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A narrative review

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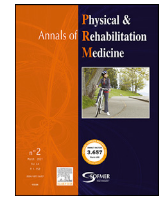

Review

State of the art of prosthesis simulators for the upper limb: A narrative review

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ABSTRACT

Background: Research into prosthesis training and design puts a burden on the small population of people with upper-limb absence who can participate in these studies. One solution is to use a prosthetic hand simulator, which allows for attaching a hand prosthesis to an intact limb. However, whether the results of prosthesis simulator studies can be translated to people with upper-limb absence using a hand prosthesis is unclear.
Objective: To review the literature on prosthetic hand simulators, provide an overview of current designs, and highlight the differences and similarities between prosthesis simulators and traditional prostheses.
Methods: A Boolean combination of keywords was used to search 3 electronic databases: PubMed, Scopus and Web of Science. Relevant articles in English were selected.
Results: In total, 52 papers were included in the review, and an overview of the state of the art was presented. We identified the key differences between prosthesis simulators and traditional prostheses as the position of the terminal device and the available degrees of freedom of the arm and (prosthetic) wrist.
Conclusions: This paper provides an overview of prosthesis simulator designs over the past 27 years and an overview of the similarities and differences between prosthesis simulators and prostheses. The literature does not provide enough evidence to establish whether the results obtained from simulator studies could be translated to prostheses. A recommendation for future simulator design is to constrain pro- and supination of the forearm of anatomically intact participants and add a prosthetic wrist that can pro- and supinate. Additional research is required to find the ideal terminal device position for a prosthesis simulator with respect to the person's hand.

Introduction

When undertaking research relating to upper-limb prostheses, researchers face limitations due to the small number of people with upper-limb absence available to engage in their studies. In addition, research relating to prosthesis training often requires novice prosthesis users to participate, which is a small sub-population. It would be unethical to deny people occupational therapy after an amputation in order to have novice prosthesis users participate in research [1], especially because being able to start training early after an amputation is an important factor with respect to prosthesis acceptance [2]. Rejection rates of hand prostheses are high: 20% to 45% [3]. Researchers strive to decrease rejection by improving the prostheses [4–6] or improving the training programmes for people with upper-limb absence [1,2,7,8]. The small population of people with upper-limb absence prevents providing power in statistical analyses.

A prosthesis simulator may solve this problem. A simulator allows for fitting a prosthesis to an intact limb, enabling anatomically intact individuals to participate as novice prosthesis users in research. This situation relieves the burden on the small population of people with upper-limb absence [1,2,7].

Because the anatomical hand is still present, the prosthetic hand is unable to be placed in an anatomically accurate position and instead must be offset. Some research groups place the prosthetic hand distal to the anatomically intact hand, which extends the forearm. Others place the prosthesis beside the anatomical hand, which misaligns the hand from the forearm axis. However, how this placement influences the results obtained using a prosthesis simulator is unknown [7].

Another question is whether the designs of prosthesis simulators are based on the same design priorities as the prostheses they need

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to resemble. To increase comfort, a lightweight prosthesis has been found as one of the highest design priorities for people with upper-limb absence [9]. Other priorities that are ranked highly and that could be relevant for prosthesis simulator design are improved harness comfort and prosthetic wrist movement. Having the same design priorities for prosthesis simulators and prostheses might indicate a good simulation.

The aim of this literature review was to provide an overview of the state of the art of prosthetic hand simulators and to compare the (bio)mechanical principles of prosthesis simulators to those of prostheses.

Methods

Search query

In October 2020, we performed a literature search of the databases Scopus, PubMed and Web of Science. The following Boolean combination of keywords was used: (("prosthesis simulator") OR ("prosthetic simulator") OR ("prosthetic hand simulator") OR ("training prosthesis") OR ("bypass prosthesis")) AND ((upper AND limb) OR (upper AND extremity) OR (hand) OR (arm)). The search was restricted to articles published in English. There were no search restrictions on publication date.

Selection criteria

Articles that reported a prosthetic hand simulator or the use of a hand prosthesis in anatomically intact individuals were included in the review process. We excluded articles that did not report the use of a physical simulator or only mentioned virtual reality or augmented reality. Initially only the title and abstract were scanned for the topic. However, if it was not clear whether a prosthesis simulator was used, the main text was read to assess whether the article matched the selection criteria. After reviewing the identified articles, the references from the included articles were also reviewed according to the same selection criteria.

