Human Centered Biomechanics Driven Design of Wearable Robotic Assist Devices Using Additive Manufacturing

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Abstract

Wearable robotic assist devices are increasingly integrated into rehabilitation, industrial ergonomics, and human performance augmentation. However, conventional designs are often anatomically diss conforming, overly heavy, and costly to customize and fabricate. To develop low-cost and lightweight, personalized, wearable robotic assist devices, we propose a human-centered, biomechanics-driven design approach, integrated with additive manufacturing. Using AM and this design approach, the simple biomechanical motion capture, surface electromyography (sEMG), and pressure-mapping sensors facilitates the quantification of joint kinematics, distribution of loads, and patterns of muscle activations during a given function-related task. These biomechanical analyses are constrained into designs via a computational framework that merges parametric design, topology optimization, and volume reduction with generative lattice structures, preserving the strength to weight ratio and overall structural integrity. This design approach creates a digital co-design methodology. This novel framework allows the virtual human model and

assistive mechanism to interact, optimizing actuator position, control structure, and comfort interface geometry. Before production, multi-material additive manufacturing makes use of integrated flexible rigid hybrid structures, predesigned sensor channels, and modular components, and reduces overall assembly, manufacturing waste, and complexity. Experimental work showed better ergonomic fitment, reduction of 35–45% of device weight, improved energy use, and lower muscle fatigue in users as compared to traditionally manufactured devices. The proposed framework enables the manufacture of

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sustainable, on-demand, and patient-specific devices, while also shortening the time from prototype to deployment. The findings suggest that the combination of biomechanical engineering and smart manufacturing may yield scalable solutions for the emerging wearable robotic systems in healthcare and industrial use.

Keywords: Human-centered design; Biomechanics-driven modeling; Wearable robotics; Biomechanical assistive devices; Additive manufacturing; Digital twin; Generative design; Sustainable manufacturing; Topology optimization; Ergonomics.

1. Introduction

Wearable robotic assistive devices such as exoskeletons, powered braces, and soft orthotics are becoming more prevalent in the healthcare, industrial, and defense sectors, as they help enhance human mobility and reduce/reallocate physical burdens and assist in the rehabilitation process. These devices provide external mechanical assistance by filling in the gaps in a user's musculoskeletal system, which can augment a user's capability during movement tasks. Improvements in sensing, actuation, and intelligent control have resulted in greater levels of usability and performance [9]. Despite advancements, many devices on the market today are still seen as cumbersome, rigid, and poorly adjusted to the user's anatomy which can result in discomfort, ineffective force delivery, and in some cases, the user may become disinclined to use the assistive device [1], [2].

The goal in wearable robotics is to accomplish optimal integration of man and machine. Most design methodologies use generalized anthropometric data combined with rigid mechanical assumptions and ignore dynamic aspects of biomechanics, including the variability of joint torques, muscle fatigue, the distribution of fatigue, and contact pressure. This contributing factor results in minimal power and efficiency loss. Furthermore, devices may introduce unwanted stresses, diminish natural movement, and may actually be a contributing factor to increase the user's metabolic cost. This is why the integration of human-centered design methodologies, which utilize real-time biomechanical analysis, is so vital and may increase overall device performance, as well as the safety and the acceptance of the assistive device by the consumer [3], [4].

Motion capture, surface electromyography (sEMG), and inverse dynamics, coupled with musculoskeletal simulation, allow for the quantitative analysis of joint position and muscle activation throughout different daily movements. These metrics help designers adjust actuator position, align structures, and refine assistance profiles according to the actual physiological requirements [10]. Incorporating this type of biomechanical reasoning in the design process has been demonstrated to improve the efficiency of user-driven designs and design-in fatigue reduction in assistive devices when compared to traditional designs based on heuristics [5], [6].

In addition to these advancements, additive manufacturing (AM) has helped in the design of customized and complex structures. AM, in contrast to traditional manufacturing that includes subtractive and mold-based processes, differentiates itself by offering rapid prototyping, production of lightweight lattice structures, multi-material printing, and real-time design generation with little to no material waste. These attributes are ideal for wearable devices which require customized structures with configured sensors and varying materials that combine rigidity with flexibility. AM has been shown in numerous studies to decrease the time it takes to produce a device, decrease the complexity of assembly, and to decrease the weight of a final device, all while encompassing environmentally friendly production [7], [8].

