Laboratory-based ergometry for swimmers: a narrative review

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INTRODUCTION: First widely available dry-land training machines for swimmers were introduced about 40 years ago. They were designed so that swimmers could perform resistance exercise whilst more-closely replicating the movements of swimming, than when using other gymnasium-based resistance training machines. This narrative review categorises and summarises what has been shown by the studies that have utilised laboratory-based ergometry for swimmers.

EVIDENCE ACQUISITION: A systematic search was conducted in PubMed, Web of Science, ScienceDirect and Scopus (1970-2018) and relevant publications were included. Publications were grouped into 4 main areas of research: (i) physiological responses to exercise, (ii) functional evaluation of swimmers, (iii) monitoring of training, and (iv) muscular work output of swimmers.

EVIDENCE SYNTHESIS: Significant differences were showed between swim bench exercise and real swimming, especially in regard to the muscles involved. The difficulties of accurate reproduction of the movements and coordinated dynamic actions of swimming have not been overcome. Nevertheless, the literature shows that the use of these devices has provided a valuable contribution to swimming physiology, while overcoming difficulties presented by attempting to make physiological measurements in the water.

CONCLUSIONS:

In spite of its limitations, laboratory-based ergometry has allowed a valuable contribution to the understanding of the physiology, effects of training and efficiency of swimming.

Key words: swimming training machines; arm pull; power output; swimming power

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Introduction

Early swimming training machines or ‘swim benches’ (SBs) were designed to improve the effectiveness of land training for swimmers. The SB comprised a biokinetic dry-land exerciser that was specially-designed to fulfill the characteristics of swimming, i.e. accommodating resistance and replication of the front crawl arm stroke.[1] Subsequently, the SB was adapted and used in physiological assessment of swimmers.[2,3,4] Adaptations to the original SB machine included inbuilt force transducers to measure power output of the arms,[5] a leg-kicking ergometer for assessment of leg power output[6] and an integrated swimming machine for simultaneous assessment of arm and leg power output.[7] Shortly thereafter, swimming scientists began to use these resistance devices to explore physiological responses to this swimming-like exercise and thus the term ‘laboratory-based swimming ergometer’ (LBSE) emerged. The particular challenges of LBSE compared to other sports-specific ergometers are: (i) the prone exercising position; (ii) the simultaneous movement of the upper and lower body limbs; (iii) the simulation of the complex movements involved in the swimming action; and (iv) the absence of propulsion, drag, hydrostatic pressure and buoyancy involved in water-based exercise. Exercise in the prone position leads to adjustments in cardio-circulatory[8] and pulmonary[9] parameters that differ from exercise in a standing (e.g. treadmill and ski ergometer) or sitting (e.g. kayak, arm-crank, rowing and cycle ergometer) position. These adjustments occur naturally during swimming. However, on a SB, these functional adjustments in physiological parameters are hindered by chest compression that limits chest expansion. Inability to expand the chest during maximal exercise can cause higher ventilation rates and undue fatigue.[10] Chest compression also acts to restrict the gravitational outflow of the blood from the lower limbs (which would otherwise occur if the activity was conducted in an upright posture). Swimming is performed through a co-ordinated action of the upper and lower body limbs. Nevertheless, it is widely accepted that forward propulsion is mainly generated by the upper limbs, which has led many researchers to focus their investigations on arm movements only.[2,11,12] However, excluding the lower limbs from physiological measurement leads to an incomplete assessment of swimming energy demands. In addition, it has been shown that leg action requires intense muscular effort.[13] Simultaneous movement of the arms and legs in the laboratory was initially not possible until the 1990s when the first leg-kicking machine that reproduced the upward and downward kicking action of the legs in the laboratory was developed.[14] Later advances in LBSE technology culminated in the development of a whole-body simulated swimming machine that provides the closest replication of actual swimming on land.[7]

Most sport-specific ergometers (cycle ergometer, treadmill, rowing ergometer) are simple to use, require little technical expertise and can perfectly replicate the sporting movement (i.e. cycling and running). Swimming is a sport that involves the simultaneous complex co-ordination of the upper, lower body and trunk during exercise in the prone or supine position. Therefore, the simulation of the complex movements involved in the swimming action is difficult to replicate on a land-based ergometer. In any case, LBSE are designed to reproduce more complex motor tasks and cannot be utilized by novices with poor technical expertise in the simulated movement. Even a slight loss of co-ordination and movement timing can have a significant impact on propulsive efficiency and drag. Moreover, LBSE cannot correctly reproduce the forces produced by the muscles out of the water: the propulsion and the drag typical of the movement through water are

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conditions that cannot be reproduced on land.[15] Clearly, LBSE do not exactly replicate the swimming movements and their limited validity has been discussed in the literature.[16]

Performing exercise in an aquatic environment also presents several effects on cardiovascular and respiratory function that differ from when exercising on land.[17] As an example, the increase in hydrostatic pressure caused by the prone body posture acts to reduce lung vital capacity, heart rate, and increases stroke volume.[18,19,20] On land, there is no forward propulsion, drag, hydrostatic pressure and buoyancy which are distinctive features of water-based exercise. In addition, water immersion presents a challenge to human thermoregulation.[17] In water, the main mechanisms of heat transfer are conduction and convection. Conductive heat loss between skin and water is approximately 20 times higher than it is between skin and air on land[21]. Therefore, the body may lose heat rapidly when immersed in water especially at low water temperatures. Thus, water immersion has implications for performance, especially in endurance swimming, which clearly can affect the reproducibility of responses to simulated swimming using ergometers in the laboratory.

This narrative review aims to report and discuss the findings of a wide range of research studies that suggest that, despite its limitations, LBSE can be used in assessment of physiological responses to exercise and in functional evaluation of swimmers and other aquatic sport participants. The review will also discuss studies that have used LBSE as a swimming training tool and for planning and evaluating swimming training. Finally, the review will focus on discussing the possibility of assessing the muscular power output of swimmers using LBSE, in a way that reflects the muscular power generated by swimmers in water. Throughout, the review will include the scientific debate about the possibility of replicating the swimming movements in the laboratory. It will therefore, present a critical appraisal of ideas relating to the contribution of LBSE to knowledge and understanding of swimmers and swimming.

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Methods

A literature search was conducted in PubMed, Web of Science, ScienceDirect and Scopus (1970-2018). These databases were searched using the following keywords/combinations appearing in the title, abstract and keyword fields of the text: “swim-bench” OR “swimbench” OR “swim ergometer” OR “simulated swimming”. The *Journal of Swimming Research* was also targeted due to the volume of research studies included on the topic of land-based ergometry studies and relevant articles were selected for detailed evaluation. Full publications and all relevant researches were retrieved and reviewed carefully. Full publications and all relevant researches were retrieved and read carefully. The search included all studies published before May 2018.

The published works that were included were papers: i) with impact factor value; ii) involved participants with specific swimming-related skills (e.g. swimmers, triathletes and water polo players); and iii) written in English. Research that was not included was papers that: i) were duplicates acquired from multiple databases; and ii) involved subjects with non-specific swimming-related technical skills (e.g. non-swimmers and clinical patients). These inclusion and exclusion criteria were deemed appropriate and consistent with the purpose of the study, which was to consider the specific use of LBSE for assessment of swimmers and swimming in participants with proficient technical swimming skill.

A total of 615 studies were initially identified after the literature search (see Figure 1). Ten other studies were included from the *Journal of Swimming Research*. After title and abstract screening 580 were excluded and 45 were selected. Duplicates acquired from multiple databases were also excluded. Full publications and all relevant research were retrieved and reviewed carefully. Then, five studies where the participants did not have the capacity to perform a proficient swimming action were excluded. The resulting 40 papers were used for the following review and no new papers satisfying the above criteria were found. The researchers categorized the studies according to their aim and content as indicated in Figure 2. The results of the study categorization and their respective findings are shown in the following section.

****** Figure 1 near here ******

****** Figure 2 near here ******

Results

The 40 studies that resulted from the screening and inclusion/exclusion criteria were categorised according to their findings. Table 1 and Table 2 provide a summary of the publications relating to physiological responses and the measurement of power output, respectively, and includes information related to: (i) the participants involved in the study, (ii) the type of LBSE used (iii) the exercise features, (iv) the movements examined, and (v) the power output values.

