ISBN: 978-628-96613-3-0. ISSN: 2414-6390. Digital Object Identifier: https://dx.doi.org/10.18687/LACCEI2026.1.1.590

Design and Fabrication of an Accessible Leg Exoskeleton Prototype

Victor Hidalgo Espinoza
Universidad de Lima, Peru, *20131879@aloe.ulima.edu.pe*

Abstract*– This article presents the design and fabrication of a leg exoskeleton using digital manufacturing tools and Industry 4.0 technologies, with a focus on 3D printing and electronic production. Two specific objectives were pursued: Design and fabricate an exoskeleton prototype using 3D printing and laser-cutting tools and develop and program the controller and user interface for optimal operation. The prototype was developed by integrating processes such as design, simulation, digital integration, computer-aided manufacturing, 3D printing, electronics design and fabrication, programming, IoT, interface development, and mobile application integration. The scope of the project is to propose a low-cost and easily manufacturable solution for individuals who require such devices or are interested in their development and production. Results: The project aimed to propose a simple and affordable system for the fabrication of an exoskeletal device intended to assist human mobility. The advantages include reduced complexity in the development and production of components, integration with other devices, incorporation of 3D printing in the fabrication of mobility assistance devices, and custom controller design. Conclusion: The project results demonstrate the feasibility of developing and producing a leg exoskeleton using affordable Industry 4.0 tools and technologies.

Keywords*-- *Exoskeleton, Rehabilitation, 3D Printing, Mechanical Design, Grassroots Innovation, Automatic Control.

I. INTRODUCTION

Exoskeletons are devices designed to provide support to individuals in specific activities. During the mid-20th century, development efforts primarily focused on enhancing user strength. However, by the end of the century, the focus had shifted toward assisting and supporting human mobility. By the early 21st century, the first commercial exoskeletons found their niche in the market, driven by improved accessibility and primarily targeting applications in the rehabilitation of spinal cord injuries and cerebrovascular diseases. This trend has continued over the past decade, offering promising and innovative options for the development of such devices. Moreover, exoskeletons represent an intersection of multiple scientific fields, including engineering, industrial design, electronics design, and systems development. In applications related to rehabilitation and support, design considerations typically include ergonomics, user integration, and predictive analysis, all aiming to restore or enhance mobility in individuals suffering from related pathologies. Given the breadth of applications and development, there is currently a diverse range of exoskeletons available, many of which are specifically designed for the rehabilitation of various body parts most related to lower limbs.

Recent advancements in lower-limb exoskeletons have focused on the optimization of the design, weight reduction, and improvements to control systems and actuators [1]. Compared to traditional methods, exoskeletons offer measurable benefits in recovery times for patients [2] [3] [4]. Furthermore, international policies—such as those promoted by the World Health Organization—have facilitated investments in the development of exoskeletons, contributing to their strengthening and wider availability. The global exoskeleton market is projected to grow from $232.5 million in 2021 to $3,044.7 million by 2031, with a compound annual growth rate of 29.4% [5]. The same study highlights a growing preference for exoskeletons equipped with linear actuators over those with passive systems and notes the increasing prevalence of spinal cord injuries as a target condition through 2031. This market trajectory supports the development of alternative fabrication methods based on emerging technologies aimed at rehabilitation. For instance, recent studies have proposed six-link exoskeleton mechanisms optimized for human anatomy, offering high trajectory precision and efficient force transmission. Moreover, control systems have been implemented to modulate the bipedal gait cycle, adapting to the specific needs of each patient.

Despite these technological advancements, many current exoskeletons remain prohibitively expensive and are not directly owned by users. Instead, these devices are often acquired through strategic partnerships between companies and healthcare institutions. One example is ReWalk's Personal 6.0 model, which is distributed through alliances with clinics and rehabilitation centers. Other notable cases include walker-based exoskeletons, which tend to be bulky, require higher institutional investment, and impose greater costs on end users. These specialized devices belong to a highly technical field of application characterized by complex and costly processes, which extend beyond the scope of the present project.

In addition, statistical data collected by INEI in 2019 indicate that 10.4% of the Peruvian population experienced a mobility-related disability. Of this group, 15% suffer from mobility impairments, while 18% experience two or more types of disabilities. Considering that the probability of recovering partial mobility may extend up to 18 months [6], during which daily activities cannot be performed in some cases, affected individuals may experience a reduction in economic income. The shown data demonstrates that a wide sector of people of unprivileged circumstances around the world, as is Peru, that spend quite a lot of time without the correct and specialized tool as could be an exoskeleton as it has been shown to be expensive and difficult to access.

That is why this article presents the development of a lower-limb exoskeleton as a simple and affordable alternative for fabrication and deployment, establishing a pathway for small-scale production using cost-effective, easily replicable materials, machinery, and methodologies. The work explores multiple dimensions—including design, manufacturing, and control programming—by integrating theoretical and applied engineering disciplines and leveraging Industry 4.0 tools such as additive manufacturing (specifically fused filament fabrication 3D printing), microprocessor development, sensors, actuators, controllers, user interface design, and processor programming. The resulting prototype validated the material feasibility of the proposed fabrication process, successfully achieving its intended functionality of assisting locomotor activity during gait, while demonstrating that lightweight, ergonomic components can be produced at reduced cost without compromising mechanical strength compared to conventionally manufactured parts.

II. Literature Review

The development of lower limb exoskeletons has emerged as a promising solution for mobility assistance, rehabilitation and improvement in individuals with motor impairments or demands physical tasks. As the global population ages and the prevalence of mobility disorders increases, exoskeleton technologies are gaining attention from both clinical and industrial sectors.

