

Review

Knee Exoskeletons Design Approaches to Boost Strength Capability: A Review

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Abstract: There are different devices to increase the strength capacity of people with walking problems. These devices can be classified into exoskeletons, orthotics, and braces. This review aims to identify the state of the art in the design of these medical devices, based on an analysis of patents and literature. However, there are some difficulties in processing the records due to the lack of filters and standardization in the names, generating discrepancies between the search engines, among others. Concerning the patents, 74 patents were analyzed using search engines such as Google Patents, Derwent, The Lens, Patentscope, and Espacenet over the past ten years. A bibliometric analysis was performed using 63 scientific reports from Web of Science and The Lens in the same period for scientific communications. The results show a trend to use the mechanical design of exoskeletons based on articulated rigid structures and elements that provide force to move the structure. These are generally two types: (a) elastic elements and (b) electromechanical elements. The United States accounts for 32% of the technological patents reviewed. The results suggest that the use of exoskeletons or orthoses customized to the users' needs will continue to increase over the years due to the worldwide growth in disability, particularly related to mobility difficulties and technologies related to the combined use of springs and actuators.

Keywords: knee exoskeletons; lower limb exoskeleton; passive exoskeletons



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1. Introduction

In recent decades, advances in the development of assistive devices have become relevant in medicine, especially in specific areas related to people's disabilities, increasing its research and technological development. One of the main causes may be the worldwide increase in the population that suffers from a disability. According to the World Health Organization (WHO), more than 1000 million people live with some form of disability; almost 200 million suffer considerable difficulties in their functioning. These mobility difficulties are increased because of the aging of the population, and it will be a cause of more significant global concern than it is now [1].

In this context, the prevalence of disability is increasing, and Mexico does not escape this problem. According to data from the National Institute of Statistics and Geography (INEGI), 7% of the population suffers from a disability, and 42.4% of disabilities are related to mobility [2]. Another factor that affects the increase in the population with disabilities is related to obesity. According to the Organization for Economic Cooperation and Development (OECD) in its report "The Heavy Burden of Obesity: The Economics of Prevention", about 73% of the Mexican population suffers from overweight, and 34% of people suffer from morbid obesity, which is the highest degree of obesity [3]. A great part

of mobility problems occurs in the knee joint, which includes two degrees of freedom (DOF), flexion-extension (x - x) and internal-external (y - y). This knee joint works essentially in compression, supporting the weight of the body during the march [4] (see Figure 1). These characteristics of operating under the action of gravity make people who suffer from obesity more prone to suffer injuries to the knee joints and develop diseases such as osteoarthritis that occur more frequently with age [5,6].

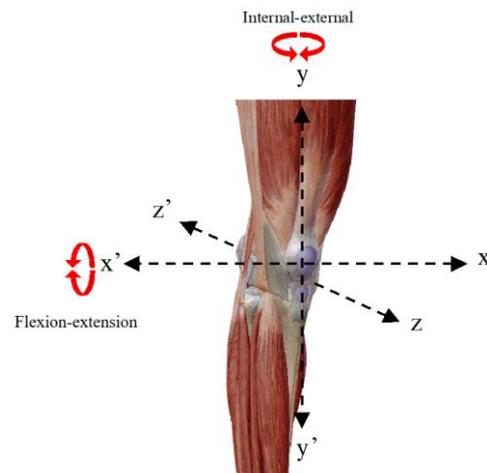


Figure 1. Degrees of freedom of the knee joint.

The research and development of devices that provide solutions to mobility problems have increased in recent decades; such is the case of the development of exoskeletons, which have been a milestone in this area [7]. Exoskeletons can be grouped based on energy use into powered exoskeletons and passive exoskeletons [8]. Powered exoskeletons are systems based on an external energy source and actuators that convert electrical, pneumatic, or hydraulic energy to mechanical work to give support and controlled movement [9–14], whereby the rehabilitation tasks turn out to be more suitable and effective than traditional methods. However, a limitation of these exoskeletons is that patients do not have control of the trajectory, which challenges patients to train personalized or appropriate movement patterns for their recovery. Passive exoskeletons do not have an external power source, so their movement is dependent on the user. These exoskeletons consist of springs, shock absorbers, and mechanical clutches to store energy or release energy during walking [15]. They are cheaper, less complex, and are likely to be better accepted by users.

Herr (2009) classified exoskeletons and orthotics into four categories: (a) serial limb exoskeletons; (b) parallel limb exoskeletons for load transfer; (c) exoskeletons of parallel extremities to increase torque, and (d) exoskeletons of parallel extremities that increase human endurance. In the present review, the terms exoskeletons and orthotics are used similarly, as mechanical devices of an anthropomorphic nature [16].

This work presents the method used to find refined information obtained in databases for both patents and scientific communications. The results section presents the bibliometric analysis of the literature and the patentometric analysis of technological surveillance. Finally, the conclusions section shows the main metrics analyzed and the technology trend to boost strength capability.

2. Review Methodology

The search strategy was divided into two parts: (1) obtaining patents and (2) obtaining scientific communications, for which in both cases, the arrangement of keywords and Boolean operators were ((knee or (lower limb)) and (exoskeletons or orthoses)). We considered a 10-year search period, that is, from 2011 to 2020 as the first filter (Filter_1). Later, the data obtained were processed for analysis by applying three filters, which are detailed in Sections 2.1 and 2.2.

2.1. Patent Search

Five search engines were used (Derwent Innovation, Espacenet, Google Patents, Patentscope, and The Lens), in which the arrangement of keywords and Boolean operators mentioned in the previous paragraph shows a growth in the patent registration of lower limb exoskeletons in the past decade (see Figure 2).

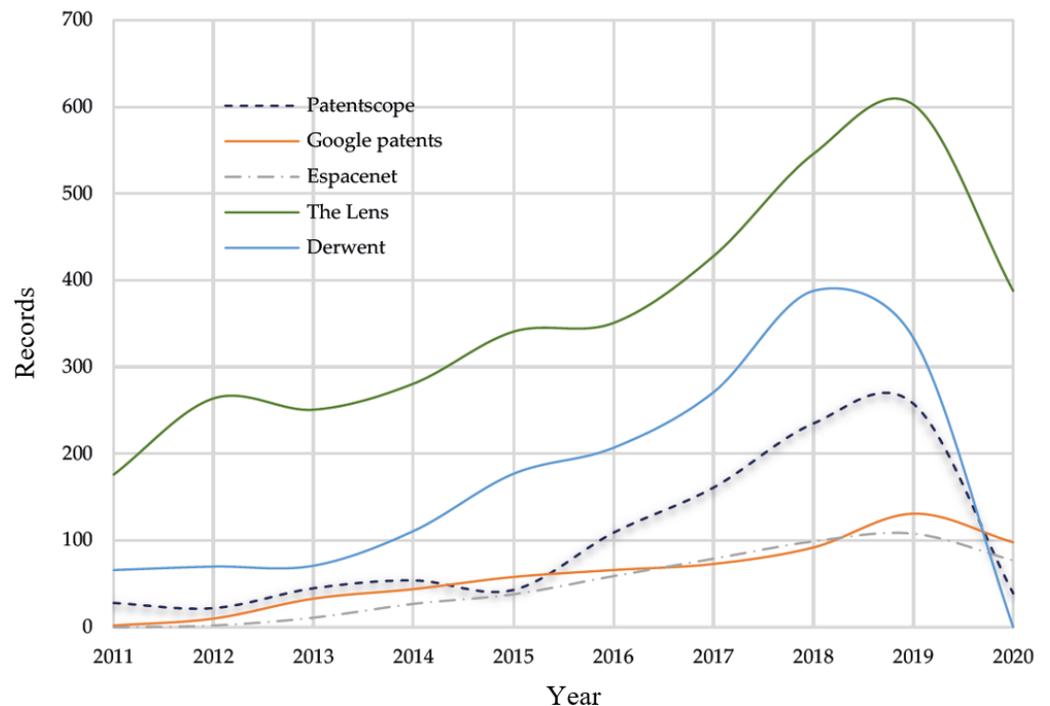


Figure 2. Documents by year.

