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Review

Foot/Ankle Prostheses Design Approach Based on Scientometric and Patentometric Analyses

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Abstract: There are different alternatives when selecting removable prostheses for below the knee amputated patients. The designs of these prostheses vary according to their different functions. These prostheses designs can be classified into Energy Storing and Return (ESAR), Controlled Energy Storing and Return (CESR), active, and hybrid. This paper aims to identify the state of the art related to the design of these prostheses of which ESAR prostheses are grouped into five types, and active and CESR are categorized into four groups. Regarding patent analysis, 324 were analyzed over the last six years. For scientific communications, a bibliometric analysis was performed using 104 scientific reports from the Web of Science in the same period. The results show a tendency of ESAR prostheses designs for patents (68%) and active prostheses designs for scientific documentation (40%).

Keywords: ankle prosthesis; prosthetic foot; lower limb rehabilitation; below-knee amputee

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1. Introduction

Below-knee amputation (BKA) is a surgical procedure that mainly originates from trauma, diabetes, and peripheral vascular diseases [1]. While it is estimated that an average person walks about 6500 steps per day, current trends suggest that 10,000 steps per day represent a healthy lifestyle [2] for which a suitable prosthesis is necessary for a BKA patient in order to achieve a complete user reintegration to his/her pre-amputation activities. These designs should adapt to different patient's activities.

In scientific documents, there is wide confusion with the terms prosthesis, prosthetic, and prostheses; prosthetic is the process to manufacture an artificial member (AM), prosthesis a component of the AM, and prostheses are all the components that make up an AM. From patents and scientific document searches, the term prosthesis is more commonly used; in this paper, prostheses and prosthesis will be used interchangeably.

Understanding the functioning of these prostheses is necessary to identify the foot movements: internal–external axial rotation, eversion–inversion, dorsiflexion (DF), and plantarflexion (PF), as shown in Figure 1. The forces acting on the human foot are distributed with 60% towards the heel and 40% towards the phalanges. The loads are distributed between the heel and the metatarsals to the fourth and fifth phalanges and towards the big toe to the second and third phalanges [3].

In order to improve and develop ankle/foot prostheses, it is necessary to know and understand present-day solutions to walking and running for BKA patients (and the people behind those solutions), so our designs meet both user and technical requirements. A state-of-the-art analysis of BKA prostheses is performed in this research.

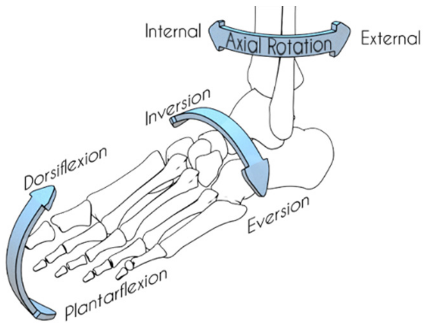


Figure 1. Different movements of the foot.

Foot prostheses can be classified as follows:

- Ankle-cushion heel (SACH-foot): This was developed in the 1950s and incorporated a compressible heel that dampens the impact on the ground while emulating a plantarflexion movement. This type of prosthesis is used for its relatively low cost and weight [4].
- ESAR, also known as ESR, was developed in the 1980s. This type of prosthesis uses a foot-modeled plate (usually carbon fiber made) that stores elastic potential energy and progressively releases it as kinetic energy [5].
- CESR prostheses aim to capture the energy that is dissipated during a gait impact. On the loading phase of stance, energy is stored by a spring and locked. Then, this energy is timely released during the terminal stance of walking using microelectronic components [5].
- Active prostheses are considered state-of-the-art prostheses due to the use of actuators, microcontrollers, or other electronic devices; usually, these work using ESAR foot systems combined with some external elements such as actuators or other electronic components. These prostheses have better control and stability during a walk cycle [6].

In the next section, it is explained how the investigation was performed for both patents and scientific communications. The Result Section presents a discussion about a new prosthesis classification according to this investigation, main authors, countries, and keywords analyzed. In the discussion Section, findings and other designs of prosthesis designs are disclosed.

2. Search Method

BKA prostheses designs vary in form and functions, so in order to understand the way these designs work, extensive patents and scientific documentation searches were performed.

2.1. Used Keywords

For the patents and scientific communications searches, the following boolean operations were used under the International Patent Classification (IPC) A61F2 belonging to artificial substitutes or replacements for parts of the body: ((Ankle OR foot) AND (prosthetic OR prosthesis OR artificial)). Dates ranges were set from 2014 to 2020. For the patent analysis, 9526 documents were found. A scientific communications search provided 406 results. Figure 2 shows the results filtered on different search engines and the total number of documents obtained in every stage, among which The Lens was the most effective.

2.2. Patent Search

For the patent search, five different search engines were used, of which four were free-source, and one was paid. The databases were Derwent analytics (842 results), Espacenet (86 results), Google patents (5539 results), Patentscope (2281 results), and The Lens (778 results), with a total of 9526 results (see Figure 2).

An initial filter was applied directly to the search engines where undesired categories and keywords were removed, in addition to a manual selection of patents directly on the website.

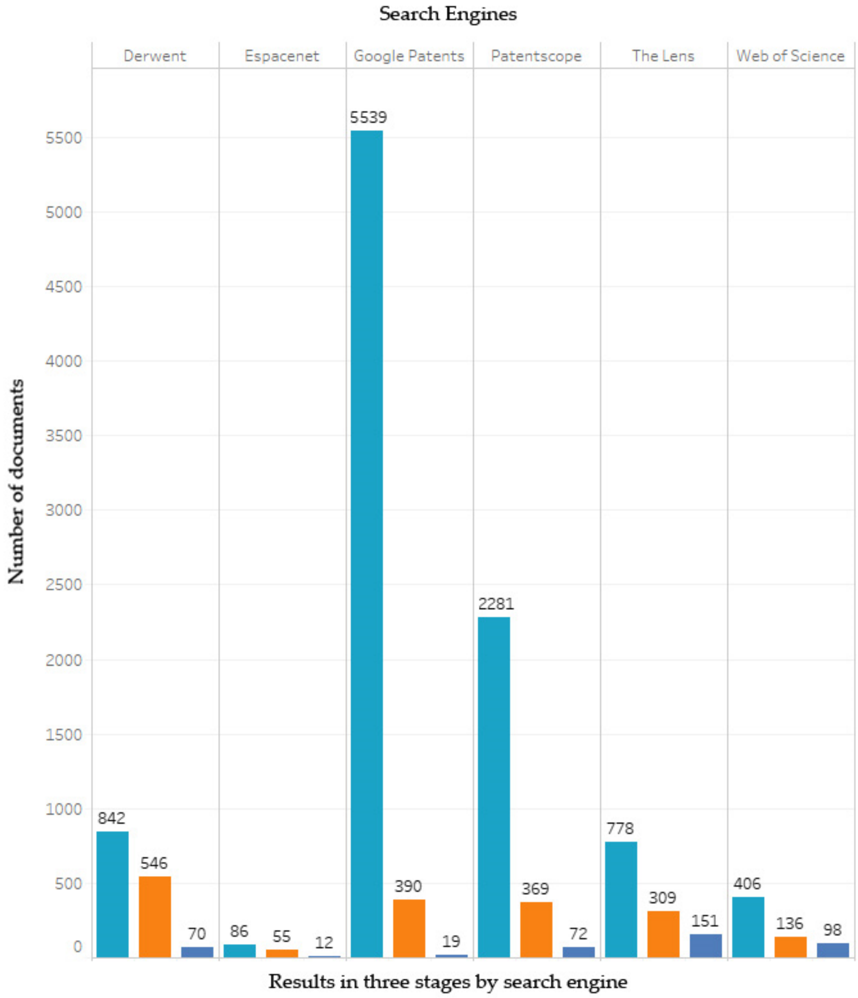


Figure 2. Search method for patents/scientific documents and total results.

Subsequently, data cleaning was performed using Open refine®. The second filter was applied to eliminate duplicates, IPC categories that did not correspond, and keywords such as heart, valve, elbow, Arthroplasty, and Orthosis. An individual selection of the patents was made, and the unwanted results were eliminated. The remaining patents were as follows: Patentscope (369), Google patents (390), Espacenet (55), Derwent analytics (546), and The Lens (309), resulting in 1669 patents.

Based on a third filter, the results of all databases were merged, and keywords such as knee, orthosis, and tibia were eliminated. Duplicated results were filtered, and the remaining patents were individually analyzed for a total result of Derwent analytics (70), Espacenet (12), Google patents (19), Patentscope (72), and The Lens (151), resulting in 324 patents directly related to ankle and foot prostheses. From Figure 2, it can be observed that although Google patents and Patentscope were the ones with more results, these contained a higher number of duplicates or undesired data.

2.3. Scientific Communications Search

For the literature analysis, the same keywords as for the patents' search were applied in the Web of Science (WOS), obtaining 406 documents related to foot/ankle prostheses. The first filter was performed directly on the website, removing undesired keywords for a total of 136 documents. Subsequently, a second filter was applied, deleting repeated and undesired results. An individual document selection was made, resulting in 97 results. Finally, a bibliometric analysis was performed using data recovery software (R studio®) and a complement for bibliometric analysis (Bibliometrix®).

3. Results

3.1. Patentometric Analysis

Among the 324 results obtained, 208 results match prostheses designs, 51 match prosthetic mechanisms (motion blocking systems, aids to align prostheses, etc.), 22 match sockets, 11 match aesthetic covers, and 10 match joints. In total, 22 results are associated with methodologies (manufacturing methods, design methods, tests). Figure 3 shows these results; the number of prosthesis designs suggests a high interest in the development of new solutions for BKA amputees.