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******Table 1 near here******

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Discussion

Physiological responses to swimming and LBSE

Studies investigating the physiological responses to LBSE showed at first that VO_{2peak} on the SB was 21.0% and 39.0% lower compared to front crawl swimming in a swimming flume or tethered, respectively.[22,23] Similar differences were also identified by Meerloo et al.[24] who postulated that both VO_{2max} and HR_{max} were significantly lower during LSBE exercise compared to tethered swimming. These differences could be explained by the lack of leg involvement in these early LBSE investigations. Later studies that used LBSE that incorporated the use of a leg-kicking ergometer reduced the difference in VO_2 to 10.0% between simulated swimming and actual full-stroke front crawl swimming.[6] This finding suggests that the differences in physiological responses between LBSE and water-based assessments are smaller when the lower body muscle groups are activated in conjunction with the upper body muscle groups. Furthermore, it might be the case that the 10.0% difference between LBSE and actual swimming when the full body is activated could be due to chest compression experienced by participants using LBSE (and is absent in the water). Chest compression, caused by the prone posture on LBSE limits ventilation during maximal exercise and hence, limits the VO_2 response.[10]

Measurement of physiological responses during actual swimming has been hindered by the complexities of available water-based assessment methods. LBSE has the main advantage that it is simpler to assess oxygen uptake, heart rate and blood lactate for given exercise intensities compared to assessments in water. Indeed, many water-based methods have enabled measurements of gas exchange and metabolic responses to swimming, but none of these methods can relate measurements to exercise intensity or power output of the limbs. LBSE has offered the possibility to relate physiological responses to exercise intensity, despite being originally introduced with aim of increasing the swimming-specific strength and power of swimmers during training.

Regarding the muscles involved, the ingestion or inhalation of supplement intended to increase physical performance could have a different effect between swimming performance and

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LSBE performance suggesting a different muscular demand between LSBE and actual swimming.[25,26,27,28] However, it was suggested that SB exercise appears to activate a considerable proportion of the musculature involved in swimming.[22] The activation of similar musculature involved in actual swimming is also supported by studies that compare LSBE exercise with stroke parameters: the modulation of the stroke rate during actual swimming and LSBE produces the same effect on VO_{2peak}..[10] Therefore, some of the mechanical movement patterns involved in the swimming action can be replicated during LSBE exercise. This notion was supported by the positive relationships found between the physiological responses during LSBE exercise and swimming performance, especially with middle distance swimming performance (400 m).[29] In addition, one study reported that LSBE exercise could reflect the specific local muscular adaptations that contribute significantly to improvements in VO_{2peak}.[22] Despite these findings that support the activation of similar musculature during LBSE and actual swimming, other authors argued that the muscles used in the two exercise forms were different (and lesser when using LSBE)

indicating that the maximal stress on the cardiorespiratory system was lower when using LSBE.[23] However, this study used a small sample of only six swimmers and did not take into account the limitations inherent in LBSE exercise i.e. chest compression and limitations of maximal ventilation. Another limiting factor for achieving similar VO_2 response and VO_{2max} during LBSE exercise compared to actual swimming is the arm movement pattern adopted on LBSE. Indeed, LBSE seems to offer a single-dimensional resistance, which is different to the three-dimensional resistance encountered in the water: according to Schleihauf[30] the recovery of the arm is performed as an ‘under-arm’ action, as opposed to ‘over-arm’ as in actual swimming. It is thought that ‘under-arm’ recovery alters the pattern of the swimming action on LBSE due to lack activation of those muscles involved in ‘over-arm’ recovery. Furthermore, the absence of body roll has also been reported as a limiting factor to involvement of the same upper body musculature during LBSE. Yanai[31] commented on the external torque forces associated with body roll and the additional demands imposed on the arms and the legs to generate sufficient amounts of fluid forces in non-propulsive directions during actual swimming. Body roll has only been possible in LBSE through the development of a whole-body LBSE. Previous versions of LBSE largely prevented body roll. Of course, any external torque forces are obviously absent during LBSE exercise.

Studies that have compared EMG data between actual swimming and LBSE have shown significant differences in timing, amplitude and frequency of muscle activity and there is a mis-match in the muscles activated in these exercise modes.[32] However, this work compared exercise

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using an arms-only LBSE and there have not been any similar studies comparing the more up-to-date whole-body LBSE which involves the simultaneous actions of the arms and legs. Perhaps, the introduction of simultaneous movement of the legs during arm movement would allow for a closer replication (and activation of musculature) of actual full-stroke swimming movement pattern.

In terms of metabolic responses to exercise, the blood lactate concentration and heart rate at the end of an arms-only test on an isokinetic LBSE were found to be similar to the end of a water polo game.[33] Also, similar values were found during whole-body LBSE and actual swimming when swimmers were compared to non-swimmers for lactate concentration[34] and stroke volume.[35] These findings support the idea of comparable physiological responses between actual swimming and LBSE, and supports the potential to detect the differences in physiological responses to exercise due to performance level, using LBSE. Conversely, Kalitsis et al.[36] showed significant differences in blood lactate concentration between a 100 m swimming test, a partially tethered swimming test and a biokinetic LBSE test, with the latter test producing the lowest lactate concentration values. However, the differences in Kalitsis et al's[36] study might, again, be explained by the lack of involvement of the lower body muscle groups during arms-only LBSE exercise compared to 100 m swimming and tethered swimming tests (full stroke involving arm and leg action).

In conclusion, the literature demonstrates a stronger relationship between the physiological parameters measured during LBSE exercise and actual swimming, when whole-body exercise is performed, rather than arms-only LBSE exercise. It may be that some physiological parameters measured during LBSE are lower compared to actual swimming. However, these differences can be explained by the chest compression, lack of body roll and external torque forces and particularly the lack of leg involvement in many LBSE investigations, which was mainly hindered by lack of a suitable ergometer to engage the leg action. More recently, an ergometer that engages both arms and legs has been developed. Therefore, LBSE seems to be a valid and reliable tool to investigate the physiological responses to exercise of the swimmer, also reflecting the changes in swimming proficiency associated with competitive swimming training.

The use of LBSE for functional evaluation of swimmers

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The issue of the LBSE as a model for the functional evaluation of swimmers has been widely studied and the effect on oxygen uptake is the main research topic. The mean results for maximal oxygen uptake when using LBSE exercise are consistently lower in age-group[37] and adult swimmers [38,39,40] when compared to the values achieved on the treadmill and cycle ergometer. However, the lower values for VO_2 achieved on the LBSE compared to the cycle ergometer and treadmill could be explained by the lower muscle mass involved in LBSE exercise (upper body muscle groups and mainly arms - compared to the larger muscle mass engaged in cycling and running). As pointed out by Swaine,[41] simulated swimming using LBSE is a more reliable type of exercise to assess functional parameters in swimmers compared to arm cranking exercise. In his study, the oxygen consumption, heart rate, and exercise intensity during exhaustive exercise were significantly different between LBSE and arm-cranking showing that LBSE simulates the movement pattern of actual swimming more closely compared to arm cranking.

Furthermore, LBSE is more suitable for assessment of the oxygen demand of the leg-kicking action of swimmers on land. Indeed, during a swimming simulation of the leg-kicking action on land, the oxygen demand is even higher than that required by the upper limbs. VO_2 was significantly higher (> 15 %) when using legs-only than with arms-only movements.[42] Moreover, the inefficient leg-kicking action and the large muscle masses involved, cause a high energy expenditure for the leg-kicking action which is associated with a low propelling efficiency, compared to the arm action.[43,44] For these reasons, some swimming scientists began to attempt to validate and design reliable ergometers to assess both the arm and leg action when using LBSE. The latest generation of LSBE permits the assessment of the power output of all limbs, and has shown that the power output of the legs is up to 40% higher than the arm power output during maximal intensity incremental exercise.[7]

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Some studies supported the validity of LSBE as an ergometer for functional evaluation of swimmers with more specificity than treadmill ergometers: Gergley et al.[22] investigated the specificity of aerobic training for upper-body exercise requiring differing amounts of muscle mass in swimmers. The findings support the idea of ‘specificity of aerobic improvement with training’ and suggest that local adaptations contribute significantly to improvements in VO_{2peak}. Furthermore, the results indicate that LBSE exercise activates a considerable proportion of the musculature involved in swimming and that aerobic improvements with LBSE training are directly transferred to swimming. With the aim to highlight the aerobic adaptations induced by training through the use of

LBSE, Konstantaki and Swaine[13] investigated movement economy and aerobic capacity after an arms-only swimming training program in competitive swimmers. More specifically, swimmers performed a six-week training program involving 20% of their swimming training in arms-only swimming. Using an incremental LBSE test, swimmers demonstrated lower aerobic cost, higher power output at ventilatory threshold and higher peak exercise intensity following arms-only swimming training compared to the control group. This study also showed that physiological adaptations to training can be detected by LBSE: in fact, high correlations between LBSE performance and the training load support the use of LBSE as a useful device for functional evaluation of swimmers.[45]

It is evident from the wide range of studies involving the leg-kicking and whole-body LBSE, that functional evaluation of swimmers is possible with LBSE. Despite the limitations on measuring the contribution of the legs, LBSE better replicates the natural swimming action compared to other available land ergometers, as it seems to engage most of the muscles activated in actual swimming.

