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REVIEW ARTICLE

Warm-Up and Performance in Competitive Swimming

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Abstract Warm-up before physical activity is commonly accepted to be fundamental, and any priming practices are usually thought to optimize performance. However, specifically in swimming, studies on the effects of warm-up are scarce, which may be due to the swimming pool environment, which has a high temperature and humidity, and to the complexity of warm-up procedures. The purpose of this study is to review and summarize the different studies on how warming up affects swimming performance, and to develop recommendations for improving the efficiency of warm-up before competition. Most of the main proposed effects of warm-up, such as elevated core and muscular temperatures, increased blood flow and oxygen delivery to muscle cells and higher efficiency of muscle contractions, support the hypothesis that warm-up enhances performance. However, while many researchers have reported improvements in performance after warm-up, others have found no benefits to warm-up. This lack of consensus emphasizes the need to evaluate the real effects of warm-up and optimize its design. Little is known about the effectiveness of warm-up in competitive swimming, and the variety of warm-up methods and swimming events studied makes it difficult to compare the published conclusions about the role of warm-up in swimming. Recent findings have shown that warm-up has a positive effect on the swimmer's performance, especially for distances greater than 200 m. We recommend that swimmers warm-up for a relatively moderate distance (between 1,000 and 1,500 m) with a proper intensity (a brief approach to race pace velocity) and recovery time sufficient to prevent the early onset of fatigue and to allow the restoration of energy reserves (8–20 min).

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1 Introduction

Warm-up routines are common practice before training and competition in almost every sport. For decades, practitioners have prescribed warm-ups to prevent injuries [1] and enhance the performance [2] of their athletes. The scientific community supports the use of warm-up, which has been reported to increase muscle temperature, stimulate the performance of muscle contraction, decrease the time to achieve peak tension and relaxation [3], and reduce the viscous resistance of the muscles and joints [4]. Additionally, the hyperthermia induced by warm-up leads to vasodilatation and increased muscle blood flow, most likely resulting in optimized aerobic function due to the higher oxygen consumption during subsequent tasks [5, 6]. Febbraio et al. [7] suggested that muscle temperature improves the efficiency of muscle glycolysis and high-energy phosphate degradation during exercise, which may be from increasing the dependence on anaerobic metabolism. We hypothesize that priming procedures that increase the body temperature optimize both aerobic and anaerobic metabolism in energy production during exercise.

Published reports also claim that warming up via physical activity might have some effects beyond the temperature-related ones. Gray et al. [8] detected a lower accumulation of muscle lactate during a 30 s sprint on a cycle ergometer after active warm-up compared with passive warm-up, despite the same starting temperature conditions. It was later confirmed that physical activity stimulates buffering capacity, maintaining the acid-base balance of the body [9, 10]. Theoretically, the increased heart rate after active warm-up [7, 11] and the higher baseline oxygen consumption at the start of subsequent practice improve oxygen delivery to the active muscles and potentiate the aerobic energy system [12]. In addition, heavy loading activities may induce high-frequency stimulation of motor neurons [13] for several minutes afterwards, and this enhanced motor neuron excitability can result in a considerable improvement in power production [14, 15]. The movement required for activity also reduces muscle stiffness [16] and increases the range of motion of the muscles involved, possibly allowing for easier, more efficient action.

Recently, some concerns have been raised about the effectiveness of the warm-up for enhancing athletic performance and preventing injuries [17–19]. Improvements in performance ranged from 1 to 20 % in sports such as cycling [20] and running [21] as well as in specific activities such as vertical jumping [22]. Warm-up also helped athletes in team sports; players were acutely ready to perform basketball, handball and baseball skills after warm-up activities [23–25]. Nevertheless, in other cases, performance was impaired after warm-up. The vertical jump height and gymnastic technical leap performance were decreased after static stretching exercises [26, 27], running performance was reduced after high-intensity warm-up [21] or after a long rest period [11], and cycling performance was impaired after cyclists performed their usually long warm-up [28].

Scientific research has not demonstrated the efficacy of warm-up. As a result, athletes and coaches design the warm-up routines based on their individual experiences. The combination of a large number of variables, the complexity of their relationship (e.g. volume, intensity and recovery interval) and the lack of a standardized warm-up complicate characterization of warm-up techniques [29]. For example, there is no scientific evidence of the effectiveness of warm-up in swimming, and studies have shown ambiguous effects of warm-up on swimming performance [30–33]. The variability of research designs (e.g. protocols, outcomes selected, swimming events, and swimmers' competitive level) makes it difficult to compare data. Therefore, the purpose of the present review is to describe the effects of warm-up in swimming performance and to recommend optimized warm-up strategies.

