

Swimming with limb absence: A systematic review

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Abstract

Swimming with limb absence is undertaken as a source of leisure or rehabilitation and forms part of the current Paralympic Games competition programme. Whilst it is often proposed that research into sport with limb absence can be limited, this study identified the volume, type and historical interest of research regarding swimming with limb absence. A modified PRISMA search protocol was adopted for this review, and five bibliographic databases were used to identify relevant articles. The review identified 24 papers which met the pre-defined inclusion criteria. The identified peer-reviewed publications dated from 1983 to 2015. The trend of publication indicated an initial focus on the design of prosthetics technology with emphasis then shifting specifically to an interest in swimming biomechanics from 2006. The overall trend of publication in this field is a positive one. In this review, four clear themes emerged. These included the general background of swimming with limb absence, the development of lower limb prosthetics technology, swimming with limb absence whilst performing the front crawl stroke and the technique used by those with unilateral elbow disarticulation. From these, four further themes have been identified for pursuit in the immediate future. This review will assist those who are interested in prescribing swimming with limb absence as a form of exercise or to those who wish to pursue it competitively.

Keywords

Amputee, swimming, prosthesis, disability

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Background

Amputation of one or more limbs creates a functional disability and may decrease the level of mobility a person may have.¹ For those with limb absence, sport provides several benefits including improvements in health, social interaction and improved body image² as well as psychosocial well-being.³ Previous research has indicated the value of prosthetics technology to both potential performance and the emotional state of the user.⁴ Ultimately, specific activity such as swimming offers rehabilitation-based benefits^{5,6} and is one of the most common forms of cardiovascular exercise for those with lower limb amputations.⁷ For those wishing to not only participate in exercise but have aspirations of competition, the Paralympic Games offers a competitive outlet for swimmers with limb absence.^{3,8,9} In addition, possessing a disability may also not be a barrier to able-bodied competitive sport. For example, South African swimmer Natalie du Toit has lower

limb amputation and has competed at both the Paralympic and Olympic Games.

Whilst other sports often require the use of advanced assistive technology,³ people with limb absence can swim easily without the need for prostheses.¹⁰ However, swimming without prostheses may create imbalances which in turn can lead to injuries.¹¹ Therefore, the use of prosthetic technology may assist in strengthening the residual limb muscles and promote functional symmetry.¹⁰ To assist this further, increasing consumer demand has now led to prosthetic technology

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now taking into account sports-specific requirements and desires.¹²

Whilst generalised peer-reviewed articles have been undertaken for those wishing to exercise generally when possessing limb absence,^{1,10} none to date have gone into any great detail into the specific nuances of swimming with limb absence and how it is performed. Both of these previous reviews excluded or generalised several of the specific studies in this area. Consequently, the two aims of this paper were to:

- (1) review swimming when possessing limb absence as a form of locomotion.
- (2) review the use of any technology which is employed to help facilitate swimming with limb absence.

Methods

A systematic review of peer-reviewed literature was conducted in early 2016. The review was completed in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) guidelines (www.prisma-statement.org/statement.htm, accessed 27/9/14). However, this protocol was modified by incorporating the article screening process, as each article was specifically identified, rather than as a single solitary stage later on in its process. Five bibliographic databases were used for this purpose. These included the Sportdiscus, CINAHL, Scopus, PsycINFO and Medline bibliographic databases. Furthermore, as per the PRISMA protocol, additional records were identified through other sources. These sources included the use of any secondary references found within the articles not identified during the main search and the use of Google Scholar.

A series of keywords were used for the database searches. A primary keyword (Keyword 1) was used in direct combination with a second keyword (Keyword 2). These two keywords used the 'AND' Boolean algebra denotation. The bibliographic database search terms are presented in Table 1.

These keywords were used for the main document search and for obtaining any additional records.

Most of the search terms emphasised the activity of swimming. It should be noted that 'triathlon' was also included due to the fact that it includes swimming as part of its three multisport disciplines.