The use of LBSE as swimming training and testing tool

Given that strength training, using dry-land regimens, may enhance the ability to produce higher propulsive forces in the water, especially in short distance events, the effects of LBSE exercise, for training purposes on land, has been widely investigated.[46] It has been generally accepted that LBSE training could generate a significant training overload for swimmers.[47] Conversely, it seems that neither training in water nor the time of the day at which training is performed, change the performance on LBSE[48]. Indeed, a leg-kicking swimming training programme does not affect leg-kicking performance during maximal simulated leg-kicking.[13]

In the belief that additional land-based training using a LBSE could aid swimmers in improving their swimming performance, several investigations employed LBSE training, in addition to, or alongside, swimming training. Significant improvements in sprint swimming performance (4.0%) after four weeks of LBSE training were reported in detrained swimmers.[2] Improvements in tethered swimming force and 400 m freestyle performance were also reported after 11 weeks of land-based training using a LBSE (2 x per week).[49] The improvements due to the LBSE training reported by these authors could be explained by the effects on VO_2 and power

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output: Sharp et al.[2] showed power output increases (19.0%) after four weeks of LBSE training in detrained swimmers; Gergley et al.[22] used 10 weeks of LBSE and actual swimming training and reported similar improvements in VO_{2peak} between LBSE training (21.0%) and in-water swimming training (19.0%) in recreational swimmers. Nevertheless, only one study supports the idea that LBSE resistance training does not improve swimming performance, although it was able to increase the resistance used during strength training by 25-35%.[50]

Changes in swimming performance with detraining have also been studied using LBSE exercise versus swimming: muscular strength on the LBSE does not diminish after four weeks of reduced training[51] and peak arm power output seemed to occur during the first and third week after the start of tapering.[52] The increased peak power output was explained as being possibly due to an increase in size, strength, velocity and power of the fast-twitch fibres, after the taper.[53] However, in one of the earliest training studies involving LBSE, Roberts et al.[4] showed no significant improvements in swimming performance in well-conditioned swimmers that used a period of training involving LBSE exercise in comparison to classic swimming training. These findings suggest that land-based training on a LBSE is effective in improving swimming-specific adaptation, which in turn translates into improved swimming performance. However, a longer training period may be needed to induce adaptations in maximal aerobic power, especially with well-conditioned swimmers.

The use of LBSE to assess the muscular work output

In relation to the issue of whether LBSE measurements of power output are related to swimming performance, research has presented conflicting evidence. Sharp et al.[2] found a close correlation between anaerobic power on a LBSE and sprint swimming performance, but two subsequent studies were not able to confirm this when analysing 25 m front crawl performance.[54,55] Hence, the studies of Bradshaw and Hoyle[54] and Johnson et al.[55] indicated that the power output measurements derived from LBSE testing are not a good predictor of sprint freestyle swimming performance. This lack of correlation with swimming performance could be explained also in this case by limitations inherent in engaging only the upper body muscle groups during early versions of LBSE exercise compared to actual swimming where the whole-body is involved in generating force and forward propulsion. Another factor may have been the inclusion of a large number of female

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and younger swimmers in Sharp et al's study[2] compared to the other two studies. These study particularities may have influenced the power-sprint relationship due to differences in muscle mass of the participants, which could in turn explain why the results were not comparable.

Moreover, the power output that is developed by the lower limbs seems to be higher than the upper limbs when using whole-body LBSE.[14,56,57] This is supported by the work of Cavanaugh and Musch[58] who reported higher leg power compared to arm power when measured using a leaper leg-strength machine, but higher leg-power output in comparison with studies that used whole-body LBSE. The lower power output achieved during whole-body exercise compared to the leaper leg-strength machine could be attributed to the differences in participating musculature and body position (simulated swimming in prone position versus leaper legs-only machine exercise in standing position). In support of this, more recently Swaine[14] reported that the legs could sustain greater power output than the arms during LBSE exercise (up to 40.0%) during 10 s of all-out exercise in highly-trained swimmers. These results are similar to those reported by Gatta et al.[57] in elite swimmers and Zamparo and Swaine[56] in well-trained swimmers.

Furthermore, since the differences in bilateral arm power can be assessed with LBSE as described by Swaine[59] and Potts et al.[60] it was possible to highlight an imbalance of about 8.0% between the left and right arm power output using an isokinetic LBSE.

The differences in power output can be attributed to different instruments used, differences in experimental design, level of training of the participants and the swimming techniques simulated.

Conclusions

Technical developments in the production of specific ergometers have certainly improved the accuracy and reliability of LBSE as an assessment tool over the past 40 years. However, the criticisms that have been made to the use of LBSE, which mainly concern the difficulties in reproducing the technical movements and the dynamic motor of the action of swimming, are difficult to overcome. LBSE was introduced with the aim to increase the swimming-specific strength and power of swimmers and it seems that these ergometers are useful as a training tool to increase swimming performance. However, there have been some studies that have shown no improvements in swimming performance following LBSE trainingThe strong relationship between physiological parameters measured during simulated dry-land and in-water swimming allow instead

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the use of this tool as a valid and reliable instrument to investigate the physiological parameters of the swimmer and monitor how these parameters change due to swimming or land-based training..

However, the swimmer must replicate the swimming stroke movements "in dry conditions" as closely as possible to the movement performed in the water (e.g. respecting the angles at the wrist, elbow and shoulder in the various phases of the arm-stroke work and recovery phases).

Even if the most recent LBSE could reproduce the swimming actions with good accuracy, there are still obvious limitations to simulation of the swimming action in the laboratory. These limitations refer to activation of different muscle groups, due to differences in movement kinematics, in comparison with actual swimming. The pulling path traveled by the hand on the LBSE is longer than in actual swimming; moreover, the forces are distributed differently in relation to the joint angles and limb trajectories. This change in stroke technique, would act to alter the movement pattern of the arm action during swim bench exercise. To further develop a land ergometer able to reproduce the swimming movements, the mechanical load of the water and the thrust direction of the swimmer's limbs would need to be taken into account. However, these are characteristics that are typically difficult to replicate in the laboratory, at least with existing technologies.

The literature presented conflicting evidence in relation to the relationship between LBSE measurements and swimming performance: the difficulty in finding a strong relationship between measured power output when using LBSE and swimming performance is probably due to the fact that the speed of swimming is determined by three different parameters: mechanical power, propulsive efficiency and drag. In tests using LBSE, only mechanical power is measured. This is in contrast to actual swimming where water properties such as propulsion, drag, hydrostatic pressure and buoyancy impact on the swimming action and contribute to propulsive efficiency and drag. To date, research work appears to have shown that the whole-body LBSE has the highest validity and is the most reliable type of simulation of swimming on land, which has been proposed in the literature to evaluate the swimmer's power output, despite the limitations of measuring the energetic contribution of the legs.

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NOTES

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

The authors give their contribution to the study as follows:

- Matteo CORTESI: Conception and design, or analysis and interpretation of data; drafting the article or revising it critically for important intellectual content; final approval of the version to be published.
- Giorgio GATTA: Conception and design, or analysis and interpretation of data; drafting the article or revising it critically for important intellectual content; final approval of the version to be published.
- Ian SWAINE: Conception and design, or analysis and interpretation of data; drafting the article or revising it critically for important intellectual content; final approval of the version to be published.
- Paola ZAMPARO: Conception and design, or analysis and interpretation of data; drafting the article or revising it critically for important intellectual content; final approval of the version to be published.
- Maria KONSTANTAKI: Conception and design, or analysis and interpretation of data; drafting the article or revising it critically for important intellectual content; final approval of the version to be published.

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TABLES

Table 1. Summary of research studies investigating the physiological responses to LBSE.

Study	**Swim Bench features**	**Exercise features**	**$VO2_{peak}$** ($ml•min^{-1}$)	**HLa_{peak}** ($mmol•l^{-1}$)	**VE_{peak}** ($l•min^{-1}$)	**HR_{peak}** ($beats•min^{-1}$)	**R_{peak}**	**Number and level of participants**	**Swim Bench movement**
Armstrong et al, 1981	Biokinetic swim bench, only arms	Discontinuous incremental arm test to exhaustion	44.5 ± 4.1 • kg^{-1}					13 (male) pubertal and competitive swimmers	Front crawl
Gergley et al, 1984	Biokinetic swim bench, only arms	Discontinuous incremental arm test to exhaustion	2211 ± 452		86.2 ± 21.0	179.8 ± 11.5	1.05 ± 0.05	9 (male) recreational swimmers	Front crawl
Kimura et al, 1990	Arm cranking, stretch cord for legs	Discontinuous incremental test to exhaustion	3600 ± 300		103.7 ± 16.6	192.5 ± 6.1	0.92 ± 0.14	11 (male) collegiate swimmers	Arm cranking
Konstantaki et al, 1998	Isokinetic swim bench, only arms	Discontinuous incremental arm test to exhaustion		5.08 ± 0.2		146.0 ± 6.0		8 (female) water polo players	Front crawl
Konstantaki et al, 1999	Isokinetic swim bench for arms and Isokinetik swim bench for legs	Incremental test to exhaustion	3000 ± 100 arms 3700 ± 100 legs	7.00 ± 0.2 arms 5.60 ± 0.6 legs				16 (male) collegiate and recreational swimmers	Front crawl
Konstantaki et al, 2004	Swim bench for arms and swim bench for legs	Incremental test to exhaustion	3690 ± 200 whole, 3220 ± 400 arms, 3150 ± 500 legs					9 (4 male - 5 female) trained swimmers	Front crawl
Konstantaki et al, 2007	Swim bench for legs	Incremental test to exhaustion	2610 ± 400					15 (male) competitive swimmers	Flutter kick
Merloo et al, 1988	Biokinetic swim bench, only arms	Incremental test to exhaustion	2790 ± 600			172.0 ± 2.0	1.10 ± 0.20	13 (8 male - 5 female) elite swimmers	Front crawl
Ogita et al, 1995	Biokinetic swim bench, only arms	3 min constant exercise	2130 ± 250	8.50 ± 2.2	99.9 ± 14.2	162.0 ± 10.0	1.29 ± 0.10	8 (male) trained swimmers	Front crawl
Oliver et al, 1989	Biokinetic swim bench, only arms	3repeats of 60s all out	26.8 ± 1.0 • kg^{-1}	7.60 ± 0.5	76.2 ± 3.8	180.7 ± 4.2	1.29 ± 0.10	22 (male) elite and collegiate swimmers	Front crawl
Rowland et al, 2009	Biokinetic swim bench, only arms	Progressive exercise test to exhaustion	23.2 ± 4.1 • kg^{-1}			172.0 ± 15.0	1.03 ± 0.08	14 (7 male - 7 female) prepubertal swimmers	Butterfly
Sexsmith et al, 1992	Biokinetic swim bench, only arms	3repeats of 60s all out	26.8 ± 1.0 • kg^{-1}	7.60 ± 0.5	76.2 ± 3.8	180.7 ± 4.2		22 (male) elite swimmers	Front crawl
Swaine et al, 1983	Biokinetic swim	Incremental test to	2550 ± 350			150.0 ± 9.0		7 (5 male - 2 female) club	Front crawl