2 Literature Search

The MEDLINE, Scielo, SPORTDiscus, ScienceDirect, Scopus, Web of Science and Google Scholar databases were searched for studies that were published from January 1955 until May 2013 (including electronic publications that were available ahead of print). This review includes studies about the effects of warm-up on swimming performance, which were identified using the following key-terms, individually and/or combined: 'warm-up', 'warm-up effects'; 'priming exercise'; 'pre-exercise', 'prior exercise', 'warm-up and performance' and 'warm-up and swimming performance'. Articles were also gathered based on references from other relevant articles. Those articles with restricted full text online were found in hardcopy form in library archives.

Studies were included in the review if they fulfilled the following selection criteria: (i) the studies were written in English; (ii) they were published in a peer-reviewed journal; (iii) they contained research questions on the effects of active and/or passive warm-up in swimming; (iv) the main outcome reported was a physiological (e.g. lactate, temperature, heart rate, or rate of perceived effort), biomechanical (e.g. stroke length, stroke frequency, or force) or performance (e.g. time and velocity) measure; and (v) healthy human participants were used. Review articles (qualitative review, systematic review, and meta-analysis) were not considered.

In the initial search, 236 studies were identified. After reading the titles, 59 articles were chosen for abstract reading. Those that were clearly not relevant or did not meet inclusion criteria were eliminated. A total of 18 original research studies on the effects of warm-up on swimming were included in our final analysis (Table 1). Fifteen studies focused on active warm-up, two studies focused on passive warm-up, and the remaining study investigated both types of practices.

Studying warm-up involves a large number of variables that interact with each other and possibly condition the results. Because of the risk in separating those variables, the findings and literature limitations were analyzed after the papers had been divided up according to active warm-up and its sub-items (swim volume, intensity, recovery/rest interval, and related/non-related warm-up) and passive warm-up.

Table 1 Physiological, biomechanical and performance changes following active and/or passive warm-up in swimming

Author	Subjects	Warm-up: Active Volume(m)	Warm-up: Active Intensity	Warm-up: Active Dry	Warm-up: Passive Mode	Changes*	Post warm-up test: Rest (min)	Intervention	Test	Parameters Assessed	Main results*
Carlile (1956) [53]	10 T (M+F)				A_1 Hot shower: 8min	ND	ND	A_1 vs. A_2 A_2:N	36.6 m	v	v: A_1>A_2
Thompson (1958) [23]	60 UT (M)	A_1 110 A_3 2.5 min	Moderate 75 % Max	A_2 Calisthenics			5	A_1 vs. A_2 vs. A_4 A_3 vs. A_4; A_4: N	T_1: 27.4 m Max T_2: 5 min Max	T_1:v T_2: Laps	v:A_1>A_2=A_4 Laps: A_3>A_4
DeVries (1959) [35]	13 T (M)	A_1 457.2	Freely	A_2 Calisthenics circuit	A_3: Massage: 10min A_4: Hot Shower: 6min	ND	"brief"	A_1 vs. A_2 vs. A_3 vs. A_4 vs. A_5 A_5: N	91.4 m Max (Crawl, breast, fly)	Time	Time: A_1<A_{2-5}
Robergs et al. (1990) [30]	8 T (M)	A_1 400 400 kick 4 x 50	82 % VO_{2max} 45 % VO_{2max} 111 % VO_{2max}			[LA-]: A_1>A_2 [H+]: A_1>A_2 HCO_3-: A_1<A_2	10	A_1 vs. A_2 A_2: N	200 m 120 % VO_{2max} (Front crawl)	HR; pCO_2; pO_2; HCO_3-; [La-]	[La-]: A_1<A_2 pCo_2:A_1<A_2 HR: A_1>A_2
Houmard et al. (1991) [36]	8 T (M)	A_1 4 x 45.7 A_2 1371.6 A_3 1188.7 4 x 45.7	95 % VO_{2max} 65 % VO_{2max} 65 % VO_{2max} 95 % VO_{2max}			No changes	5	A_1 vs. A_2 vs. A_3 vs. A_4 A_4: N	365.8 m 95 % VO_{2max} (Front crawl)	VO_2; HR; RPE; [La-]; SL	HR: A_4>$A_{1,2,3}$ [La-]: A_4>$A_{1,2,3}$ SL: $A_{2,3}$ >$A_{1,4}$
Mitchell and Huston (1993) [31]	10 T (M)	A_1 366 A_2 4 x 46	70 % VO_{2max} 110 % VO_{2max}			HR: A_1<A_2 VO_{2max}: A_1<A_2 [La-]: $A_{1,3}$<A_2	5	A_1 vs. A_2 vs. A_3 A_3: N	T_1: 183 m 110 % VO_{2max} T_2: TS Max (Freestyle)	[La-]; HR; Time; SL; VO_{2max}	T_1: HR: A_2>A_3 [La-]: A_2>$A_{1,3}$ T_2: HR: $A_{1,2}$>A_3
Romney and Nethery (1993) [41]	12 T (8M, 4F)	A_1 5 min 12 x 22.9 5 min	RPE = 12 Up to RP RPE = 14	A_2 5 min rope 5 min calisthenics circuit 5 min rope		ND	3	A_1 vs. A_2 vs. A_3 A_3: N	91.4 m Max (Freestyle)	Time	Time: A_1<A_3

