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Restoring Mobility and Independence: Evaluating the Impact of Knee Exoskeletons in Real-World Scenarios

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ABSTRACT

This review paper provides a comprehensive overview of knee exoskeletons, covering their diverse applications in movement assistance, body weight support, and rehabilitation. By synthesizing current literature and analyzing recent advancements, this paper serves as a valuable resource for researchers, engineers, and healthcare professionals interested in the field of knee exoskeleton technology. The review highlights the challenges and opportunities associated with knee exoskeletons, drawing attention to areas that require further research and development. Additionally, the paper identifies the importance of lightweight and ergonomic design considerations to enhance user comfort and acceptance. Moreover, the review paper addresses the potential societal impact of knee exoskeletons. By enabling individuals with mobility impairments to regain independence and participate more actively in society, these technological advancements have the potential to enhance the overall quality of life for millions of people worldwide. Furthermore, the integration of knee exoskeletons in rehabilitation settings offers new avenues for improving the effectiveness and efficiency of therapy, potentially reducing the burden on healthcare systems. By shedding light on the current state of knee exoskeleton research and development, this review paper aims to inspire further innovation and collaboration within the scientific community. It serves as a catalyst for interdisciplinary approaches, encouraging researchers from fields such as robotics, biomechanics, and rehabilitation to collaborate and leverage their expertise to advance the capabilities and applications of knee exoskeleton technology. Ultimately, this collective effort will lead to the creation of more sophisticated, user-friendly, and clinically effective knee exoskeletons, revolutionizing the field of human augmentation and positively impacting the lives of individuals with mobility challenges.

Keywords: Knee exoskeletons, rehabilitation, body weight support, movement assistance

1 Introduction

In recent years, the development and utilization of assistive technologies have garnered significant attention in the field of healthcare [1-2]. Among these technologies, knee exoskeletons have emerged as a promising solution for addressing the needs of individuals with knee impairments, injuries, or

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conditions. These innovative devices provide mechanical support, augmenting the function of the knee joint and aiding in the restoration of mobility [3-4]. This review emphasizes knee exoskeletons' importance for improving the quality of life and rehabilitation for people with knee-related ailments. Knee-related conditions, such as osteoarthritis, ligament injuries, and postoperative rehabilitation, pose significant challenges to patients, affecting their ability to perform daily activities and impeding their overall well-being [5-7]. Traditional treatment approaches, including physical therapy and pharmacological interventions, have limitations in terms of their effectiveness and long-term outcomes [8]. Consequently, there is a growing need for alternative interventions that can effectively address the limitations associated with knee impairments [9].

Knee exoskeletons, as wearable robotic devices designed to enhance human performance and assist with movement, have shown considerable promise in fulfilling this need [10-11]. By providing mechanical support and assisting in the movement of the knee joint, these exoskeletons have the potential to reduce pain, enhance stability, and restore functional mobility for individuals with knee-related conditions [12]. Moreover, the development of rehabilitation-focused knee exoskeletons has opened up new possibilities for therapeutic interventions and accelerated recovery [13]. Rehabilitation is a crucial aspect of knee-related conditions, aiming to improve patients' functional abilities and promote their independence [14]. Traditional rehabilitation methods often rely on manual assistance and repetitive exercises, which may lead to suboptimal outcomes due to variations in therapist skill and patient compliance [15]. Integrating knee exoskeletons into rehabilitation protocols offers several advantages, including standardized assistance, real-time feedback, and personalized adjustments based on individual needs. These features can significantly enhance the effectiveness of rehabilitation interventions, leading to improved patient outcomes and greater overall satisfaction [16].

This review paper consolidates recent advancements and findings in the field of knee exoskeletons, focusing on their importance and the benefits they provide for patients with knee-related conditions. By examining the current state of the art and highlighting notable studies, this review aims to provide a comprehensive overview of the potential of knee exoskeletons in addressing the needs of individuals with knee impairments and their role in rehabilitation. In general, the exploration of knee exoskeletons in this review paper aims to contribute to the existing body of knowledge, fostering a deeper understanding of their applications, limitations, and future directions. By elucidating the significance of knee exoskeletons and their potential benefits in the context of knee-related conditions, this review intends to facilitate informed decision-making among clinicians, researchers, and stakeholders, ultimately promoting the development and adoption of these innovative technologies in the field of healthcare.

