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Sport prostheses and prosthetic adaptations for the upper and lower limb amputees: an overview of peer reviewed literature

Mihai Bragaru1,2, Rienk Dekker1,3 and Jan HB Geertzen1,2

Abstract
Background: Sport prostheses are used by both upper- and lower-limb amputees while participating in sports and other physical activities. Although the number of these devices has increased over the past decade, no overview of the peer reviewed literature describing them has been published previously. Such an overview will allow specialists to choose appropriate prostheses based on available scientific evidence rather than on personal experience or preference.
Objective: To provide an overview of the sport prostheses as they are described by the papers published in peer reviewed literature.
Study Design: Literature review.
Methods: Four electronic databases were searched using free text and Medical Subject Headings (MESH) terms. Papers were included if they concerned a prosthesis or a prosthetic adaptation used in sports. Papers were excluded if they did not originate from peer reviewed sources, if they concerned prostheses for body parts other than the upper or lower limbs, if they concerned amputations distal to the wrist or ankle, or if they were written in a language other than English. Results: Twenty-four papers were included in this study. The vast majority contained descriptive data and consisted of expert opinions and technical notes.
Conclusion: Data concerning the energy efficiency, technical characteristics and special mechanical properties of prostheses or prosthetic adaptations for sports, other than running, are scarce.

Clinical relevance
An overview of the peer reviewed literature will enable rehabilitation specialists working with amputees to choose a prosthesis that best suits their patients’ expectations on the available scientific evidence. Identifying the information gaps present in the peer reviewed literature will stimulate new research and eventually broaden the base of scientific knowledge.

Keywords
Artificial limb, prosthesis, rehabilitation, sports

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Background
Participation in sports has been shown to help amputees improve their physical condition and overall well-being.1, 2 To engage in sports, amputees typically utilize technical aids, such as prostheses, wheelchairs or crutches. Lower limb prostheses are required for running and other sports that require a dynamic upright position. Upper limb prostheses are required for sports such as rowing or cycling so that upper limb amputees can propel or steer a boat or a bicycle. Nevertheless, there are sports in which amputees can engage freely without prostheses. For example, a lower limb amputee may have minimal or even no disadvantages when
were not considered peer reviewed. It to a scientific peer review process prior to publishing. Sources that publish information without submitting were also not included. The references cited in each paper were not included. Reviews of any type and expert opinions that is not specifically adapted for a particular sport. However, other sports require special prostheses or sport-specific prosthetic adaptations. During recent years, the development of specialized prostheses, prosthetic components and prosthetic adaptations that are used for sports has increased, leading to an increased number of sport prostheses and prosthetic adaptations that are available for amputees to use while participating in sports.6

To date, an overview of the sport prostheses and prosthetic adaptations for sports described in the peer reviewed literature has not been presented. Such an overview will enable rehabilitation specialists (i.e. physicians, prosthetists, physiotherapists and occupational therapists) who are working with amputees to choose the prostheses that is most appropriate for each patient based on the patient’s goals and the available scientific evidence. Identifying the information gaps present in the peer reviewed scientific literature concerning these devices will stimulate new research and eventually broaden the base of scientific knowledge. The peer review process is important because it increases the level of scientific quality by identifying, without bias, potential flaws and errors in research prior to it being published, thus helping to ensure reliable data. Consequently, the aim of this study is to provide an overview of the peer reviewed sport prosthesis literature for both upper and lower limbs and to identify the knowledge gaps present regarding these devices.

Review Methods
A literature search was performed in Embase, PubMed, Cinahl and SportDiscus. The search was performed using a combination of Medical Subject Headings (MESH), specifically ‘artificial limb’, ‘limb prosthesis’ (Embase, Cinahl and SportDiscus) and ‘artificial limbs’ (PubMed), along with the name of the sport investigated ‘OR’ the MESH term associated with the sport, using the Boolean operator ‘AND’. Considering that amputees often prefer to engage in sports such as swimming, skiing, golf, baseball, running, jogging, biking, cycling, bowling, kayaking, tennis and rowing, these sports were entered as free-text terms in the search.7,8 All papers published before April 2011 were retrieved.

Papers that provided detailed information on sport prostheses or prosthetic adaptations used in sports were included. Papers that did not originate from a peer reviewed source, papers concerning amputations distal to the wrist or ankle and papers written in a language other than English were not included. Reviews of any type and expert opinions were also not included. The references cited in each paper included in this study were checked for relevant publications. Sources that publish information without submitting it to a scientific peer review process prior to publishing were not considered peer reviewed.

Results
A total of 24 papers describing sport prosthesis or prosthetic adaptations for sports were included. All of the identified information concerning sport prostheses and prosthetic adaptations was organized first by the body region that it addressed (lower or upper limb) and then alphabetically by the type of sport.