Table 1 continued

Author	Subjects	Warm-up					Post warm-up test				
		Active			Passive	Changes*	Rest (min)	Intervention	Test	Parameters Assessed	Main results*
		Volume(m)	Intensity	Dry	Mode						
Akamine and Taguchi (1998) [54]	6 T (M)				A_1 Bath 36°C, CO_2 300ppm: 20min A_2 Bath 36°C: 20min	ND	10	A_1vs. A_2	4 min kick 80 % Max	RBC; HCT; WBC; PP; Chol; TG; [La-]; HR; EMG	HCT, WBC, PP, Chol: A_1>A_2 HR: A_1<A_2 [La-]: A_1<A_2 EMG: A_1<A_2
Bobo (1999) [32]	23 T (ND)	A_1 731.5	 Moderate	A_2: Bench press 3 x 6, 50 % 1RM		ND	5	A_1vs. A_2vs. A_3 A_3: N	5 x 91.4 m Max (I=3min) (Freestyle)	Time	No changes
Arnett (2002) [48]	10 T (6M, 4F)	A_1 2011.7 A_2 4023.4 A_3 663.9	A_1= A_2=A_3: Moderate			BT: AM<PM	5	AM: A_1vs.A_2 PM: A_1vs.A_3 AM vs. PM	91.4m Max (Freestyle)	Time; RPE; BT	Time: $A_{2(AM)}$>$A_{1,3(PM)}$; BT: $A_{1(AM)}$<$A_{2(AM)}$,$A_{1(PM)}$, $A_{3\ (PM)}$
Zochowski et al. (2007) [50]	10 T (5M, 5F)	A_1 300 6 x 100 10 x 50 100	 Easy Pull/kick Specific RP Easy			HR: R_1>R_2	R_1: 10 R_2: 45	R_1vs. R_2	200 m Max (1[st] technique)	HR; [La-]; RPE; Time	Time: R_1<R_2 HR: R_1>R_2
Nepocatych et Al. (2010) [43]	10 Mast (4M,6F)	A_1 45.7 45.7 A_2 >457.2 A_4 A_3 + A_1	 40 % Max 90 % Max >46m 90 % Max	A_3 5 x 1min Upper body vibration at 22Hz		RPE: A_5<$A_{1,2}$ HR: A_4<A_2	3	A_1vs. A_2vs. A_5 A_2vs. A_3vs. A_4 A_5: N	45.7 m Max (Freestyle)	Time; RPE; HR; SR	HR: A_5<A_2; A_2>$A_{3,4}$
Kilduff et al. (2011) [42]	9 T (7M, 2F)	A_1 300 6 x 100 10 x 50 100	 Easy Pull/kick Specific RP Easy	A_2 3 x 87 % 1RM Squat		ND	8	A_1vs. A_2	15 m start Max	Start time; Jump Force (PHF; PVF)	PHF: A_1<A_2 PVF: A_1<A_2
Neiva et al. (2011) [18]	10 T (M)	A_1 1000	 Freely			ND	10	A_1vs. A_2 A_2: N	30s TS Max (Front crawl)	F_{max}; F_{mean}; [La-]; RPE	F_{max}: A_1>A_2 F_{mean}: A_1>A_2

