Chapter 2

Literature Review

Motorized exoskeletons are proving to be a transformative technology in the realm of rehabilitation, particularly for addressing joint mobility limitations arising from spinal cord injuries and strokes [?]. These devices provide a unique advantage over conventional therapy by enabling long, repetitive rehabilitation sessions that would be physically taxing for both patients and therapists using traditional methods [?].

While the concept of assisting or enhancing human movement is not new, the evolution of exoskeletons, especially those with motorized joints, marks a significant advancement. Early physiotherapy tools and devices primarily focused on passive support, such as knee braces used to stabilize injured joints. These braces, while helpful for immobilization and support, do not actively assist in movement. The development of active braces, incorporating elements like springs and shock absorbers, introduced a degree of dynamic assistance, but they still lacked the controlled and powered movement offered by motorized exoskeletons [?].

The transition from passive to active systems, resulting in the emergence of motorized exoskeletons, mirrors the progression in physiotherapy towards more dynamic and engaging treatment approaches. Motorized exoskeletons represent a convergence of robotics, engineering, and medical science, reflecting the increasingly sophisticated tools being employed in rehabilitation settings. This literature review aims to provide a comprehensive overview of motorized exoskeletons and their growing role in knee rehabilitation [?].

2.1 Types of Motorized Knee Braces and Exoskeletons

Knee braces and exoskeletons come in various types, each designed for specific applications in rehabilitation, particularly for conditions affecting gait. Passive knee braces are the most basic type, offering support and stabilization to the knee joint without providing active assistance in movement [?, ?]. They are commonly used during the initial stages of rehabilitation after injury or surgery, aiding in pain management and promoting healing by restricting movement in specific directions. Active-assisted knee braces incorporate elements such as springs, shock absorbers, or mechanical clutches to provide a degree of dynamic assistance to the user's movements [?]. These braces can store energy during specific phases of gait and release it during others, assisting with joint flexion or extension. Motorized exoskeletons represent the most technologically advanced category, using actuators powered by electricity, hydraulics, or pneumatics to generate assistive forces [?, ?]. This active power assistance distinguishes them from passive and active-assisted braces.

2.1.1 Applications of Knee Braces

Exoskeletons are developed for a wide range of applications, including medical rehabilitation, military, industrial, and consumer markets [?, ?, ?, ?]. In medical rehabilitation, exoskeletons play a crucial role in assisting patients with neurological or musculoskeletal impairments to regain mobility and improve muscle strength [?, ?]. These devices are designed to provide controlled assistance or resistance during therapeutic exercises, promoting motor relearning and functional recovery. Military exoskeletons aim to enhance soldiers' strength, endurance, and load-carrying capabilities [?, ?]. They are often robust, powerful, and designed to operate in challenging environments. In the industrial sector, exoskeletons are intended to reduce worker fatigue and the risk of injuries in physically demanding tasks, such as lifting heavy objects or performing repetitive motions [?]. These devices often focus on providing support to the back, shoulders, and legs. Lastly, consumer-oriented exoskeletons are emerging, targeting individuals seeking assistance with daily activities or those interested in enhancing their physical capabilities during recreational activities [?].

2.1.2 Key Differences Between Motorized Knee Braces and Exoskeletons

Motorized knee braces and other exoskeleton types can be distinguished based on their complexity, functionality, and control strategies. Motorized knee braces typically target a single joint, the knee, with the primary goal of assisting flexion and extension. In contrast, other exoskeleton types can be more complex, encompassing multiple joints in the lower limbs, such as the hip and ankle. This multi-joint design allows them to assist with a broader range of movements, including standing, walking, stair climbing, and squatting [?]. The control systems of motorized knee braces might be simpler than those of more complex exoskeletons. They might rely on pre-programmed gait patterns or use sensors to detect the user's movement and provide assistance accordingly [?]. More advanced exoskeletons could incorporate sophisticated control algorithms, machine learning, or even brain-computer interfaces [?, ?, ?] to achieve more natural and intuitive movement assistance.

2.2 Biomechanics of Motorized Knee Braces in Physiotherapy

The knee joint plays a crucial role in contributing to mechanical work during essential movements like walking and standing up [?]. The ability to flex and extend the knee through its full range of motion is vital for performing these activities. Muscle weakness, particularly in the quadriceps, can significantly hinder knee flexion and extension, making activities like walking and standing challenging [?, ?]. This emphasizes the importance of maintaining and restoring knee function in the context of injury recovery and overall mobility.

