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Improvement on upper limb body-powered prostheses (1921–2016): A systematic review

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Abstract

Body-powered prostheses are known for their advantages of cost, reliability, training period, maintenance, and proprioceptive feedback. This study primarily aims to analyze the work related to the improvement of upper limb body-powered prostheses prior to 2016. A systematic review conducted via the search of the Web of Science electronic database, Google Scholar, and Google Patents identified 155 papers from 1921 to 2016. Sackett's initial rules of evidence were used to determine the levels of evidence, and only papers categorized in the design and development category and patents were analyzed. A total of 40 papers in the sixth level of "Design and Development" of an upper limb body-powered prosthesis were found. Approximately 81% were categorized under mechanical alteration. Most papers were patent-type documents (48%), with the *Journal of Rehabilitation Research and Development* publishing most of the articles related to the design and development of body-powered prostheses. Papers in the scope of the study were published once every 3 years in almost a century, proving that only a few studies were conducted to improve body-powered arms compared with myoelectric technology. Further research should be carried out mainly in areas that have received less attention.

Keywords

Body-powered, prosthesis, prosthetic improvement, upper limb prosthesis

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Introduction

An important goal of rehabilitation for upper limb amputees is the selection of a convenient prosthetic device that grants the best prehension and functional movement.[1] A significant number of adults and children wear body-powered prostheses despite the developments made in electrical prostheses.[2,3] The benefits of body-powered prostheses include silent action, light weight, moderate cost, durability, reliability, rough sensory feedback about the positioning of the terminal device, and simple operational mechanism with certain body movements to operate the voluntary open or voluntary close terminal device.[4–8]

Interviews with members of the Amputee Coalition of America in 2004 revealed that approximately 33.33% of upper limb amputees were not satisfied with the comfort of their prosthesis, and 18.4% of the respondents were fit with a new prosthesis at least once a year.[9] Some reports claim that 50% of upper limb amputees chose not to wear a prosthesis because the functional advantage or cosmesis did not outweigh the inconvenience of the prosthesis.[10,11] Primary indicators of prosthesis rejection include a lack of perceived functional gain, prosthesis weight, and socket discomfort.[12] Other reasons for high rejection rates are associated with high amputation levels and congenital limb loss.[13]

Users express their interest in improved wrist movement and control, overall maneuverability, coordination, and sensory feedback when considering functionality. Some other issues identified with a body-powered prosthesis system include increased body movement and task-completion period compared with a sound limb.[11] Biddiss et al.[2] reported that, although not specifically indicated in any literature, this additional gross body movement combined with the need to utilize the same

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activation force regardless of the task can cause injury to a user's body over time. Therefore, users express their desire for further improvement in the control aspect while a body-powered prosthesis system currently prevails in the area of sensory feedback. An increased grasp force is also one of the special desires of body-powered prosthesis users.

Standard upper limb body-powered prostheses have not changed significantly since their development in the 1950s, which was spurred by World War II. The *Manual of Upper Extremity Prosthetics*, first edition (1952) and the *Orthopaedic Appliance Atlas—Artificial Limbs*, first edition (1960) show no substantial difference compared with the 1985 state of the art.[14] Moreover, some or no research has been conducted to improve body-powered arms. Thus, many amputees opt for an externally powered prosthesis, and the gap of usage is large between the two types.[15]

Body-powered systems, which are either in the form of a hook or a hand, are compatible with two types of terminal devices. Hosmer Dorrance Corporation (Hosmer; Campbell, CA, USA) and Otto Bock (Otto Bock; Orthopedic Industry, Inc., Duderstadt, Germany) are the major commercial hook and hand providers for prosthetic terminal devices. TRS, Inc. designed and manufactured the upper extremity prosthetic terminal devices that can be employed for normal use and for sports and recreation, which include weight lifting, archery, ball sports, canoeing/kayaking, gymnastics, golf, swimming, and fishing.[16]