Five inclusion criteria were selected to exist as a specification for relevance for this review and were defined as:

- articles must be from peer-reviewed journal literature.
- articles must involve *specific* discussion around *swimming with an amputation* or *swimming prostheses use*.

Table 1. Summary of database search keywords.

Keyword 1	Keyword 2
Amputee	Swimming
Amputee	Swimmer
Amputation	Swimming
Amputation	Swimmer
Prostheses	Swimming
Prostheses	Swimmer
Prosthesis	Swimming
Prosthesis	Swimmer
Prosthetic	Swimming
Prosthetic	Swimmer
Water	Swimming
Water	Swimmer
Amputee	Triathlon

- articles must be produced in the English language.
- having any duplicate articles removed.

Results

In total, 475 articles were identified from the initial search. These publications were then read in full and evaluated using the inclusion criteria. Six additional records were identified from secondary sources. The total successful sample included 24 articles, and these then formed the foundation of this review.

The date range of interest in the investigation into swimming with limb absence ranged over a 32-year period from 1983 to the date of this review in early 2016. The time series data are illustrated in Figure 1.

Whilst the total number of publications is very low generally, the publication trend was shown to be increasing in frequency and volume since 2006.

The 24 papers identified using the search protocol that were judged to have met the inclusion criteria are summarised in Table 2.

Discussion

The trend and nature of publication

Thirty-one years of research evidence suggests a long held awareness of swimming as a suitable pastime for those with limb absence. However, there is a relative paucity of publications. This said, the trend of publication has typically been shown to be increasing since 2006. It is not obvious why this surge in interest has occurred. However, since much of the research stems from several of the same authors, it might well be down

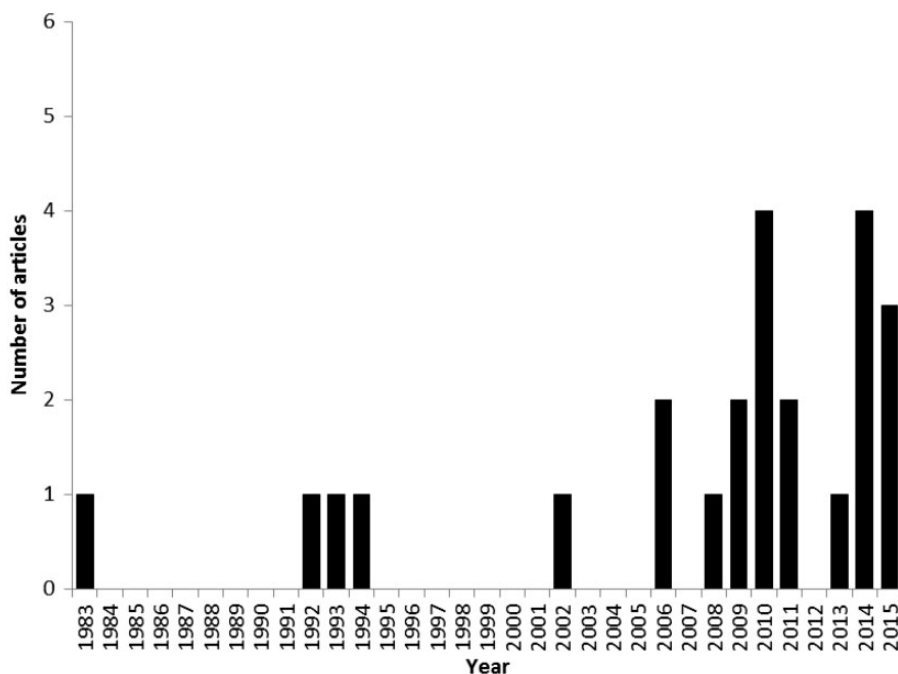


Figure 1. Review publication volume time series data.

to other factors such as long-term, clearly defined research projects.