Results

The flow diagram in Fig. 1 displays the search process from this review [10]. The search resulted in 112 articles selected from the 3 databases. Removing 66 duplicates left 46 articles to be reviewed. After scanning the abstract and title, 12 were removed. In this study, 34 articles were included from the search and 18 more articles were identified from their references and other sources. Ultimately, the review included 52 articles.

State of the art

A total of 32 different simulator designs were found, ranging in publication year from 1993 [11] to 2020 [12]. Approximately half of the studies used a myoelectric terminal device (n = 28); the others used a body-powered prosthesis (n = 23). Only one study used both on the same simulator [7]. No studies used passive hands. The myoelectric simulator developed in Groningen, The Netherlands, was used in the highest number of studies (n = 11) [1,2,13–21], with other simulators used in 1 to 4 studies. One of the myoelectric simulators was adapted for young children [22]. Most studies (n = 33) studied the effects of training strategies and practice [1,2,7,8,11–38], for example, on visuomotor behaviour [23,26,27,39] or inter-manual transfer [2,14–17,22,33]. Twelve studies tested the design of a terminal device [5,6,40–49]. Two studies assessed feedback systems designed for a myoelectric hand [50,51]. Two studies analysed object weight perception for people with upper-limb absence and anatomically intact participants [52,53]. One study explored the reachable workspace when wearing a body-powered prosthesis [54]. Finally, 2 studies focused on the design of the prosthesis simulator itself [4,55].

Socket

The sockets of the prosthesis simulators were usually made to fit multiple participants. Most sockets covered the entire forearm and hand. The sockets could be tightened around different arm sizes with Velcro (e.g. [8,47]) or BOA cable closure technology (e.g. [4,50]). One socket could be adjusted for different arm lengths [47]. In 2 of the studies, the sockets were custom-made to fit a specific participant [36,40].

Wrist

Only one article reported which prosthetic wrist was used for their prosthesis simulator [5]. This was the Otto Bock 10V30 Wrist, which could be pro- and supinated with the other hand and locked in discrete positions. Two other studies reported the use of a friction wrist [45] and a flexion wrist [36]. In 2 simulator designs, the wrist was fixed in one position, with the prosthetic hand located axially to the intact hand [4,24]. The other studies did not report the degrees of freedom of the prosthetic wrist or which wrist was used, if any.

Terminal device

The terminal device of the prosthesis simulators was usually positioned in one of 3 locations relative to the intact hand (Figs. 2 and 3): dorsal (A), axial (B) or palmar (C). One study placed the terminal device in a 20-degree angle relative to the forearm, at the palmar side of the anatomical hand [55]. All positions caused the simulator to be overlong in comparison with the anatomical arm. Three studies reported an overlength value: 12 cm [38], 18 cm [48] and 15 cm distally from the intact hand [40]. The terminal device position for most simulators was axial [2,4,7,8,12,21–25,27,29,32–39,41,43–47,52,53], 3 were palmar [5,6,42,50,51] and 3 were dorsal [40,48,54].

The type of terminal device influenced its position, for example, to make room for electrodes or a shoulder harness for control. The myoelectric simulators were operated in 3 ways: with electrodes incorporated in the sleeve [27,28], with a bracelet that could detect myoelectric signals [41], or with separate electrodes that needed to be stuck on the skin [15,22,52]. The body-powered simulators were operated by pulling a cable that was attached to a shoulder harness. One of the body-powered simulators was haptic: (pulling the cable controlled motors moved the terminal device [4]). The studies using a myoelectric simulator did not report position constraints due to the electrodes. However, for the body-powered simulators, the position of the cable connection to the prosthetic hand did constrain the possible position of terminal device to ensure that the cable could be routed to the shoulder harness without the risk of getting stuck [42,54].

Materials

The simulators were often manufactured as a brace with a frame mounted on top, forming the connection between the terminal device and the brace [4]. A few studies reported the materials for the brace (socket); some others reported just the materials for the frame. The studies reporting the brace (socket) materials used polypropylene with 1/4 inch [23] or 3/16-inch [36] thickness thermoforming plastic [43], or in the case of the Fillauer TRS simulator, EXOS laminates, which could be re-formed when heated [56]. The frames were made from ABSplus [4], carbon fibre [26,52], lightweight aluminium [33] or fibreglass [30–32,48].

