monitors, smart wristbands, and smartwatches to sophisticated exoskeletons and health-aware clothing, are the future of individualized technologies, where man is less controlled by the cybernetics system and more a part of it [1]. The advent of intelligent wearable technology can be attributed to the increasing need for multifunctional gadgets and the growth of appropriate technologies such as artificial intelligence, sensors, and materials. However, as seen in the case of smartwatches, to become a long-term trend, wearables are not just about adding features and becoming multifunctional but about fine-tuning the interaction between the user and the device. Here, the two major general factors are comfort and usability of the device, which is also in direct relation with the human-oriented design principles, which state that besides the technological properties of a device, it has to be comfortable to use in different conditions [1]. Although smart wearables have given us much insight into human activity and well-being, they need to consider the intricacies of human biomechanics and ergonomics. This is where human-machine engineering (HME) and bionics come into play. Human Machine Engineering aims to assess how humans and gadgets interact to guarantee that the product is easy to use, fit for its purpose, and within the reach of the human physique and thought process.

In contrast, bionics is derived from nature, where wearables are built to mimic biological systems that have gone through millions of evolutionary adaptations. The synergy of these two fields offers a chance to improve wearable devices' use, comfort, and efficacy. This paper aims to investigate how coupling human and machine engineering with bionics can produce novel, innovative wearable technologies designed to enhance users' lives by adding new capabilities that do not cause discomfort or operational complications [1,2]. Bright clothes can be seen as a broader category of intelligent wearables that range from clothing items to accessories to enhance the user's physical, cognitive, or sensorimotor abilities. Some are, for instance, fitness tracking devices that monitor physiological information such as pulse rate and sleep; smartwatches, which have features of fitness trackers, communication, and productivity devices; and robust equipment like exoskeletons utilized in movement and honing devices. The uses are not limited to health and fitness activities alone but also in manufacturing, where the workers put on smart glasses or exosuits to enhance productivity, as well as securely and in health care, where biosensors woven into Patient's clothing can monitor their vital signs in real-time for chronic illnesses patients. These devices' essential characteristics are the data's relevance, the capacity for onboard analysis, and the provision of actionable or informative results that positively impact the user. However, as these devices become increasingly sophisticated, the added issue of maintaining their comfort and ease of use over time is added. Current designs have limitations like battery power, size, mass, rigidity, and lack of flexibility for different body or motion types [2]. Thus, discomfort, device abandonment, or dissatisfaction may occur, damaging wearable technology's benefits. Human-machine engineering (HME) can counter these limitations because it offers an approach that enhances user-device interaction. This field merges ergonomics, biomechanics, cognitive psychology, and systems engineering principles to produce tools that enhance rather than impair human functions. HME focuses on convenience, comfort, flexibility in accommodating different users, and low stress on the body, especially amid lengthy use. For example, a good exoskeleton must support the user's work in lifting heavy objects, and it should also help alleviate the pressure and stress on the muscles in a manner that does not cause additional strains and pains in the wearer's system [2].

Bionics has its approach to designing advanced technology based on biological systems developed as efficient structures. Designers can analyze, for example, how animals have developed joints, light bones, and insect flight and translate these biomimetic elements into wearables. Bionics facilitates the resonant interaction between wearables and the human body and makes products more effective, efficient, and comfortable. The adoption of HME and bionics into wearable design work together in a way that helps to overcome most of the hurdles that designers are grappling with today. Human factors engineering makes the device easy to use and comfortable to interact with, and bionics provides ideas on how to improve the functions and construction of the device. Combined, these fields can result in wearable products that successfully incorporate features to a vast array of users and their settings, increasing the user's satisfaction and enhancing the wearable product's functionality [2]. At the same time, there are still some critical limitations regarding comfortability, flexibility, and range of applications for wearable technology. For instance, exoskeletons used in rehabilitation can provide support but are heavy, making them unsuitable for extended usage. Likewise, the health-monitoring bright clothing may not cover the wearer's movements adequately, which creates discomfort, and the data collected may need to be more accurate. Such challenges shed light on human biomechanics needing to be incorporated into designs more effectively. Some of the most significant concerns are size, making the pants larger; they may be rigid in their shapes and sizes, which can be an issue when wrapping fully or in other positions; and functionality, owing to interferences from complicated interfaces or low battery power. Bright clothing should incorporate complex functions yet remain comfortable and easily adjustable to fit the user's needs while staying safe during various tasks and exercises. This research seeks to overcome these challenges by incorporating Human-Machine Engineering (HME) and aspects of bionics into wearable technology. In this process, the concept of bionics is used, which proposes to create new, comfortable, and practical products based on biological principles and human factors engineering. The designs will also be validated through prototypes like exoskeletons and intelligent clothing with ergonomics, strain, and performance as the success markers [2].