2 Taxonomy of Previous Studies

Knee exoskeletons hold immense importance in both medical and engineering domains. They provide innovative solutions for individuals with physical impairments, offering enhanced mobility and functional assistance. Through a combination of medical expertise and engineering prowess, exoskeletons have the potential to revolutionize rehabilitation practices and improve the quality of life for many individuals worldwide. Thus, knee exoskeletons have captured the attention of researchers in recent years. In this section, the design and working principles of innovative knee exoskeletons presented in the open literature were extensively discussed, with a specific focus on their application for movement assistance, body weight support, and rehabilitation purposes.

2.1 Knee Exoskeletons for Movement Assistance

Knee exoskeletons designed for movement assistance have gained significant importance in research and clinical settings. These devices play a crucial role in enhancing mobility and functional independence for individuals with physical impairments. Extensive research in the literature highlights their potential in improving gait patterns, reducing joint loads, and promoting rehabilitation outcomes. There are many studies available in the open literature (see Figure 1). For example; Dollar et al. (2008) designed a semi-passive knee exoskeleton that facilitated running. Torque was provided with springs and DC motors. It was obtained that the load required to drive the actuator back was approximately 180 N, indicating that it reduced the torque needed to secure the spring, which served as a support during the motor's idle state [17]. Kong et al. (2011) designed a knee exoskeleton to assist human movements. The proposed system consisted of a DC motor, worm gear, a spur gear, a torsion spring, and two encoders. The maximum power consumed by the knee joint was approximately 80 watts. Consequently, it was found that the responses were distributed at frequencies above 180 rad/s, attributed to motor saturation [18]. Saccares et al. (2011) developed a system that predicts torque in knee joints to generate reference signals for devices assisting knee movement. It was observed that torque references corresponding to approximately 20% of the predicted knee torques were provided [19]. Ma et al. (2013) developed a strengthened knee orthosis for the elderly and patients with walking difficulties. The knee orthosis was fabricated from very low density polyethylene in order to conform to the shape of the human limb. It was used a 50CPR encoder and an external angle sensor for the determination of absolute knee angles. Moreover, embedded power sensors were used to control the input current and voltage in order to measure the motor torque and power. In conclusion, it has been obtained that the assistive knee brace can provide appropriate additional torque to support a normal reference pattern and human walking [20]. Gregorczyk et al. (2014) presented a quasi-passive knee exoskeleton that was designed to investigate the biomechanics of the knee joint during interaction with external impedances. The exoskeleton implemented a spring mechanism in the weight acceptance phase of the gait, allowing free motion throughout the rest of the gait cycle. Validation tests were conducted on a mechanical knee simulator, and preliminary experiments were performed on healthy adults, demonstrating that the exoskeleton assistance could partially or fully replace the function of the knee joint, resulting in consistent moment and angle profiles for other joints. These findings indicated significant motor adaptation in response to the exoskeleton's impedance, encouraging further comprehensive experiments with the device [21]. Eliott et al. (2014) introduced a parallel-elastic exoskeleton design with a clutch mechanism that enables natural kinematics during the swing phase of running by disengaging the parallel leg-spring. The design incorporates an interference clutch with an integrated planetary gear transmission, capable of withstanding high torque and low mass requirements. A control strategy utilizing onboard rate gyroscope and joint encoder sensors is implemented to lock the clutch at peak knee extension. The electromechanics, sensing, and control of the exoskeleton effectively meet the design criteria necessary to replicate the stiffness behaviors of the biological knee during running [22]. Rifaï et al. (2016) designed a knee joint exoskeleton to assist patients and the elderly in completing their daily life activities. It includes a brushless DC motor capable of providing torque up to 52 N.m. The exoskeleton was equipped with an incremental encoder that measures the angle of the knee joint, denoted as θ. Based on the experimental results, it was observed that the control torque reached an average of 8.47 Nm and a maximum of 17.6 Nm [23].

