Heliyon 10 (2024) e26060

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Advances in active knee brace technology: A review of gait analysis, actuation, and control applications

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ARTICLE INFO

Keywords:
Active knee brace
Normal gait
Sensors
Actuators
Control strategies)

ABSTRACT

This article discusses the significance of knee joint mechanics and the consequences of knee dysfunctions on an individual's quality of life. The utilization of active knee braces, which incorporate concepts of mechatronics systems, is investigated here as a potential treatment option. The complexity of the construction of the knee joint, which has six degrees of motion and is more prone to injury since it bears weight, is emphasized in this article. By wearing braces and using other support devices, one's knee can increase stability and mobility. In addition, the paper discusses various technologies that can be used to measure the knee adduction moment and supply spatial information on gait. Actuators for active knee braces must be compact, lightweight, and capable of producing a significant amount of torque; as a result, electric, hydraulic, and pneumatic actuators are the most common types. Creating control mechanisms, such as position control techniques and force/torque control approaches, is essential to knee exoskeleton research and development. These methods might make knee joint rehabilitation and assistive technology safer and more effective.

1. Introduction

The knee joint, a remarkable biomechanical marvel, plays an indispensable role in enabling humans to perform everyday activities with ease. Activities as simple as walking, standing, sitting, and running are made possible by the functionality of this joint [1]. However, when injury, osteoarthritis, or other conditions compromise the knee's integrity, individuals experience not only physical discomfort but also a significant reduction in their quality of life due to muscular deterioration, paralysis, abnormal gait, and related challenges [2,3]. Addressing the needs of these patients and assisting them in regaining a normal human gait is imperative. This review delves into the realm of knee rehabilitation technology, focusing on active knee braces, with the aim of comprehensively examining their potential to enhance the well-being of individuals with knee dysfunctions.

The motivation behind this review stems from the urgent need to address the challenges faced by patients with knee dysfunctions. Traditional passive knee braces or unloaders, while providing some support, fall short of enabling the restoration of normal knee function. They often restrict knee joint motion during the crucial standing phase and lack the capability to absorb shock, resulting in elevated metabolic costs, slower walking speeds, and increased pain compared to those without such limitations [4]. In contrast, active knee braces, empowered by robotics and mechatronics, offer a promising solution for patients with walking disabilities [5,6]. These devices not only have the potential to expedite rehabilitation but also reduce the burden on physiotherapists by providing consistent

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https://doi.org/10.1016/j.heliyon.2024.e26060
Received 30 May 2023; Received in revised form 7 February 2024; Accepted 7 February 2024
Available online 8 February 2024

and precise measurements of wearers' gait patterns [7].

This review comprehensively explores the realm of active knee braces as advanced mechatronic devices designed to restore normal gait and enhance overall performance, encompassing activities such as running, loaded walking, and regular walking [3,8,9], It delves into the essential components of these devices, including the frame, side hinges, straps, and padding, elucidating their roles in ensuring stability, comfort, and effective support [10,11]. Additionally, the review discusses the integration of sensors in cutting-edge active knee braces, highlighting their capability to track knee movement and provide valuable feedback to users and connected devices. Such sensors are pivotal in monitoring knee joint function and tracking progress during training and rehabilitation, particularly when engaging in functional activities [12–14]. Furthermore, the review touches upon the incorporation of small motors in advanced active knee braces, elucidating how these motors contribute to improving knee joint mechanics and reducing discomfort during various activities, including walking and running [15–17].

The upcoming sections of this review will provide a deeper insight into the components and functionalities of active knee braces, focusing primarily on their mechanical and mechatronic aspects. We will explore the mechanical principles and mechatronics underpinning these devices, demonstrating how they deliver controlled assistance forces and torques to facilitate user-initiated mobility. Furthermore, we will delve into the latest advancements in knee exoskeleton technology and their potential to augment power, stamina, and speed in individuals with knee dysfunctions. To conclude, we will discuss the pivotal role of active knee braces in enhancing the overall quality of life for patients and their significance within the evolving landscape of knee rehabilitation technology.

