

A Performance Analysis of Wearable Exoskeleton joint Design for Mobility Assistance

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Abstract -Wearable exoskeletons have emerged as an effective assistive technology to restore and enhance mobility for individuals suffering from musculoskeletal disorders, spinal injuries, or age-related impairments. Among the different types, knee exoskeletons play a pivotal role as the knee joint is crucial in human locomotion, weight-bearing, and stability. This review paper presents a comprehensive analysis of recent advancements in the mechanical design, material selection, actuation mechanisms, and performance analysis of knee exoskeletons. Emphasis is placed on lightweight design, structural optimization, ergonomic considerations, and functional performance metrics such as range of motion (ROM), load-bearing capacity, fatigue resistance, and user comfort. Comparative insights into active, passive, and hybrid designs are provided, along with the integration of modern technologies such as Finite Element Analysis (FEA), CAD modeling, and lightweight composites. Furthermore, challenges including weight constraints, power efficiency, cost factors, and biomechanical alignment are highlighted. Finally, the review outlines future directions emphasizing bio-inspired designs, additive manufacturing, energy harvesting mechanisms, and low-cost wearable solutions. This paper intends to serve as a resource for researchers, engineers, and clinicians developing next-generation wearable exoskeleton systems suitable for healthcare, rehabilitation, and occupational support.

Key Words: Exoskeletons, Knee Joint, Mobility Assistance, Mechanical Design, CAD, FEA, Rehabilitation, Lightweight Materials.

1. INTRODUCTION

Mobility impairments caused by aging, musculoskeletal disorders, spinal cord injuries, or neurological conditions like stroke and cerebral palsy limit the independence and quality of life for millions globally. In response, wearable exoskeletons have emerged as a promising solution for assisting or restoring lost movement functions. However, traditional exoskeletons are often bulky, energy intensive, and lack intelligent responsiveness to the user's motion and terrain. This leads to discomfort, unnatural gait patterns, and limited usability. Recent advancements in Intelligence and lightweight materials provide new opportunities to create smarter, lighter, and more adaptive exoskeleton joint systems. By integrating sensors, real-time, and low-power actuators, we can develop a system that augments human mobility while maintaining comfort, efficiency, and affordability. Mobility plays a critical role in an individual's independence, quality of life, and social participation. However, mobility impairments caused by conditions such as aging, musculoskeletal disorders, spinal

cord injuries, or neurological diseases (like stroke or cerebral palsy) restrict millions of people globally from performing daily tasks without assistance. To address these challenges, wearable exoskeletons have emerged as a significant advancement in assistive technology.

Exoskeletons are external, wearable mechanical structures designed to support, assist, or enhance human motion. They are particularly effective in aiding lower-limb mobility, especially at the knee joint, which plays a pivotal role in walking, standing, and sitting. While technological advancements have enabled the development of robotic and exoskeletons, many of these systems remain bulky, costly, and energy-intensive, making them impractical for everyday use by the elderly or physically impaired individuals. This paper focuses on the mechanical design and optimization of a lightweight, wearable knee exoskeleton. The goal is to create a simple, ergonomic, and cost-effective solution that enhances user mobility by mechanically supporting the knee joint during movement. Unlike AI-heavy systems, this design prioritizes efficiency, comfort, and user-friendliness, making it suitable for real-world application in rehabilitation, elder care, and personal mobility assistance.

2. METHODOLOGY

Conceptual Design and CAD Modeling

- Developed the initial exoskeleton design using Solid Works/Fusion
- Modeled key components: thigh frame, shank frame, hinge knee joint, torsion spring/damper, adjustable straps, and connectors.
- Incorporated ergonomic features such as lightweight materials, foam padding, and modular adjustments for different leg sizes.
- Ensured 1 Degree of Freedom (DOF) at the knee joint for flexion-extension motion .

The mechanical knee exoskeleton operates on the following principles The wearable knee exoskeleton operates on the principle of mechanical support and joint alignment to assist individuals with limited mobility. The exoskeleton is externally worn and designed to align precisely with the natural axis of the human knee. It incorporates mechanical linkages such as hinges, dampers, and spring mechanisms that facilitate the flexion and extension of the knee joint during walking, standing, or sitting activities. By mimicking the biomechanics of the human knee, the exoskeleton provides supportive torque that reduces the muscular effort required from the user. The device may also use passive or semi-active

components, like elastic bands or torsion springs, to store energy during limb movement and release it during propulsion, thereby enhancing walking efficiency.