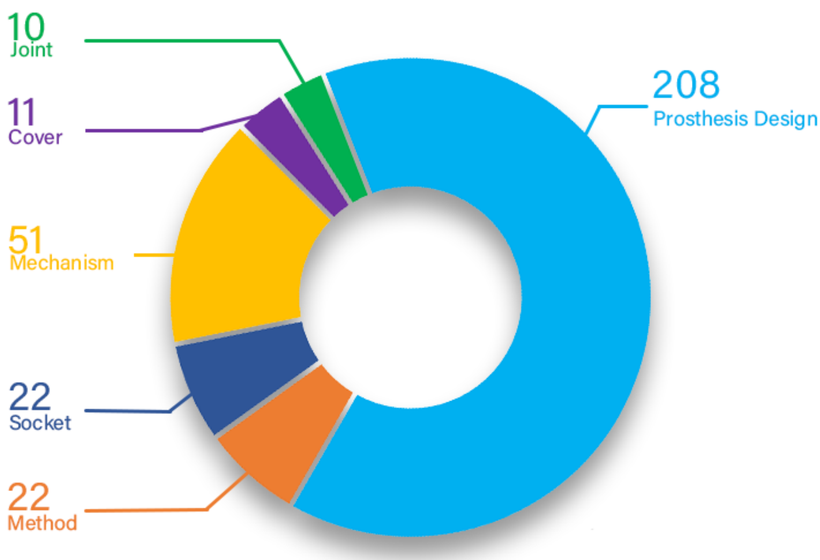


Figure 3. Categories of the patents' analysis and results by category.

The main offices in which patents are registered are the United States (178 patents), European Office (45 patents), International Office (37 patents), and China (34 patents).

Among the results, 95 refer to foot prostheses, 65 to ankle prostheses, and 48 to a combination of both, of which 182 are removable, and 26 are osseointegrated. In this investigation, only removable prostheses are considered. Table 1 shows the selected patents, the technology used, and the type of prostheses. Among removable prostheses, 135 are mechanical or propelled with the body, hydraulic (18 results), and electronic or active (29 results). These results are distributed among ESAR, CESR, active, and hybrid (which did not match any of the aforementioned technologies or they are a combination of two or more categories). From Figure 4, it can be observed that for electronic prostheses, 17 are active, three are CERS (use a controlled energy return without the use of complex devices), one is ESAR, and eight are hybrid. For hydraulic prostheses, four use electronic components, three are based on CERS, three on ESAR, and eight are a combination of three or more categories. For mechanical prostheses, 94 use ESAR systems exclusively, 26 combine different technologies (but mostly are mechanical), 13 are CERS (energy return is controlled using only mechanical devices), and two use actuators to release the energy.

Applicants and inventors in the databases were considered. Otto Bock Health Co. and Clausen Arinbjorn V. are the main applicants with ten and eight patents, respectively, from 2014 to 2020. Figure 5 shows the main applicants for BKA prostheses.

Table 1. Removable ankle/foot prostheses patents.

Cite	Title	Main Applicant	Body Part	Technology	Type
[7]	-Adjustment Device for A Lower Limb Prosthesis	Blatchford Products Limited.	Ankle	Hydraulic	Hybrid
[8]	-Below-knee Prosthesis Provided with Power Ankle	Beijing Gongdao Fengxing Intelligent	Ankle/Foot	Electronic	ESAR
[9]	-Bifurcated, Multi-purpose Prosthetic Foot	Christensen Roland J.	Foot	Mechanical	ESAR
[10]	-Bi-modal Ankle-foot Device	Hansen Andrew H.	Ankle/Foot	Mechanical	CESR
[11]	-Controlling Power in A Prosthesis or orthosis Based on Predicted Walking Speed or Surrogate for Same	Herr Hugh M.	Ankle/Foot	Electronic	CESR
[12]	-Damping Device for A Prosthesis	Ossur Hf.	Ankle	Mechanical	Hybrid
[13]	-Energy Storing Foot Plate	Iversen Edwin Kay	Ankle/Foot	Mechanical	ESAR
[14]	-Further Improvements to Ankle–foot Prosthesis and orthosis Capable of Automatic Adaptation to Sloped Walking Surfaces	Hansen Andrew H.	Ankle/Foot	Mechanical	CESR
[15]	-Joints for Prosthetic, orthotic and/or Robotic Devices	Rifkin Jerome R.	Foot	Mechanical	Hybrid
[16]	-Low Profile Prosthetic Foot	Jonsson Orn Ingvi	Foot	Mechanical	ESAR
[17]	-Lower Limb Prosthetic Device with A Wave Spring	Rubie Eric W.	Foot	Mechanical	ESAR
[18]	-Modular Prosthetic Foot	Miller Joseph A.	Foot	Mechanical	ESAR
[19]	-Orthopedic Foot Part	Otto Bock Holding	Ankle/Foot	Electronic	Active
[20]	-Passive Ankle Prosthesis with Energy Return Simulating that of A Natural Ankle	Joseph M. Schimmels	Ankle/Foot	Mechanical	CESR
[21]	-Passive orthopedic Aid in the form of a Foot Prosthesis or Foot orthosis	Otto Bock Healthcare	Ankle/Foot	Hydraulic	Active
[22]	-Power Below-knee Prosthesis with Discrete Soft Toe Joints	Beijing Gongdao Fengxing Intelligent	Ankle/Foot	Mechanical	ESAR
[23]	-Prosthetic Ankle–foot System	Universiteit Gent	Ankle/Foot	Mechanical	Hybrid
[24]	-Prosthetic Energy Storing and Releasing Apparatus and Methods	Phillips Van L.	Foot	Mechanical	ESAR
[25]	-Prosthetic Foot	Keith B. Smith	Foot	Mechanical	ESAR
[26]	-Prosthetics Using Curved Dampening Cylinders	Aaron Taszreak	Ankle/foot	Mechanical	ESAR
[27]	-A Foot with A Vacuum Unit Activated by an Ankle Motion	Duger Mustafa	Ankle	Mechanical	Hybrid
[28]	-Artificial Ankle, Artificial Foot and Artificial Leg	Falz & Kannenberg Gmbh	Ankle	Electronic	Active
[29]	-Artificial Limb Prosthesis Leg Below Knee & Above Knee	Univ Bharath	Ankle/Foot	Mechanical	ESAR
[30]	-Flexible Prosthetic Appliance	Brown Christopher A.	Foot	Mechanical	Hybrid
[31]	-Foot for Mobility Device	Sanders Michael R.	Foot	Mechanical	ESAR
[32]	-High-performance Multi-component Prosthetic Foot	Rubie Eric W.	Foot	Mechanical	ESAR
[33]	-Hydraulic Actuating Unit and Artificial Foot Prosthesis System Having the Same	Gyeonggyeongcheol	Ankle	Electronic	Hybrid
[34]	-Hydraulic System for A Knee-ankle Assembly Controlled by a Microprocessor	Xavier Bonnet	Ankle	Electronic	CESR
[35]	-Prosthesis Structure for Lower-limb Amputees	Officine Ortopediche Rizzoli Sr.	Ankle/Foot	Electronic	Hybrid
[36]	-Prosthetic Foot	Ability Dynamics Llc.	Foot	Mechanical	ESAR
[37]	-Prosthetic Foot	Frizen	Foot	Mechanical	ESAR
[38]	-Prosthetic Foot	Frizen Dzheff	Foot	Mechanical	ESAR
[39]	-Prosthetic Foot	Luder Mosler	Foot	Mechanical	ESAR
[40]	-Prosthetic Foot	The Ohio Willow Wood Company	Foot	Mechanical	ESAR
[41]	-Prosthetic Foot with a Curved Split	Jonsson Vilhjalmur Freyr	Foot	Mechanical	ESAR