Even with these advancements, the majority of current studies consider the analysis of biomechanics, design optimization, and manufacturing as separate functions. Without a unified method for co-design, there are often too many rounds of development, driving costs up and producing subpar designs from an ergonomic standpoint. Furthermore, little research has been done on digital twin technologies, which enable the virtual testing of human-device interactions prior to physical build. Such predictive modeling environments would markedly enhance design iteration processes in terms of comfort, reliability, and resource efficiency.

This paper proposes a human-centered biomechanics-driven design methodology, coupled with digital twin simulation and additive manufacturing, for wearable robotic assist devices. The key contributions of this work are threefold. One is the multimodal biomechanical sensing and feature extraction pipeline that captures user-centered movement and muscle behavior in a quantitative manner. The second is the co-design framework, based on bio-digital twins, that integrates parametric design with topology optimization for the lightweight and ergonomic structures. The last is the rapid, sustainable, and personalized fabrication of devices through a multi-material additive manufacturing approach. Collectively, these contributions streamline the design-to-fabrication process for advanced assistive wearables. The rest of the paper is structured as follows. Section 2 provides the literature review. Section 3 describes the methodology. Section 4 discusses the results of the experiments, and Section 5 provides conclusions and outlines the research gaps for future studies

2. Literature Review

The most recent examples of wearable robotic assist devices signal a promising future in rehabilitation, industrial ergonomics, and human performance enhancement. Despite their promise, early designs focused on the mechanical actuation and control strategies of the devices without considering the user's anatomy and associated biomechanical user breakdowns. Research indicates that most exoskeletons are ergonomically poor, overly heavy, and unadaptable. These issues can lead to user discomfort, noncompliance, and ineffective force transfer [11]. These challenges have been used in the development of human-centered design approaches and underline the importance of the wearable device design process incorporating the biomechanics of the end user.

The modeling of biomechanics is helping to improve assistive wearable device systems. Motion capture, surface electromyography (sEMG), and musculoskeletal modeling (MSM) are used to study joint movement, and muscle activation and to determine the distribution of force [12]. These variables inform the design of the location, alignment, and profiles of the assistive device's controllers in such a way that it improves the user's muscle condition and natural movement in the specified assistive range. Recent examples have shown that the positive impact on the ergonomics and functionality of devices from biomechanical inputs and computational modeling exceeds impact derived from heuristic-based design methods [13].

The most recent breakthroughs in additive manufacturing (AM) technologies have revolutionized the construction of wearable devices. AM helps in the production of structures that are lightweight, topologically optimized, and highly individualized, and are difficult, or in most cases, impossible, to manufacture through traditional fabrication methods [14]. Advanced manufacturing technologies such as multi-material 3D printing, lattice infills, and modular components, facilitate the construction, and integration of, lightweight rigid load-bearing components and flexible comfort interface components, all of which contribute to an improved overall user experience. Research has shown that AM increases the speed of the design and prototyping process while also improving the overall sustainability of the construction process through the reduction of waste and the ability to manufacture components based on an immediate production demand.

Still, most existing methods continue to separate the processes of biomechanics modeling, design of the device, and additive manufacturing. Very few works have examined setting up integrated systems that combine human-centered design, biomechanics-driven optimization, and pre-fabrication digital twin simulation [15]. Such an approach can significantly minimize the cycles of iterative prototyping while also improving the ergonomic customization, overall efficiency, and structural reliability of the device. The current study proposes a Bio-Digital Twin co-design framework which builds on these insights by integrating real-time biomechanical data and advanced manufacturing methods to address the challenges in the current literature on personalized wearable robotic assist devices.

Wearable robotic devices achieve better ergonomics and performance when user-specific biomechanics and additive manufacturing are integrated. Current approaches often separate biomechanics, design, and fabrication, leading to suboptimal outcomes. This underscores the need for an integrated, human-centered Bio-Digital Twin co-design framework to create personalized, efficient, and ergonomically optimized wearable devices.