There has been a change in the nature or intent of these publications over time. Earlier publications typically focused on the design and provision of prostheses technology from a clinician's point of view.^{13–15} However, since 2006, there has been greater emphasis on the biomechanical and physiological performances of swimmers with limb absence. These have highlighted that swimming with limb absence is distinctly different from those of able-bodied swimmers.

The general nature of publication has also seen a small but increasing level of interest in *competitive* swimming with an amputation. This trend reflects those reported in other sports such as running¹⁷ or those in cycling.¹⁸ Four studies specifically examined elite level participation.^{19–22} One study subsequently attempted to compare this against the able-bodied equivalent.¹⁹ However, whilst both athletic groups do swim competitively, one of these was a triathlete group which, as a sport, also comprises two other sporting disciplines thereby making it a related, yet not comparable sport. The physiology and training load of a World Champion para-triathlete have also been profiled as a case study.²⁰ It was suggested that despite their level of success in sport with a disability, it demonstrated that training volume for each of the three disciplines was lower than the able-bodied equivalent. The remaining two papers involved the study of elite athletes and these originated from the same authors. These studies investigated the daily heart rate variability of Paralympic

medallists over an 18-day²¹ and 17-week duration.²² They disclosed that daily heart rate variability existed^{21,22} and was directly affected by the level and type of amputation²¹ or disability²² that an athlete possessed. However, this conclusion is tentative when the longer duration study only had a sample of two amputees,²² although the shorter duration study tested five.²¹

The focus for any proposed prosthetic solutions have concentrated on lower limb absence. Conversely, the physiological evaluations of limb absent swimmers have focused almost exclusively on elbow disarticulation and without the use of prostheses. It is also unclear why there is limited investigation into the contribution of the lower limbs when the swimmers use of their legs has been remarked as useful for both propulsion and the maintenance of their positional equilibrium in the water.¹⁶

Unlike those typically evident in running with an amputation,¹⁷ limb absent swimming evidence has conversely seen predominately the testing of female participants.^{23–31} Whilst the age of the participants is not always specified, two studies in particular have evaluated an adolescent participant³⁰ or a mix of adolescents and young adults.³¹

Only those people with unilateral upper limb absence were typically identified in this review. Whilst some studies note the swimming characteristics of those with bilateral lower-limb absence,¹⁴ no study to date has investigated the biomechanical function of those with bilateral upper or lower limb absence. This might well be due to the limited number of participants being available.

Table 2. Summary of reviewed papers.

Literature	Study type	Aims	Number of participants	Summary
La Blanc ¹³	Prosthesis development	To develop a below-knee prosthesis to be used in water.	n/a	A proposed form of prosthetic technology using buoyance adjustment is recommended for use by those with below knee levels of absence in a wet environment.
Saadah ¹⁴	Lower limb prostheses development	To develop prosthetic limbs for swimming for both unilateral and bi-lateral amputees.	2	Two devices are proposed. (1) A flipper-based design is riveted to a polymer socket. (2) Socket devices to assist a bi-lateral amputee swimmer to walk on the poolside.
Summerford ¹⁵	Product or prosthesis development	To develop prostheses and equipment to allow those with quadruple limb absence to enjoy leisure swimming.	n/a	A fin-based design solution is offered for people with limb absence.
Mujika et al. ²⁰	Research article	A case study of an elite, world champion Para-triathlete.	1	An examination of the physiology and training load of a male elite male Para-triathlete. The athlete had produced excellent improvements from their physiological starting point but their training volume in general was lower than competitive able-bodied Olympic distance triathletes.
Edmonds et al. ²¹	Research article	Evaluation of heart rate variability of elite swimmers with a disability at an 18-day staging camp.	6	Weekly training volume was reduced. Day-to-day heart rate variability was influenced and exhibited a similar trend. However, those with a neuromuscular impairment did not follow this trend.
Edmonds et al. ²²	Research article	Evaluation of heart rate variability of swimmers with a disability over 17 weeks.	3	Heart rate variability varied massively over the assessed time period. However, the athletes swimming classification and the type/level of disability also influenced heart rate variability.
Payton and Wilcox ²³	Research article	Assessment of recreational swimmers with an upper arm absence and their subsequent velocity during the multiple phases of the front crawl swim stroke.	8	Swimmers had greater peak speed using their sound limb side during the push phase. However, the amputated side also was able to contribute to the stroke, even if it were less effective.
Lecrivain et al. ²⁴	Research article	A female with elbow disarticulation is laser scanned and then created as a computerised simulation performing front crawl. The forces acting upon the arm action is simulated.	1	The use of reverse engineering and computerised fluid dynamics successfully generated the simulated amputee swimming model.