The increasing prevalence of individuals who suffer lower limb injuries and consequently require prolonged rehabilitation highlights a critical dimension of public health. These conditions often result in reduced autonomy, limited participation in daily activities, and heightened dependence on assistive devices. Rehabilitation programs aim to restore functional independence, yet their effectiveness is closely tied to the accessibility of physical environments and healthcare services. It is estimated that 1.3 billion people have experienced some form of disability, representing approximately 16% of the global population [7]. This proportion has been increasing over the years due to various contributing factors. Accessibility must be recognized as a fundamental target in the continuum of care, ensuring that rehabilitative progress translates into genuine social inclusion. By integrating universal design principles and enforcing accessibility standards, societies can bridge the gap between medical recovery and full participation, ultimately improving quality of life for individuals living with mobility impairments. For therapeutic progress to be translated into genuine social inclusion, it is imperative to integrate the principles of universal design and to ensure compliance with established accessibility standards. Currently, there are no affordable versions available on the market that can aid users who wish to adopt this type of device.

Exoskeletons can be categorized according to several criteria. The first classification is based on the body region targeted: full-body systems assist all limbs; upper-body systems support the arms, shoulders, chest, and head; lower-body systems focus on the legs and thighs; and segmental or joint-specific systems address areas such as the knees, feet, hands, or fingers. A second classification considers the structural type: rigid exoskeletons employ hard, durable materials that attach directly to the user, whereas soft exoskeletons utilize textile-based structures with embedded actuation (e.g., cables or pneumatic actuators), prioritizing comfort and flexibility. Functionality provides another dimension of categorization: (1) active exoskeletons employ actuators (electric, pneumatic, or hydraulic) to deliver powered movement, requiring sensors, controllers, energy sources, and complex real-time control algorithms to adapt to user motion; (2) passive exoskeletons rely on mechanical elements such as springs or dampers to redistribute loads or assist motion without external power, emphasizing lightweight design, energy efficiency, and simplicity, and are often used to reduce strain in repetitive tasks; and (3) hybrid exoskeletons combine passive support with selective actuation, offering enhanced versatility, energy efficiency, and functional adaptability. Exoskeletons may also be classified by their power source, which can include electric, hydraulic, pneumatic, hybrid, or purely mechanical systems. Finally, devices can be categorized by purpose: rehabilitation and mobility recovery, performance augmentation, or specialized applications in military, clinical, research, industrial, or civilian contexts [8]. Studies suggest that robotic-assisted gait training can promote neuroplasticity, improve walking ability, and increase patient's engagement during therapy [9].

Among the development criteria, ergonomics is one of the main aspects taken into consideration by balancing mechanical efficiency with human-centered considerations to ensure safety, comfort, and usability [10]. Fit and anthropometric variation require adjustable mechanisms that allow a sufficient level of adjustment to accommodate a wide range of operators, while precise kinematic alignment is essential to prevent residual stresses and increase the risk of injury, dynamic fit, both static fit (kinematic positioning in fixed postures) and dynamic fit (interaction between the human body and the exoskeleton during movement) must be ensured for safe and efficient operation. Interfaces must optimize load transfer without generating harmful contact pressures, as poorly designed connections can compromise circulation and reduce long-term effectiveness, connected with the human body through mechanism such as clamps, cuffs, straps, and rigid shells. While firm connections are necessary for optimal load transfer, they can also cause discomfort to the operator. The weight of the exoskeleton structure may generate uneven contact pressures, increasing discomfort. For that instance, poorly designed connections can restrict blood flow and negatively affect worker health, particularly during long work shifts. Similarly, Range of Motion (ROM) and flexibility remain critical, exoskeleton structures typically employ rigid links with fixed centres of rotation for joints. This differs from biological joints, which lack a fixed rotation centre, and can resist free movement, thereby reducing ROM. The development of flexible or soft exoskeletons that use fabrics and cables for force transmission can increase freedom of movement and reduce ROM restrictions. For example, lower-limb exoskeletons have been designed with passive spherical joints to improve mobility. Finally, weight and metabolic load represent decisive factors in user acceptance, as excessive mass increases energy expenditure and shifts musculoskeletal strain. Weight is an underestimated factor that can offset the benefits of exoskeletons. The perception of wearing a heavy device may reduce user acceptance, an added mass of approximately 4 kg near the user's centre of mass can increase metabolic cost by 7–8%, and a heavy device may cause musculoskeletal disorders in other parts of the body, reducing injury risk in one area while increasing it elsewhere. To reduce weight, materials such as titanium or aluminium alloys can be used. More advanced solutions include carbon fibre components, which can achieve very low densities (down to 0.95 grams per cubic centimetre). Collectively, these dimensions highlight that exoskeleton performance is not solely a matter of engineering strength but of ergonomic integration, where biomechanical compatibility and user comfort determine the true effectiveness of the technology.

In addition, a distinct line of research on these devices has been established in recent years, as exemplified by the projects presented:

- Lower Limb of an Exoskeleton with Low Power Consumption [11], this device uses a spring segment joint between pelvic segment and foot segment that provides potential energy to reduce the consumption of system (Fig. 1).

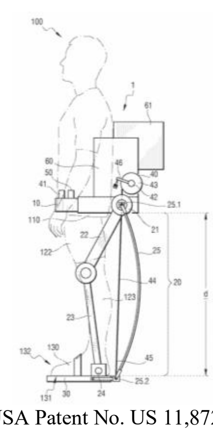

Fig. 1 USA Patent No. US 11,872,180 B2.