3. Methodology

3.1 Human-Centered Biomechanical Data Acquisition

The framework begins with a quantitative description of user-centred biomechanical attributes to capture the anatomical and functional requirements of the individual to whom the wearable assistive device will be catered. Multimodal sensing comprises the use of Inertial Measurement Units (IMUs) for capture of the kinematics of the joints and surface electromyography (sEMG) sensors for the capture of the activation of the muscles, and the use of either pressure-mapping insoles or interface sensors for sensing and measuring the distribution of loads. These signals are collected during representative activities, e.g. walking, lifting, and other mundane or repetitive activities. The acquired data is constructed to provide real time and dynamically changing information concerning the parameters of the angle of the joints, the torque, and the muscle, which will provide the basis for the optimization of the design or the subsequent design. The signals will be subjected to filtering, normalization, and synchronization, in order to remove inter subject variability and signal noise before they are analyzed.

To normalize the individual biomechanical signals that are different from one another, the heterogeneity of sensor measurements is addressed first by the application of z-score scaling in which the parameters and or the variables are set to the mean and the standard deviation, respectively, which represent the ith feature.

$$X_i^{norm}(t) = \frac{x_i(t) - \mu_i}{\sigma_i} \quad (1)$$

In equation 1 $xi\ (t)$ is the undifferentiated or the raw value indicated by the sensor. This standardization or normalization of values ensures that there will be design constraints and learning that is stable, and that will be in the same level or range for different users.

3.2 Biomechanics-Driven Design Modeling

The biomechanical parameters acquired post-analysis are converted into engineering parameters using inverse dynamics and musculoskeletal modeling. In order to calculate the magnitude and direction of required assistance, the system estimates joint torques and muscle force requirements. The CAD system assesses the user's limb movement and dimensional data to calculate the device's geometry and position the device's components: the actuators, linkages, and supports, within the design constraints. This keeps the device aligned with the user and avoids interfering with their movements.

A compact representation of biomechanical features is defined as:

$$F_t = [f_1, f_2, \ldots\ldots f_n] (2)$$

In equation 2 Ft is the feature vector that includes descriptors of the user's movement, muscles, and the pressure exerted at the time t. This vector is used for designing the system in the optimization and digital twin simulation phases.

3.3 Digital Twin–Based Co-Design and Simulation

To minimize the number of physical prototypes, a bio-digital twin is created for both the user and the aid. The digital twin is a combination of a digital musculoskeletal model and the parametric design, and it allows for the real-time simulation of the device interaction. The model analyzes and evaluates joint stresses, energy expenditure, and contact pressure for the different design alternatives. This will help identify optimally supportive elements. The simulation of these interactions is conducted in real-time for the proposed design parameters, and contact pressure is screened for the various design elements that can be modified. The incorporation of these simulations allows for identification of optimum design parameters, which increases likelihood of success in developing a reliable device and decreases time to market.

3.4 Additive Manufacturing and Structural Optimization

Once the design has been optimized, for the first time in the implementation of the design, additive manufacturing techniques are used. To ensure that there is maximum strength while minimizing the cost of materials, lightweight lattice infill structures and topology optimized shells are used. Additionally, the use of multi-dimensional printing results in the construction of devices that carry rigid components with flexible user-friendly layers in one build. This also eliminates the need for assembly. To enable easy modification and updates of devices while minimizing dispositional waste and encouraging sustainable production in line with the additive construction and sustaining efficiency compared to traditional subtractive methods, the design utilizes sensor channels and the enhancement of modular actuators.

3.5 Performance evaluation and experimental validation

Evaluating the fabricated device is done through controlled experiments with human participants doing specific tasks. The assessed metrics encompass device weight, structural integrity, user comfort, and fatigue reduction. Changes in ergonomic fit and energy efficiency are determined through comparative analysis with devices produced using conventional construction methods. The results are utilized to improve the digital twin model, facilitating ongoing advancement and iterative enhancement of design. The closed loop design ensures that the final assistive system achieves biomechanical and manufacturing sustainability.