(continued)

Table 2. Continued

Literature	Study type	Aims	Number of participants	Summary
Lecrivain et al. ²⁵	Research article	Body roll amplitude and propulsive actions of a female with elbow disarticulation are assessed via computerised simulation.	1	Body roll significantly increases the propulsive contribution from the residual upper arm.
Osborough et al. ²⁶	Research article	Ascertaining the relationship between front crawl stroke length, stroke frequency and swimming speed of mid elbow male and female unilateral amputees.	13	Stroke frequency is directly related to swimming speed but stroke length is not. Correlations exist between several anthropometric measurements and swim speed and stroke frequency.
Osborough et al. ²⁷	Research article	Comparing the behaviour of both sound and amputated side arms by male and female swimmers when performing front crawl.	13	The function of sound and amputated side arms amputated and non-amputated arms differed significantly from each other in terms of duration and behaviour during four identified phases of front crawl swimming.
Osborough et al. ²⁸	Research article	Ascertaining the impact of swimming speed upon inter-arm coordination performed by both males and females with unilateral elbow disarticulation.	13	Inter-arm coordination was not affected by swimming speed. High stroke frequency dictated swimming speed, and this was dictated by the length of time the amputated side residual limb remained in a stationary position in front of the body.
Payton et al. ²⁹	Research article	Quantification of buoyant torque and its impact on body roll experienced by female front crawl swimmers with unilateral absence.	6	Asymmetrical behaviour of body roll was witnessed. Swimmers used mechanisms other than buoyant torque to generate and control body roll.
Figueiredo et al. ³⁰	Research article	Examination of swimming speed and subsequent physiological response of an adolescent female with upper limb amputation.	1	Inter-arm coordination was different from those reported with able-bodied swimmers with increasing swimming speeds.
Jane-Lee et al. ³¹	Research article	Comparison of tethering force and stroke parameters between female able bodies and upper limb absent swimmers.	18 (9 people with amputation)	Able-bodied participants produced higher tether forces than the clinical group. Faster technique decline was also observed in the clinical group.
Gailey and Harsch ³²	Clinicians report	Introducing the needs and solutions for amputees wishing to participate in triathlon.	n/a	Use of crutches is recommended to enter the water environment. Water resistant prostheses are useful to help with the logistics of the race environment.
Colombo et al. ³³	Prosthesis development	Design of a dual purpose prosthesis for both walking and swimming.	n/a	A finite element computer simulation for both walking and swimming is validated.

(continued)