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	bench, only arms	exhaustion						swimmers	
Swaine, 1994	Biokinetic swim bench, only arms	Continuous incremental test to exhaustion	3300 ± 400			182.0 ± 8.0	1.13 ± 0.03	9 (male) high performance front crawl swimmers	Front crawl
Swaine et al, 1999	Biokinetic swim bench, only arms (SB). Arm cranking (AC)	Incremental exercise test to exhaustion	2900 ± 200 for SB, 2400 ± 100 for AC		112.4 ± 12.3 for SB, 88.9 ± 10.7 for AC	174.0 ± 2.0 for SB, 171.0 ± 2.0 for AC		25 (male) competitive swimmers	Front crawl
Swaine et al, 2010	Whole-body swimming ergometer	Incremental exercise test to exhaustion	3680 ± 650			177.7 ± 6.6		8 (male) trained swimmers	Front crawl
Zamparo et al, 2012	Whole-body swimming ergometer	Continuous incremental exercise test to exhaustion	4490 ± 170		132.0 ± 12.0	185.4 ± 4.0	1.03 ± 0.01	10 (male) trained swimmers	Front crawl

Table 2. Summary of research studies investigating the use of LBSE in assessment of muscular power output.

Study	Swim Bench features	Exercise features	Mean Power Output (W)	Peak Power (W)	Number and level of participants	Swim Bench movement
Cavanaugh et al, 1989	Biokinetic swim bench for arms Leaper leg machine for legs	90 s all out	229 ± 28 arms 538 ± 86 legs		25 (male) elite swimmers	Butterfly
Ganter et al, 2007	Biokinetic swim bench, only arms	30 s all out	120.3 ± 5.4		10 (4 male - 6 female) elite and junior swimmers	Butterfly
Kalsen et al, 2013	Technogym cable cross over apparatus, only arms	Incremental exercise test of 3 pulls	347.1 ± 72.8		20 (8 male - 12 female) trained swimmers	Front crawl
Konstantaki et al, 1998	Isokinetic swim bench, only arms	Discontinuous incremental arm test to exhaustion		79.0 ± 5.2	8 (female) water polo players	Front crawl
Konstantaki et al, 1999	Isokinetic swim bench for arms and Isokinetik swim bench for legs	Incremental test to exhaustion		114.0 ± 6.0	16 (male) collegiate and recreational swimmers	Front crawl
Reilly et al, 1991	Biokinetic swim bench, only arms	30 s all out	65.2 ± 27.1	73.8 ± 24.7	14 (7 male - 7 female) competent swimmers	Butterfly
Sexsmith et al, 1992	Biokinetic swim bench, only arms	60s all out	57.8 ± 3.2		22 (male) elite swimmers	Butterfly
Sharp et al, 1982	Biokinetic swim bench, only arms		211.7 ± 16.9		40 (18 male - 22 female) competitive swimmers	Butterfly
Sperlich et al, 2011	Isokinetic swim bench, only arms	3 trials of 50s all out	222.8 ± 41.9	298.5 ± 52.1	12 (male) elite swimmers	Butterfly
Swaine, 1994	Biokinetic swim bench, only arms	Continuous incremental test to exhaustion		149.6 ± 17.1	9 (male) high performance front crawl swimmers	Front crawl
Swaine, 1997	Swim bench for arms and swim bench for legs	Incremental exercise test		124.2 ± 9.4 arms 141.3 ± 12.7	12 (male) highly-trained swimmers	Front crawl

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			legs		
Swaine, 1997	Isokinetic swim bench, only arms	30 s all out	179.0 ± 21.9 non-injured arm 111.3 ± 18.1 injured arm	13 (5 male - 8 female) competitive swimmers	Front crawl
Tanaka et al, 1993	Biokinetic swim bench, only arms	3 maximal pulls	197.05 ± 7.5	24 (male) collegiate swimmers	Butterfly
Trappe et al, 2000	Biokinetic swim bench, only arms	4 maximal pulls	225.0 ± 10.0	6 (male) highly trained collegiate swimmers	Butterfly
Trinity et al, 2006	Arm crancking	3-5 s of maximal effort	699.0 ± 27.0	24 (male)competitive collegiate swimmers	Arm crancking
Zamparo et al, 2012	Whole-body swimming ergometer	Incremental exercise test	437.0 ± 8.0	10 (male) well trained swimmers	Front crawl

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TITLES OF FIGURES

Figure 1. Flow chart of the literature search.

Figure 2. A schematic to show the categories of SB study topics in current literature.

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Laboratory-based ergometry for swimmers: a narrative review

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INTRODUCTION: The first widely-available dry-land training machines for swimmers were introduced about 40 years ago. They were designed so that swimmers could perform resistance exercise whilst more-closely replicating the movements of swimming, than when using other gymnasium-based resistance training machines. These machines were subsequently adapted and used as measurement tools (ergometers) in an array swimming research studies. This narrative review categorises and summarises what has been shown by the research studies that have utilised this laboratory-based ergometry.

EVIDENCE ACQUISITION: A search was conducted in PubMed, Web of Science, ScienceDirect and Scopus (1970-2018) and relevant publications were included. Publications were grouped into 4 main areas of research: (i) physiological responses to exercise, (ii) functional evaluation of swimmers, (iii) monitoring of training, and (iv) muscular work output of swimmers.

EVIDENCE SYNTHESIS: Significant differences were showed between swim bench exercise and real swimming, especially in regard to the muscles involved. The difficulties of accurate reproduction of the movements and coordinated dynamic actions of swimming have not been overcome. Nevertheless, the literature shows that the use of these devices has provided a valuable contribution to swimming physiology, while overcoming difficulties presented by attempting to make physiological measurements in the water.

CONCLUSIONS: In spite of its limitations, laboratory-based ergometry has allowed a valuable contribution to the understanding of the physiology, effects of training and efficiency of swimming.

Key words: swimming training machines; arm pull; power output; swimming power

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Introduction

Early swimming training machines or ‘swim benches’ (SBs) were designed to improve the effectiveness of land training for swimmers. The SB comprised a biokinetic dry-land exerciser that was specially-designed to fulfill the characteristics of swimming, i.e. accommodating resistance and replication of the front crawl arm stroke.[1] Subsequently, the SB was adapted and used in physiological assessment of swimmers.[2,3,4] Adaptations to the original SB machine included inbuilt force transducers to measure power output of the arms,[5] a leg-kicking ergometer for assessment of leg power output[6] and an integrated swimming machine for simultaneous assessment of arm and leg power output.[7] Shortly thereafter, swimming scientists began to use these resistance devices to explore physiological responses to this swimming-like exercise and thus the term laboratory-based swimming ergometer (LBSE) emerged. The particular challenges of LBSE compared to other sports-specific ergometers are: (i) the prone exercising position; (ii) the simultaneous movement of the upper and lower body limbs; (iii) the simulation of the complex movements involved in the swimming action; and (iv) the absence of propulsion, drag, hydrostatic pressure and buoyancy involved in water-based exercise.

Exercise in the prone position leads to adjustments in cardio-circulatory[8] and pulmonary[9] parameters that differ from exercise in a standing (e.g. treadmill and ski ergometer) or sitting (e.g. kayak, arm-crank, rowing and cycle ergometer) position. These adjustments occur naturally during swimming. However, on a SB, these functional adjustments in physiological parameters are hindered by chest compression that limits chest expansion. Inability to expand the chest during maximal exercise can cause higher ventilation rates and undue fatigue.[10] Chest compression also acts to restrict the gravitational outflow of the blood from the lower limbs (which would otherwise occur if the activity was conducted in an upright posture).