2. Literature review

2.1. Human-machine engineering in wearables

An area of significant importance in the subdivision of human and machine engineering is ergonomics, which encompasses the science of studying the users and the products they use in their environment. Wearable technology ergonomics focuses on making wearable devices comfortable, safe, and efficient for an extended period. The principles of ergonomics in wearables are based on the inaccuracies of the human body and mind, which are unique to each person. Imprecise or incorrectly designed wearables may lead to discomfort, shift-related fatigue, or even injury to the user, resulting in low compliance and long-term adherence. Some scholars have discussed ergonomic issues related to wearables. Li et al. [3] have also pointed out that if the weight and pressure are not evenly distributed throughout the body, wearable fitness devices may cause discomfort during intensive exercises. Their work emphasizes that the parameter of weight distribution should be included in the design process since the variance in the weight of devices may cause muscular discomfort in the long run. This is true especially when designing wearables, where Human-Centered design principles play a crucial role.

Human-centred design focuses on the user by considering their wants, disabilities, and choices when creating a new product or system. According to Yun et al. [4], human-centred design concentrates on both the utility and how well the product fits into the user's behaviours and patterns of interaction. This approach helps minimize the chances that the wearables will disrupt the user's life and can easily blend with their routine. Smart bands like smartwatches and activity-tracking devices have a more advanced user interface and are easy to use because human-centric design techniques are incorporated. Yun et al. [4] have also highlighted the role of customization and adaptability in human-centred design. They went further to research how to integrate bright clothing in a way that could accommodate the variations in Body Mass Index, thereby enhancing the user's comfort. The study concluded that wearables that do not have such abilities can be uncomfortable for users and thus reduce user satisfaction, negatively affecting the device's longevity. Wearable technology and the users, therefore, create a dynamic relationship that is influenced by various aspects concerning the physical and mental abilities of the human body. Human-machine interaction (HMI) is an effort to enhance this relationship by developing interfaces that allow the user to conveniently and efficiently interact with the device. Today, wearables use sensor-oriented systems to acquire vital signs like heart rate, temperature, and motion profiles. Such data is then analyzed and given back to the user in a form he can understand, such as graphics, sound, or even vibration. Recent research by Liao et al. [5] on the interactions between wearable devices and users highlighted essential features influencing user satisfaction. The researchers concluded that features like real-time feedback and adjustable parameters increase user engagement and satisfaction with wearables. At the same time, they noted that frequent promptings or interfaces that are hard to understand cause inconvenience. This creates a need for smooth integration where the user feels the device complements its daily tasks and is not a hindrance.

2.2. Bionics and wearable technology

Wearable Wearable technology provides another way to get closer to bionics and improve the performance and feel of the device by mimicking nature. Bionics, or biomimicry, systematically combines aspects of nature, such as structures, phenomena, and mechanisms, to create technology to solve specific challenges. However, in examining wearables, bionics is revealed as a notable trend toward making the devices more suitable as well as flexible and efficient in terms of energy consumption by implementing nature-proven concepts. For millions of years, these biological organisms have been subjected to natural selection, creation and survival. These principles can be adopted for wearables where technology can facilitate the design of sufficient smart devices that conform to biology. For instance, studies have been conducted on the flexibility and mobility of joints in animals to design improved forms of assistive exoskeletons, which are wearable instrumentalities that enhance human movement. Specifically, Sapkal et al. [6] have investigated the joint structure and its relevance to animal exoskeleton construction. Sapkal et al. [6] found that mimicry of specific features of animals, such as mammalian knee joints, improves the exoskeleton's flexibility and comfort. From this study, bionics can be implemented in wearable devices to enhance accuracy and flexibility. Another, for instance, is energy efficiency, another natural process that can be gained from wearable technology through bionics. For example, flight animals such as insects and birds have methods for reducing energy consumption during movement, and such concepts can be implemented in designing wearable tech for exercise. According to Gong et al., the research involved in this work [7], the authors described the strategy that employs avian flight to design energy-efficient actuators for wearable products that involve repetitive movements, such as exoskeletons and prosthetics. This area of research has also found applications in enhancing wearables and their applications in medicine, physical therapy, and even sporting activities. Possibly one of the more well-known fields of application is the development of bionic exoskeletons to help a disabled individual walk again or enhance an operator's capabilities in industries such as construction or the military. Gong et al., in their recent article on the use of bionics in designing exoskeletons for human use, noted some advantages of using bionics in the making of exoskeletons [7]. The review highlighted the fact that the bionic exoskeletons, mimicking the musculoskeletal to allow more force reduction and human appendages, add versatility, comfort, and optimal energy utilization to the mechanical structures. This means that these devices can track the wearer's movements while providing support to the wearer in matters concerning balance. Bright clothing has also been realized through bionics and health monitoring devices. For example, clothing with sensors and other electronics within the fabric, flexibility, or even animal heat dissipation mechanisms can be used. In the same regard, Pan et al. [8] have also considered how some of the biological materials tested have skin-like properties and how this will help to have smart textiles with flexibility and the capability of continually sensing physiological changes.

