오픈소스 발목 외골격 로봇의 설계 및 개발

Design and Development of an Accessible Open-Source Ankle Exoskeleton

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Wearable robotics, particularly ankle exoskeletons, hold significant promise for advancing mobility, rehabilitation, and biomechanics research. However, their adoption in research is hindered by limited accessibility, high costs, and the proprietary nature of existing designs. This study addresses these challenges by introducing a fully open-source ankle exoskeleton platform, providing a customizable, and cost-effective tool for researchers. The design emphasizes accessibility through 3D-printable mechanical parts, compatibility with commercially available components, and detailed assembly instructions. Additionally, options for integrating diverse sensors such as force-sensitive resistors (FSRs) and inertial measurement units (IMUs) ensure adaptability to various experimental needs. By making this platform openly available, we aim to broaden access to wearable robotics technology, fostering innovation and supporting young scholars and underfunded institutions. This open-source design sets the stage for a new paradigm in collaborative research and development in assistive technologies, biomechanics, and beyond.

착용형 로보틱스, 특히 발목 엑소스켈레톤은 이동성 향상, 재활, 생체역학 연구 분야에서 높은 잠재력을 갖추고 있으나, 기존 설계의 독점성, 높은 비용, 제한된 접근성으로 인해 연구 현장에서 활용이 제약되어 왔다. 본 연구에서는 완전한 오픈소스 기반의 발목 엑소스켈레톤 플랫폼을 제안함으로써 이러한 문제를 해결하고, 연구자들이 활용할 수 있는 맞춤형·경제적 도구를 제공하고자 한다. 제안된 플랫폼은 3D 프린팅이 가능한 기계 부품, 상용 부품과의 호환성, 상세한 조립 안내 등을 통해 접근성을 극대화하였으며, 압력 감지 저항기(Force-Sensitive Resistor, FSR), 관성 측정 장치(Inertial Measurement Unit, IMU) 등 다양한 센서와의 결합 옵션을 제공함으로써 실험 목적에 따른 유연한 활용을 가능하게 한다. 본 오픈소스 플랫폼의 공개를 통해 웨어러블 로보틱스 기술에 대한 접근성을 확대하고, 신진 연구자 및 재정적 제약을 겪는 기관을 포함한 다양한 연구 집단에서 혁신적인 시도가 촉진될 것으로 기대한다. 나아가 본 오픈소스 설계는 보조기술 및 생체역학을 비롯한 인접 분야에서도 협력적 연구·개발의 새로운 패러다임을 형성하는 데 기여할 것이다.

Key Words: Ankle Exoskeleton (발목 외골격 로봇), Wearable robotics(웨어러블 로봇), Open-source design(오픈소스 설계)

1. Introduction

Exoskeletons have emerged as a transformative technology in wearable robotics, with applications ranging from mobility assistance and rehabilitation to enhancing human performance in industrial or military settings[1]. Ankle exoskeletons, in particular, have drawn increasing interest due to their critical role in supporting gait, improving balance, and aiding recovery for individuals with neuromuscular impairments[2]. Over the past decade, research efforts have demonstrated the potential of these devices to reduce metabolic cost, enhance endurance, and improve walking efficiency under various conditions[3-5].

Despite this progress, much of the cutting-edge innovation in exoskeleton design remains locked within proprietary or commercially developed systems. While these systems are often robust and highly engineered, their closed-source nature, specialized components, and associated high costs create barriers to entry for many researchers—especially those at smaller institutions, in underfunded labs, or in regions where access to specialized manufacturing resources is limited. This stands in stark contrast to fields such as mobile robotics, drones, and embedded systems, where the availability of open-source hardware and software platforms has democratized innovation[6]. Open-source resources in these areas have enabled rapid iteration, broad collaboration, and standardized methodologies, driving advancements that would have been difficult to achieve otherwise.

In the realm of wearable robotics, however, accessible open-source platforms are still notably scarce[7,8]. Researchers, clinicians, and engineers seeking to study or deploy ankle exoskeletons often face steep learning curves, high capital investment, and a lack of customizable designs. Without modular, low-cost reference platforms, it becomes challenging to experiment with novel control strategies, incorporate emerging sensor technologies, or adapt designs to serve unique experimental populations.