Degrees of freedom intact arm

All but one of the prosthesis simulators simulated a trans-radial level of limb absence. This level of absence allows for no

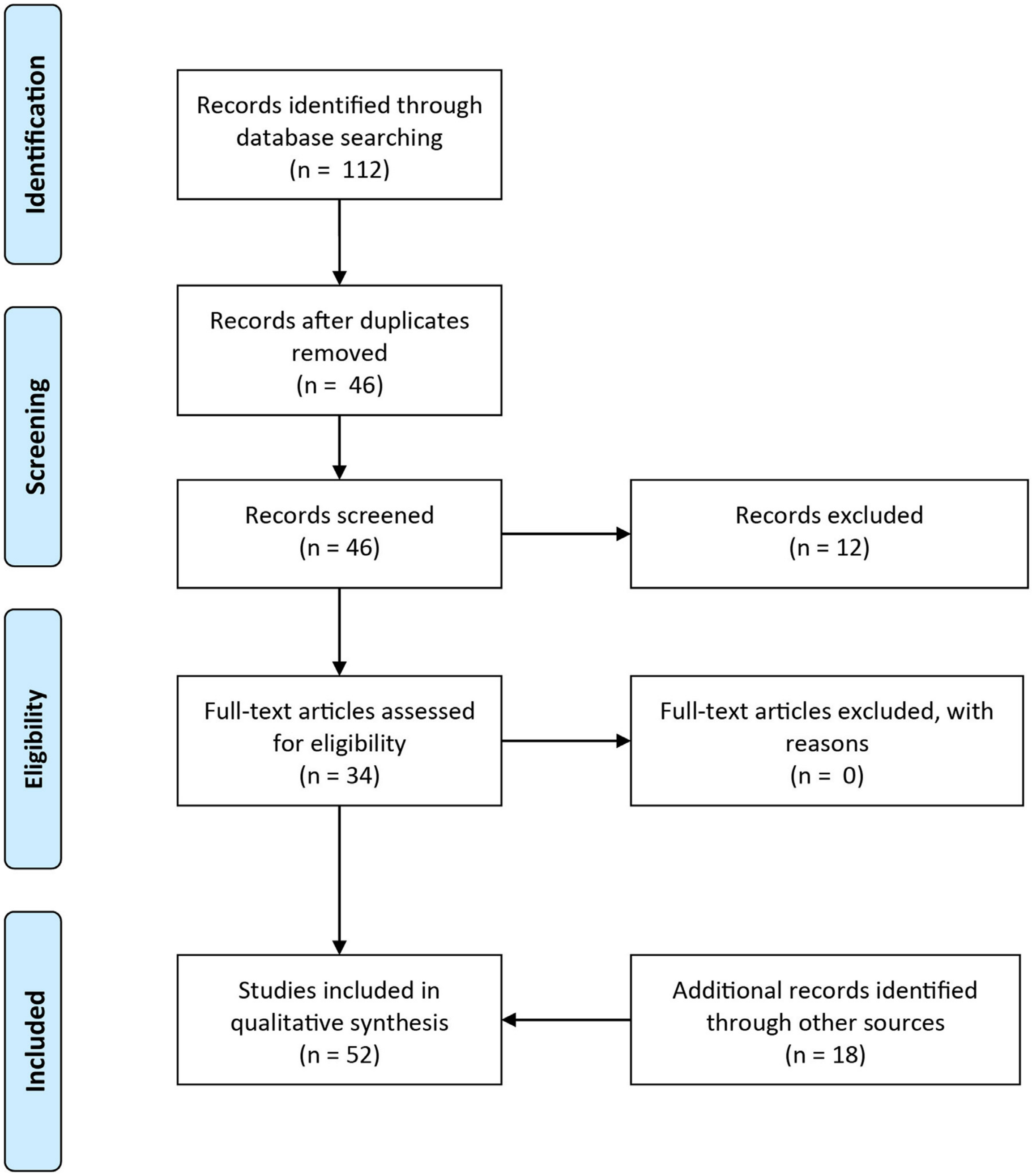

Fig. 1. Flow diagram of the literature search process [10].