- Lower Limb Exoskeleton [12], an option to users where the device supports most of the weight of body by transferring to the ground, it has an adjustable abdominal torso module (Fig. 2).

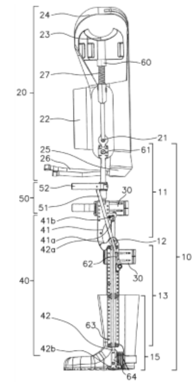

Fig. 2 European Patent No. EP 4595939.

- Lower limb rehabilitation exoskeleton mechanism with flexible joints [13], this device introduces flexible joints at each articulation that works as a passive actuator which can be adapted to user performance and needs (Fig. 3).

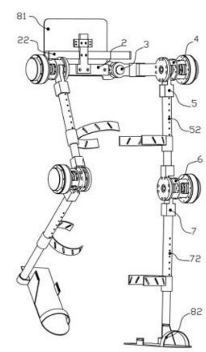

Fig. 3 China Patent No. 113133898 B.

- Energy Storage Device for an Exoskeleton [14], this device uses a subsystem that stores and releases energy when user walks, supplying aid its mobility (Fig. 4).

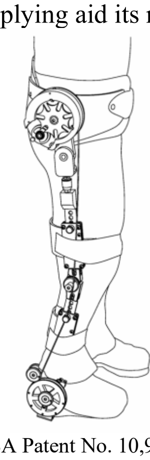

Fig. 4 USA Patent No. 10,912,666 B2.

- Exoskeleton legs to reduce fatigue during repetitive and prolonged squatting [15], this exoskeleton uses a system of links which prevents flexion over the natural motion of users, it uses an actuator to provide more power to the functionality which could be electric, pneumatic or hydraulic (Fig. 5).

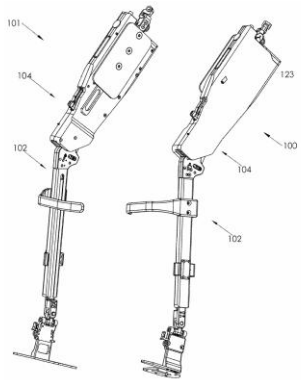

Fig. 5 USA Patent No. 12,213,934 B2.

The utilization of components manufactured from additively produced materials enables a reduction in the overall mass of structural elements. Depending on the density, production methodology, and material selected, such components can achieve the mechanical strength and durability required for functional applications. Within the current market, a variety of materials are employed in 3D printing, the most common of which include filaments of Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), and High Impact Polystyrene (HIPS). Each of these polymers exhibits distinct properties and specific requirements for processing. Among them, ABS and PLA are the most extensively adopted due to their favourable balance of performance characteristics and ease of fabrication [16].

TABLE I
Filament Comparison

	Acrylonitrile Butadiene Styrene (ABS)	Poly Lactic Acid (PLA)	High Impact Polystyrene
Technical Specification			
Density	1-1.4 gm/cm3	1.3 g/cm^3 (81 lb/ft^3)	1.0 g/cm^3 (62 lb/ft^3)
Dielectric Strength (Breakdown Potential)	15-16 kV/mm [0.59-0.63 V/mil]	-	18 kV/mm (0.7 V/mil)
Elastic (Young's, Tensile) Modulus	2 to 2.6 GPa	2.0 to 2.6 GPa (0.29 to 0.38 x 10^3 psi)	1.9 GPa (0.28 x 10^6 psi)
Elongation to Break	3.5 to 50%	6%	40%
Flexural Modulus	2.1 to 7.6 GPa	4.0 GPa (0.58 x 10^6 psi)	-
Flexural Strength	72 to 97 MPa	80 MPa (12 x 10^3 psi)	62 MPa (9.0 x 10^3 psi)
Heat Deflection Temperature	At 1.82 MPa -76 to 110°C (170-230°F) At 455 KPa- 83 to 110°C (182-230°F)	At 455 kPa (66 psi) - 65°C (150°F)	-
Strength to Weight Ratio	37 to 79 kN-m/kg	38 kN-m/kg	32 kN-m/kg
Tensile Strength	37 to 110 MPa	Ultimate (UTS) 50 MPa (7.3 x 10^3 psi)	Ultimate (UTS) - 32 MPa (4.6 x 10^3 psi)
	Proposed material		
Consumable	Creality Hyper ABS	eSUN PLA	3DSWay HIPS
Extrusion Temperature	230-270°C (446-518°F)	210-230°C (410-446°F)	230-270°C (446-518°F)
Bed Temperature	75-90°C (167-194°F)	45-60°C (113-140°F)	100-120°C (212-248°F)
Print Speed	<350 mm/s	10-300 mm/s	<350 mm/s
Impact Resistance	19kJ/m2	-	-
Traction Resistance	30,4 ± 0.6Mpa	-	-
Flex Resistance	48,1 ± 0.2Mpa	-	-
Price Filament 1.75 mm, 1 Kg (USD)	45.32	25.61	10.96

User accessibility to the acquisition of material-based 3D printers has increased significantly in recent years. At present, printers capable of processing filaments such as Acrylonitrile Butadiene Styrene (ABS) or Polylactic Acid (PLA), with configurable parameters tailored to each material, are available in a wide range of models. For example, the Creality brand offers *Creality Ender-3 V3*, which is capable to print with both ABS and PLA filaments. This model operates at a maximum printing speed of 600 mm/s, provides a build volume of 220 × 220 × 250 mm, achieves a dimensional accuracy of ±0.2 mm, supports a layer height between 0.1–0.35 mm, and maintains nozzle temperatures up to ≤300 °C. Its energy consumption is approximately 350 W, and it is commercially available at a price of around USD 180.