This study aims to address these challenges by presenting a fully open-source ankle exoskeleton platform that emphasizes affordability, modularity, and adaptability. We provide detailed computer-aided design (CAD) files compatible with cost-effective 3D printing processes, leverage readily available commercial components, and integrate flexible sensor options—including force-sensitive resistors (FSRs) and inertial measurement units (IMUs)—to accommodate a range of biomechanical and rehabilitation studies. By making all design files, assembly instructions, and documentation publicly accessible, we strive to lower the barrier to entry and invite broad participation. Our hope is that this open-source platform will catalyze collective learning, foster new multidisciplinary collaborations, and accelerate the development of more effective, user-friendly assistive technologies, ultimately benefiting researchers, clinicians, and end-users alike.

2. Exoskeleton Design

2.1 Overview

The unilateral ankle exoskeleton shown in Figure 1 and Supplementary Figure 1 focuses solely on assisting a single ankle joint without external power sources like batteries or onboard computational units. This streamlined design reduces complexity and cost, making it an accessible platform for researchers. Providing bidirectional assistance in plantarflexion (PF) and dorsiflexion (DF), it enables precise ankle motion modulation, making it ideal for biomechanical, rehabilitation, and human performance studies. With its simplicity, ease of replication, and compatibility with commercially available components, the platform supports versatile experimentation and rapid iteration in various research contexts.

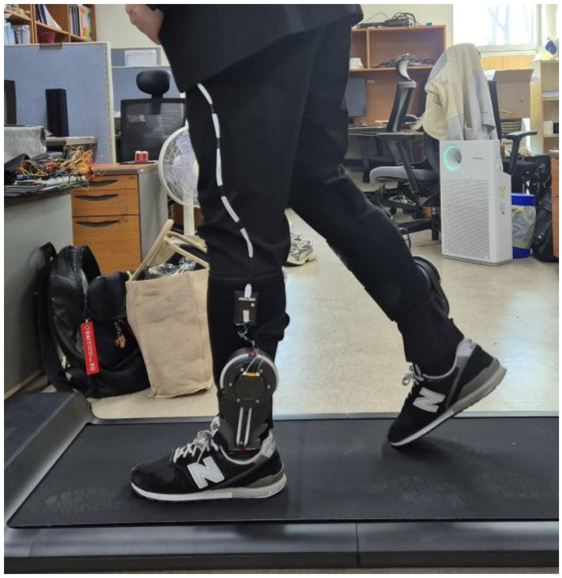

Figure 1. A participant wearing the fully open-source ankle exoskeleton during a controlled gait assessment.

2.2 Mechanical Design

A high torque-density brushless DC motor (AK60-6 V1.1, Cubemars, China) with an integrated 6:1 planetary gearbox serves as the primary actuator. Powered by a 24 V supply, this quasi-direct drive configuration delivers approximately 15 Nm of continuous torque and up to 45 Nm of peak torque at the ankle, ensuring robust assistance for various gait and rehabilitation tasks.

The gear train further enhances torque and control precision, as shown in Figure 2. Starting from the motor output, a 10-tooth pinion (Gear 1) directly drives a 20-tooth gear (Gear 2), achieving a 2:1 reduction. Co-axially mounted with Gear 2 is another 10-tooth gear that transfers power to a 25-tooth gear on the end-effector side, introducing an additional 2.5:1 reduction. Combined, these two stages yield a total 5:1 gear ratio, allowing the exoskeleton to provide substantial torque amplification at the joint. At the distal end, the end-effector assembly includes a hinge that aligns with the wearer's ankle axis, enabling controlled rotation in both plantarflexion and dorsiflexion. A modular footplate interface is attached at this hinge, accommodating a customizable carbon insole that can be tailored to individual foot sizes. By employing readily available components, a simple gear arrangement, and an easily modifiable foot interface, this mechanical design remains accessible, adaptable, and straightforward to replicate for diverse research applications.