The system is developed with ergonomics in mind, ensuring that it conforms comfortably to the user's leg while maintaining structural rigidity. This design ensures safe and effective movement assistance, especially for elderly individuals, patients undergoing physical rehabilitation, or those suffering from lower-limb weakness. Through careful mechanical optimization, the exoskeleton delivers mobility support while minimizing device weight and discomfort, making it suitable for prolonged daily use without reliance on complex electronics or active control systems hinge to provide controlled motion assistance while maintaining user comfort and safety.

3. SYSTEM ARCHITECTURE

The wearable exoskeleton knee joint system is a mechanically assisted orthotic device designed to support knee flexion and extension during walking, standing, and rehabilitation activities. The system integrates a DS servo RC digital servo motor, adjustable straps, and a mechanically aligned knee.

Table -1: Comparative Analysis of Designs

Design Type	Strengths	Limitations
Active (Motorized)	High torque, adaptable, useful for rehabilitation	Heavy, high power consumption
Passive (Spring-based)	Lightweight, low cost, maintenance-free	Limited assistance, fixed support
Hybrid (Semi-active)	Balance between adaptability and weight	Complex design, moderate cost

Mechanical Structure Description

1. Thigh Support Assembly

- Material:** High-strength polymer / aluminum alloy frame
- Function:** Anchors the system to the user's thigh and transfers reaction forces
- Features:**
 - Adjustable Velcro straps for secure fitting
 - Soft inner lining to prevent skin irritation
 - Rigid outer shell to support servo mounting

Approximate Dimensions:

- Length: 180–220 mm
- Width: 70–90 mm
- Thickness: 4–6 mm

2. Shank (Lower Leg) Support Assembly

- Material:** Polymer composite / aluminum plate

- Function:** Provides structural attachment below the knee

Features:

- Ergonomic curvature matching calf geometry
- Adjustable strap system
- Load transfer interface with knee joint

Approximate Dimensions:

- Length: 160–200 mm
- Width: 65–85 mm

3. Knee Joint Mechanism

1 Hinge Assembly

- Type:** Single-axis revolute joint
 - Degrees of Freedom:** 1 DOF (flexion–extension)
 - Axis Alignment:** Coaxial with anatomical knee axis
- Key Components:

- Steel / aluminum hinge shaft (Ø 10–12 mm)
- Deep groove ball bearings for smooth rotation
- Mechanical end stops to limit range of motion

2 Range of Motion (ROM)

- Extension:** 0–5°
- Flexion:** 0–120°
- Safety Limit:** Mechanical stops prevent hyperextension and over-flexion

4. Servo Motor Integration

1 Actuator Details

- Motor Type:** DSServo RC Digital Servo
 - Output Shaft:** Single-side spline shaft
 - Control:** PWM-based angular positioning
- Typical Specifications (Representative):
- Operating Voltage: 6–8.4 V
 - Stall Torque: 18–25 kg·cm
 - Speed: 0.12–0.16 s/60°
 - Gear Type: Metal gears

2 Servo-to-Joint Coupling Mechanism

- Coupling Method:** Direct horn-to-rotation plate connection
- Servo Horn:** CNC-machined aluminum horn
- Mounting:** Servo fixed to thigh frame via metal bracket

Design Principle:

- Servo transmits rotational torque only
- Bearings absorb axial and radial loads
- Prevents bending stress on servo shaft

5. Structural Load Path

Table - 2: Load Type Component

Load Type	Component Responsible
Body weight	Frame + bearings
Joint torque	Servo motor
Impact loads	Hinge + frame
Skin contact pressure	Soft lining & straps

6. Ergonomic and Safety Features

1 User Comfort

- Breathable foam padding
- Adjustable strap tension
- Anatomically contoured supports

2 Safety Provisions

- Mechanical end stops
- Electrical limit switches (optional)
- Emergency stop (controller level)
- Over current protection for servo

7. Manufacturing and Assembly Data

1 Manufacturing Processes

- CNC milling (hinge plates, servo brackets)
- Injection molding / 3D printing (support shells)
- Laser cutting (strap anchors)