For the power supply, the use of batteries is considered the most optimal solution, with lithium-based batteries representing the preferred option due to their favourable portability-to-capacity ratio. And to ensure optimal device performance, a continuous energy flow of 12 V is required, which is sufficient to drive most actuators currently available on the market. A configuration consisting of cylindrical lithium batteries rated at 12 V and 5 Ah, corresponding to an energy capacity of 60 W-h, is commercially available at an approximate cost of USD 19.

Given that the objective of the present project is the development of an affordable exoskeleton for the user's lower limb, the use of electric linear actuators has been selected because, in comparison with the different alternatives that fulfill the same function, the linear actuator is more commonly available, cost-effective, and straightforward to install [17]. These actuators are particularly suitable due to their reliability, as they incorporate a defined stroke limit of 200 mm and its power capacity 1000N. Furthermore, they represent cost-effective components (approximately USD 30) with high durability, which facilitates user accessibility in terms of acquisition and maintenance.

This approach enables a comprehensive quality assessment of the key factors influencing the design, development, production, integration, and optimal performance of the leg exoskeleton prototype. House of Quality has been used to reach the key process and materials that are going to be employed in the development of the exoskeleton focusing on user needs, the characteristics of each of the previously mentioned proposals were evaluated based on qualitative demand. Subsequently, features were proposed that could satisfy the weighted demand, considering the project's objectives. As a result, the predominant characteristics identified were the use of 3D printing, the type of material to be employed, and the weight of the device.

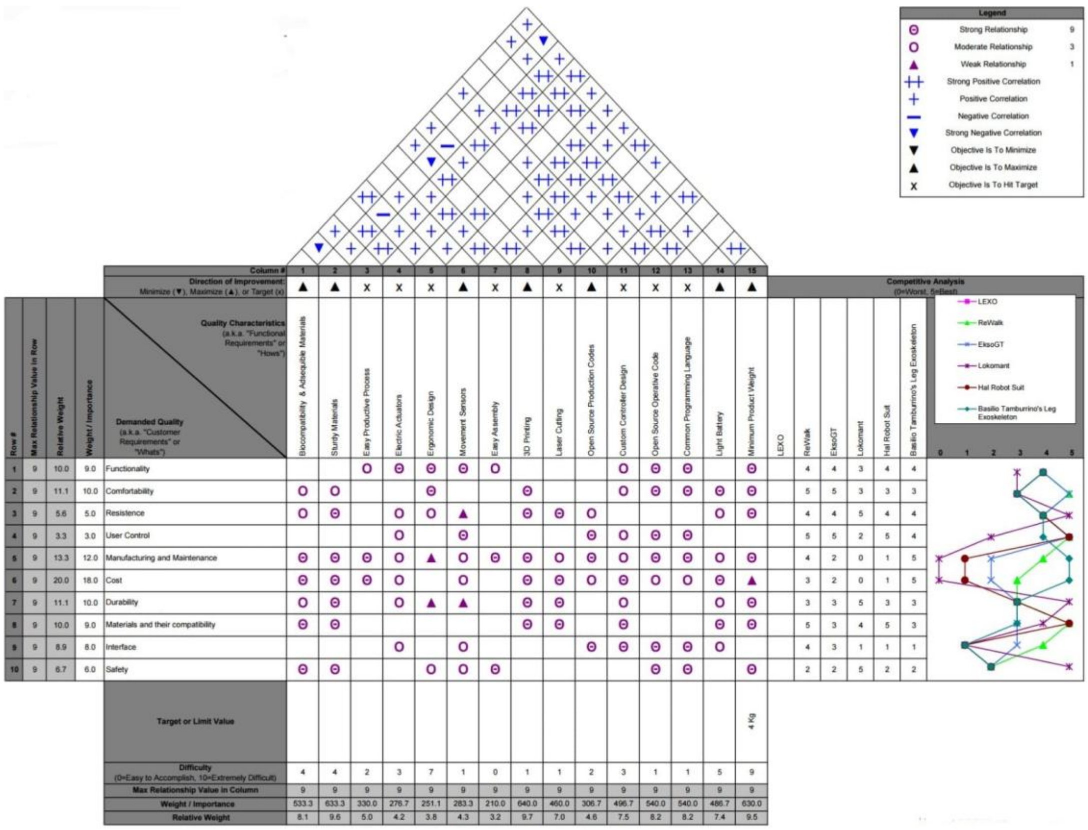

Fig. 6 House of Quality

III. METHODS

The exoskeletal device, named LEXO, was developed during the 2021 Fab Academy program at the Universidad de Lima. It exemplifies a growing trend toward creating affordable devices that assist users with lower-limb impairments in moving and performing daily activities.

This project also explores the design, functionality, and broader implications of such initiatives, which aim to meet specific needs by optimizing development and production using Industry 4.0 technologies—tools that have gained significant momentum in recent years.

Furthermore, require the integration of various production methods and diverse working environments that could provide the necessary technical and operational support to produce the pieces, design of system and integration of the device.

The development process was structured into four distinct stages, detailed below:

3.1. Stage 1: Analysis of the Current Exoskeleton Landscape, Material Sourcing, Design, and Work Environment Evaluation

The project began with a thorough study of the current state of exoskeleton technologies, alongside the identification of essential components required for building a functional lower-limb exoskeleton.

During the material sourcing phase, a distinction was made between parts that could be manufactured or processed in-house and those considered as off-the-shelf components. Materials for in-house processing included 3D printing filaments, MDF boards, copper-clad laminates, and electronic components. Off-the-shelf components included linear actuators, relays, batteries, and wiring, among others.