2. Knee joint biomechanics

The knee serves as the connecting point between the upper and lower leg bones. The knee joint has several bones, cartilage, muscles, tendons, and ligaments. The femur, tibia, and patella are the three major bones as shown in Fig. 1. Integrating anatomical structures and physiological mechanisms is necessary for knee joint stability.

When any of these structures is compromised, the knee becomes unstable, increasing the risk of injury [18].

In a range of loading scenarios, the knee preserves steadiness and control. It has two bony articulations: the femur-tibia articulation carries most of the body's weight. In contrast, the patella-femur articulation frictionlessly transfers forces produced by quadriceps femoris muscle contraction over the knee [19]. The femorotibial and patellofemoral joints, the two major knee joints, allow the knee to move in three planes: sagittal, transverse, and frontal. This permits six different degrees of mobility, including frontal plane varus and valgus stress, internal and external rotation on transverse planes, and flexion and extension on sagittal planes. The knee is prone to injuries due to its location between the body's two largest lever arms, the femur and tibia, and its weight-bearing function [18].

An advanced orthopaedic device designed to enhance and support normal knee function is the active knee brace. It incorporates integrated mechanisms, typically driven by small motors or actuators, to actively assist or resist joint movement, in contrast to conventional passive braces. Carefully crafted to offer dynamic support during a variety of activities, these braces adjust in real time to the user's motions. Constructed from robust yet lightweight materials, they promote both comfort and a full range of motion. The neural network of the brace consists of sophisticated sensors and control algorithms that continuously monitor joint position and velocity. This enables precise adjustment of torque or resistance, offering customized assistance tailored to the wearer's specific needs. Consequently, individuals with knee-related issues can experience an enhanced quality of life through a seamlessly integrated system that enhances stability, minimizes strain, and promotes a more fluid gait.

The essential components of a human gait cycle are the stance and swing phases, which alternate. As illustrated in Fig. 2 [20], the stance phase can be additionally broken down into the weight acceptance phase and the terminal stance phase. The person with knee impairments brought on by a stroke, spinal cord injury, or some other medical condition shows poorly timed or graded muscle activity. They won't lessen the muscles' normal-sized voluntary contractions, which have a significant impact on how people walk [21].

Much research has been done on the effects of the knee brace/knee assist systems. Knee adduction movement is the most common

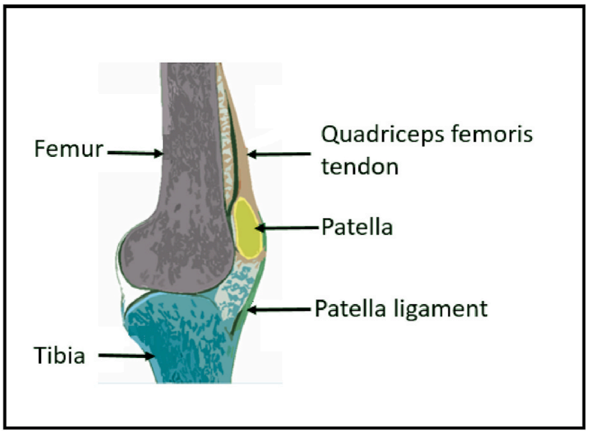

Fig. 1. The femur, tibia and patella of the knee joint.

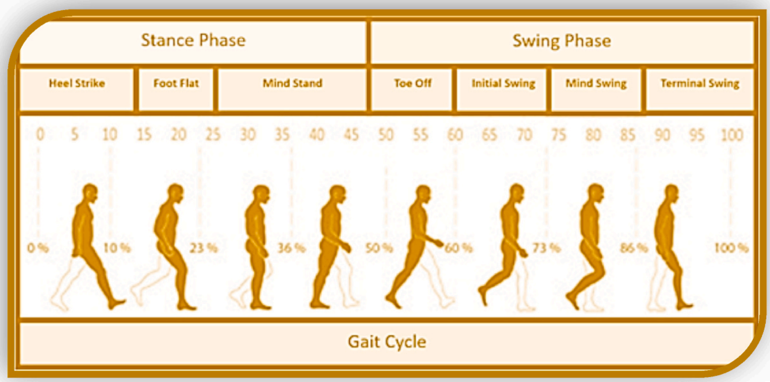

Fig. 2. Normal walking Gait cycle [20].