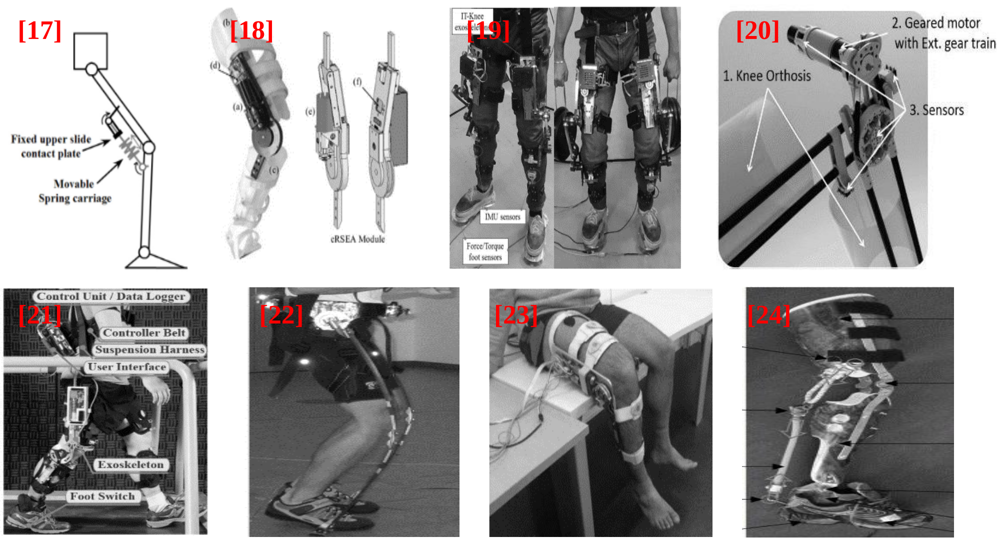

Figure 1: Structure configuration of some knee exoskeletons for movement assistance

Malcolm et al. (2018) compared the effects of a bi-articular and spring configuration that mimicked the m. gastrocnemius with a no-spring and mono-articular configuration in knee-ankle-foot exoskeletons. Nine participants were tested, and the bi-articular plus spring condition resulted in the highest reduction in metabolic cost (13%) compared to walking with the exoskeleton powered off. The bi-articular configurations reduced m. gastrocnemius EMG more than the mono-articular condition. These findings suggest that the utilization of a bi-articular configuration with a spring has the potential to improve metabolic efficiency and muscle activation in gait rehabilitation [24].

2.2 Knee Exoskeletons for Body Weight Support

Knee exoskeletons designed for body weight support are of utmost significance both in research and the literature. The open literature offers an abundance of studies (see Figure 2). For example, Beyl et al. (2011) developed a powered knee exoskeleton (KNEXO) to evaluate concepts in robot-assisted gait rehabilitation. Treadmill walking experiments were conducted with unimpaired subjects wearing KNEXO to assess the performance of the trajectory-based and torque controllers. The results demonstrated that KNEXO was capable of generating low torques during unassisted walking and providing safe and adaptable guidance in assisted mode. Pilot experiments with a multiple sclerosis patient showed that, with patient-specific controller tuning, KNEXO effectively supported and guided the knee [25]. Lee et al. (2015) presented a weight-support lower-extremity exoskeleton (LEE) design with a compliant knee joint that alleviated compressive load. The design incorporated a compliant exoskeleton knee-joint achieved through topology optimization, which was experimentally evaluated. The results indicated that the gait-based design of the LEE could be divided into two aspects: compliant coupling and body-weight support. The feasibility of the concept and the dynamic models of the passive LEE design were experimentally validated, demonstrating the effectiveness of the exoskeleton in supporting body-weight during walking and providing insights into computing internal knee forces [26]. Yuan et al. (2017) focused on designing an unpowered knee-assisting exoskeleton for weight-bearing that utilized Teflon string, pulley, and compression spring. The biomechanical analysis revealed that the knee-flexion angle could determine the type of locomotion, with a maximum flexion angle of 60º during level walking. The eccentric contour of the pulley was designed to provide nonlinear assistance torque based on the knee-flexion angle. The mechanical modeling and experimental results demonstrated that the passive exoskeleton exhibited multi-stage nonlinear assistance, offering minimal assistance during level walking and significant assistance during climbing [27]. Rogers et al. (2017) designed a pneumatic based exoskeleton for muscle activity of the knee extensors. In a preliminary evaluation with a single healthy subject, the device demonstrated a 15% decrease in rectus femoris EMG activity and an 8% increase in vastus medialis EMG activity [28]. Fan et al. (2017) designed a novel knee joint exoskeleton, which included a mechanical structure and hydraulic damper. The paper presented various studies conducted to determine the spring parameters of the exoskeleton and verify its effectiveness. These studies included forward kinematics analysis, Lagrange dynamics analysis, 3D modeling, ADAMS simulation, and comparison of moments from different sources. The results demonstrated good agreement and validated the effectiveness of the ADAMS simulation, confirming that the parameters of the hydraulic damper met the actual requirements. The simulation analysis provided essential parameters for manufacturing and served as a theoretical basis for subsequent control theory [29]. Niu et al. (2018) proposed a novel knee exoskeleton design based on a five-bar mechanism to mitigate or eliminate the misalignment. The incorporation of compliant joints between the bars allowed for adjustable stiffness and passive flexibility, accommodating the posture of the human knee joint. Kinematic analysis validated the anticipated mechanism characteristics and demonstrated the utilization of a stiffness matrix [30]. Wang et al. (2021) proposed a knee exoskeleton with an adaptive instantaneous rotation center and impact absorption for rehabilitation. They designed a novel knee exoskeleton mechanism to accommodate the physiological structure and motion characteristics of the human knee joint. The mechanism utilized a cross-configuration and calculated the stiffness of the springs based on gait motion, minimizing the average force exerted on the human body. An adaptive controller was developed to overcome uncertainties in parameters and ensure system stability, as verified through a Lyapunov stability analysis. Simulation and experimental results demonstrated the effectiveness of the controller, with a tracking error within the range of −1 to 1 degree for the knee joint angle [31]. Long et al. (2022) designed and controlled a portable and lightweight knee exoskeleton for individuals with knee dysfunction. The exoskeleton utilized a custom quasi-direct drive actuation and a transmission mechanism with three gears. They proposed an online gait generation method based on step calculation and direct measurement using IMU sensors, enabling continuous assistance during walking. The control system employed Active Disturbance Rejection Control with feedforward compensation to account for external disturbances. Experimental results showed that the knee exoskeleton provided successful assistance, with a maximum target knee angular position of approximately 50° and a control torque range of [-2 Nm, 4 Nm]. The developed exoskeleton demonstrated the potential to improve strength and endurance for individuals in their daily activities by restoring normal gait [32].