2 Fasteners

- Bolts: M3–M5, Grade 8.8
- Shaft locking: Circlips / lock nuts
- Thread locking compound applied

Table - 3 : Parameter Value

Parameter	Value
Total weight (single leg)	1.5–2.2 kg
Load capacity	Up to 90 kg user
Continuous operation	30–45 min
Alignment tolerance	±1.5°

4. DISCUSSION

The frame of a rigid exoskeleton is constructed from rigid materials such as aluminum alloy, titanium alloy, or carbon fiber composites. This design provides the exoskeleton with high stiffness and bending strength, enabling it to withstand large loads while evenly distributing forces across the body to reduce localized pressure. The frame is typically designed based on the anatomical structure of the human limbs, with support structures designed along areas such as the legs or waist. Some full-sized exoskeletons can transfer the load to the ground through their structure. Compared to traditional rigid exoskeletons, flexible exoskeletons rely on lightweight, flexible structures and soft actuation technologies, which allow for a close fit with the human body while minimizing limitations on natural movement. In this study, we focus on analyzing soft exoskeletons driven by motors and cables as the source of assistance.

Table -4: Compression between Existing and Proposed

Parameter	Existing Passive Knee Braces	Existing Powered Exoskeletons (AI Motorized)	Proposed Wearable Exoskeleton Knee Joint Design
Actuation Type	None (purely passive)	High-power motors with sensors and AI control	RC digital servo-based assisted actuation
Control Strategy	No control	Complex AI / sensor-driven algorithms	Simple PWM-based positional control

Parameter	Existing Passive Knee Braces	Existing Powered Exoskeletons (AI Motorized)	Proposed Wearable Exoskeleton Knee Joint Design
Degree of Freedom	1 DOF (limited)	Multi-DOF	1 DOF (optimized for knee flexion–extension)
Weight	Very light (<1 kg)	Heavy (5–15 kg per leg)	Lightweight (≈1.5–2.2 kg per leg)
Cost	Low	Very high	Low to moderate
Power Requirement	None	High battery consumption	Low power consumption
Mechanical Complexity	Very low	Very high	Moderate and robust
Load Handling	Limited support	High load support	Medium load support suitable for mobility assistance
Joint Alignment	Often misaligned	Actively compensated	Anatomically aligned hinge
Safety Features	Limited	Software + hardware safety	Mechanical end stops + control limits
Maintenance	Minimal	High (electronics & software)	Low
Portability	High	Low	High
Ease of Use	Easy	Requires training	Easy to operate
Suitability for Rehabilitation	Limited	Advanced but costly	Suitable and affordable
Customization	Poor	Software-based	Mechanical adjustment
Failure Risk	Low	Higher (electronics dependent)	Low to moderate

5. Result Analysis

The performance of the proposed wearable exoskeleton knee joint was evaluated through design validation, structural analysis, range of motion assessment, and functional performance comparison with existing systems. The analysis focuses on mechanical integrity, motion compatibility, load-bearing capability, and overall usability.

Structural Performance Analysis

Finite Element Analysis (FEA) was conducted on critical components of the knee joint, including the hinge shaft, servo mounting bracket, and thigh–shank interface plates. The results indicated that the maximum von Mises stress values remained well below the yield strength of the selected materials (aluminum alloy and steel), ensuring structural safety under typical human gait loads. Maximum deformation occurred near

the joint interface but was within acceptable ergonomic limits, confirming the rigidity and reliability of the joint structure.

Range of Motion (ROM) Evaluation

The designed knee joint achieved a flexion range of approximately 0° to 120°, closely matching the natural human knee motion during walking and sit-to-stand activities. Mechanical end stops effectively restricted excessive flexion and hyperextension, enhancing user safety. The smooth rotation facilitated by bearing-supported hinges resulted in minimal friction and consistent angular motion.

Actuation and Torque Transmission Performance

The DSservo RC digital servo motor demonstrated effective torque delivery through the direct horn-to-joint coupling mechanism. The actuator was able to assist knee extension and flexion during simulated load conditions without experiencing stalling or overheating. The bearing-supported design ensured that the servo transmitted only rotational torque, preventing mechanical overloading of the motor shaft.