Table 1. *Cont.*

Cite	Title	Main Applicant	Body Part	Technology	Type
[42]	-Prosthetic Foot with Dual Foot Blades and Vertically offset Toe	Lecomte Christophe Guy	Foot	Mechanical	ESAR
[43]	-Prosthetic Foot with Floating forefoot Keel	Christensen Roland J.	Foot	Mechanical	ESAR
[44]	-Prosthetic Limb	3d Systems	Ankle/Foot	Mechanical	ESAR
[45]	-Prosthetic System	Hawkins Ryan	Ankle	Mechanical	Hybrid
[46]	-Smooth Rollover insole for Prosthetic Foot	Clausen Arinbjorn Viggo	Foot	Mechanical	ESAR
[47]	-System for Powered Ankle–foot Prosthesis with Active Control of Dorsiflexion-plantarflexion and inversion-eversion	Mo Rastgaar	Ankle	Electronic	Hybrid
[48]	-Walking Controller for Powered Ankle Prostheses	Michael Goldfarb	Ankle	Electronic	Active
[49]	-Actuated Prosthesis for Amputees	Bedard Stephane	Ankle/Foot	Electronic	Active
[50]	-Additive Manufacturing Produced Prosthetic Foot	James M. Colvin	Foot	Mechanical	ESAR
[51]	-Ankle Prosthesis Assembly	Ermalyuk Vladimir Nikolaevich	Foot	Hydraulic	Hybrid
[52]	-Ankle Prosthesis Assembly of Foot	Suslov Andrej Vladimirovich	Foot	Mechanical	ESAR
[53]	-Artificial Foot	Inha Industry Partnership Institute	Foot	Electronic	Active
[54]	-Artificial Foot for Sports	Seo Jung Woong	Ankle/Foot	Mechanical	ESAR
[55]	-Artificial Foot Prosthesis System	Sogang University	Ankle	Electronic	Active
[56]	-Artificial Human Limbs and Joints Employing Actuators, Springs, and Variable-damper Elements	Massachusetts Institute of Technology	Ankle	Mechanical	Active
[57]	-Controlled Coronal Stiffness Prosthetic Ankle	Klute Glenn	Ankle	Mechanical	Hybrid
[58]	-False Foot of Carbon -fibre Composite	Beijing Baimtec.	Foot	Mechanical	ESAR
[59]	-Foot Prosthesis	Medi Gmbh & Co.	Foot	Mechanical	ESAR
[60]	-Foot Prosthesis with Adjustable Rollover	Mccarvill Sarah	Foot	Mechanical	ESAR
[61]	-Hybrid Ankle Joints	Jo Hyun	Ankle	Electronic	Active
[62]	-instrumented Prosthetic Foot	Victhom Human Bionics Inc.	Foot	Mechanical	ESAR
[63]	-Layering Technique for An Adjustable, Repairable Variable Stiffness Prosthetic Foot	Gonzalez Roger V.	Foot	Mechanical	ESAR
[64]	-Passive orthopaedic Aid in the form of a Foot Prosthetic or orthotic	Mosler	Foot	Mechanical	Hybrid
[65]	-Prosthetic Ankle Module	Ásgeirsson Sigurõur	Foot	Mechanical	ESAR
[66]	-Prosthetic Ankle Module	Nijman Jeroen	Foot	Mechanical	ESAR
[67]	-Prosthetic Ankle: A Method of Controlling Based on Adaptation to Speed	Arinbjorn Clausen	Ankle	Mechanical	Active
[68]	-Prosthetic Device and Method with Compliant Linking Member and Actuating Linking Member	Matthew A. Holgate	Ankle/Foot	Electronic	CESR
[69]	-Prosthetic Foot	Ability Dynamics Llc.	Foot	Mechanical	ESAR
[70]	-Prosthetic Foot	Ability Dynamics Llc.	Foot	Mechanical	ESAR
[71]	-Prosthetic Foot	Doddroe Jeffrey L.	Foot	Mechanical	ESAR
[72]	-Prosthetic Foot	Starker Felix	Foot	Mechanical	ESAR
[73]	-Prosthetic Foot	Sulprizio Michael Scott	Foot	Mechanical	ESAR
[74]	-Prosthetic Foot and Manufacturing Method Thereof	Kim Sa Yeop	Foot	Mechanical	ESAR
[75]	-Prosthetic Vacuum System	Ossur Hf.	Foot	Electronic	Hybrid
[76]	-Responsive Prosthesis	Howell	Foot	Mechanical	ESAR

Table 1. *Cont.*

Cite	Title	Main Applicant	Body Part	Technology	Type
[77]	-A Prosthesis or orthosis Comprising a Hinge Joint System for Functionally Assisting, Enhancing and/or Replacing A Hinge Joint of a Human or Animal Subject	Vrije Universiteit Brussel	Ankle/Foot	Mechanical	CESR
[78]	-Active Lower Leg Prosthesis Device	Sogang University	Ankle	Hydraulic	CESR
[79]	-Apparatus and Method for A Split Toe Blade	Rubie Eric W.	Foot	Mechanical	ESAR
[80]	-Artificial Ankle Joint Limb Based on Flexible Driver	Nanjing Institute of Technology	Ankle	Mechanical	Hybrid
[81]	-Artificial Foot	Hornos Pedro	Foot	Mechanical	ESAR
[82]	-Artificial Foot and Method for Controlling the Movement Thereof	Otto Bock Holding.	Foot	Mechanical	ESAR
[83]	-Bow -shaped Ankle Structure Combined Material Artificial Limb Foot Core	Lin Yusen.	Foot	Mechanical	ESAR
[84]	-Catapult Ankle and Related Methods	Rouse Elliott J.	Ankle	Electronic	Hybrid
[85]	-Dispositif De Prothese De Cheville Controle Par Une Prothese De Genou Motorisee Sensible A La Pesanteur	Millinav	Ankle	Mechanical	Hybrid
[86]	-Electronically Controlled Prosthetic System	Martin James Jay	Foot	Electronic	Active
[87]	-Fine Energy Storage Foot of Carbon	Sun Yongshang	Foot	Mechanical	ESAR
[88]	-Foot Prosthesis	Kranner Werner	Foot	Mechanical	ESAR
[89]	-Foot Prosthesis with Resilient Multi-axial Ankle	Lecomte Christophe Guy	Foot	Mechanical	ESAR
[90]	-Microprocessor Controlled Prosthetic Ankle System for Footwear and Terrain Adaptation	Palmer Michael	Ankle	Hydraulic	Active
[91]	-Novel Fine Prosthetic Foot of Comfortable Energy Storage Carbon	Guangzhou Kangmeite Prostheses Co Ltd.	Foot	Mechanical	ESAR
[92]	-Oil Pressure Ankle Joint	Ken Dall Enterprise.	Ankle	Hydraulic	Hybrid
[93]	-Overmould Attachments for Prosthetic Foot	Lecomte Christophe Guy	Foot	Mechanical	ESAR
[94]	-Prosthetic Ankle and Method of Controlling Same Based on Adaptation to Speed	Ossur Hf.	Ankle	Electronic	Active
[95]	-Prosthetic Foot	Keith B. Smith	Foot	Mechanical	ESAR
[96]	-Prosthetic Foot	Otto Bock Holding.	Foot	Mechanical	ESAR
[97]	-Prosthetic Foot	Sun Yongshang	Foot	Mechanical	ESAR
[98]	-Prosthetic Foot Structure	Cheng Yao Teng	Foot	Mechanical	ESAR
[99]	-Prosthetic Foot with Energy Transfer Medium including Variable Viscosity Fluid	Christensen Roland J.	Foot	Mechanical	ESAR
[100]	-Prosthetic Foot, System of A Prosthetic Foot and A Shoe, and Method for Adapting the Heel Height of a Prosthetic Foot	Hermann Meyer	Ankle/Foot	Mechanical	ESAR
[101]	-Prosthetic Joint with Mechanical Response System to Position and Rate of Change	Lincoln Lucas Samuel	Ankle	Mechanical	CESR
[102]	-Prosthetic Sport Feet	Clausen Arinbjorn V.	Foot	Mechanical	ESAR
[103]	-Shock Attenuation Energy -absorbing Prosthetic Foot Foot Core	Li Jingtong	Foot	Mechanical	ESAR
[104]	-Single-freedom-degree Active Type Ankle Joint Artificial Limb Based on Closed Type Hydraulic Driving System	Wang Xingjian	Ankle/Foot	Hydraulic	Active
[105]	-Systems and Control Methodologies for Improving Stability in Powered Lower Limb Devices	Vanderbilt University	Ankle/Foot	Electronic	Active
[106]	-Actuator Control System and Related Methods	Northern Arizona University.	Ankle/Foot	Electronic	Active
[107]	-Ankle–foot Prosthesis Device	Liu Yan Nan	Ankle	Electronic	Active