Subsequently, two other filters were used, denoted as Filter_2 and Filter_3, related to the international patent classification (IPC) A61H3/00 and A61F5/01. These patents belong to the group of non-surgical devices or appliances to help people walk. We applied the filters directly in the corresponding search engine, as the goal is to determine the status of the passive knee exoskeleton technique. Filter_3 has to do with the inclusion of the word knee. Finally, with the results of the databases, obtained after applying the three filters, a single record was integrated and “data cleaning” was performed using the Open Refine[®] free software. Later, we disaggregated the data and performed a manual review of each record, applying criteria to restrict and select patents of interest. This action constitutes Filter_4.

A. Inclusion criteria:

- (a) The patent belongs to a type of lower limb exoskeleton or orthosis.
- (b) The patent corresponds to a component of an exoskeleton or lower limb orthosis.
- (c) The patent describes the design or manufacturing method of an exoskeleton or lower limb orthosis.
- (d) The patent can be registered in any patent office in any country.

B. Exclusion criteria:

- (a) Related to other devices for members of the body other than the lower one.
- (b) Related to complementary systems not related to the knee joint.
- (c) Patents are found in more than one database; only the patent found in the first database was considered to avoid duplication of information.
- (d) Patents prior to 2011, considering slow progress in development and management.

This discrimination of the fourth filter (Filter_4) is made by adding all the documents obtained after Filter_3, resulting in 205 documents to which the inclusion and exclusion criteria were applied, leaving only 74 documents identified with the data of the inventor, registry office, year of publication, patent title, and registration key. Table 1 shows the effect of reducing the records when applying each filter.

Table 1. Results of the patent search.

Search Engines	Filter_1	Filter_2	Filter_3	Filter_4
Patentscope	1235	320	32	
Google patents	1254	65	4	
Espacenet	500	132	16	74
The Lens	3629	719	57	
Derwent	2000	905	96	
Total	8618	2141	205	74

2.2. Search of Scientific Communications

For the analysis of the literature, two search engines (Web of Science and The Lens) were used, in which the disposition of keywords and Boolean operators were applied, as well as the time period of 10 years as the filter (Filter_1). The number articles per year is shown in Figure 3, where a growing trend is observed in the case of the Web of Science (WoS) search engine over the entire time series, but not in the case of the data obtained with the search engine The Lens, where a clear trend is not appreciated; this may be due to the unified system of the search engine that gathers patents and academic documents in a database with the ability to identify intersections between these two types of documents.

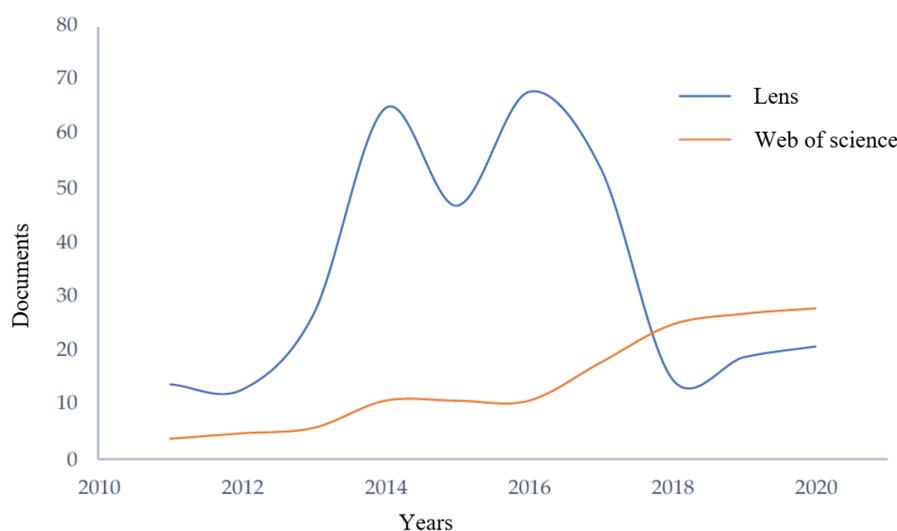


Figure 3. Annual production of articles found by two databases.

With the data obtained from each search engine, the results of both were crossed, applying a second filter (Filter_2) using inclusion and exclusion criteria to restrict and select information on the topic:

A. Inclusion criteria:

- (a) Related to the design of exoskeletons.
- (b) Related to the type of exoskeletons and orthoses focused on the type of application.
- (c) Related to tests and evaluation metrics of exoskeletons or orthoses.
- (d) Related to the exoskeletons of the lower limb or knee joint.
- (e) Related to the development of exoskeletons or orthoses.

- (f) Exoskeleton manufacturing methods.
- B. Exclusion criteria:
 - (a) Related to upper limb exoskeletons.
 - (b) Related to active or powered exoskeletons.
 - (c) Related to gait control.
 - (d) Related to electromyography (EMG)
 - (e) Duplicate registration.
 - (f) Articles prior to 2011.

Table 2 shows the reduction effect of the records when applying the inclusion and exclusion criteria. A total of 63 records were obtained performing the bibliometric analysis using R-Studio[®] and Bibliometrix.

Table 2. Number of documents obtained from search engines.

Search Engines	Filter_1	Filter_2
The Lens	343	
Web of Science	146	63
Total	489	63

3. Results

3.1. Patentometric Analysis

After filtering the documents, 74 patents related to exoskeletons, orthoses, or lower limb devices were selected; the results are shown in Table 3. The main offices from where patents were registered are the United States (23 patents), the European office (4 patents), the international office (23 patents), China (18 patents), Japan (3 patents), Republic of Korea (2 patents), and Canada (1 patent). As shown in Figure 4, the United States is the country with the highest number of patents.

Table 3. Lower limb exoskeletons and orthoses patents.

Cite	Title	Main Applicant	Body Part	Type	Technology
[17]	Knee Brace Hinges with Adaptive Motion.	Dj Orthopedics Llc	Knee	Brace	Mechanical
[18]	Knee-joint Hinge of Standing Period Control Orthosis.	Li Jianjun	Knee	Orthosis	Mechanical
[19]	Stretching Assisting Orthosis of Knee Joints.	Children’s Hospital of Chongqing Medical University	Knee	Orthosis	Mechanical
[20]	Knee-powered Radian Pulley-type Foot Drop and Hemiplegic Gait Orthosis.	Guangdong Provincial Work Injury Rehabilitation	Foot	Orthosis	Mechanical
[21]	Unlocking Adaptive Exoskeleton Knee Joint Support Plate.	Univ Electronic Science & Tech Ch	Knee	Device	Mechanical
[22]	Knee Joint Load-bearing Power Assisting Exoskeleton Device and Working Method thereof.	Fuzhou University	Knee	Exoskeleton	Electronic
[23]	Gait-based Wearable Flexible Knee Joint Robot Exoskeleton Facility.	Beijing Inst Technology	Knee	Exoskeleton	Pneumatic
[24]	Self-driven Self-adaption Gait Wearable Knee Joint Walking aid Device.	Beijing Inst Technology	Knee	Device	Mechanical

Table 3. Cont.