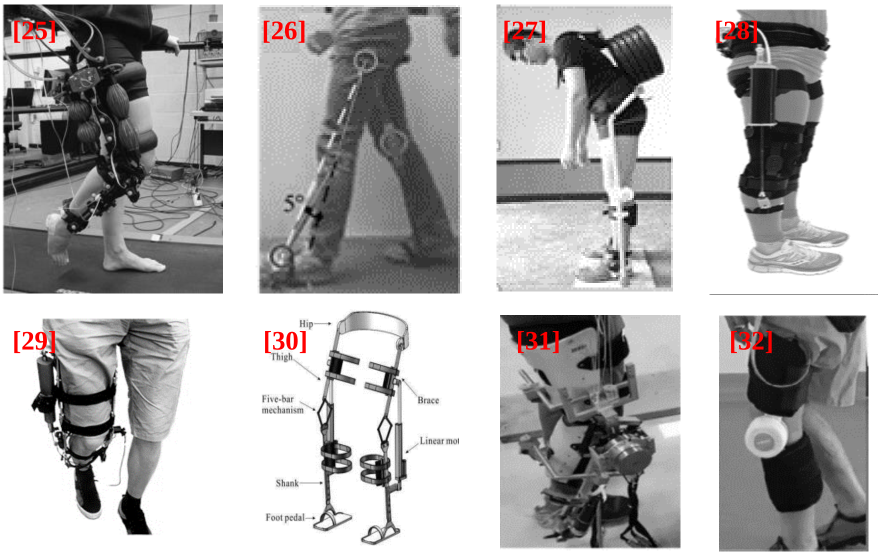

Figure 2: Structure configuration of some knee exoskeletons for body weight support