Lower limb prostheses and prosthetic adaptations for sports
Cycling
Following the assessment process, only one article concerning the use of prostheses by lower limb amputees for the purpose of cycling fulfilled our inclusion criteria, and this article addressed only trans-tibial amputees.3 Regardless of their amputation level, it is recommended that lower limb amputees who desire to cycle consult their prosthetist or rehabilitation physician before starting.9 Although one-leg cycling is possible, using a prosthesis can help to reduce inter-limb asymmetry. If the prospective cyclist wishes to use a regular prosthesis for cycling, it may be helpful to attach the prosthetic foot to the pedal using a cleat.9 Attaching a cleat to the prosthetic foot increases the effective length of the cycling prosthesis. Therefore, the effective length of the prosthesis to be used for cycling (racing) should be measured from the centre of the knee to the centreline of the cleat, and not to the heel, which is the case with a regular walking prosthesis. Additionally, the pedal should be laterally offset to allow for easier mounting and dismounting from the bicycle.9 If a leg prosthesis used for cycling is fitted with an energy-storing foot, the cyclist may experience a loss of propulsive power, especially while pushing the pedal with the amputated limb.9 This problem becomes more noticeable with an increasing cycling frequency. Consequently, a racing cyclist may feel the need to remove the foot altogether and connect the pedal directly to the prosthetic pylon using a toe cleat.9

Golf
The internal rotation of the residual limb within the socket during repetitive golf swings can result in discomfort.10 Using a torsion adaptor, trans-tibial amputees can attain greater hip rotation and, consequently, greater shoulder rotation. This will lead to improved performance while minimizing the internal rotation of the residual limb.3,10 In general, lower limb amputees may benefit more from the addition of a torsion adaptor if the amputation is located at the forefoot (the foot which is positioned slightly forward in relation to the other foot) rather than the swing foot (generally on the right side). Regardless of the amputation side, trans-tibial amputees report that the stress on their residual limb decreases with the use of a torsion adaptor.10 In contrast to trans-tibial amputees, the general range of motion
Running/Jogging

One of the first prosthetic feet designed to be used during more strenuous physical activity or sports was the Seattle Foot®. This foot included a series of fibreglass leaf springs and a rubber deflection bumper in its construction. These components provided a higher energy return than conventional prosthetic feet at that time, allowing amputees to walk and run in a pattern that is more similar to the able-bodied gait. While using Flex-Foot® running style than those using feet such as the SACH® foot, lower limb amputees were able to achieve a more energy-efficient gait. With the introduction of carbon fibre prosthetic and run in a pattern that is more similar to the able-bodied

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tional prosthetic feet at that time, allowing amputees to walk and run in a pattern that is more similar to the able-bodied gait.12,13 While using Flex-Foot Modular III® prosthetic feet, lower limb amputee runners have been able to achieve an ‘up on the toes’ sprinting position, a position that is characteristic of able-bodied sprinters. With the introduction of prosthetic feet specialized for running and sprinting, amputees can achieve higher running speeds with lower energy consumption than would be possible using regular prosthetic feet.17,18 Furthermore, using running-specific prostheses may allow amputee runners to achieve higher speeds and similar metabolic costs compared to non-amputee runners.19,20 Nevertheless, data regarding the influence of running-specific prostheses on metabolic costs and running speeds are still controversial, and more research is needed to clarify this point.21,22

While running, trans-femoral amputees may encounter more problems than trans-tibial amputees due to the increased interlimb asymmetry. One characteristic that is specific for the running style of trans-femoral amputees is the presence of a swing delay that can be up to 36% greater for the amputated side than for the non-amputated side. The swing delay is caused by the inertia of the prosthetic leg, which keeps the lower prosthetic shank from accelerating forward as quickly as the non-amputated limb. An attempt to remedy this problem was the Oklahoma cable running system. This system allowed the prosthetic lower shank to be propelled forward to achieve maximal knee extension at the moment of maximal hip flexion. With the development of more technically advance prosthetic knees, the Oklahoma cable became obsolete and therefore this system is no longer in use. Another way to reduce the extension delay caused by the inertia of the prosthesis is to lower the prosthetic knee’s horizontal axis. This modification has to be performed according to each subject’s physical and running characteristics and preferences. An additional method to improve the running style of trans-femoral amputees consists of a spring or telescopic component mounted in the lower prosthetic shank (Terry Fox Jogging Prosthesis). In addition to improving energy return, the spring provides a cushioning effect, decreasing the stress that is exerted on the residual limb upon initial contact. Unfortunately, the design of this apparatus was based on data obtained from an unimpaired able-bodied jogger. Due to the differences between able-bodied and amputee running styles, the tested prosthetic prototype did not satisfy all the biomechanical requirements of a jogging prosthesis.