Cite	Title	Main Applicant	Body Part	Type	Technology
[25]	Hip and Knee Integrated Joint Device used for Exoskeleton Robot and Exoskeleton Robot.	Hefei Inst Physical Sci Cas	Hip-Knee	Exoskeleton	Electronic
[26]	Quasi-passive Knee Joint and Ankle Joint Coupling Lower Limb Exoskeleton and Control Method thereof.	Univ Tsinghua	Knee-Ankle	Exoskeleton	Mechanical
[27]	Lower Limb Exoskeleton Knee Joint Based on Torsional Spring Clutch.	Univ Shanghai Science & Tech	Knee	Exoskeleton	Mechanical
[28]	Intelligent Knee Osteoarthritis Correction Integrated Instrument.	Affiliated Hospital to Nanchang Univ.	Knee	Device	Mechanical
[29]	A Knee Joint Exoskeleton Mechanism Driven by a Connecting Rod.	Inner Mongolia Univ. of Technology	Knee	Exoskeleton	Electronic
[30]	Lower Limb Knee Joint and Ankle Joint Assisting Exoskeleton Stiffness Adjusting Device.	Jiangsu Collection M. A.S.	Knee-Ankle	Device	Electromechanical
[31]	Lower Extremity Exoskeleton Heterogeneous Knee Joint based on Parallel Elastomer.	Harbin Institute of Technology	Knee	Exoskeleton	Electromechanical
[32]	Lower Limb Exoskeleton Structure Integrated with Self-adaptive Knee Joints and Robot.	Southern University	Knee	Exoskeleton	Electromechanical
[33]	Wearable Lower-limb Walking-assisting Exoskeleton Capable of Imitating Movement Curve of Human Knee Joint.	Hebei University of Technology	Hip-Knee-Ankle	Exoskeleton	Electronic
[34]	Knee Joint Orthosis.	Shandong First Medical Univ & Shandong Academy of Medical Sciences	Knee	Orthosis	Mechanical
[35]	Self-adaptive Variable-stiffness In-vitro Knee Joint Device with Intelligent Tensioning Function.	Tianjin University of Technology	Knee	Exoskeleton	Mechanical
[36]	Knee Orthosis.	Otto Bock Healthcare Gmbh	Knee	Orthosis	Electromechanical
[37]	Joint for Knee Orthotics, Prosthetics and Supports.	Wayd Kurt	Knee	Orthosis	Mechanical
[38]	Device for Holding the Kneecap and Knee Orthosis.	Gibaud	Kneecap	Orthosis	Mechanical
[39]	Knee Orthosis Adapted for a Prolonged Sitting Position.	Millet Innovation	Knee	Orthosis	Mechanical
[40]	Single Bar Knee-ankle-foot Orthosis.	Nagasaki Kanae Kk	Knee-Ankle-Foot	Orthosis	Mechanical
[41]	Knee Joint Mechanism of Movement Assist Device.	Honda Motor Co Ltd.	Knee	Mechanism	Mechanical
[42]	Knee Brace.	United Surgical, Inc.	Knee	Brace	Mechanical
[43]	Reciprocal Action Type Knee Brace by Different Movement in Medial-lateral Hinge.	Triple-C Medical Corporation	Knee	Brace	Mechanical
[44]	Auxiliary Apparatus for Bracing Knee.	Korea University Research and Business Foundation	Knee	Device	Mechanical
[45]	Self-Adjusting Knee Brace.	Nelson Ronald E.	Knee	Brace	Mechanical

Table 3. Cont.

Cite	Title	Main Applicant	Body Part	Type	Technology
[46]	Knee Ankle Foot Orthosis.	The Governors of The University of Alberta	Knee-Ankle-foot	Orthosis	Mechanical
[47]	Orthotic Joint and Knee-ankle-foot Orthotic Device incorporating same.	Becker Orthopedic Appliance Company	Knee-Ankle	Device	Mechanical
[48]	Orthotic System and Method utilizing Hydrostatic Compression of Soft Tissue to Unload The Knee and/or Heel up to 100%.	Leos Alexander N.	Knee-Ankle	Device	Mechanical
[49]	Knee Brace with Adjustable Bolster.	Knecht Steven S.	Knee	Brace	Mechanical
[50]	Active Knee Orthosis.	De Cortanze André	Knee	Orthosis	Mechanical
[51]	Power-Assisted Orthosis with Hip-knee Synergy.	Case Western Reserve University	Hip-Knee	Orthosis	Mechanical
[52]	Knee Brace with Tool-Less Length Adjuster.	Knecht Steven S.	Knee	Brace	Mechanical
[53]	Dynamic Load Bearing Shock Absorbing Exoskeletal Knee Brace.	Desousa Egas Jose-Joaquim	Knee	Brace	Mechanical
[54]	Knee Orthosis Device and Associated Methods.	University of Connecticut	Knee	Orthosis	Mechanical
[55]	Knee Joint Supporter.	Kowa Company, Ltd.	Knee	Device	Mechanical
[56]	Method for Controlling a Knee Orthosis.	Otto Bock Healthcare Gmbh	Knee	Orthosis	Electromechanical
[57]	Knee Orthosis for Treatment of Pcl Injury.	Medical Alliance	Knee	Orthosis	Mechanical
[58]	Artificial Knee Joint.	Fillauer Europe Ab	Knee	Orthosis	Mechanical
[59]	Adjustable Knee Brace.	Deroyal Global Healthcare Solutions Limited	Knee	Brace	Mechanical
[60]	Orthopedic Knee Brace.	Humphrey Jay C.	Knee	Brace	Mechanical
[61]	Method for Controlling an Artificial Knee Joint.	Otto Bock Healthcare Products Gmbh	Knee	Method	Mechanical
[62]	Soft Inflatable Exosuit for Knee Rehabilitation.	Arizona Board of Regents on Behalf of Arizona State University; Dignity Health	Knee	Exosuit	Pneumatic
[63]	Knee Joint Orthotic Device Manufacturing Apparatus and Knee Joint Orthotic Device Manufacturing Method, and Knee Joint Treatment Support Apparatus and Knee Joint Treatment Support Method.	CYBERDYNE Inc.; University of Tsukuba	Knee	Device	Electromechanical
[64]	Unpowered Wearable Walking Assistance Knee Equipment With Gait Self-adaptivity.	Beijing Institute of Technology	Knee	exoskeleton	Mechanical
[65]	Soft Knee Exoskeleton Driven by Negative-pressure Linear Actuator.	Beijing Institute of Technology	Knee	Exoskeleton	Pneumatic
[66]	Actuator Unit for Knee-ankle-foot Orthosis.	Suncall Corporation	Knee-Ankle-Foot	Orthosis	Electromechanical
[67]	Hip and Knee Actuation Systems for Lower Limb Orthotic Devices.	Ekso Bionics, Inc.	Hip-Knee	Orthosis	Electromechanical

Table 3. Cont.