outcome parameter for measuring effectiveness [22]. Various methods, such as instrumented gait analysis systems, employ a combination of force plates, motion capture technology, and inverse dynamics calculations to accurately estimate the knee adduction moment during both walking and running. The ground reaction forces and moments, as well as the kinematics of the lower limb, are recorded during gait, and the knee adduction moment can be calculated using inverse dynamics for combination of knee braces and foot orthoses [23]. A multisegment foot model that includes markers on the foot, shank, and thigh can be used with motion capture and inverse dynamics to estimate the knee adduction moment. This method considers the foot and ankle motion, which can affect the knee adduction moment [24]. Computational models, such as finite element analysis or musculoskeletal modelling, can simulate the knee adduction moment based on mathematical representations of the musculoskeletal system and external loads. These models can estimate the distribution of forces and moments at the knee joint during various activities [25]. Instrumented knee implants with embedded sensors can directly measure the forces and moments acting on the knee joint during activities of daily living or sports. These implants provide real-time data on knee joint loading, including the knee adduction moment [26]. The secondary outcome is decreased pain in braced patients [22]. The gait analysis method is the method of choice for measuring the performance of any active knee brace for rehabilitation and assistance purposes.shows the different types of knee braces used; different variations of valgus knee braces are used to reduce the knee adduction moment.

2.1. Gait analysis methods

Technical tools used to study human gait fall into two main categories: those based on non-wearable sensors (NWS) and those based on wearable sensors (WS) (see Table 1). The sensors in NWS systems are placed in controlled study environments where they record information on the subject's gait as they move along a path that has been designated. In contrast, WS systems enable data analysis outside the lab and record details of the human stride while the person is engaged in daily activities [41]. Non-wearable sensors can be either based on image processing or floor sensors. There are various parameters to be considered while analyzing the gait pattern, which depends on the intent of the final use, like rehabilitation or medical assistance. More importance is given to the different forces acting on each muscle in sports injury rehabilitation using an Electromyography (EMG) sensor [42–44]. In medical aid, the analysis of gait and balance impairments can help identify osteoporosis, a systemic illness marked by decreased mass of the bone, and impaired bone microarchitecture, which results in more fragile bones and a higher risk of fracture [45]. Table 2 presents a comparison of various methods for measuring the gait cycle, along with their respective accuracy measures.

Semi-subjective techniques typically involve analyses conducted in a clinical setting by a professional. Various gait-related parameters are monitored and assessed while the patient walks on a pre-planned circuit. Timed 25-foot Walks (T25-FW) are frequently used for those with multiple sclerosis. In this paradigm, a specialist times how long it takes the patient to cover a distance of 7.5 m [55]. Tinetti Performance-Oriented Mobility Assessment (POMA), another technique, requires the patient to move at least 3 m, turn around swiftly, and then return to the chair [56]. The "get up and go" test, which requires the patient to rise up from their chair, walk a short distance, turn around, and then walk back, is sometimes used to check the balance of patients [57].

2.2. Image processing

A relatively new method for calculating and obtaining a map of distances from a vantage point is depth measurement [58]. A lot of other technologies are also available that utilize the strategies to get important gait spatial data in a faster and more efficient way, based on the examination of stereo vision-captured image sequences, a 3D method for automatic gait detection is used [52] while most of the other system used mono camera, another method is time-of-flight in which cartesian coordinates in space are provided for every pixel in each frame of a sequence by the camera. Each frame's depth map estimates the subject posture using an articulated model [59]. The Structured light method is a non-intrusive and economical method that uses a Kinect sensor which does not require any type of

Table 1
Types of knee braces used for reducing knee adduction moment [27–40].