2.3 Rehabilitation Applications of Knee Exoskeletons

Knee exoskeletons are important for rehabilitation due to their ability to provide mechanical assistance and support to individuals with knee injuries or disabilities. These devices play a crucial role in promoting early mobilization, improving gait training, enhancing muscle activation, and ultimately facilitating better functional outcomes. The growing interest of researchers in knee exoskeletons is evident in the literature, highlighting their significance as a promising tool in the field of rehabilitation. It is worth mentioning that an extensive collection of studies is accessible in the open literature (see Figure 3), for example; Pratt et al. (2004) presented a one-degree-of-freedom exoskeleton that achieved high transparency by determining user intent through knee joint angle and ground reaction forces. The device applied torque across the knee, allowing the user's quadriceps muscles to relax, and utilized series elastic actuators to achieve low impedance. The presented exoskeleton enabled the wearer to climb stairs, perform deep knee bends, and carry a significant load while providing energy against gravity and maintaining user control for walking and balance [33]. Ergin et al. (2011) presented a novel active device for robot-assisted rehabilitation that accommodated transitional movements and rotation of the knee joint, ensuring alignment between human joint axes and device axes. The joint axes were automatically adjusted, guaranteeing ergonomics and comfort throughout the therapy and extending the usable range of motion for the knee joint. Moreover, the adjustability feature significantly shortened the setup time required to attach the patient to the exoskeleton, allowing for more effective exercise time. The proposed system differed from previous works by supporting both passive translational movements and independent active control of the knee joint. The prototype featured a compact design and utilized three actuators to achieve high rotational torques. A model-based impedance controller was employed to adjust interaction forces, and the exoskeleton underwent experimental characterization [34]. Huang et al. (2012) proposed a novel backdrivable torsion spring actuator (BTSA) with hybrid control for rehabilitation training and walking assistance. The BTSA integrated direct EMG biofeedback control and zero impedance control, allowing for simultaneous consideration of physical interaction, safety, and performance. The proposed mechanism achieved intrinsic safety, compliance properties, and desirable backdrivable characteristics, providing a unique approach that combined assistance control through EMG biofeedback and compliance control through zero impedance control. Simulation and experimental results demonstrated the effectiveness of the BTSA with hybrid control in achieving the desired properties [35]. Karavas et al. (2013) presented a knee exoskeleton device and its tele-impedance based assistive control scheme. The exoskeleton utilized series elastic actuation for improved and inherently compliant interaction. The paper described the exoskeleton design, the development of a musculoskeletal model, and the utilization of electromyographic signals to determine user intent and joint stiffness. The proposed tele-impedance controller effectively provided assistance and stiffness augmentation to the user's knee joint, as demonstrated in experimental trials evaluating a standing-up motion task. The results indicated that the exoskeleton device and control scheme offered natural and user-controlled assistive actions [36]. Ren et al. (2014) presented the development of a novel assistive system, FEXO knee, which combined functional electrical stimulation (FES) and a compliant exoskeleton for enhanced knee joint rehabilitation. The study focused on controlling rhythmic movements, specifically the shank swing, to showcase the effectiveness of the hybrid FES-exoskeleton approach. The research contributed by demonstrating the synergistic interaction between the exoskeleton and FES, utilizing muscle stimulation for active torque generation, and incorporating a central pattern generator for phase prediction. Initial evaluation experiments with healthy subjects demonstrated the promising performance of the hybrid FES-exoskeleton system [37]. Liao et al. (2015) developed a bionic knee exoskeleton for rehabilitation applications. The knee exoskeleton featured a mechanical structure that followed an anthropomorphic design, facilitating tibial movement through either rolling or sliding mechanisms along the femoral axis during joint articulation. Additionally, the proposed exoskeleton included a synchronous motor, a symmetrical wearable body, a fastening