Methods

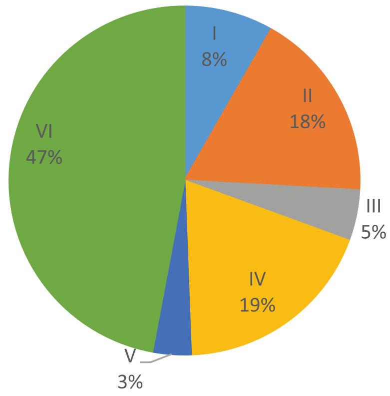
A systematic search of the literature was conducted in November 2016 using Web of Science™ Core Collection databases, Google Scholar, and Google Patent. All research areas, all types of documents including patent, and all publication years were searched and refined by only English language publications. The keywords "body-powered prosthesis,""prosthetic hand,""prosthetic harness system,""prosthetic elbow unit,""prosthetic wrist unit,""prosthetic shoulder unit," and "prosthetic terminal device" were used in the database to explore only the issues of body-powered prostheses of the upper limb. A search using similar keywords was used to find any related publications on body-powered prosthesis in Google Scholar and Google Patents.

The papers were ranked based on times cited from the highest to the lowest. The abstracts of all articles were manually reviewed by the authors to classify the publications according to Sackett's initial rules of evidence. Following Eshraghi et al.,[17] the sixth category called "Design and Development" should be added because the articles dealt with the design and development of prosthetic devices.[17] All the selected articles were reviewed and tabulated in Table 1. Levels I–V, which contain systematic reviews, randomized control trials, cohort studies, case-control studies, case series, and expert opinions, were excluded, and only Level VI, or the "Design and Development" level of evidence, was included in the study. Patents from Google Scholar were also added to the list. Most of the patents found in Google Scholar originated from Google Patents, which is a Google search engine. Papers are selected for inclusion as patents if the innovations are novel and improve the classic body-powered prosthesis system

Table 1. Papers in the sixth level of evidence (design and development) and patent.

No.	Papers	Times cited
	(Le, 1921)	6
	(H & E, 1935)	6
	(D & J, 1951)	7
	(Ober & Piatek, 1977)	4
	(Janovsky, 1980)	14
	(Bell, 1981)	47
	(Donna Meeks & Maurice LeBlanc, 1988)	0
	(Kruit & Cool, 1989)	11
	(Scribner, 1992)	24
	(M. Cupo & Sheredos, 1993)	0
	(Frey & Carlson, 1994)	14
	(R. B. Radocy & Beiswenger, 1995)	6
	(Landsberger et al., 1996)	6
	(L.E. Carlson, Frey, & Brown, 1998)	14
	(M. E. Cupo & Sheredos, 1998)	11
	(Kitayama et al., 1999)	0
	(de Visser & Herder, 2000)	27
	(B.D. Veatch, 2000)	13
	(Gow, 2002)	95
	(Sitek et al., 2004)	13
	(Yang, Pitarch, Abdel-Malek, Patrick, & Lindkvist, 2004)	32
	(Fink et al., 2005)	22
	(Mustafa, Yang, Yeo, Lin, & Pham, 2006)	7
	(Rouse, Farquharson, & Betts, 2006)	1
	(B. Veatch, 2007)	10
	(Winfrey, 2008)	19
	(B.D. Veatch & Scott, 2008)	17
	(Johnson & Veatch, 2009)	0
	(Clark, 2010)	1
	(B.D. Veatch, 2011)	3
	(Bradley D Veatch & Radocy, 2011)	0
	(Tolou, Smit, Nikooyan, Plettenburg, & Herder, 2012)	1
	(Baril, Laliberté, Gosselin, & Routhier, 2013)	27
	(Chua, Martinez, & Celik, 2014)	0
	(Latour, 2014)	15
	(Liarokapis, Zisimatos, Bousiou, & Kyriakopoulos, 2014)	0
	(Razak, Osman, Gholizadeh, & Ali, 2014)	0
	(J. Sensinger, 2014)	1
	(J. W. Sensinger, Lipsey, Thomas, & Turner, 2015)	0
	(Smit, Plettenburg, & van der Helm, 2015)	0

Table 2. Distribution of articles in terms of the levels of evidence.



Level of evidence	Type of study
I	Systematic reviewRandomized controlled trial
II	Cohort studies
III	Case-control studies
IV	Case series
V	Expert opinions
VI	Design and development

that operates using body movements. The published patents must also obtain approval from 1 of any 17 patent offices, including the United States Patent and Trademark Office, European Patent Office, China's State Intellectual Property Office, Japan Patent Office (JPO), Korean Intellectual Property Office, World Intellectual Property Organization, Deutsches Patent- und Markenamt, Canadian Intellectual Property Office, Russia, the United Kingdom, France, Spain, Belgium, Denmark, Finland, Luxembourg, and the Netherlands.[18] The distribution of articles and patents are shown in Table 2.