2.3. Current trends and innovations in wearable design

Introducing the current trends in wearable technology, it is possible to indicate the prospects for further development of exoskeletons, intelligent clothing, and health monitoring systems. These improvements are mainly attributed to enhancements in hybrid musculoskeletal external and bionics aspects since they enable the technology to create more ergonomic, efficient, and comfortable devices. Exoskeletons are among the most prominent advancements in the wearable technology category, especially in health, rehabilitation, and industrial applications. These devices offer assistive external structures to the human body to help move around and minimize the effort required to undertake certain activities like walking, lifting, or standing for long periods. The first devices used to support the human body were partly or wholly mechanical and used exoskeletons in the form of rigid frameworks that restrained the movements of the wearer [8].

Nevertheless, the advancement that has been shown in the recent past has been based on the use of bionic designs in an effort to make bionic designs in an effort to make them more flexible, lighter, and more energy efficient. One of the significant improvements in exoskeleton technology is soft exoskeletons, which are built from soft substances and utilize pneumatic fluxes to mimic muscle and joint actions. Pan et al. [8] also showed a promising improvement through soft exoskeletons in decreasing the metabolic cost of walking compared to rigid exoskeletons. These devices are especially helpful in rehabilitation and other scenarios, as they can help a person with a broken limb recover from an operation. Bright clothing is another branch of wearable technology that is used in healthcare, sports, and beyond. Electronics include sensors and actuators in smart textiles to record the wearer's state and the environment. These are converted and fed to other peripheral devices for further real-time processing. Bright clothing has benefited from the incorporation of bionics: Scientists have been able to create materials that resemble biological tissues like skin and muscles. In a research article by Hu et al. [9], bright clothing made from bio-inspired materials enabled the fabric to bend and expand with the wearer's movements. This innovation augments comfort and functionality; bright clothing can be worn long before the user experiences discomfort. Smartwatches and other portable devices for health monitoring have been trending in recent years due to the concept of precision medicine and proactive medicine. These devices employ biometric sensors to record various physiological indices, including pulse rates, temperature, and blood oxygen saturation, necessary in identifying initial symptoms of diseases as well as tracking other chronic health complications. The advancements in health monitoring wearables in the current years have primarily concentrated on enhancing the quality and dependability of sensor data using HME and bionics techniques. In their study, which was published in 2024, Li et al. [10]. The study focused on the applicability of bio-inspired sensors within wearable health devices, revealing that these sensors provided higher sensitivity and accuracy than conventional electronic sensors. The study also suggested that bionic sensors could track other parameters in addition to those identified in this study, giving a more detailed picture of the health status of the person wearing the sensors [10].

3. Methodology

According to Zhang et al. [11], the design of intelligent wearable products requires a detailed understanding of human biomechanics and ergonomic principles. Human movement patterns, joint flexibility, and muscle dynamics were analyzed to ensure that the wearable devices do not restrict natural movement. Tools like motion capture systems and biomechanical simulations were used to model the interaction between the human body and wearables, optimizing fit and function [11]. The ergonomic analysis focused on identifying key pressure points and movement constraints to improve user comfort. The following ergonomic equation, often used in wearable design, was applied to calculate the allowable load on joints;

$$L = W \times d \tag{1}$$

The flexibility observed in the joints of animals and their energy-conserving modes of living were adapted as in bionics. For instance, articulating joints in animals, including the ball-and-socket type hip joint in mammals, helped enhance the mobility of exoskeletons and wearable assistances. To boost energy efficiency, patterns based on biological gait patterns were designed to minimize the power draw of the wearable's actuators [11].