Table 1. *Cont.*

Cite	Title	Main Applicant	Body Part	Technology	Type
[108]	-Articulated orthopaedic Foot with Shock Absorption, Which Prevents the Impact Produced in Each Foot-loading Cycle When Walking or Running, Providing Natural Movement and Stability for The User	Mora Morales Miguel	Foot	Mechanical	ESAR
[109]	-Artificial Foot	Lindhe Christoffer.	Foot	Mechanical	ESAR
[110]	-Biomimetic and Variable Stiffness Ankle System and Related Methods	Rouse Elliott J.	Ankle	Mechanical	Hybrid
[111]	-Bionic Prosthetic Mechanical Foot with Parallel Joints	Xing Zhiping	Ankle/Foot	Electronic	Hybrid
[112]	-Clearance Enhancer for Lower Limb Prosthesis	Palmer Jeffrey Ray	Foot	Mechanical	ESAR
[113]	-Energy Storage Foot	Bonawei Rehabilitation.	Ankle/Foot	Mechanical	ESAR
[114]	-Foot Prosthesis	Otto Bock Holding.	Ankle/Foot	Electronic	Hybrid
[115]	-Foot Prosthesis	Sven Kaltenborn	Ankle/Foot	Hydraulic	Hybrid
[116]	-Foot Prosthesis Has Blade	Benjamin Penot	Ankle/Foot	Mechanical	Hybrid
[117]	-Foot Prosthesis with Dymic Variable Keel Resistance	Matthew J. Habecker	Ankle/Foot	Mechanical	CESR
[118]	-Foot Prosthesis with Dynamic Variable Keel Resistance	Matthew J. Habecker	Ankle/Foot	Mechanical	Hybrid
[119]	-Hydraulic Ankle	Chia-pao Cheng	Ankle	Hydraulic	Hybrid
[120]	-Hydraulic Ankle Joint	Ken Dall Enterprise.	Ankle	Hydraulic	Hybrid
[121]	-Jointless Prosthetic Foot	Boiten Herman.	Foot	Mechanical	ESAR
[122]	-Light intelligent Energy-storage Energy-releasing Ankle Prosthesis	Ye Yanhong.	Foot	Mechanical	CESR
[123]	-Limb Prosthesis System and Method	Bartlett Brian.	Ankle/Foot	Mechanical	Hybrid
[124]	-Linear Actuator for Asymmetric Power Generation and Dissipation	Michael Goldfarb.	Ankle	Electronic	Hybrid
[125]	-Lower Limb Prosthesis Comprising A Hydraulic Damping and A Vacuum Generating Mechanism	Graham Harris.	Ankle/Foot	Hydraulic	Active
[126]	-Medial-lateral Stabilizing Prosthetic Ankle/foot for Angled and Rough Ground Gait	Maitland Murray E.	Ankle/Foot	Mechanical	Hybrid
[127]	-Method for Operating A Prosthetic Ankle	Clausen Arinbjorn V.	Foot	Electronic	Active
[128]	-Modular Lower Limb Prosthesis System	Fairley Joseph.	Foot	Mechanical	ESAR
[129]	-Movement Support Apparatus	Endo Ken.	Ankle/Foot	Mechanical	CESR
[130]	-Polycentric Powered Ankle Prosthesis	Lenzi Tommaso.	Ankle	Electronic	Active
[131]	-Powered Artificial Ankle Based on Electro-hydraulic Direct Drive Technology	Huang Qi-tao.	Ankle	Hydraulic	Hybrid
[132]	-Prosthetic and Orthotic Devices Having Magnetorheological Elastomer Spring with Controllable Stiffness	Gudmundsson Ivar.	Foot	Mechanical	ESAR
[133]	-Prosthetic Ankle and Foot Combination	Moser David.	Ankle/Foot	Mechanical	ESAR
[134]	-Prosthetic Device	Fillauer Euro Ab.	Ankle/Foot	Mechanical	ESAR
[135]	-Prosthetic Device	Ramirez Christoffer.	Foot	Mechanical	ESAR
[136]	-Prosthetic Foot	Bonacini Daniele.	Foot	Mechanical	ESAR
[137]	-Prosthetic Foot	Smith Keith.	Foot	Mechanical	ESAR
[138]	-Prosthetic Foot	Willowwood Global.	Foot	Mechanical	ESAR
[139]	-Prosthetic Foot	Zamora David A.	Foot	Mechanical	ESAR
[140]	-Prosthetic Foot with Hybrid Layup	Gunnarssonn Ragnar.	Foot	Mechanical	ESAR
[141]	-Prosthetic Foot with Modular Construction	Kramer Leslie D.	Foot	Mechanical	ESAR
[142]	-Shank Prosthesis Provided with Double Foot Sole Plates	Zhang Jun.	Foot	Hydraulic	ESAR
[143]	-Spring Design for Prosthetic Applications	Prost Victor.	Foot	Mechanical	Hybrid
[144]	-Stair Ascent and Descent Control for Powered Lower Limb Devices	Vanderbilt University.	Ankle/Foot	Mechanical	ESAR

Table 1. *Cont.*

Cite	Title	Main Applicant	Body Part	Technology	Type
[145]	-Tapered Flex Plate for Prosthetic Foot	Jonsson Orn Ingvi.	Foot	Mechanical	ESAR
[146]	-Variable Bar Length Gear Five-bar Mechanism Active and Passive Ankle Artificial Limb	Univ Northwestern Polytechnical.	Ankle	Mechanical	Hybrid
[147]	-Variable Stiffness Prosthetic Foot	Sandahl David.	Foot	Mechanical	ESAR
[148]	-Adjustable Stiffness Prosthetic Foot	Smith Justin R.	Foot	Mechanical	ESAR
[149]	-Ankle–foot Prosthesis for Automatic Adaptation to Sloped Walking Surfaces	Hansen Andrew H.	Foot	Mechanical	CESR
[150]	-Artificial Ankle–foot System with Spring, Variable-damping, and Series-elastic Actuator Components	Massachusetts Institute of Technology.	Ankle/Foot	Electronic	Active
[151]	-Biomimetic Prosthetic Device	Schlafly Millicent Kay	Foot	Mechanical	CESR
[152]	-Carbon Fiber Prosthetic Foot	Nelson Ronald Harry.	foot	Mechanical	ESAR
[153]	-Compression Heel Prosthetic Foot	Parker Gene.	Foot	Mechanical	ESAR
[154]	-Foot Prosthesis	Pusch Martin.	Foot	Mechanical	ESAR
[155]	-Hydraulic Pressure Energy Storage Prosthetic Foot	Wang Zitong.	Ankle/Foot	Hydraulic	ESAR
[156]	-Hydraulic Prosthetic Ankle	Poulson Arlo Iii.	Ankle	Mechanical	CESR
[157]	-Low-energy Artificial Limb	Wang Jianhua.	Foot	Mechanical	ESAR
[158]	-Lower Limb Prosthesis	Blatchford Products.	Ankle/Foot	Electronic	Active
[159]	-Passive and Slope Adaptable Prosthetic Foot Ankle	Amiot David	Foot	Hydraulic	CESR
[160]	-Powered Ankle–foot Prosthesis	Herr Hugh M.	Ankle/Foot	Electronic	Active
[161]	-Prosthesis and Prosthetic Foot Adapter	Allermann Ralf.	Ankle/Foot	Mechanical	ESAR
[162]	-Prosthetic Ankle Joint Mechanism	Moser David.	Ankle	Hydraulic	Hybrid
[163]	-Prosthetic Apparatus and Method Therefor	Peter Gabriel A.	Foot	Mechanical	ESAR
[164]	-Prosthetic Feet Having Heel Height Adjustability	Albertson Aron Kristhjorn.	Ankle	Mechanical	CESR
[165]	-Prosthetic Foot	Friesen Jeff.	Foot	Mechanical	ESAR
[166]	-Prosthetic Foot	Grosskopf Stefan.	Foot	Mechanical	ESAR
[167]	-Prosthetic Foot	Guangdong Lanwan Intelligent Technology.	Ankle/Foot	Mechanical	Hybrid
[168]	-Prosthetic Foot	Jo Sung Hun.	Foot	Mechanical	ESAR
[169]	-Prosthetic Foot	Pusch Martin.	Foot	Mechanical	ESAR
[170]	-Prosthetic Foot Having A Function of Ankle	Kim Hyun Cheol.	Ankle/Foot	Mechanical	ESAR
[171]	-Prosthetic Foot insert and Prosthetic Foot	Mosler Loder.	Foot	Mechanical	ESAR
[172]	-Prosthetic Foot that Toe Part Can Rotate	Kim Hyun Cheol.	Foot	Mechanical	ESAR
[173]	-Prosthetic Foot with Enhanced Stability and Elastic Energy Return	Clausen Arinbjorn Viggo.	Foot	Hydraulic	CESR
[174]	-Prosthetic Foot with Removable Flexible Members	Clausen Arinbjorn Viggo.	Ankle/Foot	Hydraulic	ESAR
[175]	-Prosthetic Foot with Spaced Spring Elements	Day Jesse.	Foot	Mechanical	ESAR
[176]	-Prosthetic Foot and Prosthesis for A Lower Extremity	Radspieler Andreas.	Ankle/Foot	Mechanical	ESAR
[177]	-A Prosthetic Ankle and Foot Combination	Blatchford Products.	Ankle/Foot	Mechanical	Hybrid
[178]	-Foot Prosthesis Comprising A Damping Element	Pm Ingenierie Et Design.	Foot	Mechanical	Hybrid
[179]	-Lower Limb Prosthesis	Blatchford Products.	Ankle/Foot	Mechanical	Hybrid
[180]	-Oberschenkelprothesenpassteil	Klopf, Johannes.	Ankle/Foot	Mechanical	Hybrid
[181]	-Prosthesis or orthosis	Université Catholique De Louvain.	Foot	Mechanical	Hybrid
[182]	-Prosthetic Ankle Assembly and Ankle–foot System Comprising Same	Hein, Emily.	Ankle/Foot	Mechanical	Hybrid
[183]	-Prosthetic External Fixation Assembly for Post-amputee Ambulation	Dennis G. Haun.	Ankle/Foot	Mechanical	Hybrid
[184]	-Prosthetic Foot	Comité International De La Croix-rouge.	Foot	Mechanical	Hybrid

Table 1. *Cont.*

Cite	Title	Main Applicant	Body Part	Technology	Type
[185]	-Prosthetic Foot and Connector for Prosthetic Foot	Xiborg Inc.	Foot	Mechanical	ESAR
[186]	-Prótesis Mecánica De Pie	Instituto Tecnológico José Mario Molina Pasquel Y. Henriquez.	Foot	Mechanical	CESR
[187]	-Pyramidal Prosthetic Foot	Gosakan, Haripriya.	Foot	Mechanical	ESAR
[188]	-Single Axis Ankle–foot Prosthesis with Mechanically Adjustable Range of Motion	Mcnicholas Sara Koehler.	Ankle/Foot	Mechanical	Hybrid