Table 1 continued

Author	Subjects	Warm-up: Active Volume(m)	Intensity	Dry	Passive Mode	Changes*	Post warm-up test: Rest (min)	Intervention	Test	Parameters Assessed	Main results*
Neiva et al. (2012) [33]	10 T (M)	A_1 1000	 Freely			ND	10	A_1 vs. A_2 A_2: N	50 m Max (Front crawl)	Time; [La-]; RPE	No changes
Balilionis et al. (2012) [38]	16 T (8M, 8F)	A_1 45.7 45.7 A_2 ~1200	 40 % Max 90 % Max Freely			HR: $A_2>A_3$ RPE: $A_2>A_{1,3}$	3	A_1 vs. A_2; vs. A_3 A_3: N	45.7 m Max (Freestyle)	Time; Diving distance; Reaction; RPE; HR; SR	Time: $A_1>A_2$ HR: $A_1<A_2$
West et al. (2013) [19]	8 T (4M, 4F)	A_1 400; 200 pull 200 kick 200 drill 200 IM 4 x 50 free 200 free	 HR 40 to 60 below HR_{max} RP Easy			Tcore: $R_1>R_2$	R_1: 20 R_2: 45	R_1 vs. R_2	200 m Max (Freestyle)	Tcore; [La-]; HR; RPE; Time; SR	Time: $R_1<R_2$ [La-]: $R_1>R_2$
Neiva et al. (2013) [37]	20 T (10M, 10F)	A_1 300 2 x 100 8 x 50 100	 Easy High DPS Kick/drills; RP Easy			ND	10	A_1 vs. A_2 A_2: N	100 m Max (Freestyle)	Time; [La-]; RPE; SF; DPS; SI;	Time: $A_1<A_2$ DPS: $A_1>A_2$ SI: $A_1>A_2$

AM morning, A_x warm-up number, *BT* body temperature, *Chol* cholesterol, *DPS* distance per stroke, *EMG* electromyography signal, *F* Female, F_{max} maximal force, F_{mean} mean force, *H+* Hydrogen ion concentration, HCO_3^- bicarbonate, *HCT* hematocrit, *HR* heart rate, HR_{max} maximal heart rate, *I* interval, *IM* individual medley, [La^-] blood lactate concentration, *M* male, *Mast* master swimmers, *Max* maximal, *N* no warm-up, *ND* not determined, pCO_2 carbon dioxide pressure, *PHF* peak horizontal force, *PM* afternoon, pO_2 oxygen pressure, *PP* plasma protein, *ppm* parts per million, *PVF* peak vertical force, R_1 tested rest situation one, R_2 tested rest situation two, *RBC* red blood cell, *RP* race pace, *RPE* ratings of perceived exertion, *RM* repetition maximum, *SF* stroke frequency, *SI* stroke index, *SL* stroke length, *SR* stroke rate, *T* trained swimmers, T_1 test one, T_2 test two, *Tcore* core temperature, *TG* triglyceride, *TS* tethered swim, *UT* untrained, *v* velocity, VO_2 oxygen consumption, VO_{2max} maximal oxygen consumption, *WBC* white blood cell

[a] Results are presented in the variables that were statistically significant ($p \leq 0.05$)

3 Active Warm-Up and Swimming Performance

Active warm-up is any act of exercising, involving specific and/or non-specific body movements, with the purpose of increasing metabolic activity and heat production in preparation for an upcoming main activity [17, 34]. Active warm-up is traditionally the preferred method used by practitioners and is the most commonly investigated type; 89 % of the studies about warm-up in swimming are about active warm-up. Improvements were shown only in 67 % of the 12 studies that compared the use of active warm-up with no warm-up. Five of these studies showed an improvement in performance after warm-up, and three others suggested positive effects in the physiological and biomechanical changes. The remaining studies did not find that warm-up had any effect on swimming performance (Table 1).

The first studies suggested that warm-up allowed the swimmers to go 1 % faster for short distances (up to 91 m) [23, 35]. This positive influence was later confirmed for long distances, with a higher stroke length ($\sim$0.07 m) observed in the final meters of 368.5 m [36] and lower lactate concentrations ($\sim$2 mmol/L) after 200 m of intense swimming [30]. There were early ideas that priming exercises are beneficial to performance, but higher peaks in the lactate concentration after 2 min of high-intensity swimming (13.66 ± 2.66 vs. 9.53 ± 2.22 mmol/L; $p \leq 0.05$) have been reported [31]. Additionally, Bobo [32] failed to find significant differences in 91.4 m performance between three conditions (exercises in the water, dry land exercises, and no warm-up). The methods used could be questioned as performance was assessed using a set of five repetitions of 91.4 m freestyle at maximum intensity. In addition, beyond comparing the mean times of all repetitions performed, the author analyzed the best repetition performed, which is similar to a study that tested a single repetition. A recent study found that usual warm-up leads to improved 100 m swimming performance, prolonging the controversy [37].