Swimming is performed through a co-ordinated action of the upper and lower body limbs. Nevertheless, it is widely accepted that forward propulsion is mainly generated by the upper limbs, which has led many researchers to focus their investigations on arm movements only.[2,11,12] However, excluding the lower limbs from physiological measurement leads to an incomplete assessment of swimming energy demands. In addition, it has been shown that leg action requires intense muscular effort.[13] Simultaneous movement of the arms and legs in the laboratory was initially not possible until the 1990s when the first leg-kicking machine that reproduced the upward and downward kicking action of the legs in the laboratory was developed.[14] Later advances in

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LBSE technology culminated in the development of a whole-body simulated swimming machine that provides the closest replication of actual swimming on land.[7]

Most sport-specific ergometers (cycle ergometer, treadmill, rowing ergometer) are simple to use, require little technical expertise and can perfectly replicate the sporting movement (i.e. cycling and running). Swimming is a sport that involves the simultaneous complex co-ordination of the upper, lower body and trunk during exercise in the prone or supine position. Therefore, the simulation of the complex movements involved in the swimming action is difficult to replicate on a land-based ergometer. In any case, LBSE are designed to reproduce more complex motor tasks and cannot be utilized by novices with poor technical expertise in the simulated movement. Even a slight loss of co-ordination and movement timing can have a significant impact on propulsive efficiency and drag. Moreover, LBSE cannot correctly reproduce the forces produced by the muscles out of the water: the propulsion and the drag typical of the movement through water are conditions that cannot be reproduced on land.[15] Clearly, LBSE do not exactly replicate the swimming movements and their limited validity has been discussed in the literature.[16]

Performing exercise in an aquatic environment also presents several effects on cardiovascular and respiratory function that differ from when exercising on land.[17] As an example, the increase in hydrostatic pressure caused by the prone body posture acts to reduce lung vital capacity, heart rate, and increases stroke volume.[18,19,20] On land, there is no forward propulsion, drag, hydrostatic pressure and buoyancy which are distinctive features of water-based exercise. In addition, water immersion presents a challenge to human thermoregulation.[17] In water, the main mechanisms of heat transfer are conduction and convection. Conductive heat loss between skin and water is approximately 20 times higher than it is between skin and air on land[21]. Therefore, the body may lose heat rapidly when immersed in water especially at low water temperatures. Thus, water immersion has implications for performance, especially in endurance swimming, which clearly can affect the reproducibility of responses to simulated swimming using ergometers in the laboratory.

This narrative review aims to report and discuss the findings of a wide range of research studies that suggest that, despite its limitations, LBSE can be used in assessment of physiological responses to exercise and in functional evaluation of swimmers and other aquatic sport participants. The review will also discuss studies that have used LBSE as a swimming training tool and for planning and evaluating swimming training. Finally, the review will focus on discussing the possibility of assessing the muscular power output of swimmers using LBSE, in a way that reflects the muscular power generated by swimmers in water. Throughout, the review will include the

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scientific debate about the possibility of replicating the swimming movements in the laboratory. It will therefore, present a critical appraisal of ideas relating to the contribution of LBSE to knowledge and understanding of swimmers and swimming.

Methods

A literature search was conducted involving PubMed, Web of Science, ScienceDirect and Scopus (1970-2018). These databases were searched using the following keywords/combinations appearing in the title, abstract and keyword fields of the text: “swim-bench” OR “swimbench” OR “swim ergometer” OR “simulated swimming”. The *Journal of Swimming Research* was also targeted due to the volume of research studies included on the topic of land-based ergometry studies and relevant articles were selected for detailed evaluation. Full publications and all relevant researches were retrieved and reviewed carefully. The search included all studies published before May 2018.

The published works that were included were papers: i) with impact factor value; ii) involved participants with specific swimming-related skills (e.g. swimmers, triathletes and water polo players); and iii) written in English. Research that was not included was papers that: i) were duplicates acquired from multiple databases; and ii) involved subjects with non-specific swimming-related technical skills (e.g. non-swimmers and clinical patients). These inclusion and exclusion criteria were deemed appropriate and consistent with the purpose of the study, which was to consider the specific use of LBSE for assessment of swimmers and swimming in participants with proficient technical swimming skill.

A total of 615 studies were initially identified after the literature search (see Figure 1). Ten other studies were included from the *Journal of Swimming Research*. After title and abstract screening 580 were excluded and 45 were selected. Duplicates acquired from multiple databases were also excluded. Full publications and all relevant research were retrieved and reviewed carefully. Then, five studies where the participants did not have the capacity to perform a proficient swimming action were excluded. The resulting 40 papers were used for the following review and no new papers satisfying the above criteria were found. The researchers categorized the studies according to their aim and content as indicated in Figure 2. The results of the study categorization and their respective findings are shown in the following section.

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****** Figure 1 near here ******

****** Figure 2 near here ******

Results

The 40 studies that resulted from the screening and inclusion/exclusion criteria were categorised according to their findings. Table 1 and Table 2 provide a summary of the publications relating to physiological responses and the measurement of power output, respectively, and includes information related to: (i) the participants involved in the study, (ii) the type of LBSE used (iii) the exercise features, (iv) the movements examined, and (v) the power output values.

******Table 1 near here******

******Table 2 near here******

Discussion

Physiological responses to swimming and LBSE

Studies investigating the physiological responses to LBSE showed at first that VO_{2peak} on the SB was 21.0% and 39.0% lower compared to front crawl swimming in a swimming flume or tethered, respectively.[22,23] Similar differences were also identified by Meerloo et al.[24] who postulated that both VO_{2max} and HR_{max} were significantly lower during LSBE exercise compared to tethered swimming. These differences could be explained by the lack of leg involvement in these early LBSE investigations. Later studies that used LBSE that incorporated the use of a leg-kicking ergometer reduced the difference in VO_2 to 10.0% between simulated swimming and actual full-stroke front crawl swimming.[6] This finding suggests that the differences in physiological responses between LBSE and water-based assessments are smaller when the lower body muscle groups are activated in conjunction with the upper body muscle groups. Furthermore, it might be the case that the 10.0% difference between LBSE and actual swimming when the full body is activated could be due to chest compression experienced by participants using LBSE (and is absent in the water).

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Chest compression, caused by the prone posture on LBSE limits ventilation during maximal exercise and hence, limits the VO_2 response.[10]

Measurement of physiological responses during actual swimming has been hindered by the complexities of available water-based assessment methods. LBSE has the main advantage that it is simpler to assess oxygen uptake, heart rate and blood lactate for given exercise intensities compared to assessments in water. Indeed, many water-based methods have enabled measurements of gas exchange and metabolic responses to swimming, but none of these methods can relate measurements to exercise intensity or power output of the limbs. LBSE has offered the possibility to relate physiological responses to exercise intensity, despite being originally introduced with aim of increasing the swimming-specific strength and power of swimmers during training.

Regarding the muscles involved, the ingestion or inhalation of supplement intended to increase physical performance could have a different effect between swimming performance and LSBE performance suggesting a different muscular demand between LSBE and actual swimming.[25,26,27,28] However, it was suggested that SB exercise appears to activate a considerable proportion of the musculature involved in swimming.[22] The activation of similar musculature involved in actual swimming is also supported by studies that compare LSBE exercise with stroke parameters: the modulation of the stroke rate during actual swimming and LSBE produces the same effect on VO_{2peak}..[10] Therefore, some of the mechanical movement patterns involved in the swimming action can be replicated during LSBE exercise. This notion was supported by the positive relationships found between the physiological responses during LSBE exercise and swimming performance, especially with middle distance swimming performance (400 m).[29] In addition, one study reported that LSBE exercise could reflect the specific local muscular adaptations that contribute significantly to improvements in VO_{2peak}.[22] Despite these findings that support the activation of similar musculature during LBSE and actual swimming, other authors argued that the muscles used in the two exercise forms were different (and lesser when using LSBE) indicating that the maximal stress on the cardiorespiratory system was lower when using LSBE.[23] However, this study used a small sample of only six swimmers and did not take into account the limitations inherent in LBSE exercise i.e. chest compression and limitations of maximal ventilation.

Another limiting factor for achieving similar VO_2 response and VO_{2max} during LBSE exercise compared to actual swimming is the arm movement pattern adopted on LBSE. Indeed, LBSE seems to offer a single-dimensional resistance, which is different to the three-dimensional resistance encountered in the water: according to Schleihauf[30] the recovery of the arm is performed

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as an 'under-arm' action, as opposed to 'over-arm' as in actual swimming. It is thought that 'under-arm' recovery alters the pattern of the swimming action on LBSE due to lack activation of those muscles involved in 'over-arm' recovery. Furthermore, the absence of body roll has also been reported as a limiting factor to involvement of the same upper body musculature during LBSE. Yanai[31] commented on the external torque forces associated with body roll and the additional demands imposed on the arms and the legs to generate sufficient amounts of fluid forces in non-propulsive directions during actual swimming. Body roll has only been possible in LBSE through the development of a whole-body LBSE. Previous versions of LBSE largely prevented body roll. Of course, any external torque forces are obviously absent during LBSE exercise.