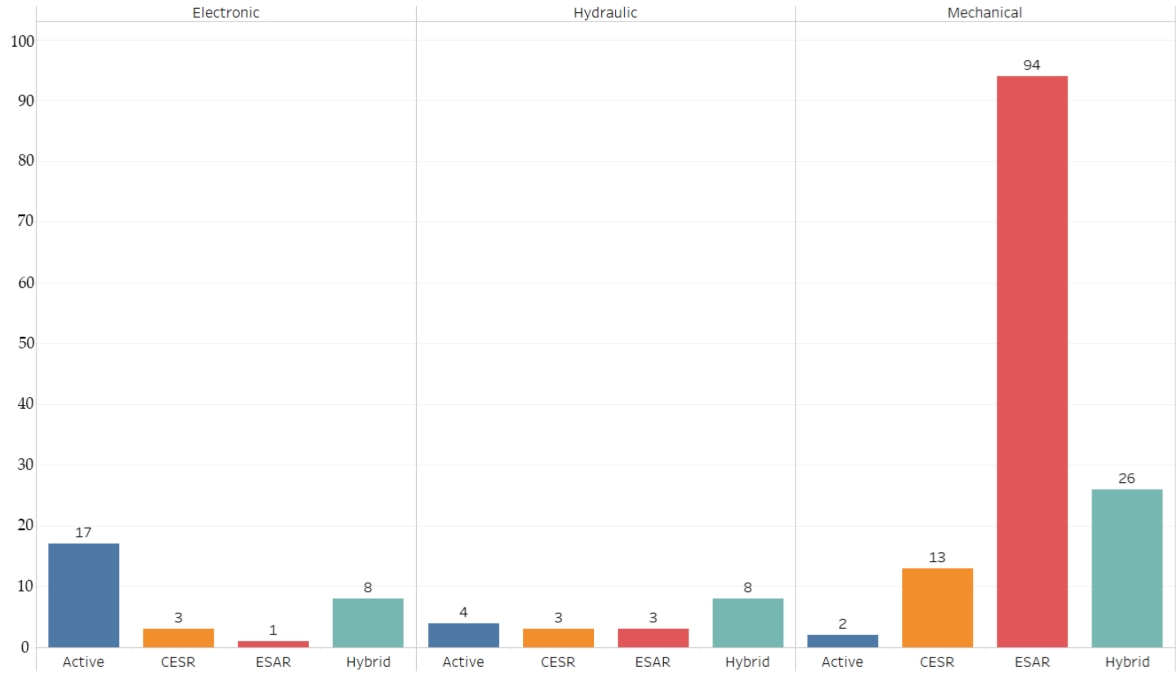


Figure 4. A display of prosthesis types in terms of electronic, hydraulic, and mechanical technology.

3.2. Scientometric Analysis

After the final filter was applied, 98 scientific documents directly related to ankle/foot prostheses were selected; results are shown in Table 2. Keywords were analyzed resulting in the top 10: gait (frequency = 15 articles), prosthesis (frequency =14 articles), prosthetics (frequency =13 articles), amputation (frequency =11 articles), biomechanics (frequency =11 articles), ankle (frequency = 8 articles), transtibial (frequency = 8 articles) prosthetic foot (frequency = 7 articles), powered prosthesis (frequency = 6 articles), and gait analysis (frequency = 5 articles). This means there is a major trend in developing prostheses devices compared with gait studies or the creation of new methodologies.

From the information obtained by the scientific documents, several aspects must be considered when designing a new prosthesis, such as aesthetics, which allows empathy between the users and their prosthesis [1], a size that permits the use of footwear, a mass corresponding to 2.5% of bodyweight [160] (literature shows an average of 2.5 kg for a 75 kg person), an ankle torque corresponding to 100–140 Nm, an ankle power between 250–300 W, and a device capable of storing and releasing energy (5–9 J)

On the authors' part, Lefeber D. and Vanderborght B. are the top authors (11 articles each). Nevertheless, Hugh M. Herr is the most cited author in this field, with five of the most cited articles.

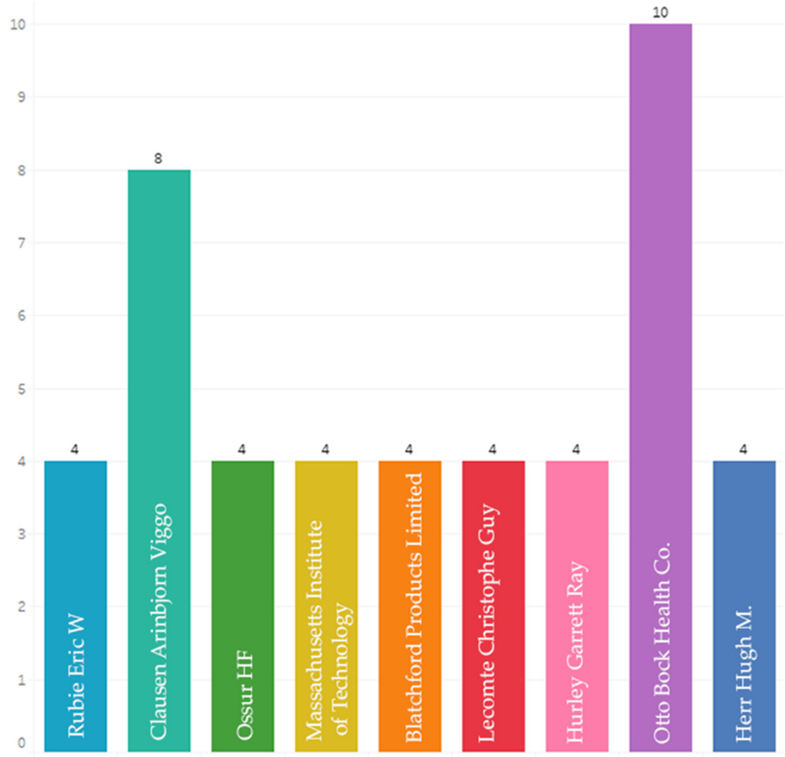


Figure 5. Top patent applicants for lower limb prosthesis.

Table 2. Articles analyzed for ankle/foot prosthesis.

Cite	Main Author	Document Topics	Year
[189]	Huang, Stephanie	Powered Ankle Prosthesis Design	2014
[190]	Sun, Jinming	Clinical Study	2014
[191]	Wezenberg, Daphne	Comparative Study	2014
[192]	Nickel, Eric	Component Design	2014
[193]	Mulder, Inge A.	Foot Prosthesis Design	2014
[194,195]	Safaeepour, Zahra	Powered Ankle/foot Prosthesis design	2014
[196]	Zhu, Jinying	Powered Ankle/foot Prosthesis design	2014
[197,198]	Ko, Chang-Yong	Clinical Study	2014–2016
[199,200]	Cherelle, Pierre	Powered Ankle/foot Prosthesis design	2014–2017
[201–203]	Simon, Ann M.	Component Design/Study	2014–2018
[204]	Caputo, Joshua M.	Gait Study	2014
[205]	Asencio, J. G.	Clinical Study	2015
[206]	Bonnet, Xavier	Comparative Study	2015
[207]	Fairhurst, Stuart R.	Component Design	2015
[208]	Realmuto, Jonathan	Component Design	2015
[209]	Hessel, A. L.	Powered Ankle/foot Prosthesis design	2015
[210]	Rouse, Elliott J.	Powered Ankle/foot Prosthesis design	2015
[211]	Flynn, Louis	Powered Ankle/knee Prosthesis design	2015
[212]	Ficanha, Evandro Maicon	Powered Ankle/foot Prosthesis design	2015
[213,214]	Rice, Jacob J.	Powered Ankle/foot Prosthesis design	2015–2016
[215]	Jimenez-Fabian, Rene	Component Design	2017
[216–218]	Shultz, Amanda H.	Component Design/Study	2015–2018
[219,220]	Kim, Myunghee	Powered Ankle/foot Prosthesis design	2015–2018
[221]	Ingraham, Kimberly A.	Powered Ankle Prosthesis Study	2016
[222]	Quesada, Roberto E.	Clinical Study	2016
[223]	Delussu, Anna S.	Comparative Study	2016
[224]	Khaghani, Alireza	Component Design	2016
[225]	Narayanan, Govindarajan	Foot Prosthesis Design	2016