Skiing/Snowboarding

A regular prosthetic foot can also be stripped to its basic components to use only the parts that are needed to attach the foot to the skis. In this way, an ankle adaptor can be directly connected to the sole of a ski boot, allowing a direct connection between the prosthesis and skis and eliminating the need for the rest of the shoe.

Snowboarding, due to the particular position of the snowboarder’s legs, requires a greater degree of movement in the ankle than skiing. Because of this, a specially designed ankle unit that allows plantar flexion and dorsiflexion as well as inversion and eversion has been shown to be more useful than regular prosthetic ankles for snowboarding.

Swimming

Both unilateral lower and upper limb amputees can swim quite easily without prostheses. The use of prostheses while swimming may help strengthen the residual limb muscles and lead to a more effective and symmetric swimming style. In addition, lower limb amputees who use prostheses may have less difficulty getting to, into and out of the pool.

Lower limb amputees who choose to use their prosthesis while swimming have to make sure that their prosthesis is waterproof. To increase propulsion while swimming, a flipper can be directly attached to the trans-tibial prosthetic socket. The total length of the flipper prosthesis should be equal to the length of the sound limb. Additionally, the vertical axis of the prosthesis needs to be laterally offset to avoid contact with the sound limb. Regardless of the type of prosthetic device that is used for swimming, there must be a secure connection between the residual limb and the socket. The use of a neoprene sleeve or a harness for trans-tibial prostheses is one means to provide a more secure fit.

Socket adaptation

The residual limb volume may vary up to 17% between the minimum and maximum volumes during competition or training. Therefore, an adjustable socket may be useful for trans-femoral amputees, whose residual limbs typically have greater muscular mass than those of trans-tibial amputees. One solution to this problem is to cut (slit) the socket on the lateral side and then fit it with an adjustable flap. This way, athletes can adjust the socket volume themselves.
When athletes use this type of socket modification, they have to be careful not to tighten the socket too much to avoid residual limb problems due to the increased pressure and reduced blood flow.\textsuperscript{32}

**Upper limb prostheses and prosthetic adaptations for sports**

**Baseball**

Due to the different upper limb movements that are specific to each action, upper limb amputees may require two different prosthetic adaptations to play baseball, one for batting and one for catching. Conventional below-elbow prostheses do not have wrist units that allow flexion-extension or lateral motions, such as abduction and adduction, movements that are required for batting. These drawbacks can be eliminated by mounting a ball-and-socket joint between the prosthetic socket and the prosthetic hand.\textsuperscript{33}

**Cycling**

Upper limb amputees use their prosthesis to grip the handle bar to steer and to operate the gears and brakes. For this purpose, any prosthetic hand that is fitted with a voluntary opening/closing mechanism should be sufficient.\textsuperscript{34} A prosthesis used during cycling competitions should be able to be used in different positions during a race, should be light and should be specific to each competitive cycling discipline. Therefore, competitive cyclists require specialized cycling prostheses.\textsuperscript{35} A prototype prosthetic device that meets the demands of a below-elbow amputee has been designed, manufactured and tested.\textsuperscript{35} For above-elbow amputees, an elbow unit can be attached to the prosthetic device. This elbow joint can be locked at different angles or can be left unlocked, allowing the cyclist to assume various elbow positions during a race.\textsuperscript{35}

**Fishing**

When fishing, upper limb amputees use their prosthesis to manoeuvre the casting rod and the spinning reel.\textsuperscript{36} In both cases, prosthetic adaptations consisting of an aluminium tube mounted at the distal end of the socket can be useful. The diameter of this tube should match the diameter of the fishing rod or the spinning reel.\textsuperscript{36}

**Golf**

Unilateral upper limb amputees can play golf without a prosthetic aid; however, a loss in control and speed will occur.\textsuperscript{37} When using prosthetics in golf, the golf club can be attached directly to the prosthesis at the distal end of the socket with the use of a special adaptor. This type of modification has been described in detail in a paper by Bhala et al.\textsuperscript{37}

**Kayaking**

Upper limb amputees typically require an adaptation that allows them to hold and manoeuvre the paddle. The USF Kayak Hand\textsuperscript{38} and the TRS Hammerhead Kayak Hand\textsuperscript{39} allow the amputee to manoeuvre the paddle in a way that is similar to an able-bodied kayaker.\textsuperscript{38,39}

**Skiing**

Upper limb amputees can choose to have their ski poles directly attached to their prosthetic sockets.\textsuperscript{27} This option may be useful to bilateral upper limb amputees because it is often difficult for them to connect and disconnect the ski poles without the use of a functioning hand.\textsuperscript{27}

**Discussion**

Twenty-four papers published between 1964 and 2011 were identified in the present study. The identified data consisted mostly of manufacturing indications and clinical commentaries. Scientific data concerning the efficiency, reliability and functionality for the large majority of the sport prostheses or prosthetic adaptations were absent. A number of expert opinions published in peer reviewed and non-peer reviewed sources were identified by the search.\textsuperscript{34,40-46} Even though the authors of these papers are respected and experienced professionals in their field, the papers themselves present little scientific data providing evidence for their claims.\textsuperscript{47} Expert opinions were not considered for this study because they represent, as their name suggests, a personal opinion based on an individual’s experience rather than on epidemiological and bio-statistical calculations. As a result, it is nearly impossible for others to address the validity, quality and unbiased nature of these reports.