Cite	Title	Main Applicant	Body Part	Type	Technology
[68]	Knee Brace with Expandable Members and Method of Using the same.	Colaco Glenn	Knee	Brace	Mechanical
[69]	Controllable Passive Artificial Knee.	The Regents Of The University of California	Knee	Exoskeleton	Mechanical
[70]	Ankle and Knee Motorized Orthosis.	Ospedale Pediatrico Bambino Gesù Irccs	Knee-Ankle	Orthosis	Electromechanical
[71]	Dynamic Force Hinge Joint for Knee Brace and Knee Brace Equipped therewith.	Knecht Steven S.	Knee	Brace	Mechanical
[72]	Knee Joint Orthosis Having Offloading Function.	Luo Yun	Knee	Orthosis	Mechanical
[73]	Knee Joint Orthosis.	Luo Yun	Knee	Orthosis	Mechanical
[74]	Knee Joint Orthosis.	Matsumoto, Hideo	Knee	Orthosis	Mechanical
[75]	Low Profile Knee Brace and Method of using same.	Djo, Llc	Knee	Brace	Mechanical
[76]	Interactive Exoskeleton Robotic Knee System.	The Hong Kong Polytechnic University	Knee	Exoskeleton	Electronic
[77]	Passive Power-conservative Artificial Knee.	The Regents Of The University of California	Knee	Device	Mechanical
[78]	Knee Joint Control Method and Lower Extremity Orthosis.	Kawamura Gishi Co., Ltd.	Knee-Ankle-Foot	Orthosis	Electromechanical
[79]	Knee Retractor.	Chang Ki Yong	Knee	Orthosis	Mechanical
[80]	Knee Joint Brace.	Matsumoto Hideo	Knee	Brace	Mechanical
[81]	Stabilizing System for a Knee Brace.	Spring Loaded Technology Incorporated	Knee	Brace	Mechanical
[82]	Actuator-equipped Knee Ankle Foot Orthosis.	Nat Univ Corp Kyoto Inst Technology	Knee-Ankle-Foot	Orthosis	Mechanical
[83]	Knee Support Orthosis Adapted to A Prolonged Seated Position. Device for Producing Knee Joint Correction Tool, Method for Producing Knee Joint Correction Tool, Device for Assisting Knee Joint Treatment, and Method for Assisting Knee Joint Treatment.	Millet Innovation	knee	Orthosis	Mechanical
[84]		Cyberdyne	Knee	Method	Electromechanical
[85]	Knee Brace and System for Custom Fabricating Knee Brace for a User.	Laboratoire Victhom	Knee	Brace	Mechanical
[86]	Orthosis, in Particular of the Knee, including Deformable Lateral Supports.	Gibaud	Knee	Orthosis	Mechanical
[87]	Limb Orthosis, in Particular Knee Brace.	Bauerfeind Ag	Knee	Brace	Mechanical
[88]	Knee Orthosis with Helicoidal Axis and Method of Design and Fabrication thereof.	2330-2029 Québec	Knee	Orthosis	Mechanical
[89]	Powered Prosthetic Knee with Battery Recharging During Regeneration Phase.	Oessur Iceland Ehf [Is]; Ossur Americas	Knee	Prosthetic	Electromechanical
[90]	Joint Mechanism, Knee Joint Assist Device, Joint Member, and Clutch Unit.	Fujikura Kasei Co	Knee	Mechanism	Electromechanical

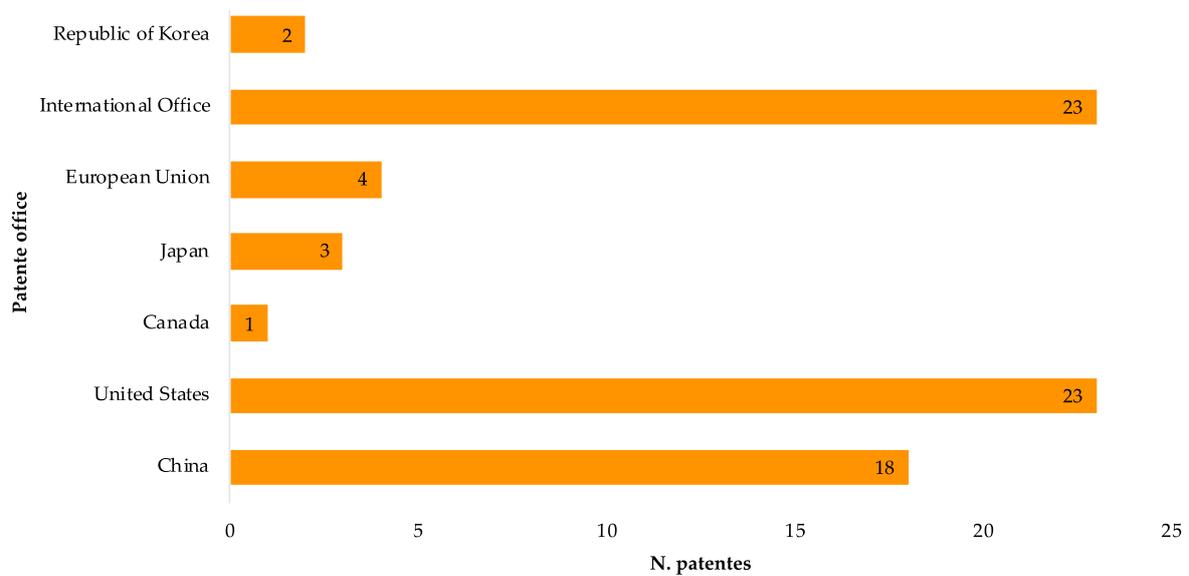


Figure 4. Patents by each patent office.

Applicants and inventors in the databases were considered. The Beijing Institute of Technology and Otto Bock Healthcare Gumbo are the main applicants, with four and three patents, respectively, from 2011 to 2020. In Figure 5, the main applicants for exoskeletons and orthosis are shown.

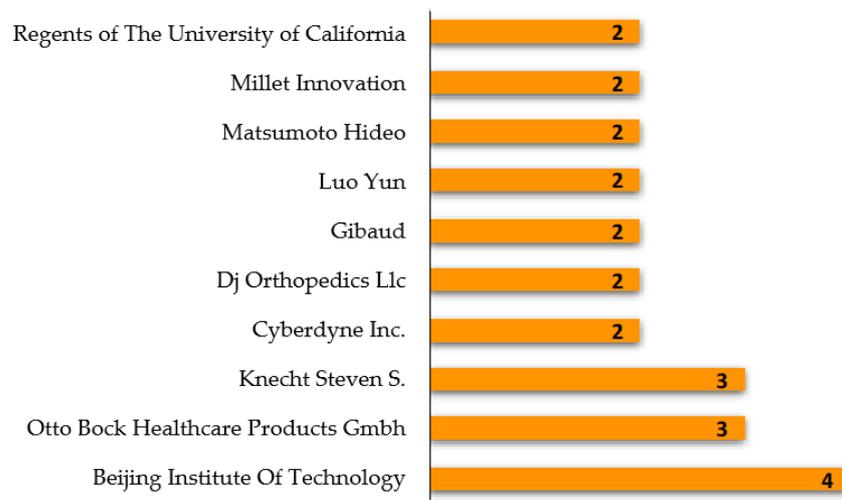


Figure 5. Top patent applicants for exoskeletons and orthosis.

In the analysis of the patents, we found that 59 documents are related to devices for the knee joint and 15 documents are related to devices for two or more joints in the lower limb, as can be seen in Figure 6.