anatomical movement at the level of the wrist (flexion/extension and abduction/adduction). For some individuals, depending on the level of absence, a limited amount of pro- and supination of the forearm is possible; however, this is often constrained by the design of the prosthetic socket [3]. For only 4 of the simulators was the pro- and supination of the anatomical forearm constrained. This was achieved by a cast that extended over the elbow joint and the olecranon [24,40] or a connection to the upper arm and the forearm and a hinge [38,47]. The other designs allowed movement of the forearm. To restrain wrist movement, the intact hand was constrained in most prosthesis simulators by a wrist brace, a handle and/or Velcro straps [4,25,29]. This was especially important in prosthesis simulators with a myoelectric terminal device because users needed to be able to contract their muscles without moving their intact hand [7].

Mass

Very few studies reported the weight of the simulator. Two studies used a bebionic hand (weight 433 g for small or 616 g for medium) connected to a carbon fibre and Velcro socket [57]. They reported an overall mass of 1008.5 g but did not specify the size of the hand [26,52]. The Fillauer TRS simulator socket used in 2 of the studies weighs 511 g without a terminal device [56]. The Fillauer TRS Pro Cuff is reported in the company's catalogue to weigh 187 g. One of the studies reported using 2 of these Pro Cuffs, so a total of 274 g (excluding any adaptations or terminal device) [6,56]. The simulator of Wilson et al. was 2.27 kg; this high weight resulted from using a counterweight to compensate for the prosthesis offset from the intact arm [55].

Commercial availability

The prosthesis simulator sold by Fillauer TRS was the only one that is commercially available [56]. It was released in 2015 and made

Fig. 2. Prosthesis simulators in 3 configurations (2.1: dorsal placement, Fillauer TRS [56]; 2.2: axial placement, De Boer et al. 2016 [14]; 2.3: palmar placement, Smit et al. 2015 [6]).

Fig. 2. Continued.

for a body-powered terminal device, which can be placed on the dorsal side of the intact hand. The simulator can easily be adjusted with a BOA system to fit multiple users or can be heated and formed to make a perfect fit for a single user. Two studies used this simulator for research [42,54]. In the study by Cuellar et al., the simulator was worn on the right arm even though it was sold as a left-handed simulator [42]. Thus, the terminal device was placed on the palmar side of the anatomical arm with an altered routing of the control cable. The possibility of using the simulator in this way was not reported by Fillauer TRS, nor was the reasoning explained in the article. All other simulators in this review were custom-made.

Upper-arm prosthesis simulator

One paper reported an upper-arm prosthesis simulator [11]. This was a body-powered prosthesis. The simulator was attached to the intact arm by a sleeve. The wrist and fingers were not operated by the wearer; only flexion and extension of the elbow was allowed.

Discussion

Simulator design

The literature search resulted in finding 32 different simulator designs, all developed over the past 27 years. Most of the simulators were used to perform research on the activity of training, which is an important factor in prosthesis acceptance [2]. Anatomically intact users are good participants for these studies because they are usually novice prosthesis users. The population is also larger, so it relieves the burden on the small population of people with upper-limb absence [1,2,7]. The aim of this literature review was to provide an overview of the state of the art of prosthetic hand simulators and to compare the (bio)mechanical principles of prosthesis simulators to those of prostheses. As reported in the state-of-the-art section, most studies using a prosthesis simulator focused on training and not on the functioning or comfort of the prosthesis.