2.2.1 Restoring Mobility and Strength with Motorized Exoskeletons

Motorized exoskeletons can play a significant role in knee injury recovery by providing external support and assistance to the weakened muscles responsible for flexion and extension [?, ?]. This assistance can help patients regain their range of motion and relearn movement patterns [?]. One key benefit is the consistent and repeatable assistance that motorized exoskeletons can provide throughout the rehabilitation session, which is an advantage over manual therapy that can vary depending on the therapist's strength and fatigue [?]. Advanced exoskeletons also offer adapted assistance and resistance, adjusting the level of support based on the patient's performance and perceived exertion, allowing

for a tailored rehabilitation program [?]. This personalized approach can potentially lead to more effective training and faster recovery. While some exoskeletons offer passive motion, research suggests that active patient participation is crucial for effective rehabilitation [?, ?]. Motorized exoskeletons can encourage this active participation by providing assistance only when needed, prompting the patient to engage their muscles [?]. This approach ensures that patients are actively involved in their recovery process, which is essential for optimal rehabilitation outcomes.

2.2.2 Comparing Motorized and Manual-Assisted Therapy Outcomes

While acknowledging the potential benefits of motorized exoskeletons in knee rehabilitation, there is a notable lack of direct comparisons between the outcomes of motorized and manual-assisted therapy [?]. This absence of comparative studies makes it challenging to definitively claim the superiority of one approach over the other. More research is needed to establish clear evidence of the effectiveness of motorized exoskeletons compared to traditional methods. There is an emphasized need for more rigorous clinical trials to evaluate the efficacy of motorized exoskeletons in various patient populations and compare different treatment approaches. These studies would be crucial in determining the true value and effectiveness of motorized exoskeletons in knee rehabilitation, potentially shaping future treatment protocols and guidelines.

2.3 Applications of Motorized Knee Braces in Rehabilitation and Physiotherapy

Motorized knee braces are being studied and applied in various rehabilitation settings. In the context of ACL and meniscal tear rehabilitation, a systematic review found moderate-certainty evidence for the use of neuromuscular electrical stimulation (NMES) to improve quadriceps strength after ACL reconstruction surgery [?]. However, the same review found that postoperative knee bracing was ineffective for improving physical function or reducing laxity in individuals recovering from ACL reconstruction [?]. The study emphasizes the need for more high-quality research on rehabilitation interventions for these injuries [?].

In stroke rehabilitation, motorized knee exoskeletons show promise in assisting patients who often experience difficulty with knee control and stability during gait [?]. Studies

suggest that robotic-assisted therapy, including the use of knee exoskeletons, combined with conventional rehabilitation, can be beneficial for these individuals [?]. Specific examples of knee exoskeletons explored for stroke rehabilitation include ABLE-KS, Keeogo, and others discussed in various studies [?]. These exoskeletons can provide adapted assistance and resistance training, potentially leading to improvements in knee flexion, gait parameters, and overall functional mobility [?]. Knee braces are used for offloading the affected knee compartment and correcting joint malalignment in individuals with osteoarthritis [?]. The focus is primarily on passive or less technologically advanced braces for this purpose.

Motorized knee exoskeletons are also being explored for other applications, including pediatric rehabilitation, such as gait training in children with cerebral palsy [?]. De Miguel Fernández et al briefly mention the use of exoskeletons in military and industrial settings for tasks requiring heavy lifting [?]. These diverse applications highlight the potential versatility of motorized knee braces in various rehabilitation and physiotherapy contexts.

2.4 Technological Components and Design

Motorized knee braces integrate advanced engineering and biomechanics to assist users with mobility. These devices typically comprise microcontrollers, motors, sensors, and actuators, working together to provide responsive support. Design considerations include biomimetic features like polycentric joints [?, ?, ?] and adaptive control algorithms [?, ?]. Recent advancements in materials and soft robotics [?, ?] are driving the development of more comfortable and efficient devices. This section explores the key components, design features, and emerging trends in motorized knee brace technology.