Table 2. *Cont.*

Cite	Main Author	Document Topics	Year
[226]	Isaacs, M. R.	Passive Ankle foot prosthesis study	2016
[227]	Grimmer, Martin	Powered Ankle Prosthesis Design	2016
[228]	LaPre, Andrew Kennedy	Powered Ankle/foot Prosthesis design	2016
[229]	Rabago, Christopher A.	Prosthesis Study	2016
[230]	Ettinger, Sarah	Study	2016
[231–233]	Esposito, Elizabeth Russell	Gait Study	2016–2018
[234]	Lacraz, Alain	Comparative Study	2017
[235]	Gardiner, James	Comparative Study	2017
[236]	Ke, Ming-Jen	Component Design	2017
[237]	Tao, Zhen	Foot Prosthesis Design	2017
[238]	Lee, Jeffrey D.	Pneumatic Ankle/foot Prosthesis design	2017
[239]	Mazumder, O.	Powered Ankle/foot Prosthesis design	2017
[240]	Anonymous	Powered Foot Prosthesis Design	2017
[241]	Weerakkody, Thilina H.	Review	2017
[242,243]	Koehler-McNicholas, Sara R.	Powered Ankle/foot Prosthesis design	2017–2018
[244]	Shepherd, Max K.	Powered Ankle/foot Prosthesis design	2017
[245,246]	Dong, Dianbiao	Powered Ankle/foot Prosthesis design	2017–2018
[247]	Lechler, Knut	Clinical Study	2018
[248]	Eslamy, Mahdy	Biomechanical Study	2018
[249]	Jayaraman, Chandrasekaran	Powered Ankle/foot Prosthesis study	2018
[250]	Hahn, Andreas	Powered Foot Prosthesis Evaluation	2018
[251]	Armannsdottir, Anna	Anathomical Study	2018
[252]	Zelik, Karl E.	Anathomical Study	2018
[253]	Gardinier, Emily S.	Clinical Study	2018
[254]	Heitzmann, Daniel W. W.	Clinical Study	2018
[255]	Montgomery, Jana R.	Clinical Study	2018
[256]	Preissler, Sandra	Clinical Study	2018
[257]	Guerra-Farfan, Ernesto	Comparative Study	2018
[258]	Yang, Ja Ryung	Comparative Study	2018
[259]	Culver, Steven	Component Design	2018
[260]	Geeroms, Joost	Component Design	2018
[261,262]	Quintero, David	Component Design	2018
[263]	Tahir, Uzma	Component Design	2018
[264]	Yin, Kaiyang	Component Design	2018
[265]	Houdijk, Han	Foot Prosthesis Design	2018
[266]	Glanzer, Evan M.	Powered Foot Prosthesis Design	2018
[267]	Bai, Xuefei	Prosthesis Study	2018
[268]	Ray, Samuel F.	Prosthesis Study	2018
[269]	Burger, Helena	Review	2018
[270,271]	De Pauw, Kevin	Anathomical Study	2018–2019
[272,273]	Gao, Fei	Powered Ankle/foot Prosthesis design	2018–2019
[274]	Sahoo, Saikat	Powered Ankle/foot Prosthesis design	2018
[275]	Schmalz, Thomas	Comparative Study	2019
[276]	Wurdeman, Shane R.	Comparative Study	2019
[277]	Zarezadeh, Fatemeh	Comparative Study	2019
[278]	Bhargava, Rakesh	Foot Prosthesis Design	2019
[279]	Zhang, Xueyi	Gait Study	2019
[280]	Bartlett, Harrison L.	Powered Ankle Prosthesis Design	2019
[281]	Agboola-Dobson, Alexander	Powered Ankle/foot Prosthesis design	2019
[282]	Convens, Bryan	Powered Ankle/foot Prosthesis design	2019
[283]	Lenzi, Tommaso	Powered Ankle/foot Prosthesis design	2019
[284]	Yu, Tian	Powered Ankle/foot Prosthesis design	2019
[285]	Popescu, Stefan-Catalin	Prosthesis Study	2019

Table 3 shows, in order, the most cited articles, and Figure 6 shows the most relevant authors in scientific documentation.

Table 3. Top 10 most cited articles in ankle/foot prosthesis.

No.	Cite	Article	Authors	Year
1	[286]	Bionic ankle–foot prosthesis normalizes walking gait for persons with leg amputation	Hugh M. Herr, Alena M. Grabowski	2012
2	[287]	Powered ankle–foot prosthesis to assist level-ground and stair-descent gaits	Samuel Aua, Max Berniker a, Hugh Herr	2008
3	[288]	Powered Ankle-Foot Prosthesis Improves Walking Metabolic Economy	Samuel K. Au, Jeff Weber, Hugh Herr	2009
4	[289]	Control of a Powered Ankle-Foot Prosthesis Based on a Neuromuscular Model	Michael F. Eilenberg, Hartmut Geyer, Hugh Herr	2010
5	[290]	Powered Ankle-Foot Prosthesis	Samuel K. Aa, Hugh M. Herr	2008
6	[291]	Design and Control of a Powered Transfemoral Prosthesis	Frank Sup, Amit Bohara, Michael Goldfarb	2008
7	[292]	The human ankle during walking: implications for design of biomimetic ankle prostheses	Andrew H. Hansena, Dudley S. Childressa, Steve C. Miff, Steven A. Garda, Kent P. Mesplayd	2004
8	[293]	Recycling Energy to Restore Impaired Ankle Function during Human Walking	Steven H. Collins, Arthur D. Kuo	2010
9	[294]	Energy expenditure during ambulation in dysvascular and traumatic below-knee amputees: A comparison of five prosthetic feet	Leslie Torburn, Christopher M. Powers, Robert Guiterrez, Jacquelin Perry	1995
10	[295]	Estimating the Prevalence of Limb Loss in the United States: 2005 to 2050	Kathryn Ziegler-Graham, Ellen J. MacKenzie, Patti L. Ephraim, Thomas G. Travison, Ron Brookmeyer	2008

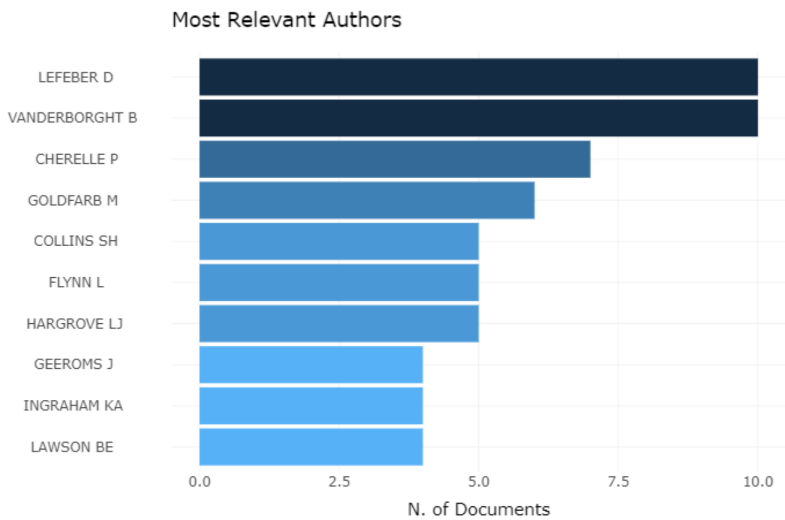


Figure 6. Top 10 most relevant authors on lower limb prosthesis design.

The United States (US) is the most productive country (46 documents), followed by Belgium (seven documents) and China (five documents). Some documents showed multiple country collaborations (Figure 7). There is a clear relation between authors, journals, and countries. For example, most of the documents submitted in the US are from IEEE magazines and Plos One; meanwhile, Europe tends to apply to Prosthetic and Orthotic international and the American society of mechanical engineers (ASME).

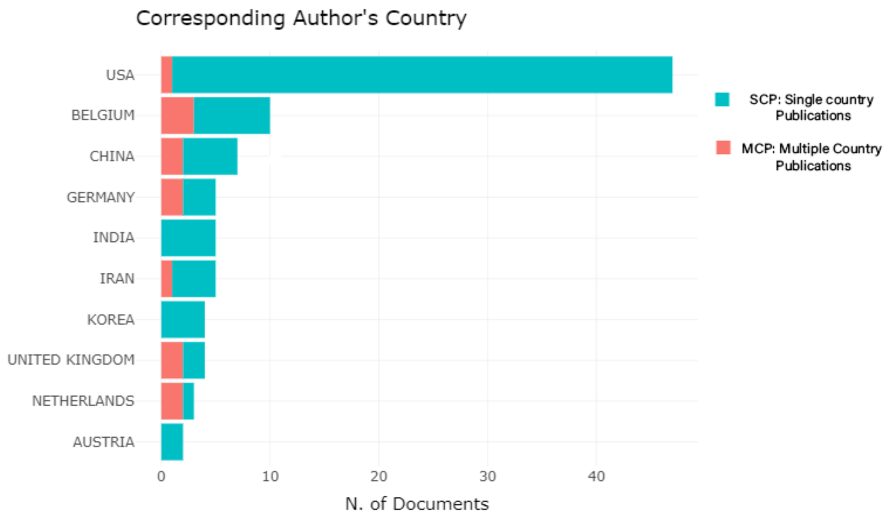


Figure 7. Most productive countries for ankle/foot prosthesis literature.

4. Discussion

4.1. Device Classification

From the selected patents and scientific documentation, a new ankle/foot prosthesis classification has been created besides ESAR, CERS, and active, based on its components and prosthesis functions.

ESAR prostheses are categorized into five different designs (see Figure 8). CERS and active categories are merged and divided into five different categories. There are some unique designs whose components cannot be grouped; these will be discussed individually.

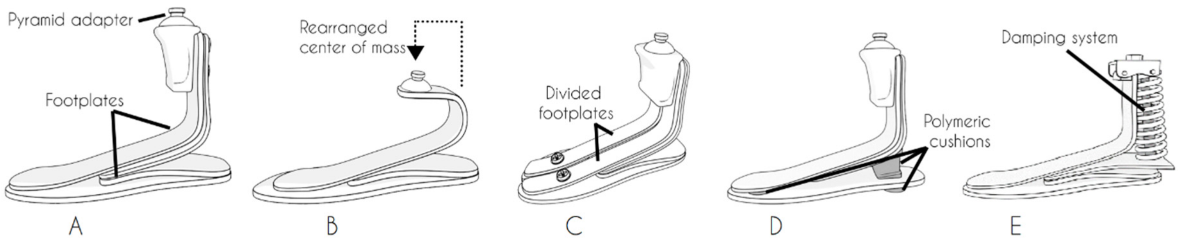
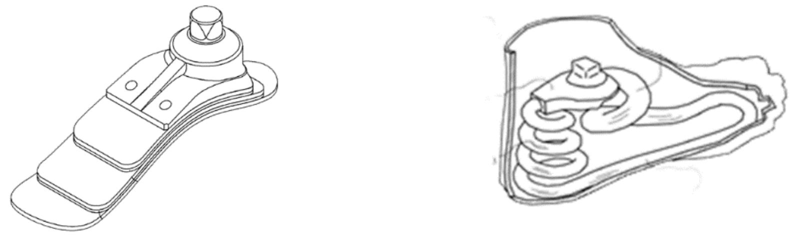


Figure 8. (**A**) General form of ESAR prosthesis, (**B**) Modified ESAR prosthesis, (**C**) ESAR with split plates, (**D**) ESAR prosthesis with cushions, (**E**) ESAR with damping system.