The publications were categorized in a Microsoft Excel spreadsheet by year of publication, institute/organization, and paper's country of origin. The inclusion and exclusion criteria were established to select the publication relevant to the review's statement of purpose. The search results were filtered to exclude papers that were not related to the upper limb prosthesis, such as papers on assistive- and rehabilitative-powered exoskeleton and hearing prosthesis. An analysis of the search result was done using the Web of Science database on the topic of body-powered prosthesis and myoelectric prosthesis to see the trend of publications over the years.

Results

A total of 201 papers related to prosthetics, including all upper limb prosthetic systems (cosmetic, body-powered, and electric hand), were found in the Web of Science™ Core Collection, and 189 were found in Google Scholar. The papers were reviewed by the authors. A total of 66 were found in the Web of Science™database, and 89 papers were related only to body-powered prosthesis were found in Google Scholar. In Sackett's initial rules of evidence, all papers from both databases (155 papers) were sorted into six levels, resulting in 12% in Level I, systematic review/ randomized controlled trial (19); 25% in Level II, cohort studies (39); 6% in Level III, case-control studies (10); 23% in Level IV, case series (35); 8% in Level V, expert opinions (12); and 26% in Level VI, design and development (40).

Papers in the sixth level of evidence, which include patents, were analyzed based on the purpose of this study. Articles in the sixth level of design and development have the citation range of 0–95 times since their publication, with an average citation of 11.85 (standard deviation: 17.23); the earliest publication was in 1921, and the latest was in 2015. Approximately 75% of the papers have been cited (30 papers), while the remaining 25% have not been cited (10 papers) in any database since publication. Table 1 shows a total of 40 publications of design and development, including 21 journal articles and 19 patents.

From the total findings, 52% are published papers and conference proceedings and 47.5% are patent documents. From the published papers and conference proceedings, 24% are extracted from conferences, such as 2016 IEEE Conference on Robotics Automation and Mechatronics, ASME 2009 International Design Engineering Technical Conferences, Computers and Information in Engineering Conference, Myoelectric Symposium, 2014 IEEE Haptics Symposium (HAPTICS), and 2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society. These are followed by the *Journal of Rehabilitation Research and Development* (19%), *Journal of Prosthetics and Orthotics* (14%), *Prosthetics and Orthotics International* (9.5%), and 4.8% each for *Journal of Medical Engineering and Technology*, WESCON/96, *Mechanism and Machine Theory, Journal of Medical Devices, Journal of Mechanical Design, Biomedical Engineering Online*, and *IEEE Transaction on Neural Systems and Rehabilitation Engineering* (Figure 1). Most of the patent documents are from Google Patent. More papers and patents were published after 2000, with the highest number of articles published in 2014 (5). The production of publications related to the design and development of body-powered prosthesis is uniform from 1921 to 1996 and increases from 1998. Among the papers, 47% are patent documents, 40% are articles, and 12.5% are the proceeding papers (Figure 2).

From a total of 21 articles and conference proceedings related to the sixth level of evidence, Delft University of Technology contributes 19% of the papers (4), which is the highest compared with the other institutions. The Department of Veterans Affairs and TRS, Inc., Boulder, contribute 10% (2), and other

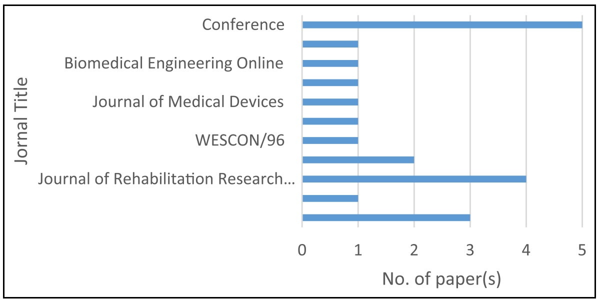


Figure 1. Published journals related to Level VI evidence.