Load-Bearing and Stability Assessment

The exoskeleton structure successfully supported dynamic loads corresponding to an average adult user during assisted walking conditions. The thigh and shank frames distributed loads uniformly, reducing localized stress concentrations. The joint exhibited stable behavior without noticeable backlash or misalignment during repeated motion cycles.

Ergonomic and Comfort Evaluation

The adjustable strapping system and soft inner padding significantly improved wearer comfort during extended use. The ergonomic contour of the support frames minimized pressure points and allowed free movement of surrounding muscles. The lightweight design reduced fatigue, making the system suitable for prolonged rehabilitation or mobility assistance sessions.

Comparative Performance Analysis

Compared to passive knee braces, the proposed design offered active assistance and improved motion control. In contrast to fully powered exoskeleton systems, it achieved a favorable balance between functionality and simplicity, with lower weight, reduced power consumption, and easier maintenance. This positions the proposed system as a cost-effective and practical alternative for mobility assistance.



Fig. 1(c) – Servo Motor Mounting on Thigh Frame



Fig. 1(d) – Servo Horn and Knee Joint Coupling



Fig. 1(e) – Knee Hinge Assembly with controller and battery



Fig. 1(a) – Overall Wearable Knee Exoskeleton Assembly



Fig. 1(b) – Side View of Knee Joint Mechanism



Fig. 1(e) – Knee Hinge Assembly with controller and battery

Fig 1(a) illustrates the complete assembled view of the wearable knee exoskeleton system mounted on the human leg. The system consists of thigh and shank support frames connected through a mechanically aligned knee hinge. Adjustable Velcro straps and soft inner lining are visible, ensuring secure attachment and user comfort. The overall configuration demonstrates the compact and ergonomic nature of the design suitable for mobility assistance.

Fig 2.(b) presents the side view of the knee joint mechanism, highlighting the single-axis hinge aligned with the anatomical knee axis. The hinge assembly facilitates controlled flexion and extension while restricting unwanted rotational motions.

The placement of the actuator housing relative to the joint ensures efficient torque transmission without imposing structural loads on the motor shaft.

Fig 1 (c) shows the DSservo RC digital servo motor mounted on the thigh support frame using a rigid metallic bracket. The mounting configuration ensures that the servo body remains stationary relative to the thigh, while only the output shaft contributes to joint actuation. This arrangement minimizes vibration and improves motion stability.

Fig 1 (d) illustrates the mechanical coupling between the servo output shaft and the knee joint rotation plate. A metal servo horn is fixed onto the servo spline and bolted to the rotating knee plate, enabling direct torque transmission. This coupling method reduces backlash and enhances positioning accuracy.

Fig 1(e) depicts the internal hinge structure incorporating ball bearings. These bearings support axial and radial loads generated during walking, ensuring smooth rotation and protecting the servo motor from excessive mechanical stress. The thigh support structure with adjustable straps and soft padding. The design evenly distributes pressure over a larger surface area, enhancing comfort during prolonged usage.

Adjustable Strap and Velcro System

Presents a close-up view of the Velcro strap mechanism used for fastening the exoskeleton to the leg. The adjustable straps allow quick fitting for users with different leg dimensions.

Soft Inner Lining and Ergonomic Padding

Highlights the soft inner lining used at all user-contact points. The cushioning material minimizes skin irritation and pressure concentration, thereby improving long-term wear ability.

6. CONCLUSION

Wearable knee exoskeletons hold immense potential to restore mobility, support rehabilitation, and improve quality of life for millions of individuals worldwide. While significant advancements have been made in terms of mechanical design, materials, and actuation methods, there remain critical challenges related to weight, efficiency, cost, and adaptability. Future research must focus on lightweight, bio-inspired, and cost-effective solutions that combine ergonomics with performance, making knee exoskeletons suitable for both clinical rehabilitation and daily mobility assistance.

The soft exoskeleton is a wearable assistive device that provides support through flexible materials or cable systems. Compared to traditional rigid exoskeletons, flexible exoskeletons rely on lightweight, flexible structures and soft actuation technologies, which allow for a close fit with the human body while minimizing limitations on natural movement. In this study, we focus on analyzing soft exoskeletons driven by motors and Bowden cables as the source of assistance.

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