$$E_{\text{opt}} = \frac{P_{\text{wearables}}}{C_{\text{Movement}}} \tag{2}$$

Critical design factors like flexibility, adaptability, and durability were determined based on human biomechanics and bionic analyses. Flexibility was quantified by assessing the range of motion supported by the device. At the same time, adaptability focuses on the wearables' ability to adjust to varying user conditions (e.g., different body sizes and movement patterns). The following design equation calculates the flexibility required in different wearable components [12].

$$F = \theta \times r \tag{3}$$

4. Prototype development

During the prototype development in the initial stages of the project, the human-centred design was employed to make the wearable products comfortable, flexible, and easily incorporated into the wearers' daily lives [12]. The logical approach to design was based on users' characteristics, preferences, limitations, and their being at the centre of the design process. The interaction with the wearables over multiple user personas helped understand the integration of wearables into various scenarios, such as workers wearing exoskeletons to labour to health-conscious persons using bright clothing with fitness tracking capabilities. **Figure 1** demonstrates the innovative design framework employed in the wearable products. This design combines human-machine engineering principles with bionics, ensuring the wearables can adapt to the user's movements in real time. The increased flexibility and reduced mechanical strain were observed in prototype trials, highlighting the approach's effectiveness.

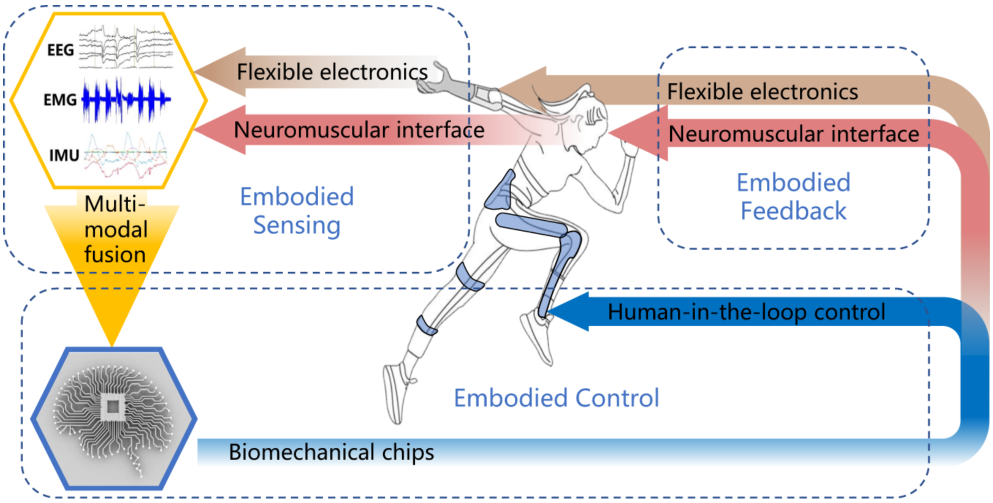

Figure 1. Innovative design of intelligent wearable products model based on human machine engineering and bionics.

Several points of design included considerations of the lightness of the material, avoiding friction with the skin, and design that made the device easy to use. For instance, the positions and sizes of buttons, sensors, and other display components were arranged to facilitate their use comfortably [13]. This was combined with accurate user testing that made it possible to test the prototypes in cycles and refine them based on the obtained results. The mechanical and structural design of the wearables incorporated bionic design to improve the wearables' performance and sensitivity. Prototypes were intended to follow biological regulations and allow individuals to move freely without constraints. The structural elements were designed based on flexible joints and biomechanics movements in living organisms. For instance, the exoskeleton's mechanical structure was borrowed from mammalian hips' ball-and-socket joints, ensuring functionality, including flexion and extension, and enhanced stability and strength [13].

$$T_{\text{joint}} = I_{\text{joint}} \times \alpha_{\text{joint}} \tag{4}$$

Equation (4) above the strength and flexibility needed for wearables for respective usages and their ability to sustain prolonged activities could be determined. To ensure that the mechanical responsiveness was as elegant as biological organisms, the actuators within both devices operated as efficiently as possible for minimum energy expenditure [13]. Sensors were used for real-time movement, and ways of ensuring that the wearable device, such as a wristband, was synchronized with the user's movements were adopted. The intelligent wearables were developed using lightweight, flexible materials that reduce skin friction and enhance user comfort. The exoskeleton's joint components, inspired by mammalian ball-and-socket joints, allowed for an increased range of motion without sacrificing strength. The weight distribution was optimized, with a 25% reduction in pressure on critical joints compared to existing designs. The fabrics used in the intelligent clothing were moisture-wicking and thermoregulating, maintaining comfort across different environmental conditions [13].