Reference	Brace type	Outcome
Croce et al. [27]	Pneumatic unloading knee brace	Incorporating inflatable air bladders for improved peak knee adduction moment.
Dessery et al.[28]	Custom Valgus knee brace [three-point bending brace, valgus and external rotation brace, ACL brace]	The study compared three knee braces for medial knee osteoarthritis and found that they provided similar pain relief and improvement in function during gait.
Draganich et al.[29]	Conventional brace, custom brace	The effectiveness of self-adjustable custom and off-the-shelf bracing in the treatment of varus gonarthrosis.
Fantini Pagani et al. [30]	Conventional valgus unloader brace	Using a valgus orthosis reduced the knee adduction moment during walking and running in male subjects with varus alignment.
Fantini pagani et al. [31]	Conventional valgus brace	Valgus knee brace was more effective than lateral wedge insoles in reducing knee adduction moment in patients with medial knee osteoarthritis.
Fu et al.[32]	Conventional valgus knee brace	Orthotic treatment, particularly lateral-wedged insoles with arch support, can reduce pain and improve gait in Chinese patients with medial knee osteoarthritis.
Johnson et al. [33]	Conventional valgus brace	Knee brace combining pneumatic joint unloading and active swing assist showed improvements in gait parameters and pain levels in knee osteoarthritis patients.
Jones et al.[34]	Conventional valgus brace	Both valgus knee braces and lateral wedge insoles were found to reduce the external knee adduction moment and knee adduction angular impulse in patients with medial knee osteoarthritis.
Laroche et al. [35]	Valgus and external rotating brace	Distraction-rotation knee brace can significantly alter knee mechanics and improve gait function in patients with medial knee osteoarthritis
Lamberg et al. [36]	Conventional valgus knee brace	Wearing a decompressive knee brace for 2- and 8-weeks reduced knee adduction moment in individuals with medial compartment knee osteoarthritis.
Lindenfeld et al. [37]	Custom Valgus knee brace	Patients with varus gonarthrosis can considerably lessen joint loading by using valgus bracing.
Moyer et al. [38]	Custom Valgus knee brace	In individuals with varus alignment and knee osteoarthritis, utilizing a custom-fit valgus knee brace and custom-made foot orthotic concurrently can lower the knee adduction moment.
Orishimo et al. [39]	Conventional valgus brace	Valgus unloader bracing is effective in normally aligned individuals and can be used as an alternative to non-weight-bearing protocols after cartilage restoration procedures.
Ramsey et al. [40]	Custom Valgus knee brace	Bracing for medial compartment osteoarthritis of the knee may reduce pain by reducing muscle cocontractions and mechanically stabilizing the knee.

Colour	*Brace Type*
	Conventional
	Non- Conventional

markers to track the gait movement [53,60] and the infrared thermography method which uses an infrared thermal camera to capture the videos and then using combination of wavelet transform and skeleton theory the gait information is extracted [54].

2.3. Floor sensing

Pressure or force monitors and moment transducers track the subject's gait as they walk on the sensors installed along the floor on so-called "force platforms" or instrumented walkways [61]. Fig. 3 shows a floor-sensing prototype system that can help in gait analysis. The system uses 1536 individual sensors arranged in rectangular strips with a sample rate of 22 Hz, three features are extracted for gait analysis which are stride length, stride cadence and time on toe to time on heel ratio features.

3. Actuators for active knee brace

Actuators should be lightweight and produce high torque; some of the most commonly used actuator types are electric, pneumatic, and hydraulic. Much research has been going on to improve the current actuators; a detailed discussion will be done in the next session. Table 3 shows the various actuators used; the most common type of classification can be done based on the mode of power pack used. The electrical, pneumatic, and hydraulic type is broader classifications, but different researchers suggest many variations.