There have been inconclusive results on a swimmer's performance for shorter distances after warm-up. One study reported that warm-up did not have any favorable effects on 50 m crawl performance [33], while participants in another study had a trend toward significantly faster times on the 45.7 m freestyle ($\sim$0.2 s; $p = 0.06$) and higher propelling force with 30 s of maximal tethered swimming ($\sim$13 % for the mean force and 18 % for the maximal force; $p \leq 0.05$), as reported by Balilionis et al. [38] and Neiva et al. [18], respectively, for warm-up. However, no differences were found among the other variables measured in these studies (e.g. perceived exertion, highest post-blood lactate concentration, stroke rate, dive distance and reaction time), which weakens these findings.

The effects of active warm-up depend on several components such as volume, intensity and recovery time [39, 40]. Some changes in the characteristics of the external training/warm-up load could be essential to influencing the subsequent performance and the results obtained. Furthermore, dry-land movements are usually performed before swimmers enter the pool, and the effects of these movements should not be disregarded. The relevance of these presented categories and their effects on swimming performance require deeper analysis.

3.1 Dry-Land Warm-Up

Dry-land warm-up is any type of active practice performed out of the water; dry-land warm-up includes calisthenics, strength/activation exercises and stretching. Swimmers often perform some sort of physical activity out of the water (e.g. arm rotation) before entering the water to activate the body. However, these exercises are used to complement and not as an alternative to the in-water warm-up. Six studies have focused on the effects of dry-land warm-up as a different type of active warm-up other than the usual in-water procedures.

Three studies have shown that the use of calisthenics exercises does not influence swimming performance compared with the no warm-up condition [23, 35, 41]. Although there were no statistically significant differences, the results of Romney and Nethery [41] showed that swimmers were 0.65 s faster in the 91.4 m freestyle with dry-land warm-up than without warm-up. This difference corresponds to an increase of 1.23 % in performance, which can substantially affect a swimming race.

With regard to strength exercises, Bobo [32] found no differences in the 91.4 m freestyle between no warm-up and bench press practice. The author claimed that the amount of weight used may not have been heavy enough to stimulate the swimmers and may have interfered with the results. In fact, Kilduff et al. [42] showed no differences in the 15 m starting time after activation with loaded squats (3×87 % of 1 maximal repetition) compared with in-water warm-up. These weight exercises with a high load can have positive effects by inducing high-frequency stimulation of motor neurons [13], resulting in an improved rate of force production, which has already been confirmed for explosive efforts [15]. Strength exercises involving large major muscle groups, with few repetitions and high loads, could better prepare swimmers for competing.

An interesting method of dry-land exercise was used by Nepocatych et al. [43] in master swimmers, adapting a swim bench with an attached vibration device. This allowed the swimmers to simulate the proper swimming technique while being exposed to five sets of 1-min vibrations. The authors found no differences in the 45.7 m freestyle time between the vibrations and in-water warm-up. Although they are not easy to apply, developments could arise from this research, and new alternative warm-up procedures should be investigated and applied to higher-level swimmers.

In most swim meets, there is a considerable time interval between the in-water warm-up and the swimming event, diminishing its possible beneficial effects [19]. Moreover, some facilities do not have an extra swimming pool available, requiring swimmers to rely on alternatives to in-water warm-up. Dry-land warm-up is a possible warm-up procedure, which is supported by some studies. It is also recommended that the whole body should be stimulated instead of focusing on specific muscle groups. To the authors' knowledge, no study on the addition of these practices to in-water warm-up has been conducted, even though it could be a method of optimizing the swimmer latency period between the warm-up and the swimming event.

Swimmers commonly use stretching exercises, but, to the best of our knowledge, no study has been conducted on the effects of stretching on swimming performance. Additionally, little attention has been given to the question of stretching as a practice that influences injury risk. By reducing muscle strain and increasing the range of motion of joints [1, 44], stretching is expected to reduce the resistance of movement, allowing for easier movement that optimizes the activity and prevents muscle and joint injuries. Despite these possible benefits, pre-exercise static stretching does not produce a reduction in the risk of overuse injuries [45], and it could lead to a severe loss of strength and performance impairment [46]. Yet, a decrease in strength when using dynamic stretching exercises has not been demonstrated [47], suggesting that stretching may be part of a warm-up routine if these are usual practices of the swimmers. Further investigation is needed to determine the effects of stretching alone as well as in combination with other warm-up activities.