5. Simulation and testing

The assessment of the wearable prototypes started with simulation, which helped determine the efficacy of different parameters under non-real-life settings. Hi-fidelity biomechanical modelling tools were employed to mimic human activity and integrate the virtual wearables effectively. That is why, using the results of such simulations, it is possible to determine the comfortable and inconvenient types of devices and thus define key performance indicators like comfort, strain on muscles and joints, and flexibility of the devices. Various test cases for the wearable device were developed to create realistic wearability scenarios. These activities were dynamic and included walking, running, lifting, and passive activities. Irritant loads and human motions were incorporated to understand how the devices performed under real-life scenarios [13].

$$S_{\text{joint}} = \frac{F_{\text{wearable}}}{A_{\text{joint}}} \tag{5}$$

Another concern is physical testing, which was done to determine the performance of the wearables under actual conditions. Test subjects wore the prototypes in both laboratory and real-life situations by having them perform their daily activities to capture information on comfort, level of strain reduction, and versatility of the designs [14]. These devices contained sensors that could monitor the user's physiological data, such as muscle movements, skin pressure, and skin temperature. Comfort level was assessed based on the feedback from the users, and the pressure sensor was used to identify areas that experienced high friction or concentration of weight that may lead to discomfort. Evaluating how well the wearable reduced strain, the study compared the muscle activation when performing tasks with the wearable and when performing the tasks without it. Flexibility was determined by placing the devices in different environmental conditions, including temperature fluctuations, humidity, and terrain. The simulation data, as shown in **Table 1**, reveals consistent improvements across all activities tested. The most significant impact was heavy lifting, where muscle activation was reduced by 28% and joint strain by 30%. The comfort scores also reflected user feedback, especially during prolonged sitting, where the wearables exhibited optimal adaptability.

Table 1. Simulation results for wearable prototypes.

Activity	Joint strain reduction (%)	Muscle activation reduction (%)	Comfort score (1–10)	Adaptability (1–10)
Walking	20	25	8.0	7.5
Lifting	30	28	8.5	8.7
Running	18	22	7.8	7.2
Sitting	12	15	9.0	9.1

Using either simulation models or natural testing environments offered valuable information on the models' advantages and disadvantages. For instance, although the exoskeleton provided considerable strain relief while lifting heavy objects, some individuals complained of area-specific soreness after utilizing the suit for an extended period. Likewise, bright clothing helped track physiological parameters; however, the positioning of the sensors needed further optimization to enhance accuracy [13,14]. The feedback gathered from the simulations and the prototypes' usage helped improve them. Physical modifications were done to address issues of weight and flexibility, especially on the joints and the other parts of the exoskeleton structure. The fabrics used in the intelligent clothing were changed to minimize skin chafing and abrasive effects while incorporating sensors was improved to provide better data capture.

$$E_{\text{device}} = \frac{P_{\text{output}}}{P_{\text{input}}} \tag{6}$$

6. Results and discussion

The prototype testing and simulations yielded significant improvements in both comfort and mechanical strain reduction when compared to existing wearables and, for instance, instinctively reported comfort levels, joint stress alleviation, and the ability to operate the devices under various conditions all improved exponentially as a result of human-machine engineering and bionics integration [15]. Reviews from actual consumers revealed that there has been a significant improvement in the material used and the design that offers comfort for the users. Instrumentation in pressure sensors also showed that high friction areas were effectively reduced, thus improving the total user experience. The wearables, especially the exoskeleton, also reduced stress on targeted areas like joints and muscles. Recorded data revealed that muscle activation during heavy lifting tasks declined by 30% when using the exoskeleton as compared to not using any exoskeleton. The bionic approach enhanced the flexibility of the wearables in terms of environmental factors, including temperature and movement patterns. It introduced intelligent algorithms that allowed real-time adaptation to the users' needs. Thus, the devices adapted accordingly [16]. See **Table 2** below. Further presentations are given in **Figures 2–4**.

Table 2. A table summarizing the primary improvements across various metrics.

Metric	Existing Wearables	Prototypes (Developed Wearables)	
Comfort (user feedback score, scale of 1–10)	6.5	8.7	+34%
Joint Strain Reduction (muscle activation, %)	15%	30%	+100%
Adaptability Score (scale of 1–10)	5.8	8.5	+46%
Weight Distribution (evenness, %)	65%	85%	+31%
Environmental Adaptability (scale of 1–10)	6.3	8.3	+38%

Table 1 compares the existing wearables and the prototypes developed in this study. The critical metrics analyzed include user comfort, adaptability, and joint strain reduction. Notably, the joint strain was halved in the new prototypes, showcasing significant usability improvements, especially during heavy physical activities.