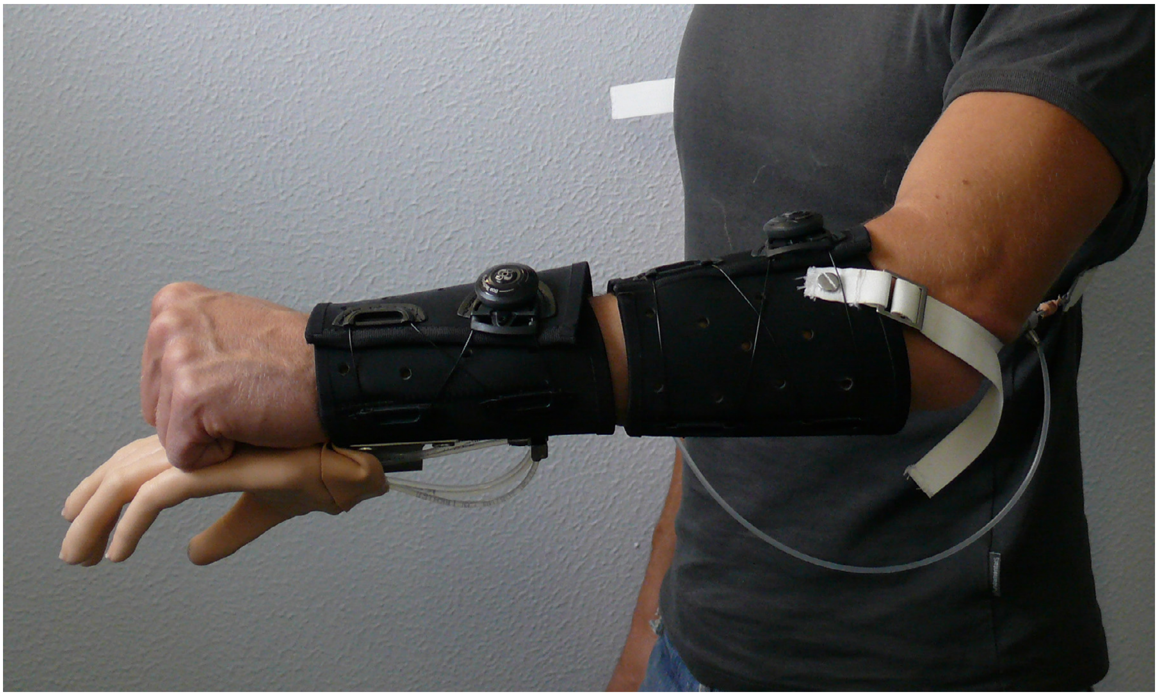

Fig. 2. Continued.

Degrees of freedom forearm

People with upper-limb absence, especially users of body-powered devices, desire a functional prosthetic wrist that is able to rotate to compensate for the loss of pro- and supination of the forearm [9]. We found mention of a prosthetic wrist in only 3 of the articles. These wrists could be operated with the other hand [5,36,45]. Only 4 of the prosthesis simulators constrained pro- and supination of the forearm of the anatomically intact user [24,38,40,47]. Thus, the other designs would allow an anatomically intact participant to compensate for the lack of degrees of freedom of the prosthetic wrist with pro- and supination of the forearm. People with upper-limb absence at trans-radial level are not always able to do this, which might influence study results if they were reproduced in a population of prosthesis users.

Position of terminal device

An obvious difference between people with upper-limb absence and anatomically intact participants is the absence of the hand. Therefore, the position of the terminal device is an important design choice for a prosthesis simulator. Ideally, the prosthetic hand should be placed on the same place as the intact hand. Most simulator designs placed the terminal device in line with the intact hand. Only about one-quarter of the designs placed the terminal device somewhere other than axially [5,6,40,42,48,50,51,54–56]; 3 of these were used with a myoelectric device [40,48,55].

Three positions were commonly used for the terminal device: dorsal, axial or palmar from the intact hand. Placing the terminal device on the dorsal or palmar side can solve several practical issues, such as ensuring that the cable runs smoothly along the socket or