3.1. Electrical actuators

The orthosis has a built-in motor that delivers torque to the knee joint to help with rehabilitation exercises. Due to their high power density, remarkable efficiency, and low maintenance requirements, brushless DC motors are frequently used in robotic exoskeletons and prostheses. Compared to conventional brushed DC motors, they also provide greater speed control and torque response. Fig. 4(B) and (C), and Fig. 5 shows a brushless D.C motor-based active knee brace. The motor driver and microcontroller allow fine control of the brushless DC motor's speed and torque output [71]. The back drivability of the motor is considered an important parameter when selecting an actuator for the knee joint as it facilitates natural and efficient movement within an active knee brace, it also decreases the activation of the quadriceps during various activities, such as transitioning from sitting to standing. Additionally, the use of back-drivable actuation results in reduced noise levels [72–74].

3.2. Hydraulic actuators

Systems that operate and are managed by fluid physics are implemented using hydraulic actuators [62]. Accurate identification of an exoskeleton system's dynamics is critical for building a controller that reacts compliantly to external forces, which can improve the strength and stamina of a human wearing an exoskeleton [65]. A novel active knee brace with seven degrees of freedom can support a payload of up to 75 kg while walking at a pace of 1.3 m/s [75].

3.3. Pneumatic actuators

Because pneumatic actuators have a high power-to-weight ratio, they are well-suited for wearable devices such as knee orthoses. Compared to other actuators, they provide a smooth and continuous motion. Pneumatic actuators are quiet and make little noise when in use. Compared to other actuators, they are less expensive and easier to maintain. Pneumatic muscles are naturally flexible, allowing them to replicate the behaviour of genuine muscles and joints. Compared to other actuation methods, pneumatic muscles can result in smoother and more natural movement [70–72]. Fig. 4 A shows a pneumatic actuator-based exoskeleton. An artificial pneumatic muscles type actuator provides plantar flexor torque with a walking speed of up to 1.5 m/s and good back drivability; however, it provides good torque characteristics and is much heavier [73]. Despite having an excellent weight-to-power ratio, pneumatic actuators primarily have two drawbacks: low bandwidth and modelling error [74].

4. Power consumption of active knee braces

An active knee brace's precise power usage is influenced by a variety of elements, including its actuation mechanism, battery capacity, walking distance and control algorithms. The power consumed at the knee joint is generally measured in watts and this depends on different activities like standing, slow walking, normal walking and fast walking and would be in the range of 5, 18, 22 and 40 W respectively [76]. The knee brace/prosthesis can be classified as active, passive, and hybrid. The hybrid type is a combination of both active and passive. The details of power consumption of one gait cycle for normal walking are given in Table 4 [77]. Design and evaluation of a hybrid passive-active knee prosthesis on energy consumption.

5. Control system

Braces and straps firmly connect the wearer's lower limbs to the knee exoskeleton, creating a single system. The user's knee joint and the knee exoskeleton share typical motions thanks to the knee exoskeleton's help. Control techniques are crucial in advancing knee exoskeletons because of the physical connection between the wearer and the device. To ensure the wearer's safety and comfort, an appropriate control technique can be used to generate the assistive torque in accordance with the wearer's movements, intentions, and

Table 2
Types of gait analysis systems.

Reference	Method	Accuracy	Type
Zhang J, Novak A et al. [46]	Inertial sensors	Angle Coeff. Mult. Corr. > 0.96 [71]	Wearable Sensors
Howell A, Kobayashi T et al. [47]	Pressure sensors	Pressure correlation R > 0.95	
Frigo C, Crenna P [48].	EMG	SNR = 0.25 μV @ 200 Hz	
Dominguez G, Cardiel E. et al. [49]	Goniometer	R = 0.999 with measures taken with mechanical Goniometer	
Middleton L, Buss A. et al. [50]	Pressure sensor mats and platforms	80% recognition rate	Non-Wearable Sensor
Derawi M, Ali H, Cheikh F [51].	Time of Flight	2.66%–9.25% EER recognition	
Liu H, Cao Y, Wang Z [52].	Stereoscopic Vision	70.18% recognition rate	
Clark R, Pua Y. et al. [53]	Structured Light	Correlation R = 0.89 with inertial and pressure sensor measures	
Xue Z, Ming D [54].	IR Thermography	78%–91% recognition	

demands.