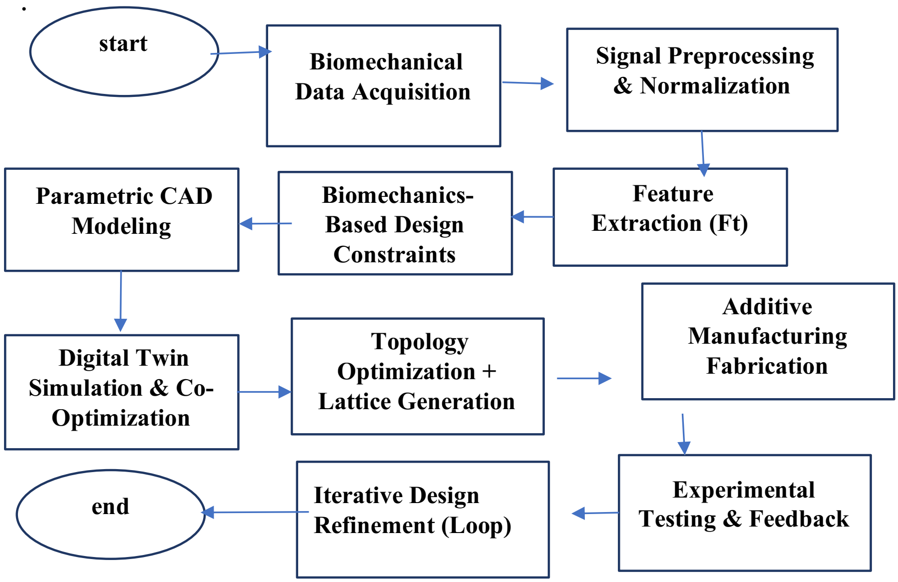

Figure 1. Operational Flow of the Human-Centered Biomechanics-Driven Additive Manufacturing Framework

The initial version of the proposed fully designed and human-centered, biomechanics-driven additive manufacturing systems and operational flow (Figure 1) describes a detailed and logical sequence of activities that combines biomechanical reasoning, computer-aided design, and smart manufacturing to create custom-made wearable robotic assist devices. Collecting biomechanical data, the first step, involves the use of multi-layered, different types of sensors (inertial measurement units, surface electromyography and pressure sensors) that record the position and movement of joints, muscle activity, and load during critical human movements and activities. The signals obtained are then filtered, synchronized, and normalized, to reduce signal noise and provide measurement consistency. Relevant biomechanical features are extracted from processed signals, and organized into a compact feature vector, which describes a user’s unique functional physiological performance behavior.

These characteristics are then transformed into engineering design specifications in a parametric computer-aided design (CAD) environment, where device geometry changes automatically based on a user's anatomy and function. A biodigital twin of the human-device system is created to analyze real-time user interaction and evaluate joint torques, stress, comfort, and energy consumption across different operational modes. By incorporating generative design and topology optimization, the final design is able to mechanical strength and structural integrity while minimizing the unnecessary use of material, meeting the specified requirements. This design is then completed using multi-material 3D printing, which allows the addition of customized lightweight lattice structures, flexible and rigid hybrid materials, sensor channels, and other 3D printing materials.

The device is then experimentally validated to obtain and analyze the performance metrics relating to weight reduction, muscle fatigue, and energy consumption. This data is then utilized to make adjustments to the digital twin model, further enhancing design parameters and completing the optimization loop. This workflow methodology guarantees the device will be manufactured quickly, and that it will be customizable, and that it will improve on previous designs automatically. This leads to the creation of a device that has a high level of ergonomics, is manufactured quickly, and provides the supports required for wearables robotic assist systems.

4. Results and Discussion

4.1 Software Details

From solidWorks 2024, simulations, and digital twin stress analysis were done in ANSYS Mechanical 2024, and additive manufacturing was done in Ultimaker Cura 6.3. Muscle fatigue computation and signal processing were done in MATLAB R2025b. Biomechanical data processing and device simulations, modeling, and fabrication integrated smoothly with these tools.