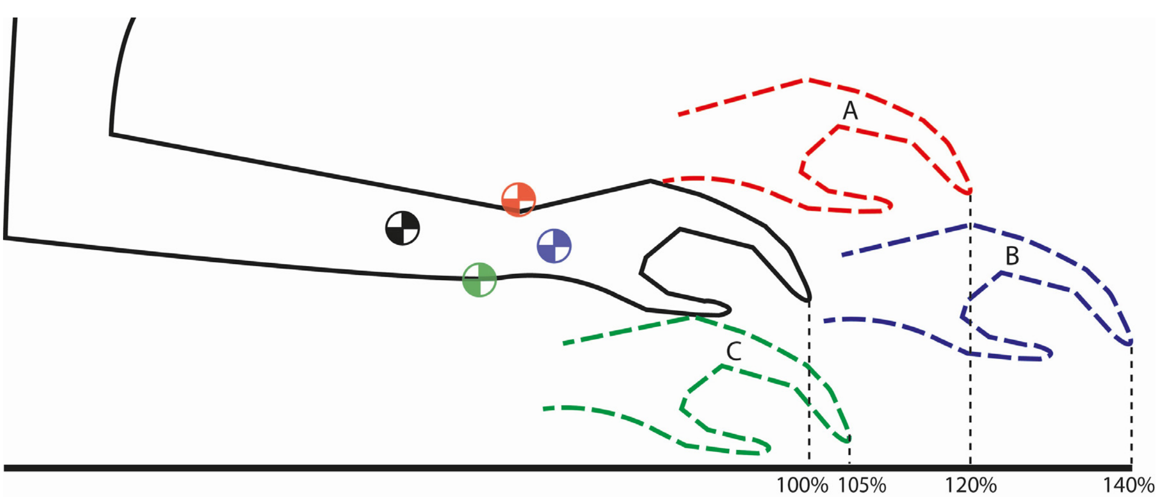

Fig. 3. Positions of terminal device with the corresponding estimated position of centre of mass and estimated overlength percentage with respect to the intact arm as caused by the simulator in 3 positions (A: dorsal; B: axial; C: palmar).

limiting the moment of inertia that the prosthesis simulator adds to the arm. Overlength estimations respective to the intact arm are reported in Fig. 3: the axial position (B) extends the forearm and hand by 40%. The arm being overlong affects not only the centre of mass but also how individuals move. Individuals retract their shoulder to compensate for the difference in length of their contralateral arm and the simulator [7]. This compensation especially affects bimanual tasks and could change the kinematics of the task as compared with performing it with the intact arm or with a prosthesis without overlength. The arm being overlong also has an effect on tasks in which the individual has to reach because the moment of inertia of the arm is changed [2]. An advantage of placing the prosthesis at the dorsal or axial position is that the view of the prosthesis is not blocked [40]. The palmar side (C) artificially extends the length of the arm by the smallest amount; however, the line of sight to the prosthesis is blocked. Novice users need to look at a prosthetic hand more often than they do at their intact hand, to successfully complete the same task [26]. There is not enough evidence available to be able to choose the ideal position of the terminal device because the 3 positions each have advantages and disadvantages. A future study could explore the differences in performance with different simulator setups by using a counterbalanced design.

Comfort

Prosthesis users reported improving comfort as a design priority for research, but in simulator studies comfort is hardly mentioned [9]. The topics that prosthesis users mentioned specifically were a higher harness comfort and lower prosthesis weight. With a short residual limb, a heavy prosthesis can be uncomfortable and it can be harder to operate a prosthesis [24]. Simulator studies did not report any information about harness comfort. However, prosthesis simulator weigh was reported for 3 designs [52,55,56]. In the other studies, the weight was not reported, which is unexpected for 2 reasons. The first is that in multiple studies, the weight of the simulator is reported as the cause of an unexpected difference in performance between men and women [20,32,33]. Not reporting the weight disallows comparing results to other studies. The second reason is that even in a study in which the design priority for the terminal device was to make it lightweight, no information was reported about the weight of the simulator [6]. A reason for not elaborating on comfort in these studies might be due to the prosthesis simulators usually being worn for only a single trial and not all day long. Mild discomfort may be more acceptable for a short time rather than during daily use. Nevertheless, discomfort, for example due to weight or harness discomfort, might affect the results of a study.

Rehabilitation

Novice users require training in the use of a prosthesis. This training should start as soon as possible after being fitted with a prosthesis [32]. A prosthesis simulator can assist with the rehabilitation program. The possibility of inter-manual transfer means that the simulator can provide the opportunity for the individual to train by using their contralateral limb while the wound from their amputation is still healing [2]. Inter-manual transfer is the principle that an acquired skill in one hand can be transferred to the other hand. After training with a prosthesis simulator, control of the prosthesis using the other hand can improve significantly [2,14–17]. This effect was also significant in a study including young children [22]. A possible difference between research and practice is that anatomically intact research participants can wear the simulator on 2 equal-length limbs with equivalent hand positioning. If people with upper-limb absence practice with a simulator, transfer to the prosthesis might be different because of a difference in the moment of inertia and the intersegmental dynamics between the 2 sides [2]. One study explored inter-manual transfer in a cohort of people with upper-limb absence [14]. The group with upper-limb absence performed significantly better than the control group. The control group consisted of anatomically intact participants who were using a prosthesis simulator for the first time in this study. The study shows that inter-manual transfer between a prosthesis and a prosthesis simulator is possible. The difference between this study and general practice was that during normal therapy, the intact side would be trained in order to improve the use of the prosthesis. However, in this study, because of the prior experience of the prosthesis users, the limb absent side was used as the trained side, and the effects of inter-manual transfer from the prosthesis to the simulator was assessed. Therefore, we do not know whether people with upper-limb absence can transfer skills from their intact hand to their prosthesis. Future research in inter-manual transfer should focus on answering this question.