2.4.1 Sensors

Motorized knee braces incorporate various sensors to monitor user motion and provide data for the control system. Inertial Measurement Units (IMUs) are commonly used to track the wearer's movements and estimate gait parameters. IMUs typically consist of accelerometers, gyroscopes, and magnetometers, which measure linear acceleration, angular velocity, and orientation respectively. By combining data from these sensors, IMUs enable the control system to determine knee joint angles, angular velocities, and

acceleration profiles, allowing for real-time gait analysis and assistance. For example, in [?], four IMUs are installed on the thigh and shank to detect the movement status of the user's lower limbs in real time.

Force and torque sensors measure the forces and torques applied at the knee joint, which is crucial for implementing force control strategies and estimating the user's intended movement. Some designs incorporate force/torque sensors directly into the knee joint structure to measure interaction forces between the brace and the user's leg [?]. Plantar pressure sensors, embedded in the insole of the shoe, measure the pressure distribution under the foot. These sensors provide valuable information about the user's gait cycle, including heel strike and toe-off detection, and center of pressure (COP) measurement, offering insights into balance and gait stability [?].

Angle sensors, such as incremental encoders, are commonly used to measure the angular position and velocity of the knee joint. By tracking the rotation of the joint, encoders provide feedback to the control system, enabling precise position and velocity control of the motor [?]. Rotary encoders are also utilized to measure the actual knee angle, enhancing the accuracy of joint alignment and control [?].

The specific types and configurations of sensors used in motorized knee braces vary depending on the design objectives, target user group, and control strategies employed. The integration of multiple sensor modalities allows for a more comprehensive understanding of user motion, enabling the development of sophisticated control algorithms and ultimately contributing to a more effective and personalized assistive or rehabilitative experience.

2.4.2 Actuators and Motors

Actuators in motorized knee braces play a crucial role in powering and controlling these devices. Electric motors are a prevalent choice due to their controllability, efficiency, and responsiveness. Brushless DC Motors (BLDC) are favored in many designs due to their high power-to-weight ratio, efficiency, reliability, and precise control capabilities [?, ?]. These characteristics make them well-suited for wearable applications where weight, battery life, and accurate assistance are crucial. For instance, one study utilized a compact BLDC motor with a transmission system incorporating a ball screw, cable drive, belt transmission, and gear motor to achieve a high torque output of 18 N m for a knee exoskeleton [?]. Besides BLDC motors, other electric motor technologies, such as DC motors coupled with ball screws, are also employed in some knee exoskeletons [?, ?].

Pneumatic actuators, which utilize compressed air to generate force, offer advantages in terms of lightweight, compliance, and inherent safety. Pneumatic Artificial Muscles (PAMs) are one type of pneumatic actuator that contracts when filled with compressed air, known for their lightweight, compliance, and inherent safety [?, ?, ?]. Another study explored the use of vacuum-actuated rotary actuators in a soft knee exoskeleton [?], utilizing negative pressure to generate rotational motion.

Series Elastic Actuators (SEAs) combine an electric motor with a spring in series, enabling more compliant and energy-efficient actuation. The spring acts as a buffer, absorbing shock and storing energy during certain phases of movement [?, ?]. SEAs have been researched in the context of lower-limb exoskeletons, including a design incorporating a Bowden cable driven by SEAs to assist knee flexion and extension [?].

The selection of an actuator for a motorized knee brace depends on factors like power and torque requirements, weight and size constraints, controllability and responsiveness, energy efficiency, and the specific application requirements [?]. Actuators are often paired with transmission systems to amplify torque output, achieve the desired range of motion, and optimize performance. Commonly used transmission systems include harmonic drives, planetary gearboxes, cable drives, and belt transmissions [?, ?]. For example, a knee exoskeleton designed for energy harvesting utilized a complex transmission system involving gears, a ratchet mechanism, and a planetary gearbox to capture negative work from the wearer's knee motion during specific gait phases [?].

The development of actuators for motorized knee braces involves a careful consideration of various factors to achieve a balance between performance, weight, efficiency, and user comfort. The choice of actuator technology can significantly influence the device's overall functionality and therapeutic effectiveness.