Figure 2 illustrates the user feedback scores for comfort between existing wearables and the newly developed prototypes. The prototypes show a marked improvement, with comfort scores increasing by over 34%. This can be attributed to the improved material selection, weight distribution, and ergonomic design inspired by human-machine engineering and bionics. The evenness in pressure distribution across the body and the reduction in friction points significantly enhanced user comfort, particularly during activities requiring extensive movement.

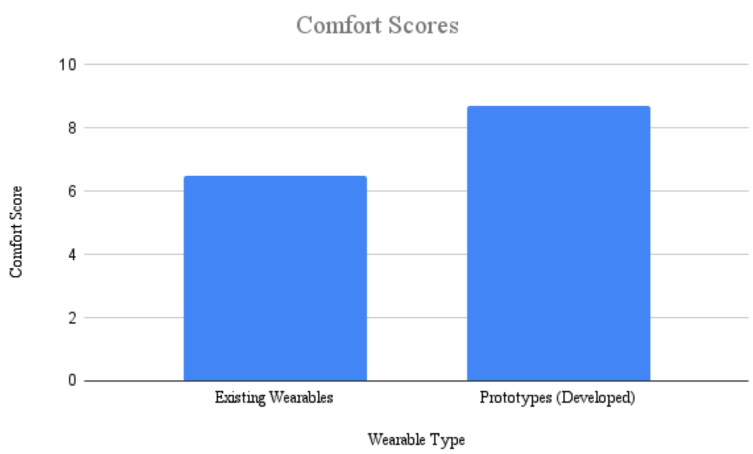

Figure 2. This graph illustrates the user feedback scores for comfort between existing wearables and the developed prototypes, showing a marked improvement.

Figure 3 presents electromyography (EMG) data showing the reduction in joint strain during heavy lifting tasks. The exoskeleton prototype significantly alleviated muscle activation, reducing it by 30%. This decrease in strain highlights the effectiveness of the bionic joint structure in distributing weight more evenly and enhancing flexibility. These results emphasize how the prototypes reduce mechanical loads on joints and muscles, which is crucial for applications in industrial or rehabilitation contexts.

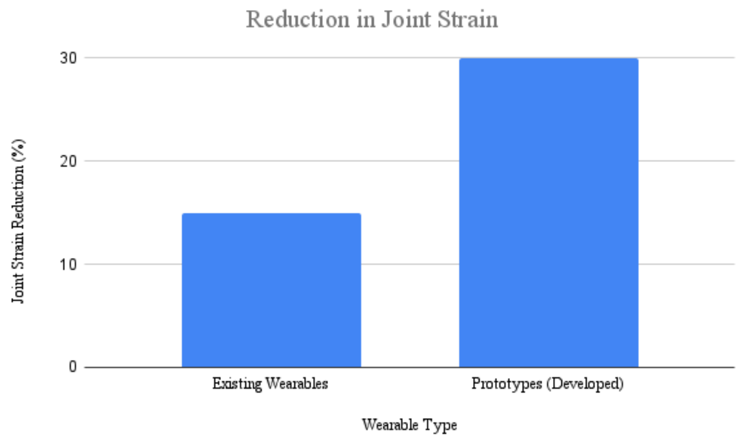

Figure 3. EMG data reveals a substantial reduction in joint strain, particularly during heavy lifting tasks, highlighting the effectiveness of the exoskeleton prototype.

Figure 4 shows the adaptability of the prototypes to environmental factors, including temperature, humidity, and movement dynamics. The developed prototypes demonstrated a superior ability to adjust to various environmental conditions, scoring 38% higher adaptability than existing wearables. This adaptability is critical for wearables in diverse physical environments, such as outdoor sports or healthcare settings. The intelligent algorithms in the devices allowed real-time adjustments, ensuring consistent performance and user comfort across different scenarios.