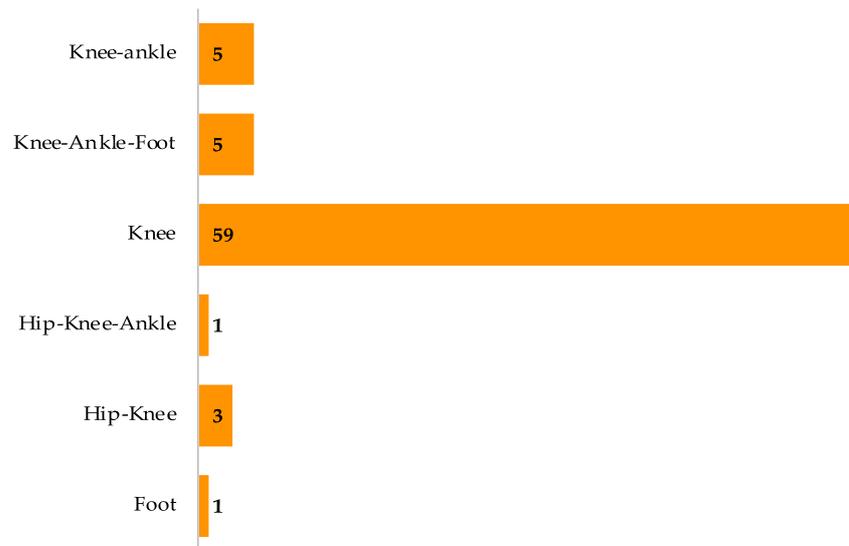


Figure 6. Documents by lower limb joint.

Among the 74 results obtained, 29 results match with orthoses, 16 with braces, 14 with exoskeletons, 7 with devices, 2 with mechanisms, and 1 with exo-suit and prostheses. In addition, three results are associated with methodologies (manufacturing methods, design methods, tests). Figure 7 shows the resulting patents and the distribution with the part of the body of the lower limb that they cover.

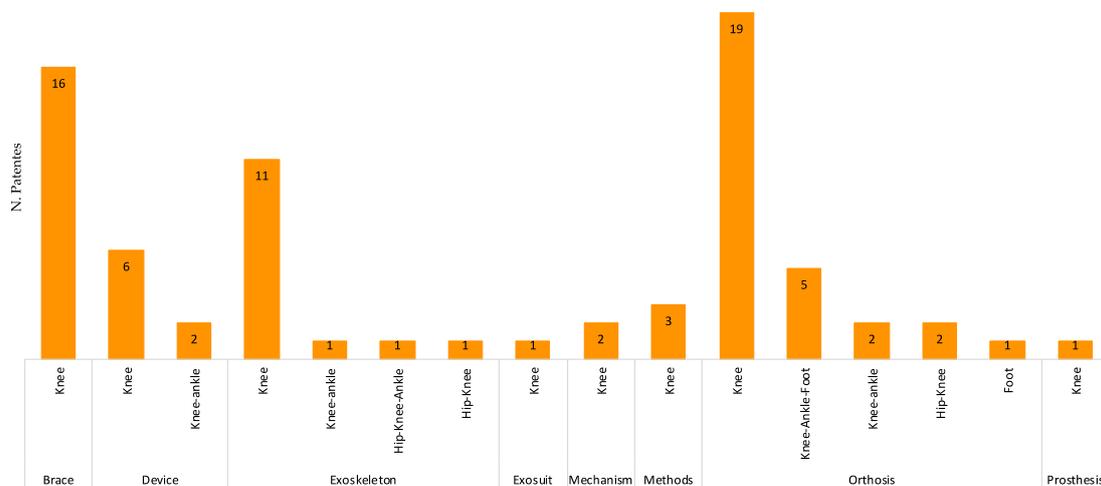


Figure 7. Description of the patents and main coverage.

From the patent data, 59 refer to patents related only to the knee joint. In 45 patents, their predominant technology is mechanical, using cams, hinges, pivoting arms, elastic bands, springs, and springs as the main elements to carry out the mobility of the joint. In 11 patents, the predominant technology is electromechanical–electronic using actuators, servomotors, motors, and a combination of motor–spring with which they carry out the movement of the device. For three patents, the technology used is pneumatic, in which the movement of the devices is made using soft elements. Table 3 shows the selected patents, the technology used, the type of device, and the part of the lower limb that they cover. Figure 8 shows the technology used in the patents and the main elements with which they carry out the mobility of the device.

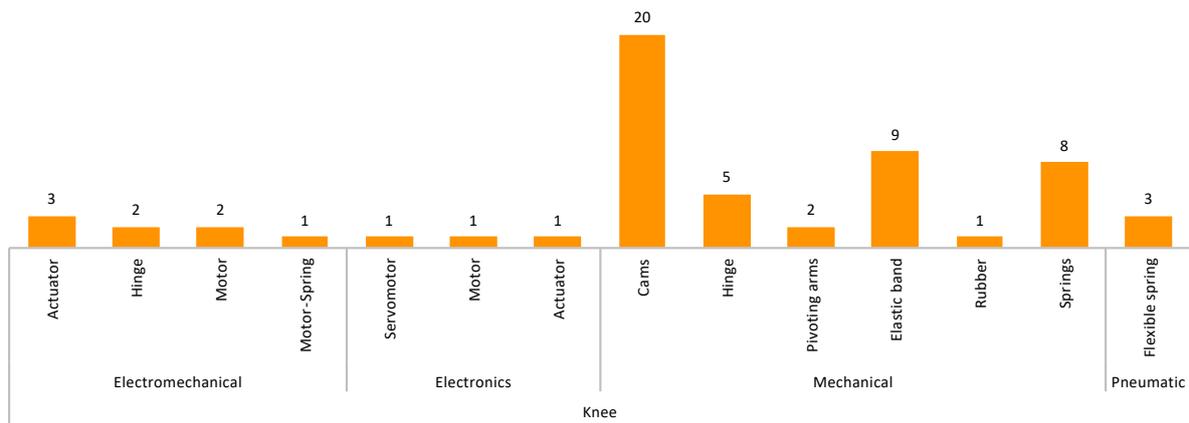


Figure 8. Type of technology used in the knee joint.

3.2. Scientometric Analysis

The following keywords were analyzed: lower limb (frequency = 12 articles), exoskeleton (frequency = 11 articles), knee (frequency = 9 articles), control (frequency = 5 articles), design (frequency = 4 articles), rehabilitation (frequency = 4 articles), passive (frequency = 4 articles), joint (frequency = 3 articles), gait (frequency = 3 articles), orthosis (frequency = 2 articles), development (frequency = 2 articles), powered (frequency = 2 articles), and assistance (frequency = 2 articles) (see Figure 9). From the information obtained by the scientific documents, the characteristics of study subjects were as follows: average weight of 75 kg, a knee torque corresponding to 95–150 Nm, and the power in the knee between 50–235 Watts in the movement of flexion and extension.

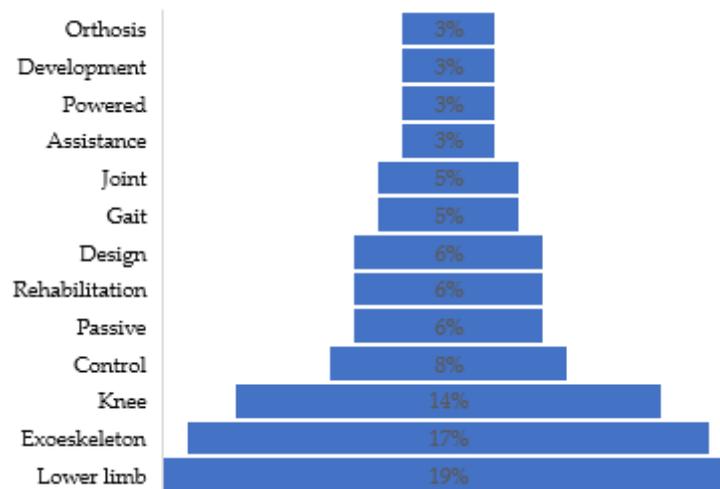


Figure 9. Main keywords found in scientific documents.