3.2 In-Water Warm-Up: the Effect of Volume

The acute effects of different warm-up volumes on swimming performance have been previously researched in four studies; two found positive effects for volumes between 1,000 and 1,500 m compared with a lower volume (i.e. lower than 200 m). A higher volume (1,371.6 m) allows the swimmers to maintain higher stroke length (3.76 %) in the last meters of 365.8 m at ~95 % of maximal oxygen consumption (VO_{2max}), with similar values of blood lactate concentration and heart rate [36]. This was later corroborated for shorter testing distances, verifying better 45.7 m performance (1.22 %) after warming up for approximately 1,300 m (men: 1,257 ± 160 m; women: 1,314 ± 109 m) instead of a 91.44 m warm-up [38]. It is possible that the lower volume was not sufficient to cause significant metabolic changes during the performance trial. In fact, the same result was verified by Nepocatych et al. [43] in master swimmers, with no changes in the 45.7 m freestyle after two short warm-ups (91.4 m and more than 450 m).

The remaining study on the influence of warm-up volumes did not find differences in the 91.4 m freestyle when warming up for either 2,011.7 or 4,023.4 m with similar intensities [48]. Swimmers may expend too much energy during warm-up, or they may not have enough time after warm-up to replenish their phosphocreatine and adenosine triphosphate levels, compromising the energy supply and negatively affecting their performance. For instance, swimmers traditionally complete long warm-ups, even for short races, to achieve greater water sensitivity and to be better prepared for the competitive event. However, a long duration of exercise has a higher energy consumption that can contribute to the early onset of muscle fatigue, especially for high intensities [49].

When subjected to a continuous activity at moderate intensity, the body increases its temperature and stabilizes between 10 and 20 min after the start [39]. Although this time could be set as a rule of thumb, the volume of the warm-up performed before swimming competitions differs considerably. The first study on active warm-up verified that swimming for 110 m or 2.5 min [23] positively affected swimming performance. The level of the swimmers (untrained) may explain these positive results with such a light warm-up volume. With lower physical preparedness, a shorter volume is required to activate the body to the main task. A slightly longer warm-up, as required in the study by De Vries [35], allowed verification of the improvements in swimming performance of competitive swimmers (457 m).

Nevertheless, the volumes presented were completed in less than 10 min; this could be the reason why the following studies focused on longer warm-ups. Using the control condition of no warm-up, the 91.4 and 100 m freestyle times and a propelling force in 30 s of tethered swimming were improved after approximately 15 min of swimming (~1,000) [18, 37, 41]. Moreover, a warm-up of 1,000 m reduced the changes in the acid-base balance after 200 m (2 min) of intense swimming [30].

There are some studies in which performance was similar or even impaired after warm-up when compared with the no warm-up condition. There were no differences in the 91 m freestyle after 731.5 m of moderate swimming [32] or on the 50 m front crawl after 1,000 m of habitual warm-up [33]. Some possible reasons for these results are the time between warm-up and maximal swimming (not allowing a sufficient time to recover) and/or the volume and intensity of the warm-up, which most likely were not sufficient to cause desirable metabolic effects.

We propose a total warm-up volume of a 15–20 min duration (between 1,000 and 1,500 m) for swimming events up to 3–4 min. There is a trend toward increasing the volume of warm-up in the morning. The reasoning behind this is the need for extra body activation due to adaptation to the circadian rhythm. However, Arnett [48] found that the swimmers still perform better on the 91.4 m in the afternoon even when a longer warm-up (4,023.4 vs. 2,011.7 m) was performed in the morning (58.48 $\pm$ 5.69 and 56.86 $\pm$ 4.87 s, respectively; $p \leq 0.05$). This result suggests that performance is significantly higher in the late afternoon, independent of the previous warm-up volume performed.