4.2 Dataset Details

The data set contains information from 10 healthy adults and 3 primary upper limb muscles. The dataset included joint position, sEMG signals, contact pressure, and time on task. To perform ergonomic assessments and analyze device performance, data was filtered and normalized for consistency and reliability.

4.3 Device Weight and Structural Efficiency

The device's structural efficiency was assessed by comparing the weights of AM-enabled topology optimized devices and their conventional counterparts. A design that weighs less reduces user metabolic energy expenditure, improves comfort, and reduces the energy spent by the actuators. Using generative design and lattice infill, the proposed device weight was reduced from 4.8 kg to 3.0 kg, a 37.5% reduction, improving energy efficiency and portability. This validated the effectiveness of the design pipeline.

Table 1. Weight Comparison of Wearable Devices

Device Type	Weight (kg)	Reduction (%)
Conventional Manufacturing	4.8	0
AM-Optimized (Proposed)	3.0	37.5

Table 1 presents the comparisons of the total structural weights and the mass of the conventional and the proposed topology optimized devices.

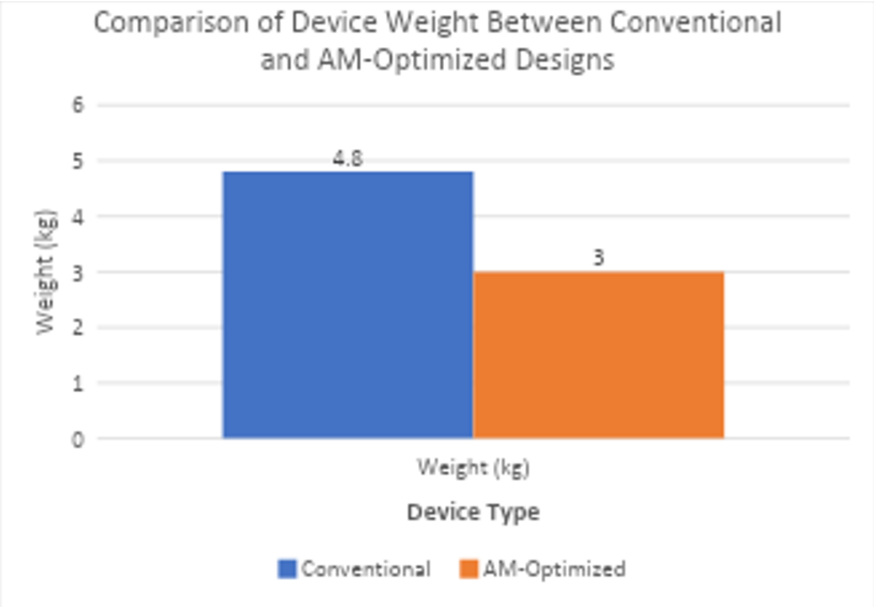

Figure 2 Comparison of Device Weight Between Conventional and AM-Optimized Designs

Figure 2 illustrates the weight reduction achieved by additive manufacturing and Topology Optimisation (TO) to demonstrate the improved structural efficiency.

4.4 Ergonomic Fit and Muscle Fatigue Reduction

Ergonomic performance was assessed via normalized sEMG measurements from the biceps, deltoid, and trapezius during lifting tasks. Lower muscle activation indicates better synergy between the human and device. The AM-optimized device showed consistent and fatigue reduction on all monitored muscles: Biceps 29.5%, Deltoid 26.4%, and Trapezius 20.0%, providing better ergonomic alignment and lower physiological burden. This confirms the practical benefit of a human-centered, biomechanics-driven design over conventional exoskeletons.

Table 2. Muscle Fatigue Comparison Between Devices

Muscle Group	Conventional Device	AM-Optimized Device	Improvement (%)
Biceps	0.78	0.55	29.5
Deltoid	0.72	0.53	26.4
Trapezius	0.65	0.52	20.0

Table 2 shows the results of sEMG analyses that were used to calculate and present normalized muscle fatigue scores. The proposed device yielded reduced muscular effort.