2.4.3 Materials and Structural Design

Materials and structural design play crucial roles in the development of motorized knee braces, with emphasis on weight reduction, durability, comfort, and alignment with human anatomy. Lightweight materials are a primary focus to minimize the metabolic burden on the wearer. Polycarbonate, known for its strength and biocompatibility, is suitable for fabricating structural components [?]. Aluminum and titanium, with their high strength-to-weight ratios, are commonly used in knee exoskeletons [?]. PLA, a biodegradable and biocompatible plastic, offers design flexibility through 3D printing for

customized fabrication [**?**].

Soft materials are integrated to enhance comfort and adaptability. Adjustable straps and foam padding secure the device and provide cushioning [**?**, **?**, **?**]. Some designs incorporate resistant textiles to create soft exosuits that conform to the body's shape, with strategically placed pneumatic actuators for assistive forces [**?**].

Structural design significantly influences functionality, comfort, and alignment with natural knee movement. Anatomical considerations are crucial, often involving multi-linkage systems like four-bar linkages to replicate the knee's polycentric motion [**?**, **?**]. Bio-inspired designs aim to closely mimic anatomical features and movement patterns, such as adjusting the knee joint center position relative to the femur and tibia based on joint angle [**?**].

Adjustability features accommodate different body sizes and limb alignments through adjustable straps, telescoping segments, and joint axes [**?**, **?**]. Customization through 3D printing allows for patient-specific braces [**?**]. However, challenges persist in structural design, including soft tissue movement affecting alignment [**?**], the need for accurate joint axis alignment [**?**], and balancing functionality with size and weight constraints [**?**].

Ongoing research continues to explore innovative materials, fabrication techniques, and design approaches to address these challenges and develop more effective, user-friendly motorized knee braces.

2.4.4 Design Features and Resistance/Assistance Mechanisms

Design features and resistance/assistance mechanisms in motorized knee braces focus on active systems designed for rehabilitation, with several key aspects being emphasized. Polycentric joints are highlighted as important for replicating the natural biomechanics of the knee joint [**?**, **?**, **?**]. This biomimicry often involves using polycentric joint designs that more accurately mimic the complex motion of the human knee, including its slight translational movements during flexion and extension, potentially improving comfort and effectiveness. Adaptive control algorithms are also crucial, with sources highlighting the importance of control systems that can adapt to the user's needs and abilities [**?**, **?**, **?**, **?**]. These adaptive algorithms might adjust the level of assistance or resistance based on the user's performance, gait phase, or perceived exertion, creating a more personalized and responsive rehabilitation experience.

Wilmart et al provide some insights into advances in materials and control systems. The use of lightweight materials, such as carbon fiber, is mentioned in the context of reducing the weight of exoskeletons [?]. This reduction in weight can improve user comfort and reduce the energy required for movement. Additionally, the field of soft robotics is briefly touched upon, with one source mentioning the development of soft exoskeletons using flexible materials and pneumatic actuators [?]. This emerging field holds promise for creating more comfortable and adaptable exoskeletons, potentially suitable for a wider range of users.

2.5 Advancements and Emerging Trends

Research in motorized knee braces and exoskeletons is advancing rapidly, with a focus on enhancing user experience, improving treatment efficacy, and expanding applications for rehabilitation and locomotion assistance. Design advancements are moving beyond simple hinge mechanisms to more closely mimic natural knee movement. Polycentric joint designs for knee exoskeletons aim to replicate the translational movement of the human knee during flexion and extension [?]. Self-aligning mechanisms are being developed to automatically adjust alignment with the user's knee, improving fit and reducing complications [?, ?]. Soft exosuits utilizing flexible materials and pneumatic actuators offer enhanced comfort and adaptability [?, ?].

Technological improvements incorporate smart sensors, AI integration, and adaptive control systems. IMUs provide real-time motion tracking [?], while foot pressure sensors gather data on gait cycles and balance [?]. Torque sensors enable precise control of assistance levels [?]. AI integration is emerging as a trend, enabling personalized assistance and gait adaptation [?]. Adaptive control systems optimize functionality by continuously adjusting assistance based on sensor feedback, detecting gait phases, and adapting to individual user capabilities [?, ?, ?, ?, ?].

These advancements, combining sophisticated sensors, bio-inspired designs, and cutting-edge materials, are driving the creation of more intelligent, comfortable, and effective motorized knee braces and exoskeletons. This evolution holds significant potential for transforming rehabilitation practices, enhancing mobility, and improving quality of life for individuals with mobility impairments.