Table 2. Continued

Literature	Study type	Aims	Number of participants	Summary
Nakashima et al. ³⁴	Lower limb prosthesis development	Design of a dual purpose prosthesis for both walking and swimming by a swimmer with a transfemoral limb absence.	1	A proposed design was experimentally simulated and validated by a participant with improvements in their swimming ability and comfort.
Yoneyama and Nakashima ³⁵	Prostheses development	A swimming upper arm prostheses for use when specifically performing front crawl is developed.	n/a	The prostheses design was determined based on initial simulations, prototyped and validated using a preliminary examination.
Hanspal and Niveen ³⁶	Research article	Obtaining consensus (using the Delphi technique) for the needs, design and supply of prosthetic limbs used in water-based environments.	40	Swimming was the not the main need for design in this case. Consensus on supply indications is obtained by the panel. In conclusion, water activity prosthetic limb supply was recommended based on a three-point framework.
Osborough et al. ³⁷	Research article	Comparing the behaviour of leg to arm coordination by male and female swimmers with amputations when performing front crawl.	13	Due to their disability, swimmers with arm amputations functionally adapt their leg to arm limb timing and motor organisation to perform front crawl.
Martin ³⁸	Research article	Use of the athletics identity measurement scale to psychologically assess athletes with a disability identity.	10	A four-factor framework of identity, applied to disability athletes supported earlier work applied to able-bodied athletes in a previous study.
Hill et al. ³⁹	Review article	An overview of assistive technology that is available for athletes with mobility conditions (notably amputees).	n/a	The implications of athletes using such technology are raised and a quantitative comparison to demonstrate a clear difference between amputees and non-amputees is undertaken.

Many of the selected studies in this review typically used a case study approach or utilised a low number of participants of less than five.^{13–15,19,20,24,30,32–35} Only 10 included studies used a participation pool greater than five.^{23,26–29,31,36–38} However, four of these studies indicate that the participant population number and type were identical.^{26,27,28,37} In these studies, it is likely that the same participation pool of 13 people were used across several empirical studies. This caveat can make findings limited in scope if they are intended to be applied to a wider population. It should also be noted that one author has contributed significantly to this field of study with co-authorship of nine of the recorded 24 results in this review.

Four clearly defined themes emerged during this review. The first, third and fourth directly addressed aim one of this paper, whereas the second addressed aim two. These themes are proposed as:

- Setting the context of swimming with limb absence.
- Lower limb prosthesis development.
- Swimmers with limb absence performing the front crawl swim stroke.
- The swimming technique of those with unilateral elbow disarticulation

Setting the context of swimming with limb absence

Swimming is a desirable pastime by those who possess limb absence.³⁶ This activity is also pursued within competitive environments.^{32,38} Prosthetic limbs may be requested by those wishing to swim³⁶ but they are not always essential.³² The case for sourcing or prescribing specific swimming prostheses has to be evidence based, awarded on merit and not merely issued on account of product availability.³⁶ The supply of any specialised water-based prostheses by rehabilitation professionals has been proposed as using three prescriptive levels of importance and that every source centre should have a written policy clarifying such issue.³⁶ However, it is important to note that beyond the mere functionality or performance of swimming-specific prostheses, exclusivity, self-identity, social identity and negative affectivity are all of relevance to limb absent swimmers.³⁸ Whilst this proposition was derived exclusively from athletes, such considerations may well be of relevance to any person wishing to pursue recreational swimming or by those intending to design adaptive technology for them.

Development of lower limb prostheses

It has been possible to create functional below the knee level prostheses for swimming that are either water

resistant^{13,32} or are specifically tailored to generate propulsion in water.^{14,39} However, it has also been suggested to not only consider the act of swimming but also transit to (and from) the location of the body of water itself. This has been achieved with a dual purpose prosthesis,^{33,34} two separate prostheses designs¹⁴ or no prosthesis at all but with the recommended alternative of crutches or a wheelchair.²⁸ Whilst dual purpose prostheses could suggest a functional compromise, this has been minimised in the case of a design solution for a swimmer with a transfemoral amputation.³⁴ In this case, by using either the forces evident in swimming when performing a flutter kick, it allows the foot to pivot at the ankle (but not at the knee) and thereby maximise its propulsive properties and minimise its hydrodynamic drag. The ankle range of motion was limited to a range between the foot being fully dorsiflexed and plantarflexed. The use of an extension coiled spring in the ankle region provided a tuneable adjustment to the motion and stiffness of the foot motion when in the water, as it performs the downward motion of the limb when performing the flutter kick and this affected the performance of the swimmer. Whilst the devices swimming performance could be improved through further reduction of hydrodynamic drag, more effective propulsion or an increase in buoyancy, it provides a prosthesis which possesses a 'natural' appearance³⁴ when in use either in or out of the water. A simpler dual purpose solution has also been to use a limb that does not allow dynamic movement at a joint but instead utilises a prosthesis that locks the prosthetic foot in either plantar flexion or a dorsiflexed position and this is then manually adjusted when entering or swimming in the body of water³² such as in a competitive triathlon. However, it is important to note that in most competitive pool swimming, the use of prostheses is currently illegal, but the development of such technology for recreational should still be of interest.³⁵ With this in mind, when swimming for recreation, the solutions can therefore be less restrictive and therefore in-water prostheses propulsion has been maximised through the use of fins or flippers. The size, orientation and position of these should be carefully considered to avoid contact with the sound limb.¹⁴