For the design and development of custom parts, the following software tools were employed:

- Eagle for circuit board design and electronics
- Fusion 360 for 3D modelling and simulation
- Arduino IDE for programming

Fig. 7 Modelling of the Device.

3.2 Stage 2: Production, Interface Design, and Programming

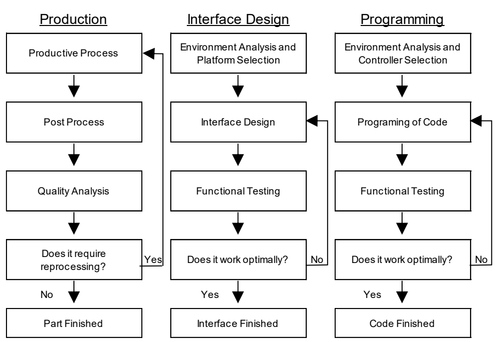

Fig. 8 Diagram of *Stage 2*

The production phase was executed according to the availability of machinery and personnel, with many parts being fabricated in parallel. Some components require rework to ensure functionality. The user interface was developed using App Inventor, an open-source software platform known for its simplicity and intuitive design. Programming was performed in C++, which is compatible with the AtMega328p microcontroller chip used in the device.

The production of the components was carried out using two 3D printers. For the fabrication of the joints, a MarkForged printer was employed, while a MakerBot printer was used for manufacturing the enclosure of the electronic parts. The controller board was produced with a Roland milling machine, after which the components were added through SMD soldering. It is worth noting that an AtMega 328p processor was used, the same processor found in Arduino UNO boards.

For the cutting process of the MDF sheets, a laser cutting machine was employed. However, this process can also be carried out using alternative methods and therefore does not strictly require the use of the machine.

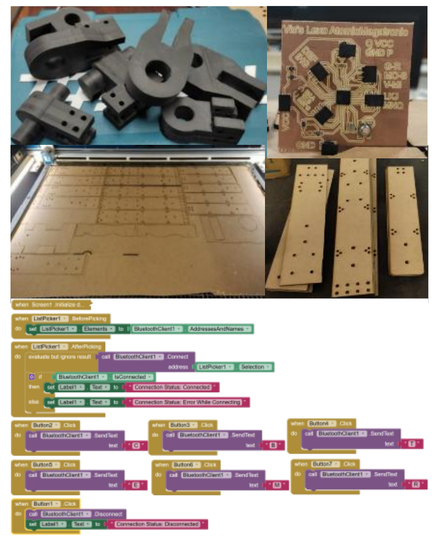

Fig. 9 Production of Pieces.

3.3 Stage 3: Assembly, Integration, and Initial Testing

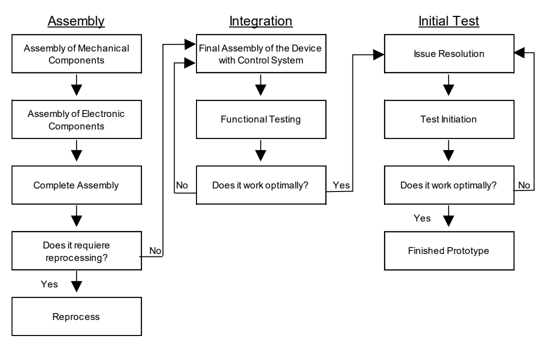

Fig. 10 Diagram of *Stage 3*

The assembly process was divided into three major components:

1. Mechanical assembly: Joining the fabricated and processed structural parts.
2. Electronic assembly: Integrating controllers, electronic components, power supply, and actuators.
3. Final integration: Merging the mechanical and electronic subsystems.

For the assembly of the mechanical section, bolts and nuts were required to secure the components. At this stage, the previously fabricated parts were joined together.

Fig. 11 View of the Exoskeleton Body.

For the electronic assembly, various components were required, including the processor fabricated in the previous section, relays to distribute the necessary power to the actuators, the power supply, the processor itself, and the electric linear actuators.

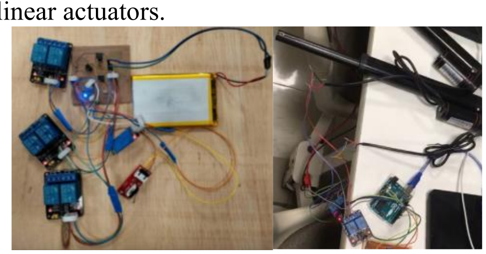

Fig. 12 View of Controller (Left) and Actuators (Right).

The final assembly was subsequently performed, in which all parts were integrated.

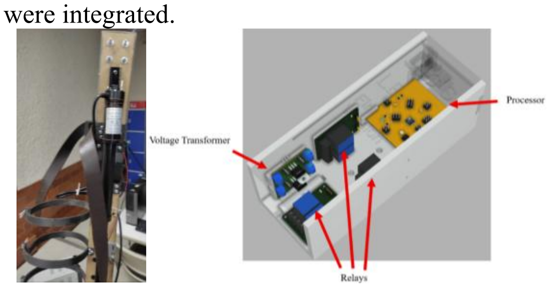

Fig. 13 View of Mechanical and Electronic Integration.

3.4 Stage 4: Final Adjustments, Objective Verification, and Presentation

The final stage involved refining the project and presenting it as a complete prototype. The fulfillment of the original objectives was verified, and the device was showcased as a tangible, functional outcome.

Fig. 14 View of LEXO (Leg Exoskeleton).