A wireless sensor system provided accurate and repeatable measurements of knee joint angles during static and dynamic movements. It can be a reliable tool for measuring knee joint angles in clinical and research settings. A wireless inertial sensor system's accuracy and repeatability in measuring knee joint angles during static and dynamic movements are perfect [80,81]. With a mean tracking error of fewer than 3°, the position control strategy based proportional integral derivative controller to regulate the exoskeleton's torque with the intended knee joint angle set by the user system could precisely maintain the knee joint angle during movements. The position control system's precise and quick regulation of the exoskeleton's torque can increase the security and efficiency of knee joint rehabilitation and assistive devices [82]. In knee exoskeletons, a force/torque control ensures that the wearer's movements are aided rather than hindered [83]. There should be a minimum amount of impedance, and the system should be independent of human physical properties to accurately control the force where human-machine interaction occurs [84]. While implementing a force control strategy, it is challenging to get the right balance between response time and stability of the system due to the small bandwidth of the force sensor; to overcome this, a disturbance measuring method needs to be implemented when using force control [85–87]. Accelerometers and encoders provide a centre of mass information that can be used to determine user intentions, like walking, sitting, or engaging in other activities [88].

6. Conclusion

Daily activities require the knee joint, and knee dysfunctions can meaningfully reduce a patient's quality of life. While active knee braces utilizing robotic technologies can provide controlled assistance force or torque for user-initiated mobility and may potentially

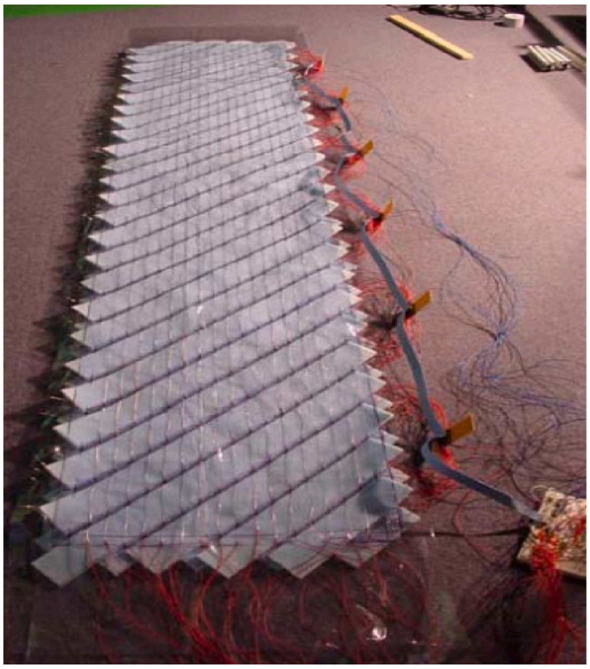

Fig. 3. Force sensing prototype sensor [61].

Table 3
Type of actuators, control strategy, and sensor used in an active knee brace [62–70].

Reference	Type of Actuator	Control strategy	The sensor used for intent detection
Zoss et al. [62]	Linear hydraulic actuator cylinder	--	Force sensor
Cestari et al. [63]	Stiffness-controlled actuator using an electric motor	Force Control	Force sensor, torque sensor
Jafari et al. [64]	Adjustable stiffness drive	--	Four position sensors, one torque sensor
Ghan et al. [65]	Hydraulic actuator	--	Force and Pressure sensor
Bacek et al. [66]	Novel modular compliant knee joint Actuator	Torque control	Torque sensor
Ashmi et al. [67]	Double-acting pneumatic cylinder	proportional–integral–derivative controller and Sliding mode control	Accelerometer
Ashrafiuon et al. [68]	DC motor	Hybrid- Impedance control, admittance control	Inertial Measurement Unit [IMU], Force sensors, Position sensors, Electromyography [EMG] sensors
Fite et al.[69]	DC motor	Impedance control	Load cell, joint motion sensor
Claros et. al. [70]	D.C. motor	--	Force sensor