Whereas other designs utilise a conventional silicon liner and thermos plastic socket,³⁴ an older design did not¹⁴ and merely attached an acrylic socket to the fin. However, this example is now nearly 25 years old. Whilst the fit of the prostheses to the residual limbs stump has not been specifically investigated when swimming, conventional socket liners can be used, and neoprene (typically used in the watersports industry as a material for wetsuits) has been recommended as a method of securing the prostheses socket to the stump.¹⁴

Swimmers with limb absence performing the front crawl swim stroke

In swimming generally, the stroke used to perform it can vary. To date, the front crawl stroke has been the only method of swimming propulsion that has been investigated.^{19,23–31,37} Aside from limb absence (and any resultant compensation strategies), no fundamental difficulties in performing the stroke have been reported for those with limb absence. However, all reported studies to date focus almost exclusively on unilateral elbow disarticulation. It is not known how technique would be influenced by other amputation types or multiple limb absences. However, it has been demonstrated that the level and type of amputation would affect the daily heart rate variability of swimmers.^{21,22}

Ultimately, it is suggested that the best way for a person to improve their swimming ability is by joining a conventional community swimming programme.³² However, more recent evidence suggests that the technique to generate increased swimming speed is different between able-bodied and those who have upper limb absence.²⁵ In addition, swimmers with limb absence have been shown to produce lower forces when tethered when sprinting over short durations when compared to able-bodied swimmers.³¹ Therefore, it is proposed that whilst conventional swimming environments might well be appropriate, there will be subtle nuances and differences in technique, attainable training volume and coaching methods, if maximal swimming performance is the ultimate goal.

The swimming technique of those with unilateral elbow disarticulation

Whereas able-bodied swimmers can encounter resistive drag of their upper arm during propulsion,¹⁶ people with upper limb absence can still use their residual limbs to generate effective propulsion through their limb's conventional stroke rotation.^{24,31} They can also create positive propulsion during the 'push' phase²³ but not towards the end of the 'pull' phase.²⁵ The timing of such phases is different between the sound and amputated limbs^{28,30,31} and vary based on the swimmers speed²⁸ even if the overall pull and recovery times have been shown to not change with an increase in speed.³⁷ The stroke rate when performing a 30-s maximal effort has been demonstrated to be similar between swimmers who are able-bodied and those who possess an arm amputation. However, when the point of fatigue is reached, those with a limb amputation see their stroke rate degrade faster.³¹ Upper limb absence elicits the use of coordinated compensation strategies to

maintain the stable repetition of the overall arm cycle behaviour^{27,28,30,31,37} and notably at the point of fatigue.³¹ Nonetheless, due to this asymmetry, a swimmer can be subjected to a $35 \pm 5\%$ intracyclic fluctuation in swimming speed.²³ This imbalance is potentially due to the absent hand and forearm that would ultimately produce major propulsive forces in swimming.²⁴ It should be noted that the case study nature and the occasional use of computer simulation tools to simulate the forces involved²⁵ may overestimate or underestimate any specific imbalances. For example, some simulated studies have used limited degrees of freedom of the arm action when simulating a swimmers arm.²⁴ Despite the limitations of such techniques, the general declaration of such reported imbalances is a consistently held view across multiple studies using different approaches. This suggests that an absent arm is still of positive impact to swimming front crawl³¹ but that an affected limb contributes less to swimming speed than the unaffected arm. As a result, the resultant swim speed is lower for people with arm absence than it is for able-bodied participants^{26,31} with lower tethered force production over short distances.³¹ Likewise, further asymmetry has been evident in the arm-to-arm phases in those with single-arm amputation but not in their kicking phases.³⁷ In this case, a six beat kick is recommended for performance.³⁷ In general though, the differences between athletes who are able-bodied and those possessing some level of limb absence is also reflected competitively, whereby the 100 m world record times (as of 2012) were 15–20% slower than when compared to able-bodied times.³¹