A large variety of sport prostheses and prosthetic adaptations can be found on manufacturers’ websites. Almost all of the major manufacturers of prosthetic components have at least one product that is specifically designed for use during participation in sports. In addition, patients’ or prosthetists’ association websites may represent valuable information sources for individuals searching for sport prostheses or prosthetic adaptations for sports. The number of young traumatic amputees is expected to rise in the coming years, mainly due to armed conflicts or dangerous hobbies. Consequently one can expect that the request for specialized sport prostheses will also increase. Therefore besides thoroughly testing their devices, prosthetic manufacturers should also use their available resources to develop new specialized prosthetic devices for sports and physical activities.
The relative lack of scientific data available on sport prostheses and prosthetic adaptations for sports may be partially explained by the fact that there are a limited number of amputees who engage in sports and/or physical activities\textsuperscript{1,3,8,48} and even fewer who engage in sports at elite levels. Another explanation may be that the vast majority of sport prostheses or prosthetic adaptations for sports are not thoroughly tested or that the results of these tests have not been published in peer reviewed journals. Thorough testing would require a series of biomechanical tests performed in laboratory settings that are later followed by a thorough analysis of the data gathered. Most of the papers we identified consisted of observations or manufacturing indications that clearly lacked the phases we described above. Considering the increasing importance of evidence-based medicine, prosthetic manufacturers and developers of new prosthetic technologies should aim to provide information about their products through studies published in unbiased peer reviewed journals. The peer review process helps to increase the level of scientific quality by identifying potential flaws and errors in research prior to publishing.

A discrepancy in the amount of available data was also noticed between various types of sports. For example, the majority of the data concerning kinematic analyses and efficiency tests that were performed on prosthetic devices were specifically focused on running or jogging prostheses. This finding can be explained by the fact that running is a principal component of many other sports, thus the data provided by these studies can be quite easily extrapolated to other sports. Another explanation may be the larger number of athletes who are practising this sport (running) and the increasing presence of mass media at these events. Therefore, we can understand the fact that some authors choose to address this topic in various reviews, including systematic reviews, expert opinions or clinical commentaries.\textsuperscript{49,50} The presence of these data is most welcome, considering the scarcity of scientific information that is available in this field. Nevertheless, one must consider that running or jogging can represent difficult skills for the average lower limb amputee to master. An array of factors, including fitness level, adequate training, associated comorbidities and prosthesis, may influence the ability to run or jog of lower limb amputees. Additionally with a more proximal level of amputation the interlimb asymmetry increases\textsuperscript{1} and therefore makes it even more difficult to acquire and maintain a dynamic alternating period of support and non-support on both intact and amputated limb.\textsuperscript{51}

Professional athletes or amputees who participate in competitive sports should consider that specialized sport prostheses could potentially improve their athletic performance. The best way to acquire a prosthesis that is optimally fitted to one’s needs and capabilities is to collaborate closely with a sport coach and prosthetic technician. In this way, a prosthesis can be modified and adapted to each specific individual based on their specific athletic and physiological attributes.

In the future, researchers, clinicians and manufacturers in the field of sport prostheses should focus on conducting clinical studies in which the technical characteristics and performance of sport prostheses and prosthetic adaptations for sports are thoroughly tested and later published in peer reviewed journals. This will hopefully minimize the gaps identified in the scientific knowledge of this field, as shown by this review. Ultimately, the data generated by the close collaboration of researchers, clinicians, prosthetists and manufacturers will lead to an increase in participation in sports and physical activities of upper- or lower limb amputees.

Conclusion
The data identified in the peer reviewed literature concerning sport prostheses and prosthetic adaptations for sports were scarce and mostly descriptive in nature. However, the utility of running prostheses and prosthetic components has been substantially documented by peer reviewed literature. More efforts should be made by researchers, clinicians and prosthetists alike to publish data concerning the energy efficiency, technical characteristics and special mechanical properties of sport prostheses in peer reviewed publications.

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Conflict of interest
We certify that no party having a direct interest in the results of the research supporting this article has or will confer a benefit on us or on any organization with which we are associated.

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