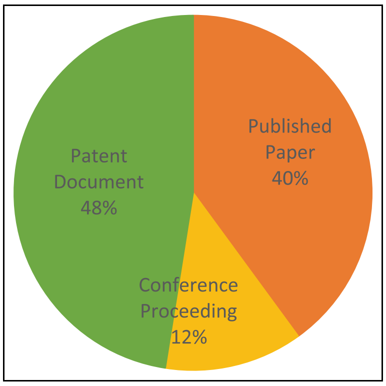


Figure 2. Type of document of records.

institutions publish only one paper (4.8%) on the sixth level of evidence. Other institutions include the Institute of Biomedical Engineering, University of New Brunswick (1), Hyogo Assist Technology Research and Design Institution, Hyogo Rehabilitation Center (1), Biomedical Engineering Department University of Malaya (1), Department of Kinesiology San Francisco State University (1), School of Mechanical Engineering National Technical University Athens (1), PhysioNetics LLC (1), Occupational Therapy Consultant Glen Park Avenue (1), Department of Mechanical Engineering, University of Colorado (1), Rancho Los Amigos National Rehabilitation Center (1), Arizona State University (1), Engineering Research Facility, the University of Iowa (1), School of Mechanical & Aerospace Engineering, Nanyang Technological University, and Université Laval (1).

For the patents, ADA Technologies, Inc. has three patents (16%), and the other patents are from Viennatone Gesellschaft M.B.H., United States Army, Centralny Osrodek Techniki Medycznej, Lothian Primary Care NHS Trust, Rehabilitation Institute of Chicago, Shriners Hospitals for Children, Invisible Hand Enterprises, Northrop Aircraft, Inc., University Technology Corporation, Texas A&M University, and Hand Rehabilitation Foundation. With regard to the country of origin, papers and patents originated from the United States (54%), Europe (11%), Canada (6%), Japan (3%), Singapore (3%), and Malaysia (3%). The

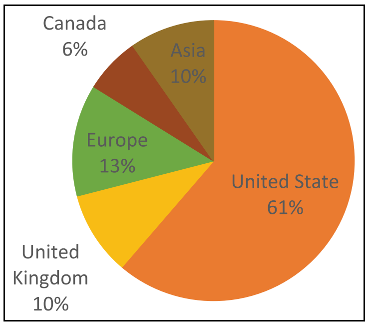


Figure 3. Country of origin of published papers, conference proceedings, and patent documents.

countries of origin of four patents are unidentified (Figure 3).

The analysis on the topics body-powered prosthesis and myoelectric prosthesis in the Web of Science shows 275 and 985 results, respectively. The record count over publication years in Figure 4 shows the trend of publications from 1980 to 2016.

Discussion

This study aims to list and analyze the published papers and patents related to improvement by different authors before 2016 on upper limb body-powered prosthesis. It also aims to give a general idea of an upper limb prosthetist or a biomedical engineer who works closely with the users. This study provides ideas and inspirations for future improvement. From 155 records searched using the keywords "body-powered prosthesis," 21 published papers related to design and development, and 19 patents were found. This systematic review aims to find all papers related to the topic published before 2016, and the earliest paper found was published in 1921. From 66 journal articles and conference proceedings, 89 patents of 47% of the searched papers (journal articles and conference papers) fall under the design and development category. This category represents the top study type, followed by case series (19%) and cohort studies (18%). This outcome shows that the improvement of body-powered prosthetic systems with the concept of utilizing body movement to operate the prosthesis remains one of the desirable areas of study in prosthetics.

The review suggests that the improvement has two categories based on the material selection and mechanical alteration. For material selection, the authors replace the components with alternative materials, which have better characteristics to operate and increase the efficiency of prosthesis. For example, Carlson[19] used Spectron™ 12 cable made of Spectra™ fiber, an ultra-high molecular weight that extends the chain polyethylene fiber and exhibits high tensile strength and toughness, high abrasion resistance, and good ultra-violet resistance combined with low specific