Colour	Sensor
(blue)	Hydraulic actuator
(yellow)	Pneumatic actuator
(green)	Electrical actuator
(orange)	Variable Stiffness Actuator

speed up the rehabilitation process, passive knee braces are limited in their ability to help regain normal knee function. A mechatronics gadget called the active knee brace combines mechanical, electrical, electronic, and computer science principles. Aside from a frame, straps, side hinges, padding, and sensors for improved knee joint mechanics and movement support, advanced active knee braces may also have motors. The intricate anatomy of the knee joint, which provides stability and motion, comprises bones, cartilage, muscles, tendons, and ligaments. Due to its location and role in weight-bearing, the knee joint is vulnerable to injuries and is essential for maintaining stability and control in various loading circumstances. Six degrees of mobility are possible at the knee joint because it can move in three separate planes. The stance and swing stages of a person's gait cycle are affected by knee limitations, which can result in improperly timed or graded muscle activation that impairs gait performance. People frequently employ knee braces and support devices to increase knee stability and mobility. Knee adduction mobility and a decline in discomfort are two indicators of how well these systems work. Several techniques, such as instrumented knee implants, multisegment foot models, computational models, and instrumented gait analysis systems, are available to assess knee adduction moment.

Several technologies, such as time-of-flight, structured light, infrared thermography, depth measurement, and stereoscopic vision, enable the rapid and efficient collection of essential spatial gait data. These technologies utilize pressure or force monitors and moment transducers, allowing for the calculation and mapping of distances from a specific viewpoint, as well as the tracking of gait on force platforms or instrumented walkways.

Active knee braces require small, lightweight actuators that can deliver a lot of torque, and electric actuators in particular, brushless DC motors are frequently employed because of their high power density, efficiency, and speed control. Active knee brace's

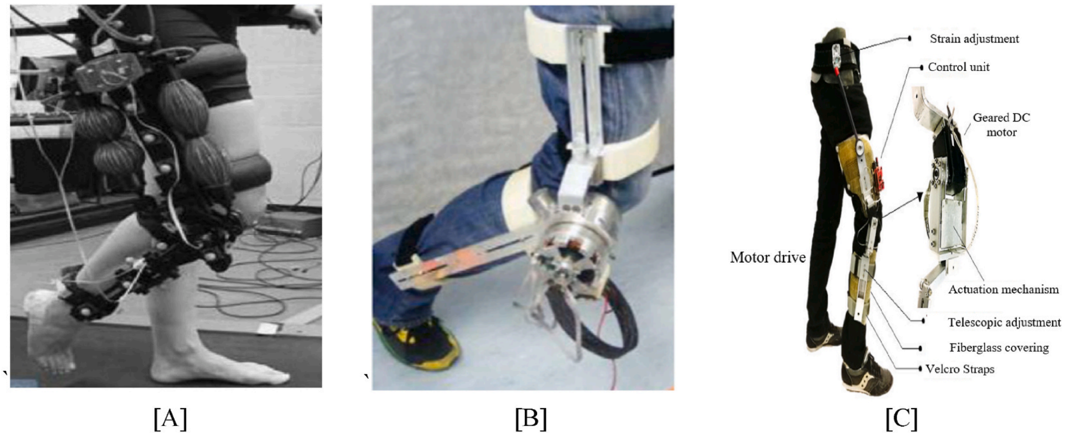

Fig. 4. Varieties of active knee braces using different actuation principles [A] Knee exoskeleton [78]. [B] Knee exoskeleton developed by Karavas et al. [79]. [C] Claros et al., 2016 [70].