Studies that have compared EMG data between actual swimming and LBSE have shown significant differences in timing, amplitude and frequency of muscle activity and there is a mis-match in the muscles activated in these exercise modes.[32] However, this work compared exercise using an arms-only LBSE and there have not been any similar studies comparing the more up-to-date whole-body LBSE which involves the simultaneous actions of the arms and legs. Perhaps, the introduction of simultaneous movement of the legs during arm movement would allow for a closer replication (and activation of musculature) of actual full-stroke swimming movement pattern.

In terms of metabolic responses to exercise, the blood lactate concentration and heart rate at the end of an arms-only test on an isokinetic LBSE were found to be similar to the end of a water polo game.[33] Also, similar values were found during whole-body LBSE and actual swimming when swimmers were compared to non-swimmers for lactate concentration[34] and stroke volume.[35] These findings support the idea of comparable physiological responses between actual swimming and LBSE, and supports the potential to detect the differences in physiological responses to exercise due to performance level, using LBSE. Conversely, Kalitsis et al.[36] showed significant differences in blood lactate concentration between a 100 m swimming test, a partially tethered swimming test and a biokinetic LBSE test, with the latter test producing the lowest lactate concentration values. However, the differences in Kalitsis et al's[36] study might, again, be explained by the lack of involvement of the lower body muscle groups during arms-only LBSE exercise compared to 100 m swimming and tethered swimming tests (full stroke involving arm and leg action).

In conclusion, the literature demonstrates a stronger relationship between the physiological parameters measured during LBSE exercise and actual swimming, when whole-body exercise is performed, rather than arms-only LBSE exercise. It may be that some physiological parameters measured during LBSE are lower compared to actual swimming. However, these differences can be

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explained by the chest compression, lack of body roll and external torque forces and particularly the lack of leg involvement in many LBSE investigations, which was mainly hindered by lack of a suitable ergometer to engage the leg action. More recently, an ergometer that engages both arms and legs has been developed. Therefore, LBSE seems to be a valid and reliable tool to investigate the physiological responses to exercise of the swimmer, also reflecting the changes in swimming proficiency associated with competitive swimming training.

The use of LBSE for functional evaluation of swimmers

The issue of the LBSE as a model for the functional evaluation of swimmers has been widely studied and the effect on oxygen uptake is the main research topic. The mean results for maximal oxygen uptake when using LBSE exercise are consistently lower in age-group[37] and adult swimmers [38,39,40] when compared to the values achieved on the treadmill and cycle ergometer. However, the lower values for VO_2 achieved on the LBSE compared to the cycle ergometer and treadmill could be explained by the lower muscle mass involved in LBSE exercise (upper body muscle groups and mainly arms - compared to the larger muscle mass engaged in cycling and running). As pointed out by Swaine,[41] simulated swimming using LBSE is a more reliable type of exercise to assess functional parameters in swimmers compared to arm cranking exercise. In his study, the oxygen consumption, heart rate, and exercise intensity during exhaustive exercise were significantly different between LBSE and arm-cranking showing that LBSE simulates the movement pattern of actual swimming more closely compared to arm cranking.

Furthermore, LBSE is more suitable for assessment of the oxygen demand of the leg-kicking action of swimmers on land. Indeed, during a swimming simulation of the leg-kicking action on land, the oxygen demand is even higher than that required by the upper limbs. VO_2 was significantly higher (> 15 %) when using legs-only than with arms-only movements.[42] Moreover, the inefficient leg-kicking action and the large muscle masses involved, cause a high energy expenditure for the leg-kicking action which is associated with a low propelling efficiency, compared to the arm action.[43,44] For these reasons, some swimming scientists began to attempt to validate and design reliable ergometers to assess both the arm and leg action when using LBSE. The latest generation of LSBE permits the assessment of the power output of all limbs, and has shown that the power output of the legs is up to 40% higher than the arm power output during maximal intensity incremental exercise.[7]

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Some studies supported the validity of LSBE as an ergometer for functional evaluation of swimmers with more specificity than treadmill ergometers: Gergley et al.[22] investigated the specificity of aerobic training for upper-body exercise requiring differing amounts of muscle mass in swimmers. The findings support the idea of 'specificity of aerobic improvement with training' and suggest that local adaptations contribute significantly to improvements in VO_{2peak}. Furthermore, the results indicate that LBSE exercise activates a considerable proportion of the musculature involved in swimming and that aerobic improvements with LBSE training are directly transferred to swimming. With the aim to highlight the aerobic adaptations induced by training through the use of LBSE, Konstantaki and Swaine[13] investigated movement economy and aerobic capacity after an arms-only swimming training program in competitive swimmers. More specifically, swimmers performed a six-week training program involving 20% of their swimming training in arms-only swimming. Using an incremental LBSE test, swimmers demonstrated lower aerobic cost, higher power output at ventilatory threshold and higher peak exercise intensity following arms-only swimming training compared to the control group. This study also showed that physiological adaptations to training can be detected by LBSE: in fact, high correlations between LBSE performance and the training load support the use of LBSE as a useful device for functional evaluation of swimmers.[45]

It is evident from the wide range of studies involving the leg-kicking and whole-body LBSE, that functional evaluation of swimmers is possible with LBSE. Despite the limitations on measuring the contribution of the legs, LBSE better replicates the natural swimming action compared to other available land ergometers, as it seems to engage most of the muscles activated in actual swimming.

The use of LBSE as swimming training aid

Given that strength training, using dry-land regimens, may enhance the ability to produce higher propulsive forces in the water, especially in short distance events, the effects of LBSE exercise, for training purposes on land, has been widely investigated.[46] It has been generally accepted that LBSE training could generate a significant training overload for swimmers.[47] Conversely, it seems that neither training in water nor the time of the day at which training is performed, change the performance on LBSE[48]. Indeed, a leg-kicking swimming training programme does not affect leg-kicking performance during maximal simulated leg-kicking.[13]

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In the belief that additional land-based training using a LBSE could aid swimmers in improving their swimming performance, several investigations employed LBSE training, in addition to, or alongside, swimming training. Significant improvements in sprint swimming performance (4.0%) after four weeks of LBSE training were reported in detrained swimmers.[2] Improvements in tethered swimming force and 400 m freestyle performance were also reported after 11 weeks of land-based training using a LBSE (2 x per week).[49] The improvements due to the LBSE training reported by these authors could be explained by the effects on VO_2 and power output: Sharp et al.[2] showed power output increases (19.0%) after four weeks of LBSE training in detrained swimmers; Gergley et al.[22] used 10 weeks of LBSE and actual swimming training and reported similar improvements in VO_{2peak} between LBSE training (21.0%) and in-water swimming training (19.0%) in recreational swimmers. Nevertheless, only one study supports the idea that LBSE resistance training does not improve swimming performance, although it was able to increase the resistance used during strength training by 25-35%.[50]

Changes in swimming performance with detraining have also been studied using LBSE exercise versus swimming: muscular strength on the LBSE does not diminish after four weeks of reduced training[51] and peak arm power output seemed to occur during the first and third week after the start of tapering.[52] The increased peak power output was explained as being possibly due to an increase in size, strength, velocity and power of the fast-twitch fibres, after the taper.[53] However, in one of the earliest training studies involving LBSE, Roberts et al.[4] showed no significant improvements in swimming performance in well-conditioned swimmers that used a period of training involving LBSE exercise in comparison to classic swimming training. These findings suggest that land-based training on a LBSE is effective in improving swimming-specific adaptation, which in turn translates into improved swimming performance. However, a longer training period may be needed to induce adaptations in maximal aerobic power, especially with well-conditioned swimmers.

The use of LBSE to assess muscular work output

In relation to the issue of whether LBSE measurements of power output are related to swimming performance, research has presented conflicting evidence. Sharp et al.[2] found a close correlation between anaerobic power on a LBSE and sprint swimming performance, but two subsequent studies were not able to confirm this when analysing 25 m front crawl performance.[54,55]

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Hence, the studies of Bradshaw and Hoyle[54] and Johnson et al.[55] indicated that the power output measurements derived from LBSE testing are not a good predictor of sprint freestyle swimming performance. This lack of correlation with swimming performance could be explained also in this case by limitations inherent in engaging only the upper body muscle groups during early versions of LBSE exercise compared to actual swimming where the whole-body is involved in generating force and forward propulsion. Another factor may have been the inclusion of a large number of female and younger swimmers in Sharp et al's study[2] compared to the other two studies. These study particularities may have influenced the power-sprint relationship due to differences in muscle mass of the participants, which could in turn explain why the results were not comparable.