From the previous analyses, it can be determined that the general form for ESAR prosthesis is similar to the one illustrated in Figure 8A and mostly differs in form; sometimes, a single talon plate is aggregated, or the disposition of the plates may vary. In other cases, as in Figure 8B, the center of mass is moved, and the plates are rearranged. In the variation represented by Figure 8C, the foot plates are divided, so the prosthesis emulates eversion and inversion movements. In Figure 8D, some polymeric cushions are aggregated, replacing the use of extra plates. Figure 8E shows the usage of different types of damping systems (springs, actuators, etc.) that replace some plates. All of these designs use pyramid adapters as a connection between the prosthesis and transtibial components.

There are some variations for ESAR prostheses that use a simple plate arrangement to adjust the return of energy (see Figure 9A). Other designs use a single spring bar that regulates the energy storage/release (see Figure 9B).

For CERS prosthesis, the model by Endo Ken [129] (see Figure 10) considers a locking mechanism that preserves the energy storage in the spring. This energy is released upon the foot movement during the terminal stance. This impulse, in combination with the ESAR foot, provides necessary torque during the walk cycle.



A B

Figure 9. (**A**) Multiple plates prosthesis, (**B**) Single spring prosthesis by Kim Sa Yeop [74].

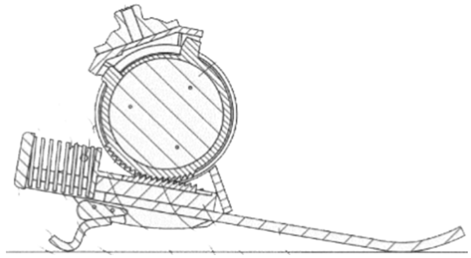


Figure 10. CERS prosthesis by Endo Ken [129].

Active prostheses can be categorized by the components they use into three types: Multi-Array Prostheses (MAP), Low Powered Prostheses (LPP), and Controlled Adaptative Stiffness (CAS). For MAP, the form is similar to the one shown in Figure 11. It uses an ESAR composite foot (E), and a DC motor (A), usually a 200 W Maxon® connected to a ball-screw transmission (C) that moves the linkage system (D) upward/downward and converts motor rotary motion into linear motion. In some cases, the motor is located instead of the spring (G) and connected to (C) using a timing belt. The linkage system (D) is in charge of connecting different mechanisms and allows plantarflexion and dorsiflexion movements; it may be composed of cables and/or pulleys, a bar mechanism, or crank sliders. F and G, depending on the prostheses, represent springs or actuators (pneumatic, electric, or hydraulic), for which torque varies from 100 to 140 Nm. Sometimes a parallel spring is aggregated due to the demanding torque requirements, and it aims to reduce the loads supported by the linkage system. Spring (G) saves energy during plantarflexion and dorsiflexion and supplements it during the swing phase. Housing (B) allocates all the electronic systems and provides stability to the system. The pyramid adapter (H) provides a connection between the transtibial components and the prosthesis. Some models have a lock mechanism, so the prosthesis could be used in a passive mode. See Figures 11–15.

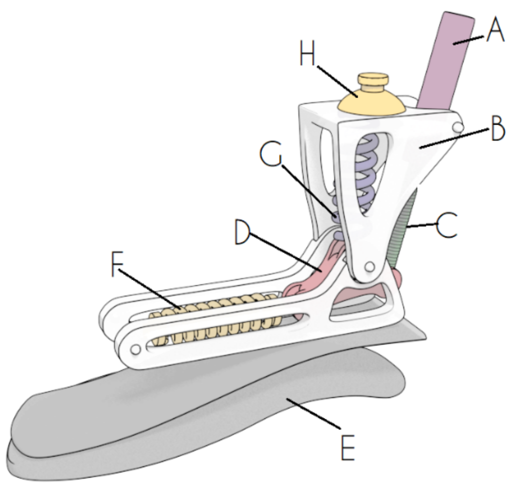


Figure 11. MAP active ankle–foot prosthesis.

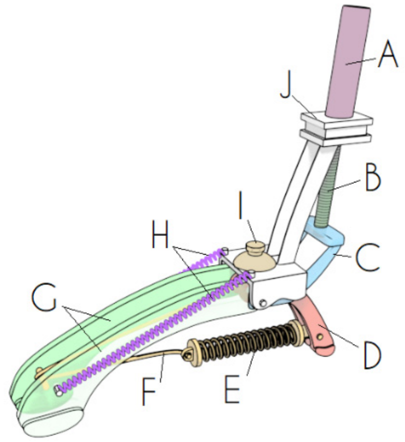


Figure 12. LPP active prosthesis.

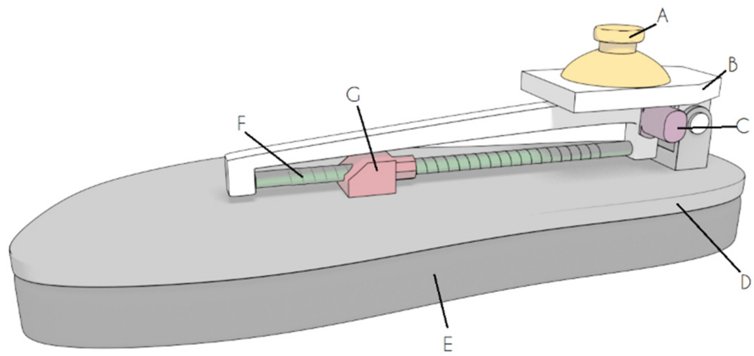


Figure 13. CAS Prosthesis.

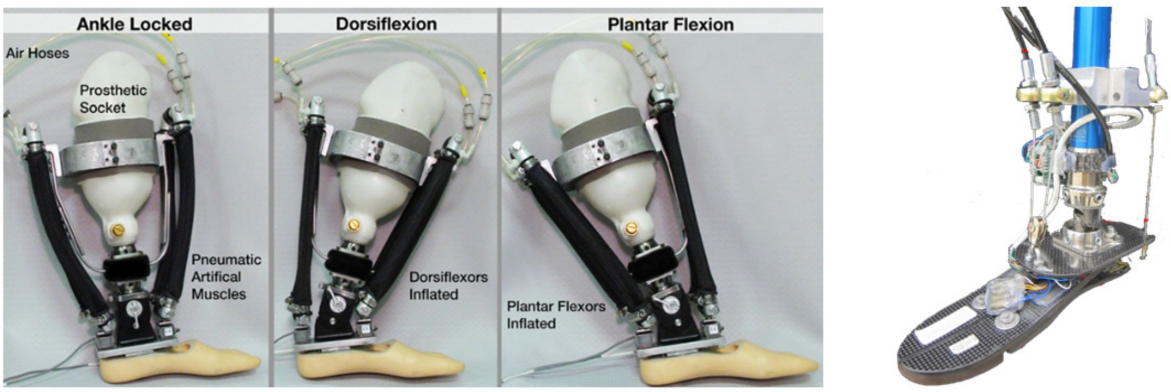


Figure 14. (**A**) Experimental powered lower limb prosthesis by Huang et al. [189] and (**B**) two DOF cable-driven ankle–foot prosthesis by Ficanha et al. [213].

Another powered prosthesis design is the LPP shown in Figure 12. It aims to reduce the necessary power required by the actuators. It contains different Footplates (G and C), which in some designs (similar to the AMP Foot 2.1 [199]) are merged into a single plate. In another case such as the VSPA Foot [245], footplates (G) are individually controlled, allowing eversion–inversion movements; the DC motor (A) is located in a Housing (J) and rotates the Ball screw transmission (B), which moves the Footplate (C) up or down, allowing plantarflexion and dorsiflexion movement. Heel (D) may be composed of a flexible plate; ankle stiffness is provided by Springs (H) and (E). Depending on the model, two Springs (H) are used when there are individually controlled Footplates, and Spring (E) is used when (G) and (C) are merged. In this case, Spring (E) is attached directly to

Footplate (C). Spring (E) is elongated using a Pulley system (F) connected to the Footplate (C). The pyramid adapter (I) provides a connection between the transtibial components and the prosthesis. Designs for this model use an external power supply that is not integrated into the main prosthesis body.