IV. Result and Discussion

This project was developed over a 12-week period as a final assignment. It represents the successful integration of multiple systems and development methods, utilizing production techniques that are relatively uncommon in the field of exoskeleton design.

Focus on 3D printing as the primary manufacturing method due to its suitability for producing complex geometries and its flexibility with materials, most of which are lightweight and, depending on the method, offer sufficient mechanical strength. The control interface design developed for this project provides an intuitive way to control functions. The use of simulation played a crucial role in the project's development, software like Eagle and Fusion 360 were used extensively to fabrication of electronic controller and modeling, part-by-part analysis, and virtual assembly of the prototype—ensuring compatibility and optimizing the final fit. And the use of folded MDF (medium-density fiberboard) as structural material system designed provides an increase of rigidity and flexibility without the need for specialized CNC machining setups. Reduces cost of production to an estimated USD 278.18, divided by:

- Cost of materials that LEXO requires to produce single parts.

TABLE II
Bill of Materials

Material		Material Cost		Prototype Require	
Type	Description	Base	Qty.	Usage	Total
Filament	ABS	4.532	USD/ 100g	1,302.88	59.05
MDF Sheet	2135x 2440 mm	10.00	USD/ Unit	0.75	7.50
Electric Linear Actuator	1000N, 200mm stroke	30.00	USD/ Unit	2	60.00
2 Channel Relay Module	DC 5V, 10A	2.50	USD/ Unit	3	7.50
Hex Screw & Cap Screw	L: 25mm, Stove Bolt	0.40	USD/ 10 Unit	60	2.40
20P DuPont Cable Rainbow	L: 5m	20.00	USD/ Unit	1	20.00
AtMega	328p	8.00	USD/ Unit	2	16.00
Ceramic Electronic Board	Square Side: 200mm	2.50	USD/ Unit	1	2.50
Electronic Component	Resistors, capacitors, others	6.00	USD/ Part	1	6.00
Lithium Battery	60 W-h	19.00	USD/ Unit	1	19.00
Total Cost of Materials (USD)					199.95

- Cost of process LEXO parts.

TABLE III
Bill of Materials

Process	Production Scale	Cost of Service	Currency
3D Printing	19 Parts	34.74	USD
Cutting	5 Times per Piece & Holes	13.49	USD
Milling & Soldering	3 Circuit Boards	30.00	USD
App Design (AppInventor)	App Control	Free	-
Total Cost of Production (USD)		78.23	

The use of a custom controller designed with precisely the components and layout required for optimal function, also reduced material usage and overall device weight by allowing the controller to adapt to the device rather than the other way around. The use of electric linear actuators selected alternative actuation methods to reduce costs providing same functionality. Therefore, the system has a total power consumption of 36.77 W approximately and the battery capacity is around 60 W-h, providing the system with an autonomy of 1 hour and 38 minutes.

TABLE IV
Power Consumption

	Current		Voltage		Power	
Action Parts	Qty	Unit	Qty	Unit	Qty	Unit
Controller (AtMega 328p)	54	mA	5	V	0.27	W
Relays	100	mA	5	V	0.50	W
Electric Linear Actuator	3	A	12	V	36.00	W
Total System Consumption (W)					36.77	
Battery Capacity (W-h)					60	

The knee constitutes one of the most critical flexion points in the design of lower-limb assistive devices. Torque simulation for the knee joint yielded a maximum value of 200 N·m, corresponding to an estimated applied force under normal operating conditions of the prototype. This magnitude illustrates the mechanical demand required to sustain flexion–extension cycles in assisted gait. As the outcome derives from theoretical modelling, it should be regarded as a preliminary estimation of actuator performance, emphasizing the necessity of subsequent experimental testing to confirm efficiency and structural reliability.

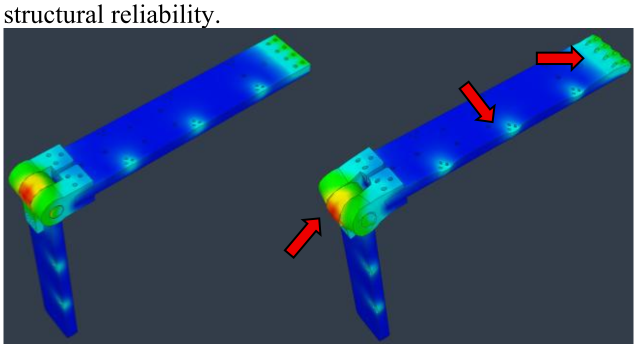

Fig. 15 LEXO's knee Stress Simulation

Preliminary trials with the prototype indicated a clear benefit in assisted gait experiencing smoother walking cycles and reported less fatigue compared to unassisted locomotion. Observations confirmed that the exoskeleton alleviated part of the mechanical demand on the lower limbs, leading to an approximate 20% reduction in load, thus validating the potential of a low-cost, digitally fabricated device to provide meaningful support in mobility tasks.

Ultimately, the goal of this project was to propose a simple and accessible system for the fabrication of an exoskeletal device to assist human mobility. The approach is grounded in the use of modern design tools and manufacturing methods that have gained widespread adoption in recent decades—particularly 3D printing and custom electronics—at a scale accessible to enthusiasts and individual users.