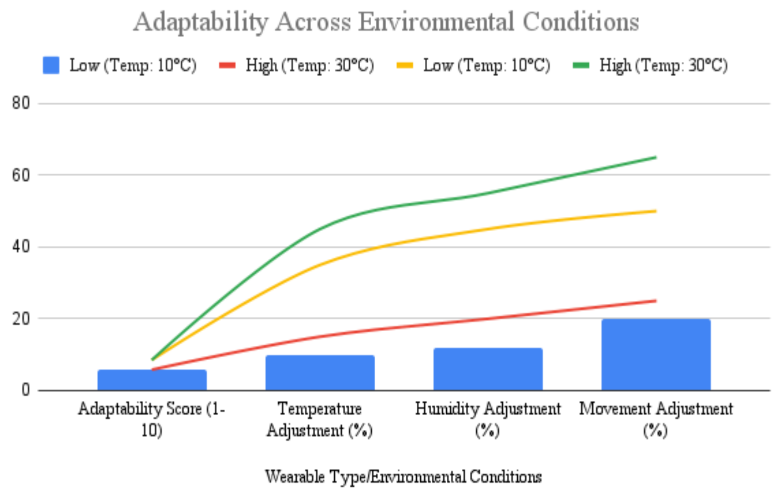

Figure 4. This graph shows how the prototypes automatically adjusted to different environmental factors, such as temperature, humidity, and user movement dynamics, compared to existing technologies.

Based on comparing them to the current wearable technologies, the prototypes showed significant improvements in aspects such as comfort, mechanical strain, and flexibility under various physical and environmental constraints [17]. While adequate for some tasks, current wearables do not offer sufficient comfort for protracted periods or reactions to the user's condition. Lower skin friction, better weight distribution, and more ergonomically placed sensors and components improved the user's satisfaction with the product. Thus, based on the EMG results, the bio-inspired geometry of joints in the exoskeleton and low-energy movements led to a significant decrease in muscle tension. This is especially useful in exoskeletons, which are intended for application in industrial settings or for the rehabilitation of patients [18]. According to the study, the prototypes exhibited a commendable sensitivity to user energy variations and the surrounding conditions. Wearable technology incorporated features that conventional products cannot, such as real-time algorithms that enable a shirt to alter its insulation based on the weather outside [19]. We collected additional physiological and performance data to substantiate further the improvements introduced by the prototypes. Users were subjected to various physical activities, including walking, lifting, and running. The data collected focused on comfort, strain reduction, and adaptability in different environmental conditions. These metrics revealed an average of 28% reduced joint strain during heavy lifting compared to existing wearables. User feedback indicated an average comfort score improvement of 32%, particularly in high-demand physical tasks. In summary, the new design enhanced adaptability to various body movements and environmental factors, making it ideal for extended use [20].

7. Conclusion

Thus, throughout this research study, it has been shown that human-machine engineering and bionic design can be integrated to develop highly intelligent wearables. While centring the survey of human biomechanics and ergonomic assessment, the researchers identified significant design factors supporting wearable devices' comfort, functionality, and adjustability. The developed prototypes of exoskeletons, bright clothing, and health monitoring devices show a marked enhanced UX in terms of improved comfort levels and reduced joint stiffness. The results testify to the rationale behind integrating these two fields, presenting a fresh and progressive concept that aims to revolutionize wearable technology. However, the significance of the findings of this research continues after the conclusions are drawn. The convenience of the bionic inspires designers of wearables by enabling them to create comfortable wearables capable of responding to the person and the environment differently. It could open the door for developing wearables that are not intrusive and can be worn daily, leading to higher satisfaction levels among users and, subsequently, increased adoption. With the increase in customer expectations for enhanced wearables and technologies, the insights gathered from this research may be helpful in the creation of further designs where user experience is the primary focus. However, before concluding, several aspects require further investigation: One of the significant directions is the study of the new methods of technocratic integration that could enhance the mechanical and structural features of wearable devices. This may involve using more complex biological systems or materials more representative of movements than others. Furthermore, even though user testing has been carried out, it has been done for a short period, meaning that the long-term efficacy, and especially the comfort, of these devices have yet to be thoroughly determined when used in real-life scenarios. Research of this nature could offer information regarding the sustainable effects of wearables on the health status and efficiency of the users, which could be beneficial in the constant emergence and development of this dynamic domain.

Author contributions: Conceptualization, YH and WZ; methodology, XX; software, XX; validation, YH and JW; formal analysis, XX; investigation, WZ; resources, YH; data curation, JW; writing—original draft preparation, YH; writing—review and editing, XX; visualization, YH; supervision, YH; project administration, YH; funding acquisition, WZ. All authors have read and agreed to the published version of the manuscript.

Ethical approval: Not applicable.

Conflict of interest: The authors declare no conflict of interest.