Control of terminal device

Another factor that should be considered when conducting research with anatomically intact participants, is the biomechanical differences between an anatomically intact person and someone with congenital limb absence or amputation. The absence of a limb could affect an individual's potential to operate a prosthesis. Children with congenital limb absence are less strong than their peers for both their affected and intact side [58]. This observation could influence research because it might be easier for someone who is anatomically intact to operate a body-powered terminal device than for a person with congenital limb absence. The reconstruction of muscles or impairment of muscles in individuals with an amputation or congenital limb difference can also have an impact with respect to the generation of control signals for myoelectric prostheses. Anatomically intact individuals are able to make more consistent muscle patterns as compared with those with an amputation [59]. Thus, controlling a prosthesis for someone with upper-limb absence could more difficult than is represented by research studies that use only anatomically intact participants.

Commercially available devices

The simulator by Fillauer TRS is the only commercially available body-powered prosthesis simulator [56]. Two research studies use this simulator. What is surprising is that in one of these studies, a left-handed prosthesis simulator was worn on the right hand [42]. The reason for switching sides was not reported directly, but it does place the terminal device on the palmar side of the hand. This placement is convenient because the cable from the used terminal device originates from the palm of the prosthetic hand as well. The TRS simulator has been available since 2015. We do not know why more recent research studies on body-powered prostheses opted to make their own device instead of buying an off-the-shelf solution [5,6,8,12,23,29,37,38,47].

Strengths and limitations

A limitation of this literature review is that in some articles, the use of the prosthesis simulator is not mentioned in the abstract or keywords of the article. Therefore, finding available literature with a structured search is difficult. This situation was solved by adding articles from the citations of other articles. However, some papers may still have been missed. Future articles should explicitly mention in the abstract, keywords and the text that a prosthesis simulator was used. The articles did not elaborate on the design choices that were made in the manufacturing process of the prosthesis simulators. Thus, the overview of the state-of-the-art section and the overview of differences and similarities of prosthesis simulators and prostheses were less in depth than was anticipated at the review onset. Despite this limited detail, this review was still able to present an overview of the prosthetic hand simulator designs of the past 27 years. This article could be used as a starting point for further research in which the design of a simulator is more important. A recommendation for future simulator design would be to constrain the forearm rotation for anatomically intact participants and to add a rotatable wrist in order to be more representative of prosthesis use. The ideal position and orientation of the terminal device needs to be explored because the information from this review is not enough to formulate a conclusion about the optimal setup.

Conclusions

The first aim of this review was to provide an overview of the state of the art of prosthetic hand simulators. Information about the designs of the past 27 years is reported. The second aim was to provide an overview of the differences and similarities of prosthesis simulators compared to prostheses to determine whether the results of prosthesis simulator studies can be translated to prosthesis users. Although reducing prosthesis weight is an important design priority for people with upper-limb absence, this was not addressed in simulator studies. The key differences between prostheses and prosthesis simulators are the position of the terminal device (with respect to the anatomical hand) and the available degrees of freedom of the forearm and prosthetic wrist. One of the studies showed that prosthesis users were able to use a prosthesis simulator without practice, so there may be a level of similarity between prostheses and simulators. Thus, a simulator may be a good tool for therapy, through intermanual transfer. The literature included in this review does not provide enough evidence to answer whether results obtained with a prosthesis simulator can be translated to prosthesis users. Currently, prosthesis simulator studies appear to be undertaken to facilitate recruitment of large numbers of participants for research studies or to develop and pilot protocols before larger studies of prosthesis user cohorts. Recommendations for future simulator designs are to constrain the pro- and supination of the forearm of anatomically intact participants and add a prosthetic wrist that can pro- and supinate to simulators. Additional research is needed to find the ideal terminal device position for a prosthesis simulator.

Conflict of interest

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