Moreover, the power output that is developed by the lower limbs seems to be higher than the upper limbs when using whole-body LBSE.[14,56,57] This is supported by the work of Cavanaugh and Musch[58] who reported higher leg power compared to arm power when measured using a leaper leg-strength machine, but higher leg-power output in comparison with studies that used whole-body LBSE. The lower power output achieved during whole-body exercise compared to the leaper leg-strength machine could be attributed to the differences in participating musculature and body position (simulated swimming in prone position versus leaper legs-only machine exercise in standing position). In support of this, more recently Swaine[14] reported that the legs could sustain greater power output than the arms during LBSE exercise (up to 40.0%) during 10 s of all-out exercise in highly-trained swimmers. These results are similar to those reported by Gatta et al.[57] in elite swimmers and Zamparo and Swaine[56] in well-trained swimmers.

Furthermore, since the differences in bilateral arm power can be assessed with LBSE as described by Swaine[59] and Potts et al.[60] it was possible to highlight an imbalance of about 8.0% between the left and right arm power output using an isokinetic LBSE.

The differences in power output can be attributed to different instruments used, differences in experimental design, level of training of the participants and the swimming techniques simulated.

Conclusions

Technical developments in the production of specific ergometers have certainly improved the accuracy and reliability of LBSE as an assessment tool over the past 40 years. However, the criticisms that have been made in relation to the use of LBSE, which mainly concern the difficulties in reproducing the technical movements and the dynamic motor patterns of the actions of

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swimming, are difficult to overcome. LBSE was introduced with the aim to increase the swimming-specific strength and power of swimmers and it seems that these ergometers are useful as a training tool to increase swimming performance. However, there have been some studies that have shown no improvements in swimming performance following LBSE training. The strong relationship between physiological parameters measured during simulated dry-land and in-water swimming allow the use of this tool as a valid and reliable instrument to investigate the physiological parameters of the swimmer and monitor how these parameters change due to swimming or land-based training.

However, the swimmer must replicate the swimming stroke movements "in dry conditions" as closely as possible to the movement performed in the water (e.g. respecting the angles at the wrist, elbow and shoulder in the various phases of the arm-stroke work and recovery phases). Even if the most recent LBSE could reproduce the swimming actions with good accuracy, there are still obvious limitations to simulation of the swimming action in the laboratory. These limitations refer to activation of different muscle groups, due to differences in movement kinematics, in comparison with actual swimming. The pulling path traveled by the hand on the LBSE is longer than in actual swimming; moreover, the forces are distributed differently in relation to the joint angles and limb trajectories. This change in stroke technique, would act to alter the movement pattern of the arm action during swim bench exercise. To further develop a land ergometer able to reproduce the swimming movements, the mechanical load of the water and the thrust direction of the swimmer's limbs would need to be taken into account. However, these are characteristics that are typically difficult to replicate in the laboratory, at least with existing technologies.

The literature presented conflicting evidence in relation to the relationship between LBSE measurements and swimming performance: the difficulty in finding a strong relationship between measured power output when using LBSE and swimming performance is probably due to the fact that the speed of swimming is determined by three different parameters: mechanical power, propulsive efficiency and drag. In tests using LBSE, only mechanical power is measured. This is in contrast to actual swimming where water properties such as propulsion, drag, hydrostatic pressure and buoyancy impact on the swimming action and contribute to propulsive efficiency and drag. To date, research work appears to have shown that the whole-body LBSE has the highest validity and is the most reliable type of simulation of swimming on land, which has been proposed in the literature to evaluate the swimmer's power output, despite the limitations of measuring the energetic contribution of the legs.

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NOTES

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The authors give their contribution to the study as follows:

- Matteo CORTESI: Conception and design, or analysis and interpretation of data; drafting the article or revising it critically for important intellectual content; final approval of the version to be published.
- Giorgio GATTA: Conception and design, or analysis and interpretation of data; drafting the article or revising it critically for important intellectual content; final approval of the version to be published.
- Ian SWAINE: Conception and design, or analysis and interpretation of data; drafting the article or revising it critically for important intellectual content; final approval of the version to be published.
- Paola ZAMPARO: Conception and design, or analysis and interpretation of data; drafting the article or revising it critically for important intellectual content; final approval of the version to be published.
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TABLES

Table 1. Summary of research studies investigating the physiological responses to LBSE.

Study	**Swim Bench features**	**Exercise features**	**$VO2_{peak}$** ($ml•min^{-1}$)	**HLa_{peak}** ($mmol•l^{-1}$)	**VE_{peak}** ($l•min^{-1}$)	**HR_{peak}** ($beats•min^{-1}$)	**R_{peak}**	**Number and level of participants**	**Swim Bench movement**
Armstrong et al, 1981	Biokinetic swim bench, only arms	Discontinuous incremental arm test to exhaustion	44.5 ± 4.1 • kg^{-1}					13 (male) pubertal and competitive swimmers	Front crawl
Gergley et al, 1984	Biokinetic swim bench, only arms	Discontinuous incremental arm test to exhaustion	2211 ± 452		86.2 ± 21.0	179.8 ± 11.5	1.05 ± 0.05	9 (male) recreational swimmers	Front crawl
Kimura et al, 1990	Arm cranking, stretch cord for legs	Discontinuous incremental test to exhaustion	3600 ± 300		103.7 ± 16.6	192.5 ± 6.1	0.92 ± 0.14	11 (male) collegiate swimmers	Arm cranking
Konstantaki et al, 1998	Isokinetic swim bench, only arms	Discontinuous incremental arm test to exhaustion		5.08 ± 0.2		146.0 ± 6.0		8 (female) water polo players	Front crawl
Konstantaki et al, 1999	Isokinetic swim bench for arms and Isokinetik swim bench for legs	Incremental test to exhaustion	3000 ± 100 arms 3700 ± 100 legs	7.00 ± 0.2 arms 5.60 ± 0.6 legs				16 (male) collegiate and recreational swimmers	Front crawl
Konstantaki et al, 2004	Swim bench for arms and swim bench for legs	Incremental test to exhaustion	3690 ± 200 whole, 3220 ± 400 arms, 3150 ± 500 legs					9 (4 male - 5 female) trained swimmers	Front crawl
Konstantaki et al, 2007	Swim bench for legs	Incremental test to exhaustion	2610 ± 400					15 (male) competitive swimmers	Flutter kick
Merloo et al, 1988	Biokinetic swim bench, only arms	Incremental test to exhaustion	2790 ± 600			172.0 ± 2.0	1.10 ± 0.20	13 (8 male - 5 female) elite swimmers	Front crawl
Ogita et al, 1995	Biokinetic swim bench, only arms	3 min constant exercise	2130 ± 250	8.50 ± 2.2	99.9 ± 14.2	162.0 ± 10.0	1.29 ± 0.10	8 (male) trained swimmers	Front crawl
Oliver et al, 1989	Biokinetic swim bench, only arms	3repeats of 60s all out	26.8 ± 1.0 • kg^{-1}	7.60 ± 0.5	76.2 ± 3.8	180.7 ± 4.2	1.29 ± 0.10	22 (male) elite and collegiate swimmers	Front crawl
Rowland et al, 2009	Biokinetic swim bench, only arms	Progressive exercise test to exhaustion	23.2 ± 4.1 • kg^{-1}			172.0 ± 15.0	1.03 ± 0.08	14 (7 male - 7 female) prepubertal swimmers	Butterfly
Sexsmith et al, 1992	Biokinetic swim bench, only arms	3repeats of 60s all out	26.8 ± 1.0 • kg^{-1}	7.60 ± 0.5	76.2 ± 3.8	180.7 ± 4.2		22 (male) elite swimmers	Front crawl
Swaine et al, 1983	Biokinetic swim bench, only arms	Incremental test to exhaustion	2550 ± 350			150.0 ± 9.0		7 (5 male - 2 female) club swimmers	Front crawl

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Swaine, 1994	Biokinetic swim bench, only arms	Continuous incremental test to exhaustion	3300 ± 400			182.0 ± 8.0	1.13 ± 0.03	9 (male) high performance front crawl swimmers	Front crawl
Swaine et al, 1999	Biokinetic swim bench, only arms (SB). Arm cranking (AC)	Incremental exercise test to exhaustion	2900 ± 200 for SB, 2400 ± 100 for AC		112.4 ± 12.3 for SB, 88.9 ± 10.7 for AC	174.0 ± 2.0 for SB, 171.0 ± 2.0 for AC		25 (male) competitive swimmers	Front crawl
Swaine et al, 2010	Whole-body swimming ergometer	Incremental exercise test to exhaustion	3680 ± 650			177.7 ± 6.6		8 (male) trained swimmers	Front crawl
Zamparo et al, 2012	Whole-body swimming ergometer	Continuous incremental exercise test to exhaustion	4490 ± 170		132.0 ± 12.0	185.4 ± 4.0	1.03 ± 0.01	10 (male) trained swimmers	Front crawl

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Table 2. Summary of research studies investigating the use of LBSE in assessment of muscular power output.