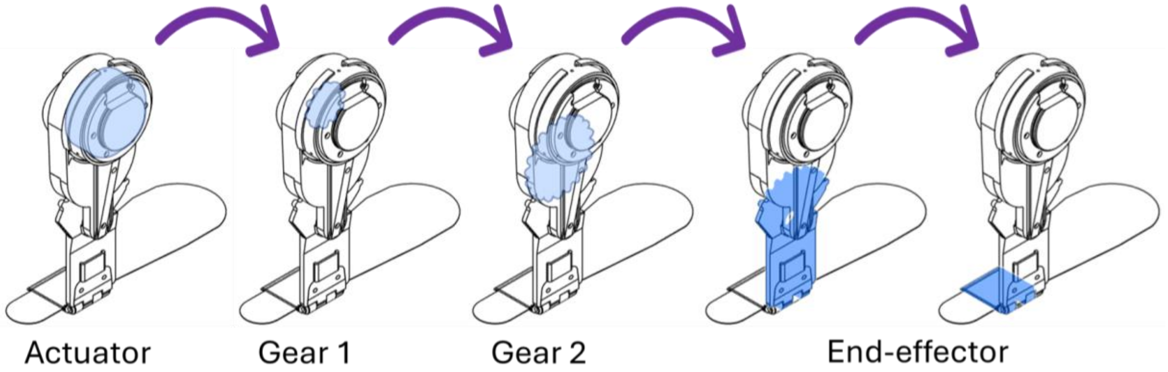

Figure 2. Power transmission from the actuator through a two-stage (5:1) gear train to the ankle end-effector

2.3 Sensor Fusion

The design of the ankle exoskeleton accommodates a variety of sensing modalities by incorporating dedicated cable routing paths and mounting points, ensuring clean integration and easy modification. Internal channels and strategically placed attachment points allow researchers to neatly route wires from sensors to a central data acquisition hub, minimizing clutter and preserving the device's form factor.

In the current implementation, force-sensitive resistors (FSRs) are embedded within the foot interface to capture ground reaction forces and foot contact patterns. Specifically, three FSRs are placed under the toe region, one in the mid-sole area, and two in the heel, enabling detailed pressure mapping across the foot. This arrangement facilitates the analysis of stance dynamics, gait phase detection, and load distribution during walking or rehabilitation exercises.

An inertial measurement unit (IMU) mounted on the user's calf further enriches the sensor suite, providing real-time kinematic data such as orientation, angular velocity, and acceleration. By fusing information from the FSRs and IMU, the system can offer nuanced insights into gait biomechanics, foot-strike patterns, and joint control strategies.

Beyond these specific examples, the exoskeleton's modularity and cable management design enable straightforward integration of additional sensors, such as electromyography (EMG) electrodes, strain gauges, or optical encoders. Researchers can easily adapt the sensor suite to fit their experimental needs, fostering a highly customizable platform for real-time feedback, closed-loop control, and advanced biomechanical analysis.

2.4 Fabrication and Assembly

All primary mechanical components are designed for additive manufacturing and can be readily produced using standard desktop 3D printers. In the prototype described here, PLA was chosen for its ease of printing and low cost. However, for increased strength and durability, alternative materials such as PETG, nylon, or carbon fiber-reinforced filaments may be employed depending on the application's demands.

The assembly process follows the sequence illustrated in Supplementary Figure 2 - 12. Each piece is designed with integrated features to ensure proper alignment, and standard M3 fasteners are used to secure the components. By adhering to these standardized hardware sizes, researchers can readily source replacement parts or modify the assembly as needed.

Post-processing steps, such as light sanding or the application of thread-locking compounds, may further improve fit and stability. Additionally, cable routing channels are included to facilitate the clean integration of wires from sensors and actuators, minimizing interference and maintaining device aesthetics.

By balancing ease of fabrication with mechanical robustness, this open-source design remains adaptable to a wide range of research environments. Users are encouraged to experiment with materials, printer settings, and minor geometric adjustments to optimize performance and longevity.