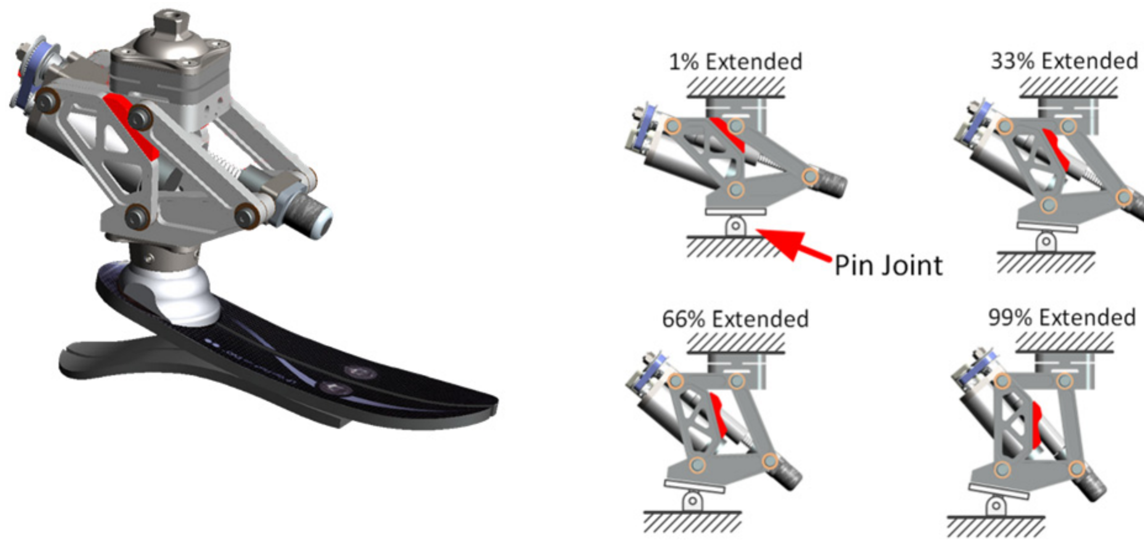


Figure 15. A robotic ankle–foot prosthesis by LaPre [229].

CAS prostheses (see Figure 13) are mainly based on an ESAR foot (D), and in some cases complemented with a Cushion (E). The main goal of this prosthesis is the modulation of the stiffness during different stages of a gait cycle. This is granted by moving a Slider (G) along the length of the foot. Depending on the gait cycle, this slider moves forward and backward, providing the necessary stiffness to adapt to different situations such as walking, running, or climbing stairs, and it is controlled by a DC motor (C). A linkage system could be provided by a Ball screw transmission (F) or pulleys and belts. Motor (C) could be programmed to adapt to different activities. Housing (B) provides support for all the components and allows one degree of freedom (DOF) for the foot. The pyramid adapter (A) provides a connection between the transtibial components and the prosthesis.

4.2. Other Designs

Some designs do not correspond to the categories previously described. These designs are the pneumatic foot prosthesis by Huang et al. [189] (see Figure 14A), where DF and PF are managed by two artificial muscles each, so stiffness and PF torque are easier to control. It is capable of emulating 3 DOF and is controlled via a desktop computer. Another design is the two DOF cable-driven ankle–foot prosthesis by Ficanha et al. [213], where instead of using pneumatic systems, it uses pulleys and Bowden cables that are externally controlled by two motors (Maxon EC-4), see Figure 14B. Both systems have an external power source and are capable of emulating foot eversion and inversion movements.

Another case is the robotic foot prosthesis made by Lapre [229]. This device aims to actively align the foot during different stances of the gait cycle using a four-bar linkage system to rotate and translate the foot with the use of a single actuator. It works using an ESAR foot and a DC motor (Maxon® EC-30 200 W) that moves a Ball screw transmission via a belt drive. As this actuator system (motor and ball screw) contracts, it extends and shifts the foot center (see Figure 15).

4.3. ESAR Analysis

Most of the active prostheses use ESAR foot to generate enough power to initiate the gait cycle. From the patentometric and scientometric analysis, it is evident that types A, B, and C are the most used (see Figure 8). A structural analysis was performed to make a comparison between these types. Carbon-fiber footplates and a concrete floor were used. A load of 785 N was applied on the prosthesis upper faces obtaining a maximum deformation on the Y-axis of 0.63, 0.33, and 0.67 mm for types A, B, and C, respectively (see Figure 16). Meanwhile, deformations on A and C mostly occur on the ankle; B shows major flexibility along the foot. The red color shows maximum displacements on the foot connection with the body, but blue shows no deformation.

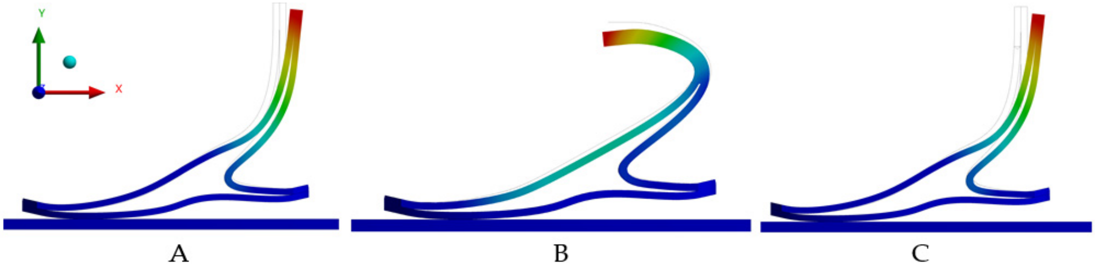


Figure 16. Comparative static analysis of ESAR prosthesis.

According to the structural analysis, B tends to offer major elastic energy compared to A and C, as shown in the instep colored in green/blue.

To compare the effectiveness during a walk cycle on uneven terrain, prostheses A, B, and C were analyzed using the same velocity and loads. Figure 17 shows a clear advantage of (C) over the other two models, thanks to the uneven deformation on its divided footplates, as shown for the displacement colored in red.

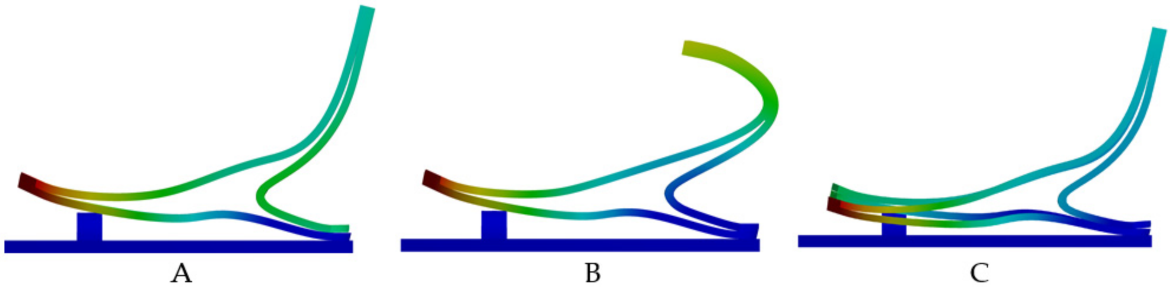


Figure 17. Results of deformations on uneven terrain.

5. Conclusions

The number of results per database does not reflect the effectiveness of each search engine. For this research, priority was given to search engines that provided useful data such as direct links to patents, the inventor's name, and IPC codes. Nevertheless, there are some difficulties with some of them, such as the lack of options for filtering results or IPC categories, among others. Besides, some applicants may be included in the name of their companies (for example, Herr Hugh in Massachusetts Institute of Technology); this is because some search engines only show the applicant/owner's name instead of the inventor. In some cases, there is a lack of consistency between the author's names in different patents (for example, Smith Keith and Smith, Keith, B.); these kinds of inconsistencies were clustered, but still, results could not be entirely precise.

The United States has 56% of patent applications and 34% of scientific documents registered. These results do not necessarily display that they produce most of the knowledge on this topic, but because of the language, most of the search engines are capable of accessing the data, unlike languages such as Spanish, Chinese, or languages spoken in India. Therefore, some designs could remain undiscovered for this investigation.

Based on the obtained results, it can be established that for this study, the effectiveness per search engine is as follows: Derwent 8.4%, Google patents 0.34%, Patentscope 3.2%, The Lens 19.9%, and Espacenet 13.95%.

The classification of the 208 prosthesis patents related to prostheses designs was obtained according to the main technology used; results show that the ESAR mechanical prosthesis is the main patent object by 44%, although claims are different for each one. All of them can be classified based on the five ESAR categories presented in this document. Outcomes also show a tendency for the use of ESAR regardless of the technology used. For 151 removable foot/ankle patent prostheses analyzed, 53% use only ESAR-type prosthesis, and 90% use ESAR in its components. From these, the more commonly used were selected and compared using Ansys, with no major differences between A and C, but for B, results show a more elastic foot thanks to its mass-centered design.

The significant trend in the use of ESAR prostheses may be because of their lower cost and greater energy efficiency. Different designs are used according to the user's lifestyle.

The minimum amount of components found for designing an active prosthesis is a DC motor, housing, a power transmission unit, a composite foot or equivalent, an energy storage device (springs, locking systems), a linkage system, an energy power supply, and a prosthesis/socket connector. From these components, most prostheses use a Maxon® Brushless motor between 12 and 200 W. Power variations are mostly due to the gear ratio used (the more power, the lower the gear ratio), springs with stiffness between 60–445 kNm, and a Li-ion battery between 12–24 V. From these components it is especially important to consider when designing a BKA prosthesis the linkage system that needs to support most of the necessary loads, and it must be capable of tolerating at least 2 kN (for an 80 kg patient) without any failure.

Materials also play a vital role in supporting loads with 4000/5000 duty cycles per day; that is why aluminum, carbon fiber, and other composites are used in fabrication, and sometimes load reduction along the system is necessary and archived using a parallel spring arrangement.

The current development of batteries allows active prostheses to obtain enough power and charge duration without adding extra mass and weight, but for hydraulic and pneumatic prostheses, power supply currently is a problem because most of these systems are connected externally and the mass could reach up to 15 kg. Nevertheless, these systems are more efficient in mimicking human ankle movements.

For BKA prostheses, continuous growth in the development of active ones is estimated. Even though actual prostheses are capable of emulating three degrees of freedom, there is space for a complete body-integrated ankle/foot prosthesis.

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