mechanism, and a DC motor. Consequently, the proposed mechanical exoskeleton allowed for both directions of movement to be actuated, covering the entire range of motion observed in a healthy knee joint [38]. Chen et al. (2016) presented a compact, modular, and portable knee-ankle-foot robot for stroke patients to conduct overground gait training in outpatient and home settings. The robot incorporated a novel compact series elastic actuator designed for safe human-robot interactions, utilizing low-stiffness translational and high-stiffness torsion springs to maintain compliance throughout a gait cycle while delivering peak force. The optimized mechanical design, lightweight materials, and stable force control enabled effective assistive force during overground walking, as demonstrated by reduced muscle activation and maintenance of a normal gait pattern in experiments with healthy subjects [39]. Kamali et al. (2016) presented a knee exoskeleton robot that was designed to assist individuals with lower extremity weakness or disability during the sit-to-stand movement. The study proposed a novel method for generating trajectories using a library of sample trajectories based on initial sitting conditions, utilizing dynamic movement primitives. An exponential sliding mode controller was employed to guide the robot along the predicted trajectory. The hardware development involved the use of MATLAB's xPC Target toolbox and a data acquisition card. Experimental tests with a male adult showed that the exoskeleton reduced the average power required by the user's knee during sit-to-stand movements [40]. Witte et al. (2017) designed and constructed a tethered knee exoskeleton with a lightweight frame and comfortable four-point leg contact. The exoskeleton, weighing 0.76 kg, featured structural compliance, joint angle, and torque measurement capabilities, and was actuated by two off-board motors. Through torque control using proportional feedback with damping injection and iterative learning, the exoskeleton achieved accurate torque measurement with low RMS error and demonstrated effective torque tracking during treadmill walking. The authors intended to utilize this knee exoskeleton to explore robotic assistance strategies for enhancing gait rehabilitation and human athletic performance [41]. Khamar et al. (2018) designed a knee exoskeleton that assisted knee flexion/extension movements and proposed a control method based on a nonlinear disturbance observer (NDO) and backstepping sliding control (BSC). The integrated human shank and exoskeleton model took into account the sitting position, and the NDO was employed to reduce the impact of uncertainties and external disturbances in the system modeling. The BSC, combined with the nonlinear observer and optimized using a genetic algorithm (GA), demonstrated improved performance in terms of reducing disturbance rejection time, chattering, and tracking error. Simulation and experimental results confirmed the effectiveness of the proposed controller in accurately tracking reference positions while considering identification errors and external disturbances [42]. Lyu et al. (2019) developed an EMG-controlled knee exoskeleton for home use, aimed at assisting stroke patients in their rehabilitation. The exoskeleton utilized an easy-to-don EMG sensor to acquire and process the subject's EMG signals using a Kalman filter, enabling autonomous control. A new game design was introduced to enhance patient engagement in the training process. Initial tests with healthy subjects demonstrated the feasibility of using EMG signals to control the exoskeleton, with subjects showing improved control performance and increased game scores after 20-block training. The setup process was simplified, and the time lag of EMG signal processing was significantly reduced, making this rehabilitation tool suitable for home use without the need for a therapist. It had the potential to enhance rehabilitation intensity and outcomes in the early phase of stroke rehabilitation [43]. Thomas et al. (2021) provided a review of the lower extremity musculature around the knee and proposed a design for a lower extremity knee exoskeleton. The review emphasized the geometry of the musculature, which served as the basis for the proposed device design. The exoskeleton aimed to create a mechanical advantage at the knee joint to assist individuals with quadriceps weakness or atrophy caused by knee conditions such as Osteoarthritis or Patellofemoral Pain Syndrome. Physical testing and model calculations were conducted to assess the strength capacity and function of the design, and the results showed significant similarity to the body's calculated maximum applied moment, particularly with the nonlinear model [44].