Regarding the authors, we find that Mohammed S. is the main author (six articles); however, Meng W. is the most cited author in this field (see Table 4 and Figure 10).

The United States is the most productive country (14 documents), followed by the United Kingdom (13 documents) and China (7 documents) (see Figure 11).

Table 4. Top authors’ production over time.

Author	Year									
	2012	2013	2014	2015	2016	2017	2018	2019	2020	
Mohhamed, S.		2	1	1		1		1		
Amirat, Y.		2	1			1				
Rifai, H.		1	1	1		1				
Vitiello, N.				2	1	1				
Agrawal, SK		1		2						
Cempini, M.				1	1	1				
Domingo, A.			2		1					
Han, C.	1		1		1				1	
Hyun, DJ						2		1		
Lam, T.			2					1		
Li, J.						1	1		1	
Tu, X.						2		1		

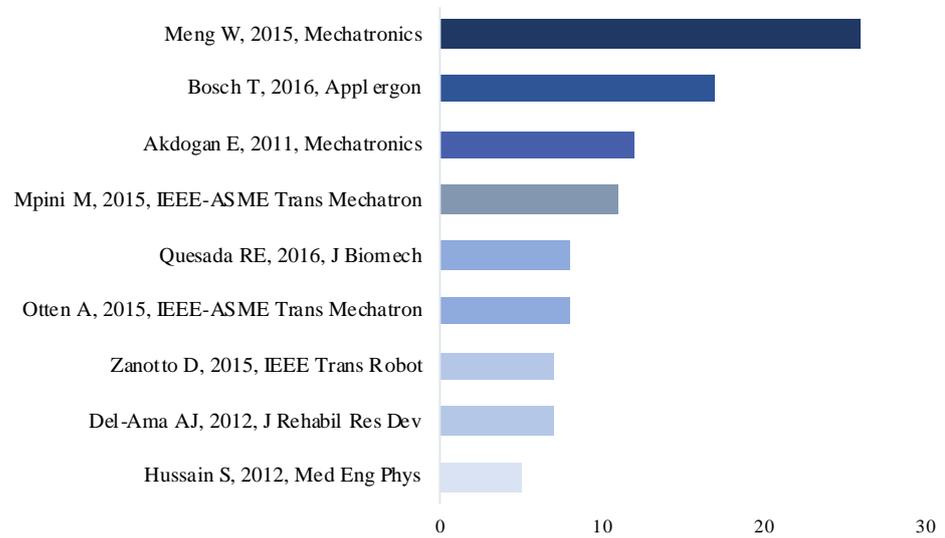


Figure 10. Most cited documents.

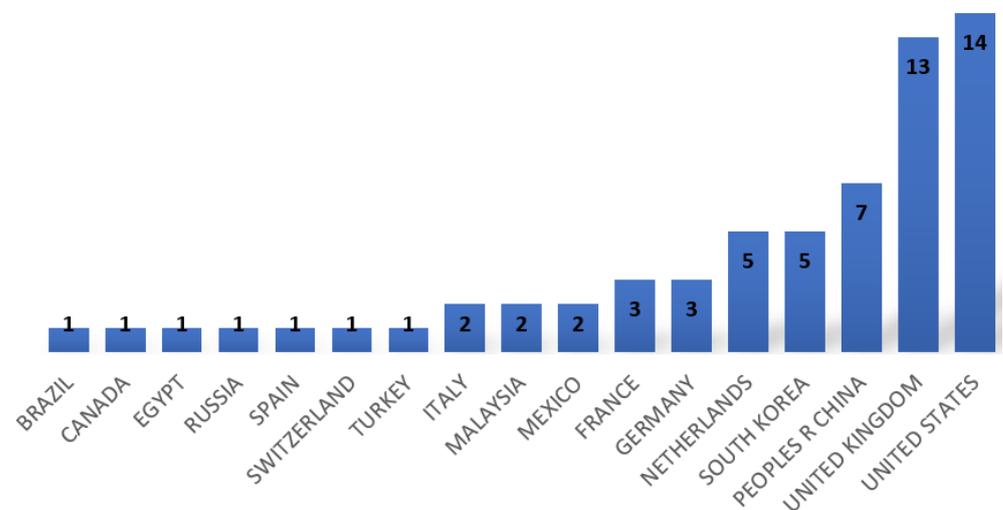


Figure 11. The most productive countries in developing exoskeletons for the knee joint.

Table 5 shows the selected articles, used in the scientometric analysis used, results of the databases and selection criteria.

Table 5. Articles analyzed about knee exoskeletons.

Cite	Main Author	Title	Year
[91]	Heike Vallery	Complementary limb motion estimation for the control of active knee prostheses	2011
[92]	Sancisi, N.	A one-degree-of-freedom spherical mechanism for human knee joint modeling	2011
[93]	Jungwon Yoon	An Adaptive Foot Device for Increased Gait and Postural Stability in Lower Limb Orthoses and Exoskeletons	2011
[94]	Nam, Y	Calculation of Knee Joint Moment in Isometric and Isokinetic Knee Motion	2011
[95]	Akdogan, E	The design and control of a therapeutic exercise robot for lower limb rehabilitation: Physiotherabot	2011
[96]	Kim, K	Development of the Exoskeleton Knee Rehabilitation Robot Using the Linear Actuator	2012
[97]	Mefoued, S	Toward Movement Restoration of Knee Joint Using Robust Control of Powered Orthosis	2013
[98]	Lalami, ME	Output feedback control of an actuated lower limb orthosis with bounded input	2013
[99]	Thomas C. Bulea	Stance-controlled knee flexion improves stimulation-driven walking after spinal cord injury.	2013
[100]	Andrew Q. Tan	Evaluation of lower limb cross planar kinetic connectivity signatures post-stroke	2014
[101]	Sujay S. Galen	Isometric hip and knee torque measurements as an outcome measure in robot-assisted gait training	2014
[102]	Yan, H.	Design and validation of a lower limb exoskeleton employing the recumbent cycling modality for post-stroke rehabilitation	2014
[103]	Seungnam Yu	Design Considerations of a Lower Limb Exoskeleton System to Assist walking and Load-Carrying of Infantry Soldiers	2014
[104]	Lukas Jaeger	Brain activation associated with active and passive lower limb stepping	2014
[105]	Walid Hassani	Powered orthosis for lower limb movements assistance and rehabilitation	2014
[106]	Antoinette Domingo	Reliability and validity of using the Lokomat to assess lower limb joint position sense in people with incomplete spinal cord injury	2014
[107]	Kamran Shamaei	Design and Evaluation of a Quasi-Passive Knee Exoskeleton for Investigation of Motor Adaptation in Lower Extremity Joints	2014
[108]	Mohammed, S	Robust Control of an Actuated Orthosis for Lower Limb Movement Restoration	2015
[109]	Louis Flynn	Ankle-knee prosthesis with active ankle and energy transfer	2015
[110]	Meng, W.	The recent development of mechanisms and control strategies for robot-assisted lower limb rehabilitation	2015
[111]	Dominic James Farris	Revisiting the mechanics and energetics of walking in individuals with chronic hemiparesis following stroke: from individual limbs to lower limb joints.	2015
[112]	Damiano Zanotto	Knee Joint Misalignment in Exoskeletons for the Lower Extremities: Effects on User's Gait	2015
[113]	Seung-Kook Jun	Smart Knee Brace Design with Parallel Coupled Compliant Plate Mechanism and Pennate Elastic Band Spring	2015
[114]	Shamaei, K	Biomechanical Effects of Stiffness in Parallel with the Knee Joint During Walking	2015
[115]	Viet Anh Dung Cai	Transparency enhancement for an active knee orthosis by a constraint-free mechanical design and a gait phase detection based predictive control	2016
[116]	Zhang, F.	iLeg- A Lower Limb Rehabilitation Robot: A Proof of Concept	2016
[117]	Elena Garcia	An Active Knee Orthosis for the Physical Therapy of Neurological Disorders	2016

Table 5. Cont.