TABLE V
LEXO Specs

Specifications	
Frame Materials	ABS & MDF
Total Cost	278.18 USD
Weight	7 Kg
Dimension w/o Rings (L, W &H)	161x99.57x1020.85 mm
Dimension with Rings (L, W &H)	161x241.92x1020.85 mm
Maximum Torque	200 N.m
Load Reduction	20%
Battery Capacity	60 W-h
Power Consumption	36.77 W
Autonomy	1 h 38 m
Processor	AtMega 328p
Interface	Android

4.1. Discussion

According to the results presented, a comparative analysis was conducted with other devices currently available on the market, such as:

- Hypershell X Go, an exoskeleton designed for outdoor activities, combining a lightweight structure (2.5 kg) with a moderate torque capacity of 200 N·m. Its autonomy reaches 15 km or 4 hours, enabling extended walking or running support. With a price of USD 699, it represents a balance between affordability and functional mobility assistance, offering a 20% load reduction.

Fig. 16 Hypershell X Go

- AI Powered Bionic Exoskeleton, this device emphasizes compactness weighing only 2.2 kg. Although its torque capacity is limited to 15 N·m, it provides mobility support with autonomy of 10 km or 4 hours. In the other hand, priced at USD 1,299, twice more than Hypershell model, limits its affordability.

Fig. 17 AI Powered Bionic

- DNSYS X1 Lite Exoskeleton, this device stands out for its high torque capacity of 350 N·m, despite its minimal weight of 1.8 kg. Designed for outdoor mobility, it achieves a 30% load reduction and autonomy of 15 km or 4 hours. At USD 899, it offers a strong performance-to-cost ratio, making it one of the most technically capable low-cost exoskeletons in the comparison.

Fig. 18 DNSYS X1 Lite

- Agilik (Bionic Power), this exoskeleton is primarily oriented toward rehabilitation and gait assistance, with a torque capacity of 80 N·m and a weight between 3–4 kg. Its most distinctive feature is the high load reduction of 50%, which significantly enhances rehabilitation outcomes with an autonomy of 6 km or 6 hours, it provides sustained support. Nevertheless, its cost (~USD 5,000) places it in a higher price range compared to other low-cost alternatives.

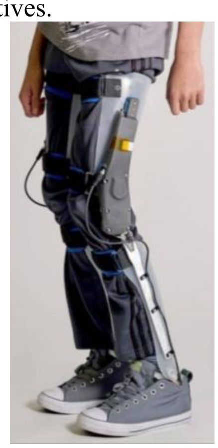

Fig. 19 Agilik (Bionic Power)

A comparative table was developed to evaluate the performance of different exoskeleton models.

TABLE VI
Comparative Table

Product	Approx. Price	Weight	Max Torque	Load Reduction	Autonomy (Km / Hours)
LEXO	USD 278.18	7 kg	200 N·m	Moderate (20%)	4 km / 1.3 h
Hypershell X Go	USD 699.00	2.5 kg	200 N·m	Moderate (20%)	15 km / 4 h
AI Powered Bionic	USD 1,299.00	2.2 kg	15 N·m	Moderate (20%)	10 km / 4 h
Dnsys X1 Lite	USD 899.00	1.8 kg	350 N·m	Moderate (30%)	15 km / 4 h
Agilik (Bionic Power)	~USD 5,000.00	3–4 kg	80 N·m	High (50%)	6 km / 6 h

The LEXO prototype, conceived as a low-cost alternative (USD 278), exhibits a distinct performance profile compared to the other devices represented in the radar chart (Fig. 20). Its relatively high weight and limited autonomy constrain its applicability in extended operational scenarios, positioning it primarily as a research-oriented prototype. In contrast, the others device demonstrates its strengths as DNSYS X1 Lite's superior torque output (350 N·m) combined with a lightweight design (1.8 kg), while the Hypershell X Go achieves a balance between affordability and moderate autonomy (4 h). The AI Powered Bionic emphasizes reduced weight (2.2 kg) and enhanced load reduction (30%), albeit with limited torque capacity (15 N·m). Finally, the Agilik system prioritizes clinical applications, offering extended autonomy (6 h) and high load reduction (50%), though at a substantially higher cost. Within this comparative framework, LEXO emerges as an accessible entry point for academic experimentation, contrasting with more advanced designs that optimize biomechanical support, endurance, or torque generation.

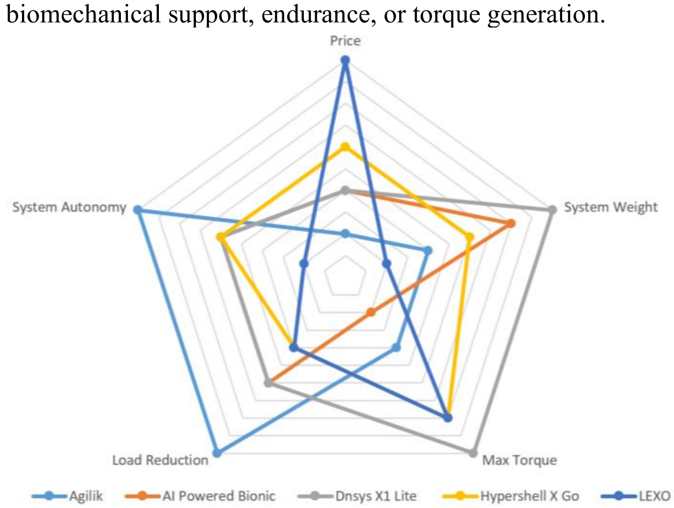

Fig. 20 Comparative Chart with Current Devices

4.2. Limitations

Despite LEXO demonstrating the feasibility of a low-cost exoskeleton prototype, its ergonomic limitations may hinder long-term applicability. The device's weight (7 kg) may increase metabolic demand and user fatigue, while rigid joint alignment fails to replicate natural kinematics, potentially causing residual stresses. Prolonged use may also lead to discomfort from uneven load transfer and localized pressure points. These factors highlight the need for further refinement in weight reduction, dynamic fitness, and interface design to ensure that affordability does not compromise safety and clinical effectiveness.