Study	**Swim Bench features**	**Exercise features**	**Mean Power Output (W)**	**Peak Power (W)**	**Number and level of participants**	**Swim Bench movement**
Cavanaugh et al, 1989	Biokinetic swim bench for arms Leaper leg machine for legs	90 s all out	229 ± 28 arms 538 ± 86 legs		25 (male) elite swimmers	Butterfly
Ganter et al, 2007	Biokinetic swim bench, only arms	30 s all out	120.3 ± 5.4		10 (4 male - 6 female) elite and junior swimmers	Butterfly
Kalsen et al, 2013	Technogym cable cross over apparatus, only arms	Incremental exercise test of 3 pulls	347.1 ± 72.8		20 (8 male - 12 female) trained swimmers	Front crawl
Konstantaki et al, 1998	Isokinetic swim bench, only arms	Discontinuous incremental arm test to exhaustion		79.0 ± 5.2	8 (female) water polo players	Front crawl
Konstantaki et al, 1999	Isokinetic swim bench for arms and Isokinetik swim bench for legs	Incremental test to exhaustion		114.0 ± 6.0	16 (male) collegiate and recreational swimmers	Front crawl
Reilly et al, 1991	Biokinetic swim bench, only arms	30 s all out	65.2 ± 27.1	73.8 ± 24.7	14 (7 male - 7 female) competent swimmers	Butterfly
Sexsmith et al, 1992	Biokinetic swim bench, only arms	60s all out	57.8 ± 3.2		22 (male) elite swimmers	Butterfly
Sharp et al, 1982	Biokinetic swim bench, only arms		211.7 ± 16.9		40 (18 male - 22 female) competitive swimmers	Butterfly
Sperlich et al, 2011	Isokinetic swim bench, only arms	3 trials of 50s all out	222.8 ± 41.9	298.5 ± 52.1	12 (male) elite swimmers	Butterfly
Swaine, 1994	Biokinetic swim bench, only arms	Continuous incremental test to exhaustion		149.6 ± 17.1	9 (male) high performance front crawl swimmers	Front crawl
Swaine, 1997	Swim bench for arms and swim bench for legs	Incremental exercise test		124.2 ± 9.4 arms 141.3 ± 12.7 legs	12 (male) highly-trained swimmers	Front crawl
Swaine, 1997	Isokinetic swim bench, only arms	30 s all out		179.0 ± 21.9 non-injured arm 111.3 ± 18.1 injured arm	13 (5 male - 8 female) competitive swimmers	Front crawl
Tanaka et al, 1993	Biokinetic swim bench, only arms	3 maximal pulls		197.05 ± 7.5	24 (male) collegiate swimmers	Butterfly
Trappe et al, 2000	Biokinetic swim bench, only arms	4 maximal pulls		225.0 ± 10.0	6 (male) highly trained collegiate swimmers	Butterfly
Trinity et al, 2006	Arm crancking	3-5 s of maximal effort		699.0 ± 27.0	24 (male)competitive collegiate swimmers	Arm crancking
Zamparo et al, 2012	Whole-body swimming ergometer	Incremental exercise test		437.0 ± 8.0	10 (male) well trained swimmers	Front crawl

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TITLES OF FIGURES

Figure 1. Flow chart of the literature search.

Figure 2. A schematic to show the categories of SB study topics in current literature.

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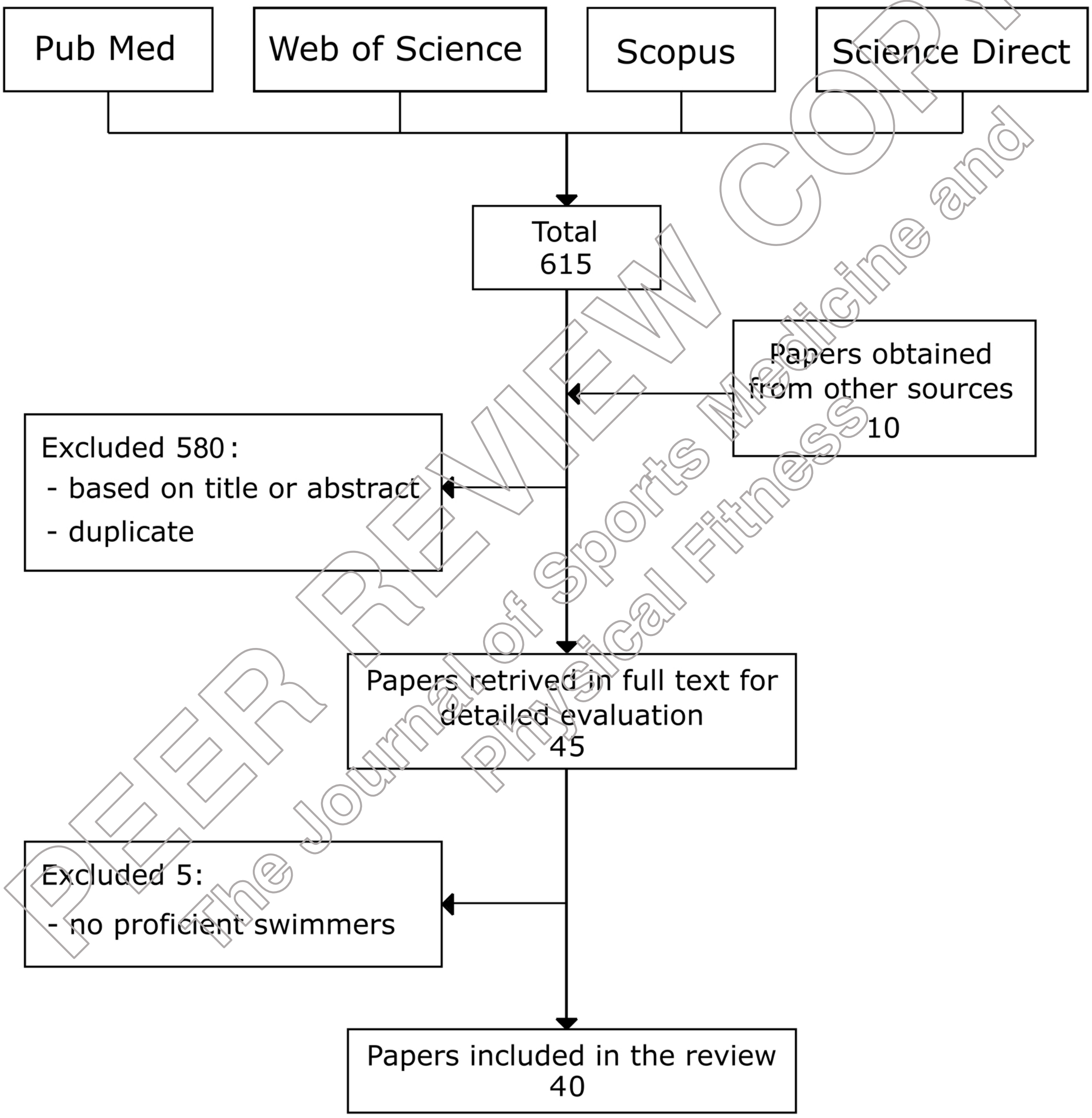

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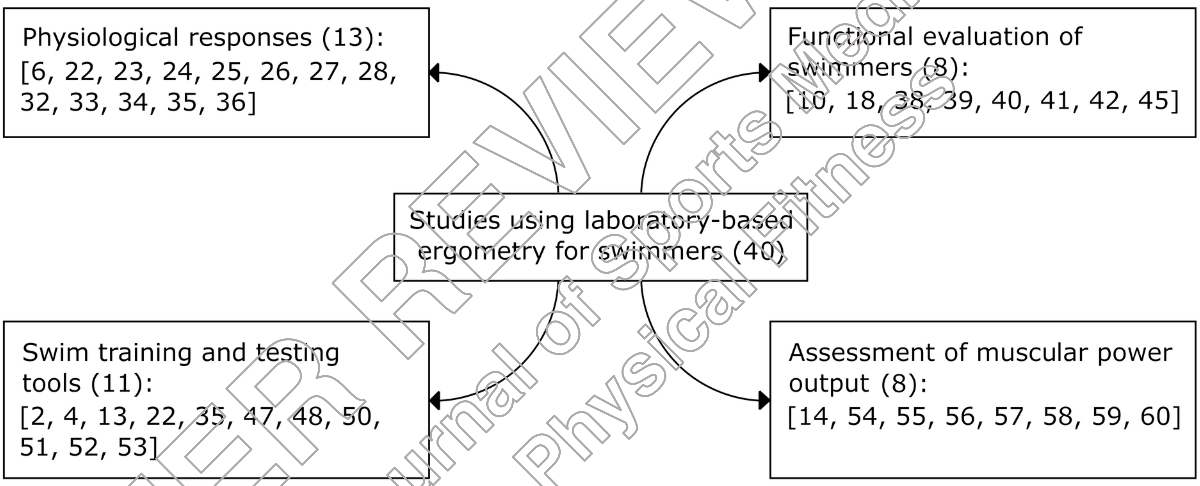

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