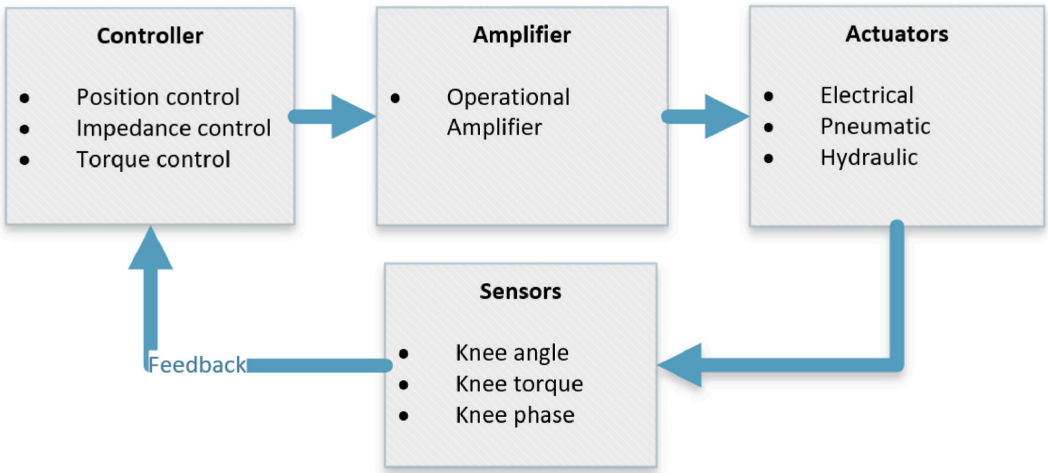

Fig. 5. Feedback control system representing active knee brace control loop.

motor driver and microcontroller allow precise control of the motor's speed and torque output to help with therapeutic exercises. Ongoing research into active knee braces aims to enhance the existing actuators and create new technologies. Other standard actuators in wearables like knee orthoses include hydraulic and pneumatic actuators. Pneumatic actuators use air pressure to regulate the system, whereas hydraulic actuators use fluids. Both types are suitable for wearable devices due to their benefits, like a high power-to-weight ratio and smooth motion. Compared to other actuation techniques, pneumatic muscles can lead to smoother and more natural movement. Building a compliant controller that responds to external forces and boosts the strength and endurance of the user wearing the exoskeleton depends on accurately identifying the exoskeleton system's dynamics.

Control mechanisms are crucial in developing knee exoskeletons to maintain the wearer's security and comfort. A position control strategy based on a proportional integral derivative controller can perfectly preserve the knee joint angle during movements. A wireless sensor system can reliably record knee joint angles during static and dynamic movements. In knee exoskeletons, a force/

Table 4
Power consumption breakdown for normal walking across gait cycle phases by different knee braces.

Normal walking Gait cycle	Active knee brace energy consumption range [J]	Passive knee brace energy consumption [J]	Hybrid knee brace energy consumption [J]
0–15%	0 to 20	0	3
16–46 %	21 to 30	0	3 to 15
47–60 %	30 to 40	0	15
61–72 %	40 to 45	0	15
72–100 %	45 to 60	0	15

torque control ensures the wearer's movements are aided, not restricted. These methods may improve the safety and effectiveness of knee joint rehabilitation and assistive technology.

Much research has been done in the field of active knee brace. However, some problems, like the system's overall weight, remain to be answered. Most designs do not include the weight of the power pack, like for generating air pressure in a pneumatic system and pressure in a hydraulic line, as these parts are much heavier. Electric motors require only batteries for their work. Sensor fusion is not used in extensive forms, like some recent research exploring the possibilities of using EMG and IMU sensors to get battery accuracy of intent recognition compared to relying on the same type of sensor. Controller implementations use either position, force, or torque type of controller with PID tuning. Further research can be done on exploring a hybrid control strategy, which can use a nonlinear controller and incorporate the artificial intelligent control strategy for learning and training purposes for the next generation of active knee brace.

CRediT authorship contribution statement

Udayan Trivedi: Writing – original draft. **Anand Y. Joshi:** Supervision, Investigation, Funding acquisition.

Declaration of competing interest

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.

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