Additionally, the device's joint mechanisms do not allow for the natural freedom of movement of the knees or hips, resulting in limited comfort for the user. Regarding the clamps, the design employed is functional; however, it proves to be insufficiently comfortable during frequent use or prolonged periods of operation.

Future work will therefore focus on integrating advanced lightweight materials to reduce metabolic load and on enhancing the control system to improve gait synchronization. Specific strategies include reducing structural weight through lighter composite materials such as acrylic sheets or alloys to mitigate complications from moisture caused by natural human perspiration, incorporating flexible joint mechanisms to achieve a more natural dynamic fit, and refining interface design to ensure appropriate load distribution. Furthermore, scaling production methods and exploring open-source dissemination strategies could broaden accessibility and foster collaborative improvements in low-cost assistive technologies.

V. Conclusions

The LEXO project demonstrates the feasibility of designing and fabricating a lower-limb exoskeleton using accessible Industry 4.0 tools such as 3D printing, laser cutting, and microcontroller programming. The integration of low-cost materials and digital processes enabled the development of a functional prototype that balances affordability with mechanical strength, validating the potential of technology-driven innovation aimed at accessibility.

The results confirm that fabrication through 3D printing and low-cost electronic components can significantly reduce complexity and production costs, reaching an estimated total of USD 278.18. The energy autonomy of approximately 1 hour and 38 minutes, together with the simplicity of the control system, demonstrates that assistive devices can be developed with limited resources without compromising basic functionality.

Beyond technical validation, LEXO provides a socially relevant approach by proposing an accessible alternative for sectors where conventional exoskeletons remain prohibitively expensive. This prototype opens the possibility of small-scale production and fosters open collaboration, contributing to the democratization of assistive technologies and the inclusion of these to individuals with reduced mobility in low-resource contexts.

Acknowledgment

The author would like to thank his family and partner for their patience and encouragement throughout the duration of this research project.

Special thanks are extended to Professor Eduardo Cieza for invaluable guidance and mentorship, which greatly shaped the direction of this study.

References

[1] S.V. Kotov et al, “Efficiency of leg exoskeleton use in rehabilitation”, *Experimental and Applied Biomedical Research*, vol. 22, no. 3, pp. 257-264, September 2021.

[2] A. Plaza, M. Hernandez, G. Puyuelo, E. Garces and E. Garcia,, “Lower-Limb Medical and Rehabilitation Exoskeletons: A Review of the Current Designs”, *IEEE reviews in biomedical engineering*, vol. 16, pp. 278-291, January 2023.

[3] D.M.G. Preethichandra et al. “Passive and Active Exoskeleton Solutions: Sensors, Actuators, Applications, and Recent Trends”, *Sensors*, vol. 24, no. 21, pp. 42, 2024.

[4] S.A. Elprama, B. Vanderborght and A. Jacobs, “An industrial exoskeleton user acceptance framework based on a literature review of empirical studies”, *Applied Ergonomics*, vol. 100, April 2022.

[5] L. Dash, T. Shaikh and E. Prasad, “Medical Exoskeleton Market by Type.”, January 2023. AlliedMarketResearch: A11183. [Online]. Available: https://www.alliedmarketresearch.com/medical-exoskeleton-market-A11183

[6] M.F. Veintimilla, “Diseño e implementación de un dispositivo electrónico para la rehabilitación de extremidad inferior en pacientes con pérdida de movilidad parcial”, January 2023. [Online]. Available: http://dspace.unach.edu.ec/handle/51000/10324

[7] World Health Organization, “Disability.”, March 2023. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/disability-and-health

[8] J. A. de la Tejera, R. Bustamante-Bello, R.A. Ramirez-Mendoza and J. Izquierdo-Reyes, “Systematic Review of Exoskeletons towards a General Categorization Model Proposal”, *Applied Sciences*, vol. 11, no. 1, pp. 25, January 2021.

[9] J. Mehrholz, S. Thomas, J. Kugler, M. Pohl and B. Elsner. “Electromechanical-assisted training for walking after stroke: Update of the Evidence.”, *Cochrane Database of Systematic Reviews*, vol. 10, no. 10, Octuber 2020.

[10]P.M. Kuber and E. Rashedi, “Product ergonomics in industrial exoskeletons: potential enhancements for workforce efficiency and safety.”, *Theoretical Issues in Ergonomics Science*, vol. 22, no. 6, pp. 729-752, 2021.

[11]Franck Geffard, D. P. (2024, January 16). *United States of America Patent No. US 11,872,180 B2.*

[12]JOAN, S. C. (2025, August 6). *European Patent Office Patent No. EP 4595939*

[13]董明杰, 袁. 李. (2023, January 13). *China Patent No. CN 113133898 B.*

[14]Jessica Zistatsis, J. B. (2021, February 9). *United States Patent No. US 10,912,666 B2.*

[15]Wayne Tung, M. V. (2025, February 4). *United States Patent No. US 12,213,934 B2.*

[16]V.G. Gokhare, D.N. Raut and D.K. Shinde, “A Review paper on 3D-Printing Aspects and Various Processes Used in the 3D-Printing”, International Journal of Engineering Research & Technology, vol. 6 no. 6, pp. 953-958, 2017.

[17]T. Slucock, “A Systematic Review of Low-Cost Actuator Implementations for Lower-Limb Exoskeletons: a Technical and Financial Perspective”, *Journal of Intelligent & Robotic Systems*, vol. 106, no. 3,pp. 31, November 2022.