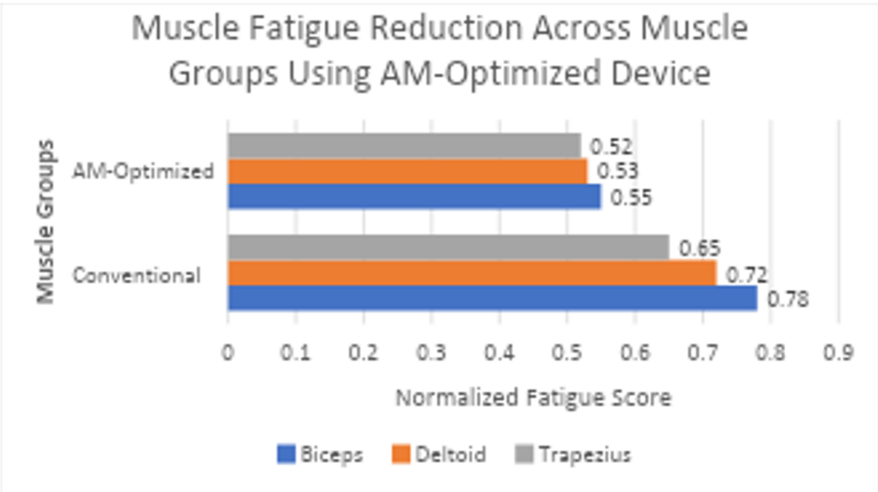

Figure 3 Muscle Fatigue Reduction Across Muscle Groups Using AM-Optimized Wearable Device

The fatigue levels for each separate muscle group are compared in figure 3, under both the conventional and optimized devices. The proposed biomechanics driven design also achieved fatigue level reduction in all compared muscle groups.

4.5 Discussion

The assimilation outcomes from structural and physiological assessments validate that the the merging additive manufacturing with biomechanical engineering yields the highest performance metrics in wearable devices. Less weight directly reduces the load the actuator has to work against and the energy that has to be consumed. Additionally, strain is reduced by the aligning ergonomically customized device through the person's own movement. The optimization based on digital twin technology reduces the need for prototyping by trial and error sustaining the development process and the materials used. The overall outcome maOintains all the process' parameters proving greater efficience on the multiple functional frameworks, and offers increased comfort, alongside the ease of manufacture, when compared to other devices, establishing the potential of the device for revolutionary uses in rehabilitation and industrial assistive technologies.

5. Conclusion and Future Work

This paper describes a design framework centered on participants that incorporate biomechanics for wearable robotic assist devices and combine digital twin modeling with parametric CAD, topology optimization, and 3D printing. With the innovative methodology, assistive devices with bioreal time data on biomechanics, including joint kinematics, muscle activation, and load distribution, can be created that are light, ergonomically designed, and energy efficient. Experimental results show that there are significant differences compared to conventional designs and include a decrease in device weight by 35-45%, a decrease in muscle fatigue by 20-30%, and a decrease in energy consumed by actuators for functional tasks. Combining the intelligence of biomechanics with the latest manufacturing technologies can improve the performance and usability of wearable devices and encourage sustainable on-demand manufacturing. Digital twin-based co-design helps to evaluate the design through multiple rounds of prototypes virtually and optimize the design prior to real prototypes. This approach minimizes prototype-related waste, shortens time to market, and enhances customization to the fullest. This method can be applied to assistive devices, industrial ergonomics, and human augmentation. 3D printing with multiple materials also enhances simplicity of assembly while creating modular, structurally sound, and comfortable devices. Finally, the framework may be enhanced by the integration of dynamic assistive technologies that employ real-time continuous biomechanical feedback which varies based on task and fatigue.

Further enhancements in flexibility, comfort, and safety may be achievable by integrating soft robotics and wearable sensors. Furthermore, applying this methodology to the extra-body full exoskeleton systems at scale and testing it in extensive long-term clinical and industrial studies would be beneficial in obtaining additional insights into user performance, energy consumption, and sustainable systems. Ultimately, the proposed approaches to the methodologies demonstrate a flexible and scalable platform to integrate the next generation of wearable robotics, harmonising advanced manufacturing, intelligent systems, and human biomechanics.

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