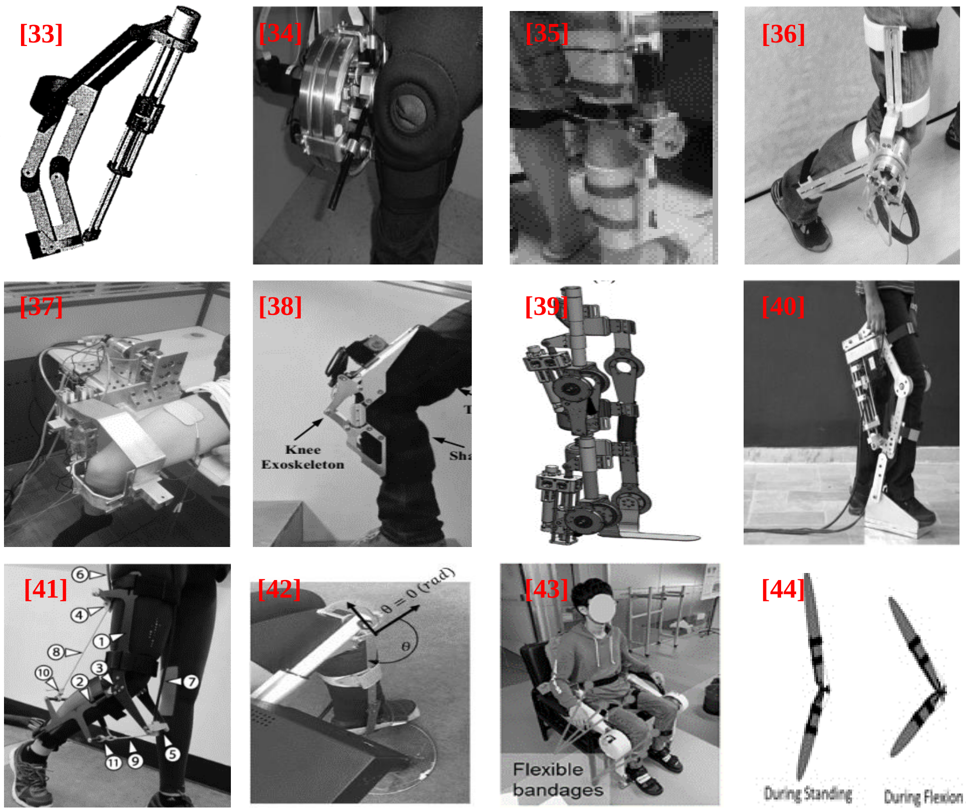

Figure 3: Structure configuration of some knee exoskeletons for rehabilitation applications

3 Conclusions

In conclusion, knee exoskeletons have emerged as a promising technology with significant potential for enhancing the rehabilitation process and improving the quality of life for individuals with knee-related impairments. Through a comprehensive review of recent literature, it is evident that knee exoskeletons offer several key benefits. First and foremost, knee exoskeletons provide mechanical support and assistance, thereby reducing the load on the affected knee joint during movement. This support can alleviate pain, enhance stability, and promote proper biomechanics, facilitating the recovery and rehabilitation of patients with knee injuries or conditions. The ability to customize the level of assistance based on individual needs and progression further highlights the versatility of knee exoskeletons as a rehabilitation tool. Moreover, knee exoskeletons enable early mobilization and intensive training, which are crucial for promoting muscle strength, range of motion, and functional recovery. By facilitating repetitive and controlled movements, these devices can enhance neuromuscular activation, proprioception, and coordination, ultimately leading to improved gait patterns and functional outcomes. The integration of advanced sensing and control mechanisms in knee exoskeletons allows for real-time monitoring and adjustment of the assistive forces, ensuring optimal assistance and adaptability to changing user requirements. This technological advancement, combined with user-friendly interfaces and intuitive designs, promotes user acceptance and compliance with the rehabilitation process. Furthermore, the utilization of knee exoskeletons in a rehabilitation setting has the potential to enhance patient engagement and motivation. The provision of immediate feedback, gamification elements, and interactive training scenarios can create an engaging and enjoyable rehabilitation experience. This aspect is particularly important as it addresses the psychological and emotional aspects of recovery, encouraging patients to actively participate in their rehabilitation journey. As for the implications of this review, it is expected to provide valuable insights and guidance to researchers and practitioners in the field of rehabilitation and knee exoskeletons. The synthesized findings underscore the potential of knee exoskeletons in improving clinical outcomes, emphasizing the need for further research and development in this area. Moreover, this review highlights the importance of multidisciplinary collaborations, involving experts from biomechanics, robotics, physiotherapy, and clinical domains, to advance the design and implementation of knee exoskeletons for effective rehabilitation. Further research and development efforts are warranted to optimize the design, control, and clinical integration of these devices, ensuring their widespread availability and accessibility for the benefit of patients worldwide.

4 Declarations

4.1 Study Limitations

None.

4.2 Acknowledgements

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4.3 Funding Source

None.

4.4 Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

4.5 Authors’ Contributions

Hamid ASADI DERESHGI provided supervision and guidance throughout the review process, ensuring the methodological rigor and integrity of the study. He participated in the conceptualization and design of the review, critically reviewed and revised the manuscript, and provided valuable intellectual contributions. He offered expertise in the field of knee exoskeletons and contributed to the final approval of the manuscript.

Ersin GOSE assisted in the conception and design of the review study, contributed to the selection and screening of relevant literature, and provided critical revisions to the manuscript for important intellectual content. He played a key role in synthesizing the information from the reviewed papers and ensuring the coherence of the narrative.

Dilan DEMIR contributed to the critical evaluation and synthesis of the reviewed literature, ensuring the accuracy and integrity of the information presented.

Hasan GHANNAM contributed to the data collection process by identifying and retrieving relevant papers, and contributed to the development of figures included in the manuscript.

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