The relationship between swim speed, stroke length and stroke frequency with an upper-arm level of absence can exhibit the same basic characteristics as able-bodied swimming.²⁶ The overall participant swimming speeds (as a result of adjustment in these parameters) have been shown to vary between studies,^{23,26} but this may have been affected by an inconsistent approach by researchers to allow (or disallow) the use of a contributory leg kick for propulsion.²⁶ It is also speculated that if the residual limb does contribute to any propulsive forces, any variation in speed would also be as a consequence of the variation in the level of impairment (such as stump length) between the participants. Either way, several studies have agreed that stroke frequency and not stroke length is the influencing factor in swimming speed performed by those with some level of arm absence.^{27,30} This influences swim velocity and is typically irrespective of gender and anthropometric variation.²⁶ However, when swimming at high speeds, this is predominantly influenced by the length of time the residual limb is held in a stationary position in front of the body.²⁸ Therefore, it may help

swimmers improve further by reducing this delay so as to allow the swimmer to increase their stroke frequency and then ultimately their speed.

The impact of body roll (rotation) during the stroke has also been demonstrated to positively affect the propulsive forces of an arm absent swimmer.²⁵ The angle of this body roll has been demonstrated to exhibit asymmetrical behaviour varying from $41 \pm 8^\circ$ of the shoulder and $30 \pm 5^\circ$ of the hip (on the unaffected arm) to $32 \pm 6^\circ$ of the shoulder and $23 \pm 6^\circ$ (of the affected arm).²⁹ However, the buoyant torque (postulated to be solely responsible for body roll behaviour) was proposed to not be the only control mechanism for this roll.²⁹

Ultimately, literature regarding swimming with an amputation is in a state of relative infancy, but this review revealed four clearly defined themes. From these, it is felt that a further four themes would build directly on the material identified in this review in the future. These include:

- the further refinement of prosthetic technology to allow an increased level of participation in recreational swimming.
- an increased understanding of swimming using the front crawl stroke when possessing other levels (or types) of limb absence.
- an increased understanding of the front crawl stroke when performed specifically by competitive or elite swimmers with limb absence.
- an assessment of participants with limb absence using a swim stroke other than front crawl.

Conclusion

The aims of this paper were to review swimming when possessing limb absence as a form of locomotion and to review the use of any technology which is employed to help facilitate swimming with limb absence. Five bibliographic databases were used to systematically identify peer reviewed literature that met these aims by using a modified PRISMA search protocol. Twenty-four publications, dating from 1983 to 2015, were subsequently identified. From these, four clear themes emerged. These include a general context of swimming with limb absence, the development of lower limb prostheses technology, swimming with limb absence whilst performing the front crawl swim stroke and the swimming technique of those with unilateral elbow disarticulation. As a result, four immediate research opportunities were identified that would build on these themes. As it stands, this review assists practitioners who are interested in prescribing swimming as a form of exercise or to those engaging with those who wish to pursue it competitively.

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Guarantor

The guarantor is the lead author (B Dyer) (BD).

Contributorship

BD researched the literature and both BD and SD conceived the study and conducted the review analysis. BD gained the ethical approval. BD wrote the first draft of the manuscript. All authors reviewed and edited the manuscript and approved the final version of the manuscript.

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