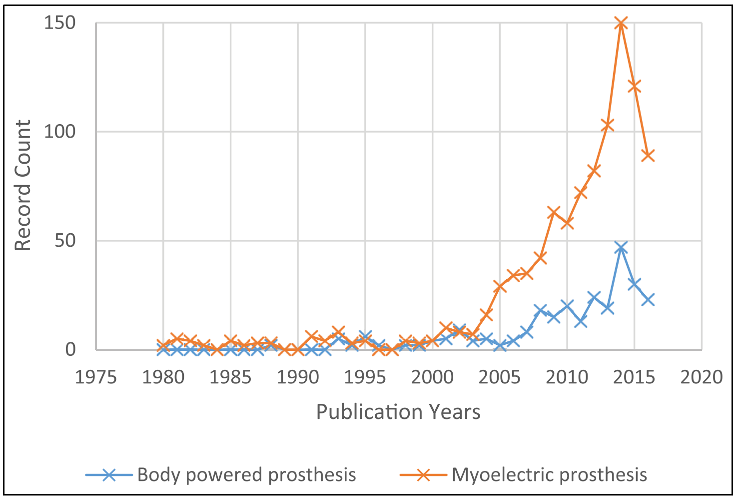


Figure 4. Result analysis of body-powered and myoelectric prostheses based on publication year in the Web of Science database.

gravity. These characteristics and Spectra's natural lubricity resulted in the selection of materials for evaluation as an alternative to standard stainless steel cable.[19] For mechanical alteration, changes were made on the control mechanism of body-powered prosthesis. Cupo and Sheredos[10] provided above-elbow body-powered prosthetic users with more efficient, versatile control and operation of their existing, cable-operated, positive-locking elbow and wrist components by developing the modular electromechanical lock actuator.[20] The combination of material selection and mechanical alteration categories was presented by Kitayama et al.,[21] who added a pulley in the cabling system of a body-powered prosthesis to reduce the opening force at different elbow positions; the addition also enabled full terminal device opening at large elbow flexion angles while utilizing a low-friction cable liner to increase the cable operating efficiency.[21] For patents, 100% of the inventions are in the mechanical alteration category. The improvement in the aspect of material selection and mechanical alteration designed by different authors was intended to achieve improved efficiency of the prosthesis on the user. Out of 21 papers, 17 are in the mechanical alteration category (81%), 3 are the combination of both mechanical alteration and material selection category (14.3%), and 1 is not placed in any category (4.76%). No paper focuses on material selection alone. Thus, the prosthetist may need to focus on the scope that is given less attention to improve body-powered prostheses in the future.

The paper that was cited the most (47) was published in 2002[22] by a patent entitled "Upper Limb Prosthesis," followed by[23] a patent entitled "Dual operated lateral thumb hand prosthesis," and[24] a journal article entitled "Mechanism and Machine Theory."[22–24] Figure 5 shows that the papers published before 2009 are cited more than the works published after 2008. Therefore, the number of citations is dependent on the number of years since the papers were published. This finding seems logical because scientific papers are usually cited 1 or 2 years after publication and reaches peak citation about 10 years after publication.[25] The

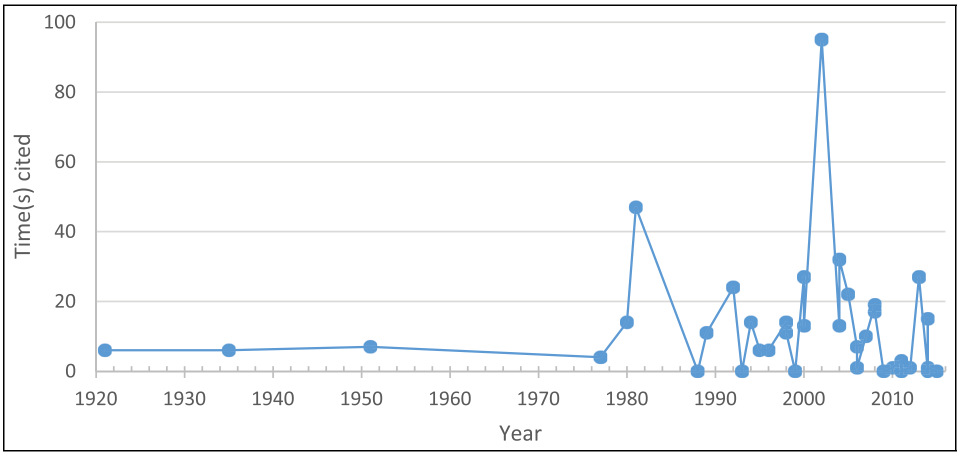
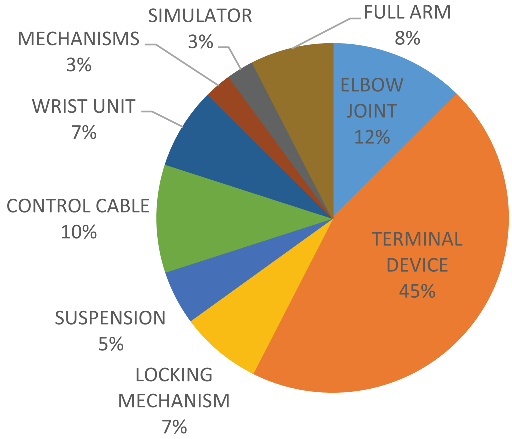