3.3 In-Water Warm-Up: the Effect of Intensity

The two studies on the use of different warm-up intensities in swimming found no effects on performance. Houmard et al. [36] were the first authors to compare the effects of two different intensities of priming exercises on performance ($\sim$65 % VO_{2max} of continuous swimming vs. warm-up including 4 $\times$ 45.7 m at $\sim$95 % VO_{2max}), and no differences were found in heart rate, stroke length or blood lactate concentration after 365.8 m front crawl at $\sim$95 % VO_{2max}. Because volume was the same in the two experimental conditions, the study did not use a specific, intensive set to optimize performance. These conditions may result in extra energy expenditure and most likely influenced the concentration of metabolites, thus impairing swimming performance. In fact, warming up at 110 % VO_{2max} instead of 70 % VO_{2max} led to elevated lactate concentrations (13.66 $\pm$ 2.66 vs. 9.53 $\pm$ 2.22 mmol/L; $p \leq 0.05$) after 183 m freestyle at high-intensity [31]. The 5-min recovery period after warm-up could have been insufficient for reducing the residual effects of the priming exercises. The accumulation of lactate was higher after high-intensity warm-up (6.97 $\pm$ 1.97 vs. 2.27 $\pm$ 0.81 mmol/L; $p \leq 0.05$), which could have contributed to the higher values obtained after performance. Additionally, the lower volume performed during the high-intensity warm-up compared with the low-intensity warm-up did not allow sufficient activation of the aerobic metabolism. However, the heart rate (159.9 $\pm$ 7.7 vs. 148.0 $\pm$ 9.5 bpm; $p \leq 0.05$) and VO_{2max} (4.18 $\pm$ 0.45 vs. 3.23 $\pm$ 0.24 L/min; $p \leq 0.05$) after the warm-up showed cardiovascular alterations that might be indicative of enhanced aerobic metabolism for the high-intensity priming exercises, regardless of the volume performed.

Despite the uncertainties about including high-intensity swimming sets in the warm-up procedures, it seems better to use high-intensity swimming sets instead of not warming up. Robergs et al. [30] found that lactate concentrations after 200 m of intensive front crawl swimming were lower when the warm-up included 4 $\times$ 50 m at 111 % VO_{2max} (8.7 $\pm$ 0.8 mmol/L vs. 10.9 $\pm$ 0.5 mmol/L; $p \leq 0.05$). Furthermore, including a short-distance swimming set with increased intensity over the repetitions was effective for 91 m maximal freestyle [41]. The time performed was reduced by 0.75 s compared with when there was no previous warm-up; thus, short distances at race pace could optimize performance. Thus, a short-distance set that is built up from low intensity to race-pace velocity in the last repetition could be used to improve subsequent performance by stimulating the energy systems that are recruited in the competitive event [39, 40]. Nevertheless, when high-intensity swimming is performed during warm-up, it should be used with caution to avoid the early fatigue and compromising the subsequent swimming performance.

3.4 Recovery Time After Warm-Up

Active warm-up seems to improve the performance with periods of recovery up to 20 min, mainly related to temperature mechanisms [19, 40]. The time gaps between the end of the in-water warm-up and the start of the competition/test used in the research studies were 3 min [38, 41], 5 min [31, 32], 8 min [42], and 10 min [18, 30, 33, 37]. Nevertheless, according to our knowledge, the effect of different time intervals between warm-up and the main task was only studied by Zochowski et al. [50] and West et al. [19]. The 200 m times were 1.38 and 1.48 % better with 10-min [50] and 20-min rest periods [19], respectively, instead of 45 min of rest. The maintenance of an elevated core temperature during shorter intervals[19], and the higher heart rate at the start of exercise which potentially increased baseline oxygen consumption [50], are the possible mechanisms responsible for the improved performance. In addition, the post-activation potentiation effect of warm-up, which happens around the 8th min of recovery [42], possibly allowed swimmers to start at an optimized power.

In real competition venues, it is almost impossible to take less than 8–10 min between finishing the warm-up and the swimming event. Warming up is more effective when it is sufficiently intense to activate the physiological processes that will be required in the competition event, with a recovery time that should be between 8 and 20 min, allowing for replenishment of phosphocreatine [51]. The literature only focuses on the effects of different intervals in the 200 m swimming event, and the various competitive distances and techniques could demand different recovery periods. Moreover, considering the studies of Saez Saez Villarreal et al. [15], it would be interesting to know how different muscle activations (e.g. using high-intensity exercises or loaded concentric actions) can extend the effects of warm-up as well as how swimmers can benefit from improved performance after a longer rest.