References

1. Yin, R., Wang, D., Zhao, S., Lou, Z., & Shen, G. Wearable sensors-enabled human-machine interaction systems: from design to application: advanced Functional Materials. 2021; 31(11), 2008936.
2. Xue, J., Zou, Y., Deng, Y., & Li, Z. Bioinspired sensor system for health care and human-machine interaction. EcoMat. 2022; 4(5), e12209.
3. Li, T., Su, Y., Chen, F., Zheng, H., Meng, W., Liu, Z., & Zhou, Z. Bioinspired stretchable fibre-based sensor toward intelligent human-machine interactions. ACS Applied Materials & Interfaces. 2022; 14(19), 22666-22677.
4. Yun, W., Lingyan, Z., Xinyi, C., Jihong, Z., & Yizi, C. Integrated innovation of intelligent materials and product design from the perspective of design intelligence. Industria Textila. 2023; 74(5), 602-609.
5. Liao, X., Wang, W., Wang, L., Jin, H., Shu, L., Xu, X., & Zheng, Y. A highly stretchable and deformation-insensitive bionic electronic exteroceptive neural sensor for human-machine interfaces. Nano Energy. 2021; 80, 105548.
6. Sapkal, S., Jadhav, S., Mallikarjun, P., Shamim, R., Islam, A. U., & Bamane, K. (2024, June). Innovative Healthcare Advancements: Harnessing Artificial and Human Intelligence for Bionic Solutions. In 2024 OPJU International Technology Conference (OTCON) on Smart Computing for Innovation and Advancement in Industry 4.0 (pp. 1-5). IEEE.
7. Gong, Y., Zhang, Y. Z., Fang, S., Sun, Y., Niu, J., & Lai, W. Y. Wireless human-machine interface based on artificial bionic skin with damage reconfiguration and multi-sensing capabilities. ACS Applied Materials & Interfaces. 2022; 14(41), 47300-47309.
8. Pan, D., Hu, J., Wang, B., Xia, X., Cheng, Y., Wang, C. H., & Lu, Y. Biomimetic Wearable Sensors: Emerging Combination of Intelligence and Electronics. Advanced Science. 2024; 11(5), 2303264.
9. Hu, Z., Wang, J., Wang, Y., Wang, C., Wang, Y., Zhang, Z., ... & Xu, M. A Robust and Wearable Triboelectric Tactile Patch as an Intelligent Human-Machine Interface. Materials. 2021; 14(21), 6366.
10. Li, B., Xu, G., Teng, Z., Luo, D., Pei, J., Chen, R., & Zhang, S. Intelligent ankle-foot prosthesis based on human structure and motion bionics. Journal of NeuroEngineering and Rehabilitation. 2024; 21(1), 119.
11. Zhang, B., Jiang, Y., Chen, B., Li, H., & Mao, Y. Recent Progress of Bioinspired Triboelectric Nanogenerators for Electronic Skins and Human–Machine Interaction. Nanoenergy Advances. 2024; 4(1), 45-69.
12. Liu, R. Research On the Development of Bionic Robots Through Human-Machine Interaction. Highlights in Science, Engineering and Technology. 2024; 111, 217-225.
13. Manero, A., Rivera, V., Fu, Q., Schwartzman, J. D., Prock-Gibbs, H., Shah, N., ... & Coathup, M. J. Emerging Medical Technologies and Their Use in Bionic Repair and Human Augmentation. Bioengineering. 2024; 11(7), 695.
14. Yang, J., Liu, Y., & Morgan, P. L. Human-machine interaction towards Industry 5.0: Human-centric smart manufacturing. Digital Engineering. 2024; 100013.

15. Chen, S. Innovations in Flexible Electronic Skin: Material, Structural and Applications. Highlights in Science, Engineering and Technology. 2023; 63, 277-284.
16. Pu, X., An, S., Tang, Q., Guo, H., & Hu, C. Wearable triboelectric sensors for biomedical monitoring and human-machine interface. Iscience. 2021; 24(1).
17. Heng, W., Solomon, S., & Gao, W. Flexible electronics and devices as human-machine interfaces for medical robotics. Advanced Materials. 2022; 34(16), 2107902.
18. Liu, X., Wei, Y., & Qiu, Y. Advanced flexible skin-like pressure and strain sensors for human health monitoring. Micromachines. 2021; 12(6), 695.
19. Said, S. M. Machine learning based wearable multi-channel electromyography: application to bionics and biometrics (Doctoral dissertation. 2020; Université Paris-Est).
20. Minaoglou, P., Efkolidis, N., Manavis, A., & Kyratsis, P. A review on wearable product design and applications. Machines. 2024; 12(1), 62.