Figure 5. Times cited against year of publication/patent.

Table 3. Scopes of improvement on body-powered prosthesis.



Terminal device	Dual-operated lateral thumb hand prosthesis[23]
	Body-powered hand prosthesis with low operating power for children (Kruit & Cool, 1989)
	Hand prosthesis cooperating finger-like and thumb-like units[29]
	Body-powered prehensor with variable mechanical advantages (prehensor with two modes, "Variable Mechanical Advantage (VMA)," and conventional "free-wheel" mode)[30]
	Force-directed design of a voluntary closing hand prosthesis[31]
	Inexpensive upper extremity prosthesis for use in developing countries[32]
	Multi-fingered hand prosthesis[24]
	Prosthetic hand having a conformal, compliant grip and opposable, functional thumb[33]
	Prehensor device with pulley systems[34]
	Heavy-duty prosthesis with split hook terminal device and universal adjustable interface[35]
	Simplified prosthetic device[36]
	Prosthetic split hook terminal device with adjustable pinch force, functional grasping contours, and illumination[37]
	Underactuated anthropomorphic prosthetic gripper[38]
	Underactuated robot fingers for partial hand amputation[39]
	Gripping device with switchable opening modes[40]
	Gripping device with switchable opening modes[28]
	Prosthetic hand with articulated finger and hydraulic system[41]
Elbow joint	Artificial arm with jointed sections, which may be actuated by body movements[42]
	Artificial arm with elbow lock and selective control of forearm flexion or hook operation[43]
	Artificial elbow mechanism featuring bending and active locking mechanisms[44]
	Artificial elbow joint that comprises a detent wheel rotatably mounted on the forearm and fixedly connected to the upper arm; the detent wheel has a periphery that defines a series of detent notches and a lug affixed thereto and projects from the periphery[45]
	Mechanically operable pivoting wrist, elbow, and/or shoulder joints[22]
Control Cable	Independent elbow and terminal device control; electromechanical lock actuator used in conjunction with existing cable-operated, positive-locking elbow, and wrist component[46]
	Control cable with pulley and slippery cable housing[21]
	Sure-lok device that mechanically locks body-powered control cables in response to myoelectric signal[47]
	Anchoring system for a prosthetic device that includes a fastener to secure the base directly to the skin of the wearer[48]
Wrist Unit	Mechanical design of a cable-driven 3-degree-of-freedom (DOF) wrist prosthesis that mimics human arm anatomy with parallel structure[49]
	A multi-function body-powered prosthetic wrist unit that provides over 270° of smooth pronation and supination rotation with a plurality of indexed rotation locking positions[50]
	Generating wrist movement with an ultrasonic sensor[51]
Full Arm	Artificial arm with a hand terminal device, wrist unit, and locking elbow mechanism[52]
	Improved body-powered hand for toddlers equipped with a nonbinding clutch mechanism that provides a secure capture and self-energizing mechanical principle that enables easy insertion of objects into the hand[53]
	Enhanced-functionality prosthetic limb is disclosed, comprising a prosthetic hand or gripping device and forearm, which may be body-powered or motor-powered and targeted primarily for pediatric use[54]
Locking Mechanism	Electromechanical lock actuator used in conjunction with existing cable-operated, positive-locking elbow and wrist component[46]
	Locking mechanism for voluntary closing prosthetic prehensor[55]
	Cable lock device for prosthetic and orthotic devices[56]
Suspension	Prosthesis system without shoulder harness[57]
	Transradial (below-elbow) design that combines the proven effectiveness of supracondylar (modified muenster) suspension with new silicone socket technology[58]
Mechanism	Concept for stiffness compensation of body-powered hand prosthesis and cosmetic glove[59]
Simulator	Body-powered prosthesis simulator with real-time adjustment of gripper stiffness and cable control stability[60]

chronological trend of top cited articles is in accordance with previous findings, and the results indicate that the peak recognition of important papers in a field can be obtained in a period of 10–20 years.[26]