Cite	Main Author	Title	Year
[118]	Michael Windrich	Active lower limb prosthetics: a systematic review of design issues and solutions	2016
[119]	Michael S. Cherry	Running With an Elastic Lower Limb Exoskeleton.	2016
[120]	Vouga, T	EXiO-A Brain-Controlled Lower Limb Exoskeleton for Rhesus Macaques.	2017
[121]	Y. Feng	Research on Safety and Compliance of a New Lower Limb Rehabilitation Robot.	2017
[122]	Kopitzsch, Rm.	Optimization-based analysis of push recovery during walking motions supports the design of rigid and compliant lower limb exoskeletons.	2017
[123]	Jun Zhu	Unidirectional variable stiffness hydraulic actuator for load-carrying knee exoskeleton:	2017
[124]	Ho-Jun Kim	Development of a Passive Knee Mechanism for Lower Extremity Exoskeleton Robot.	2017
[125]	Santhakumar Mohan	Design, development and control of a 2PRP-2PPR planar parallel manipulator for lower limb rehabilitation therapies.	2017
[126]	Zachary F. Lerner	The Effects of Exoskeleton Assisted Knee Extension on Lower-Extremity Gait Kinematics, Kinetics, and Muscle Activity in Children with Cerebral Palsy.	2017
[127]	Samuel L. Nogueira	Global Kalman filter approaches to estimate absolute angles of lower limb segments.	2017
[128]	Hala Rifai	Toward Lower Limbs Functional Rehabilitation Through a Knee-Joint Exoskeleton.	2017
[129]	Michael R. Tucker	Design and Characterization of an Exoskeleton for Perturbing the Knee During Gait.	2017
[130]	Juan M. Castellote	Evidence for Startle Effects due to Externally Induced Lower Limb Movements: Implications in Neurorehabilitation.	2017
[131]	Kosuke Kitahara	Target-directed motor imagery of the lower limb enhances event-related desynchronization.	2017
[132]	Yang Liu	A novel cable-pulley underactuated lower limb exoskeleton for human load-carrying walking.	2017
[133]	R.K.P.S. Ranaweera	Development of A Passively Powered Knee Exoskeleton for Squat Lifting.	2018
[134]	Muhammad Aizzat Zakaria	Forward and Inverse Predictive Model for the Trajectory Tracking Control of a Lower Limb Exoskeleton for Gait Rehabilitation: A simulation modeling analysis.	2018
[135]	Syed Faiz Ahmed	Robotic Exoskeleton Control for Lower Limb Rehabilitation of Knee Joint.	2018
[136]	Ronnapree Chaichaowarat	Unpowered Knee Exoskeleton Reduces Quadriceps Activity during Cycling.	2018
[137]	Bo Li	Biomechanical design analysis and experiments evaluation of a passive knee-assisting exoskeleton for weight-climbing.	2018
[138]	Yosuke Eguchi	Standing Mobility Device with Passive Lower Limb Exoskeleton for Upright Locomotion.	2018
[139]	Steffen Ringhof	Does a Passive Unilateral Lower Limb Exoskeleton Affect Human Static and Dynamic Balance Control?	2019
[140]	Rafael Mendoza Crespo	An Adaptable Human-Like Gait Pattern Generator Derived from a Lower Limb Exoskeleton	2019
[141]	Yang, Mx	Development and control of a robotic lower-limb exoskeleton for paraplegic patients	2019
[142]	Zhao, Yj	The control system research of the brain-controlled medical lower limb exoskeleton	2019
[143]	Christian Di Natali	Design and evaluation of a soft assistive lower limb exoskeleton	2019
[144]	Fangzheng Wang	Design and simulation analysis of an improved wearable power knee exoskeleton.	2019

Table 5. Cont.

Cite	Main Author	Title	Year
[145]	Bing Chen	Knee exoskeletons for gait rehabilitation and human performance augmentation: A state-of-the-art.	2019
[146]	Ho-Jun Kim	Development of a Passive Modular Knee Mechanism for a Lower Limb Exoskeleton Robot and Its Effectiveness in the Workplace	2020
[147]	De La Tejera, JA	Smart health: the use of a lower limb exoskeleton in patients with sarcopenia	2020
[148]	Tu Yao	An Adaptive Sliding Mode Variable Admittance Control Method for Lower Limb Rehabilitation Exoskeleton Robot	2020
[149]	Lavrovsky, E.	About the Operator's Gaits in the Passive Exoskeleton of the Lower Extremities when Using the Fixed Knee Mode	2020
[150]	Libo Zhou	Design of a passive lower-limb exoskeleton for walking assistance with gravity compensation	2020
[151]	Ettore Etenzi	Passive-elastic knee-ankle exoskeleton reduces the metabolic cost of walking.	2020
[152]	Chang Yihua	A Lower Limb Exoskeleton Recycling Energy from Knee and Ankle Joints to Assist Push-off	2020
[153]	Wen, Y	Online Reinforcement Learning Control for the Personalization of a Robotic Knee Prosthesis	2020

4. Discussion

In this review of 74 patents and 63 scientific articles, different designs were used to find similarities to guide and facilitate new proposals that may arise in the future. We conclude that using a regulated and slender structure forms the basis of the construction of the exoskeleton design for the knee joint, generally identifying two types of movement: (a) rotation, which achieves flexion and extension of the knee, and (b) rotation and translation, which reproduce more naturally the articular movement of the knee. The design can be scaled to active or passive exoskeletons depending on the force element that is used, and the number of joints of the lower limb that can be included can be expanded.

On the other hand, the number of records per database does not reflect the effectiveness of each search engine. For this research, priority was given to those who provided useful data, such as direct links to patents, the inventor's name, and IPC codes. However, there are some difficulties in processing the records due to the lack of options to filter results or IPC categories. Moreover, some applicants may be included in the name of their companies. This is because some search engines only show the name of the applicant or owner rather than the inventor. In some cases, there is a lack of coherence between the names of the authors in different patents (for example, Chen shuyan and Shuyan, C.). These kinds of inconsistencies were grouped together, but still, the results could not be entirely accurate; the significance of this error does not affect the classification of every system.

This work is helpful to researchers and developers concerned with making proposals more functional to patients and therapists. The patients can know in detail the solutions existent in the market and increase confidence in the kind of device they are using or intend to use, comprehending its operating features, which help to assimilation and adopt medical technology.

4.1. Structural Support Elements

Based on the selected patents and scientific documentation, it is observed that the design of exoskeletons or knee orthoses consists of a rigid structure that is fixed to the side of the joint attached to the leg by means of elastic bands or straps. This structure can be one or two in parallel, embracing the knee joint from the sides, constituting the main structure in the design. Generally, it is made up of three parts: an upper part that is fixed to the leg above the knee, a lower part fixed below the knee, and a joint axis that allows flexion and extension of the mechanical structure of the exoskeleton (see Figure 12).