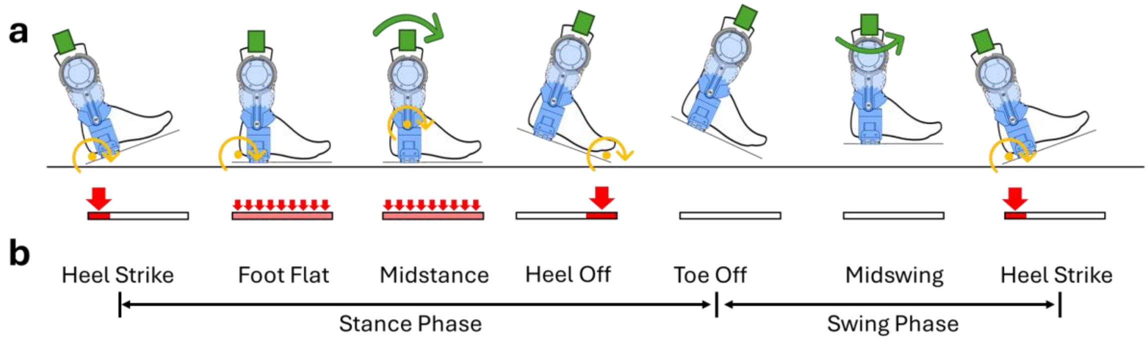

Figure 3. Representative kinematic behavior of the ankle exoskeleton across a single gait cycle. (a) Key ankle positions and device orientations at heel strike, foot flat, midstance, heel off, toe off, and midswing. (b) Corresponding stance and swing phases, highlighting changes in ground contact and device alignment throughout the cycle.

3. Discussion & Limitations

The open-source ankle exoskeleton presented here represents a significant stride toward accessible and customizable wearable robotics solutions. By emphasizing affordability, modularity, and compatibility with readily available components, this platform lowers the barriers for laboratories and institutions that may not have extensive funding or specialized manufacturing capabilities. Such democratization of technology can promote broader collaboration, encourage rapid iterative improvement, and ultimately accelerate the development of new strategies for gait rehabilitation, biomechanical analysis, and human performance enhancement.

A key strength of this design lies in its integrated sensing capabilities. As illustrated in Figure 3, the combination of force-sensitive resistors and an inertial measurement unit enables effective segmentation of the gait cycle into distinct phases. By detecting characteristic contact patterns at the toe, mid-sole, and heel in conjunction with kinematic data, the exoskeleton can reliably identify events like heel-strike and toe-off without additional complex instrumentation. This ability to capture essential gait metrics directly from the current hardware confirms that the platform is sufficient for many practical applications. Researchers can leverage these insights to implement closed-loop control strategies, fine-tune assistance profiles, and adapt the system to individual user needs, all while maintaining a streamlined and cost-effective setup.

Nevertheless, certain limitations must be acknowledged. The current prototype's primary reliance on 3D-printed PLA components, although beneficial for initial prototyping and cost reduction, may limit its long-term durability and load-bearing capacity. More robust materials, such as carbon fiber-reinforced filaments, could be substituted for more demanding use-cases, albeit at higher cost and fabrication complexity. Additionally, while the exoskeleton's torque and range of motion are adequate for many controlled or laboratory-based studies, further field testing and iterative refinements may be necessary to ensure reliable operation across diverse environments and user populations.

Cable management and sensor calibration present another area for ongoing improvement. Although the design integrates routes for clean cable routing and facilitates the addition of various sensors, changing experimental demands or environmental factors may require additional shielding, more rigorous calibration routines, or advanced signal processing to maintain data quality.

In summary, the open-source approach and integrated sensing capabilities of this ankle exoskeleton have demonstrated tangible benefits for real-time gait phase detection and adaptation. While limitations in materials, environmental robustness, and long-term performance remain, these challenges can be addressed through incremental refinements and community-driven enhancements. The framework established here provides a solid foundation for continued advancement, fostering an evolving ecosystem of accessible, innovative solutions that better meet the diverse needs of researchers, clinicians, and end-users.

4. Conclusion

This work has introduced a fully open-source ankle exoskeleton platform designed with affordability, modularity, and adaptability at its core. By integrating readily accessible 3D-printed components, commercially available actuators, and versatile sensor configurations, we have lowered the barrier to entry for researchers, clinicians, and students working in gait rehabilitation, biomechanics, and wearable robotics research. The demonstrated capability to reliably identify gait phases—based solely on force-sensitive resistors and inertial measurement units—underscores the platform's readiness for practical experimentation and closed-loop control strategies.

While certain limitations, such as material strength and environmental robustness, remain avenues for future improvement, the presented design establishes a solid foundation for iterative enhancements, customization, and community-driven innovation. As researchers build upon this open-source framework, we anticipate the accelerated development of new rehabilitation protocols, sensor modalities, and assistive strategies that can adapt to individual user needs. Ultimately, this open platform has the potential to foster richer collaborations across disciplines, expand the accessibility of advanced wearable robotics, and contribute meaningfully to improving mobility and quality of life for individuals worldwide.

Data availability

The detailed description of the ankle exoskeleton of this work and its CAD files are available on our GitHub repository at ***https://github.com/mintlabkorea/open-source-ankle-exoskeleton***

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