The countries that contribute the highest number of work related to the design and development of body-powered prosthesis are the United States (54%), Europe (11%), Canada (6%), Japan (3%), Singapore (3%), and Malaysia (3%). Campbell[27] stated that the dominance of the United States can be attributed to the high research funding and the large community of American scientists. Moreover, American authors usually prefer publishing in American journals and are more likely to cite other American papers.[27] Asian countries have been trained in this field for more than 20 years because of war, landmines, and natural disasters, but few papers originate from Asian countries. Approximately 1,285,000 people in the United States live with limb loss, and 50,000 new amputations are performed annually according to information from the National Center for Health Statistics. Many users still employ body-powered prosthesis despite the advancement in electrical prosthesis in Western countries.

The scope of improvement (Table 3) includes body-powered terminal device, control cable, body harness, wrist unit, elbow lock system, new control mechanism, and simulator, all of which are given focus by different authors. Some authors focus on the specific scope of improvement, while some work on several scopes of improvement in one paper.[9] Cupo and Sheredos[10] focus on the control of both elbow joints, terminal device, cable recovery system using Spectra 1000® cable, and adjustable forearm length.[10] The highest number (22.5%) of papers focus on above-elbow level of amputation, 10% deal with below-elbow level of amputation, 67.5% work on the invention that can be used by above- and below-elbow amputees, and only 8% (1) deal with the partial hand amputation.

Most papers work on the improvement of the terminal device (45%), followed by elbow joint (12%), control cable (10%), full arm (8%), wrist unit (8%), elbow lock (7%), and suspension (5%). The other scopes of improvement, which are discussed in less than two papers, include a new concept of prosthetic mechanism and a prosthesis simulator.

The Web of Science Results Analysis shows that the interest in the external and body-powered prosthetic system, as measured by the number of papers published, has increased since 2000. Body-powered take up is slightly delayed and runs roughly one-third of the external-powered rate. The record count for both systems moves together since 1980 and reaches the highest number of papers published in 2014 but later declines. The decline may be an artifact of the method of surveying or the way the journals collect the data. We assume that the data seem to show not a disinterest but a low interest in body-powered prosthetic system, given that we only analyze a part of the curve.

Conclusion

This report is a systematic review of papers related to the design and development of upper limb body-powered prosthesis. A search on the Web of Science database, Google Scholar, and Google Patent on body-powered prosthesis resulted in 66 design and development study type of papers, which include published articles and conference proceedings and 89 patent document type of papers related to body-powered prosthesis prior to December 2015. All the records are assessed and analyzed by the authors and included in this paper. The authors worked on different aspects of improvement, ranging from terminal device, elbow joints, complete full arm, prosthesis simulator, mechanisms, wrist unit, control cable, suspension, and locking mechanisms. The papers were published between 1921 and 2015, which is a time frame of almost a century or an average of one publication every 3 years, to make it possible for the authors to safely say limited research is conducted to improve body-powered arms. Although researchers have worked on this area of study since 1921, all the modifications and improvement were not implemented because most of the amputees still use the conventional body-powered prosthesis. Prosthetists or biomedical engineers are responsible for new inventions, especially in those scopes that are less discovered by previous authors. More participations from prosthetists from Asian countries are expected, such as Vietnam, Cambodia, India, and Thailand, because they mostly use a non-technology prosthesis, which includes the body-powered prosthesis. The limitation of this paper includes the use of just three databases and few search keywords. The recommendation of this paper is to improve the method of search and analysis for more precise data. All the studies listed have attempted to improve certain functional aspects associated with body-powered prosthetic use to maximize users' functionality and quality of life. Further research should be conducted especially in the lacking scopes of improvement. Thus, the newly developed system can be widely used and make a body-powered prosthetic system highly operable.

Declaration of conflicting interests

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