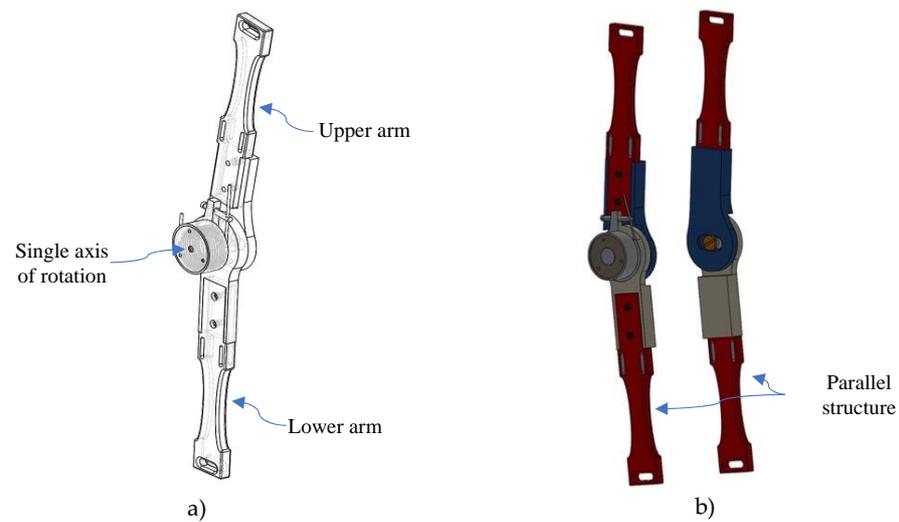


Figure 12. Basic governed structure of attached exoskeleton: (a) one-sided; (b) two-sided.

4.2. Union Types

In patents and research articles, we find two different designs in the joint. The first kind of design allows the flexion and extension of the exoskeleton structure through a hinge with a single axis of rotation in the simplest and most generalized way. It provides the exoskeleton with a movement of a degree of freedom. The second is the union through a mobile axis, which is achieved in three ways: pivoting arms, cams, and polycentric pulleys, providing the exoskeleton with two degrees of freedom due to the linear displacement during the rotation that occurs when the axis moves during rotation (see Figure 13).

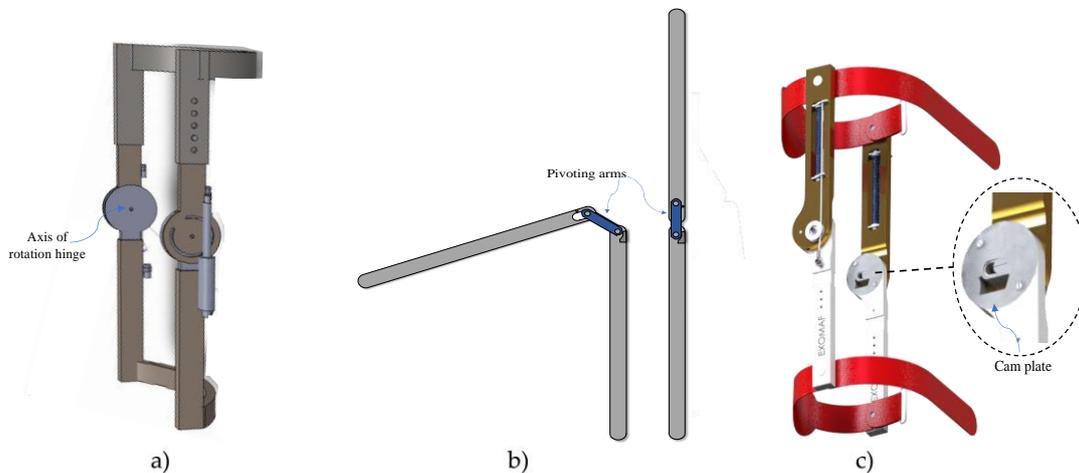


Figure 13. Type of union: (a) hinge; (b) pivoting arms; (c) cam.

4.3. Types of Force Elements Used

The two variants in the design of the exoskeleton structure are the basis for building active or passive knee exoskeletons. In the first case, actuators (pneumatic/electric) are added to the structure that provides the force for bending and joint extension; the basic structure is generally with a fixed axis. The second case is by means of springs, cams, or elastic elements that are added to the design to store and release the energy obtained from the march; the structure can be of a fixed or mobile axis (see Figure 14).

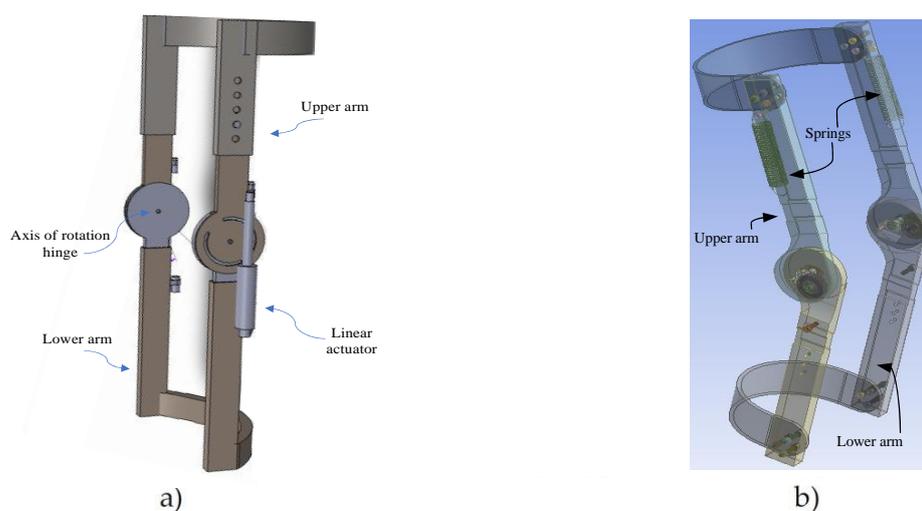


Figure 14. Type force element used: (a) active (actuator); (b) passive (springs).

From the documents (patent and research articles), we can determine that the designs, on average, have a range of mobility of the structure from 0 to 120 degrees, and the actuators, on average, provide a torque of 95 to 150 Nm and power from 50 to 235 watts. On average, when it comes to the use of springs, they generate a force of approximately 85 N.

5. Conclusions

Exoskeletons and knee orthoses are rigid structures articulated with one or more degrees of freedom, to which elements that provide force on the structure are attached. In principle, they are of two types: (a) elastic components such as springs or bands, that when deformed, store energy to later release it, and (b) electromechanical components, which are generally based on electric motors that transform electrical energy into mechanical energy. There are design proposals where the force is provided by a soft element actuated pneumatically.

Although in principle, the technologies used remain the same, the trend in the design of exoskeletons customized to the needs of users has led to the development of lighter components and the combination of elastic elements with electromechanical elements, generating semi-active designs which are more versatile. This review shows that the United States is the country with the highest number of patents and scientific documents related to exoskeletons, orthopedic devices, and knee devices. Therefore, some designs could have been left out of this investigation.

The contribution of these results focuses on knowing, especially among therapists and patients, the usefulness of classifying the knee exoskeletons and their relationship with energy expenditure and comparative energy cost and gait efficiency. In addition, this work contributes to the formulation of the design presented in Sections 4.1–4.3 as a topology optimization for new knee orthoses.

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