4 Passive Warm-Up and Swimming Performance

Increases in muscle and core body temperature could be achieved without physical activity by the use of external heating, such as hot showers, saunas and heated vests [39]. These practices are commonly known as passive warm-up, through which the swimmers most likely benefit from the effects of temperature-related mechanisms without spending energy. A variation in the muscle temperature of 1 °C improves the muscle's contractile properties and modifies performance by 2–5 % [52]. Therefore, passive warm-up could be suggested as a practice for maintaining the temperature between warm-up and the swimming event. However, heating cannot exceed 39 °C for the core temperature, as overheating negatively affects motor drive and muscular performance [52].

Three studies examined the effects of different passive procedures on swimming performance with conflicting results. Carlile [53] demonstrated that swimmers submitting to 8 min of a hot shower or a 10-min massage attained 1 % higher swim velocity in 36.6 m than swimmers without warm-up procedures. Conversely, De Vries [35] verified that a 10-min massage did not influence the 91.44 m performance, which was instead positively influenced by active warm-up. Thus, while the first study noted the positive influence of passive warm-up in swimming performance, there have been more studies questioning these results. The applicability of these findings should be weighed, as several decades have passed from the time when research occurred. In fact, although there are few studies about active warm-up in swimming and the findings are contradictory, the gap is even larger in regard to passive warm-up. The large range of passive procedures, the unfamiliarity with some of those techniques and a possible deviation of attention to active warm-up, which is the most relevant form of pre-exercise, could be some of the reasons for this scarcity.

The understanding of the effects of different passive procedures is also important for optimizing swimming performance. Two different practices of passive heating were tested, and a carbonated bath at 36 °C was more effective than a normal bath at the same temperature and duration of 4 min of kicking exercise [54]. The authors proposed that this method be adopted by swimmers because it tends to reduce the lactate concentration, heart rate and electromyography response of the rectus femoris, suggesting higher muscle efficiency and less fatigue. However, the low experience level of swimmers and the non-existence of comparison with active warm-up, call into question its efficiency.

Currently, there is no evidence-based information about the effects of passive warm-up procedures in swimming performance and the unclear indications cannot support the reliably of these methods, making them uncommon. However, it is not unusual to see swimmers completely dressed up (sometimes with a jacket over a sweat suit), near starting blocks, just before starting the race. The use of external sources of heating most likely allows the swimmers to extend the effects of the active warm-up that was performed some time before. Beyond investigating the effects of passive warm-up, we should try to understand how it could be used when there is a long resting time after the active warm-up or even as a complement to active warm-up.

5 Effect on Different Performance Events

The Olympic competition schedule for swimming includes distances from 50 to 1,500 m in the pool and 10,000 m in open-water swimming. As presented in Table 1, swimming events performed in the pool are the main focus in warm-up related studies. Corresponding to efforts ranging from less than 30 s to more than 15 min, it is expected that these different events are stimulated by different warm-up approaches as well. Considering the studies that used a control condition (without warm-up), three of the six studies that tested swimming distances up to 50 m or the equivalent effort in time presented better performance after warm-up [18, 23, 53]. Some uncertainty continues on distances up to 100 m, with three of four studies showing improved performance [35, 37, 41], as well as between the 100 and 200 m, with one of two studies mentioning lower lactate values and higher heart rate [30]. Times on the distances above 200 m were improved after warm-up when considering all of the studies presented [23, 36]. Considering that only submaximal tests were performed and mainly focused on physiological variables, longer warm-ups should be indicated when the competition distance is longer.

Table 2 Possible recommendations for active warm-up prior to competitive swimming

Setting	Recommendation
Main suggestions	
In-water warm-up	Volume 1,000–1,500 m
	Moderate intensity
	Drills focusing on stroke efficiency
	Short distances at race pace
	Recovery period 8–20 min
Alternative suggestions	
Dry-land warm-up	Total body stimulation
	Calisthenics—moderate intensity
	Strength exercises—short sets, heavy loads[a]
	Vibration exercises on adapted swim bench[a]

[a] Hypothesized only

Researchers have focused mainly on the shorter distances, but the positive effects of warm-up seem more consistent for distances above 200 m, reinforcing the possible positive effects of aerobic metabolism stimulation during warm-up procedures. Moreover, the positive changes in performance on distances under 200 m were lower than 1 % for the time improvement, and it is unclear how much of this effect was due to warm-up. Caution has to be taken when studying any measure of performance, and, for instance, it is important to show by how much that performance measure would be expected to vary day-to-day or test-to-test. Researchers should be aware of the deficient knowledge about the effects of warm-up in the different competition distances and swimming techniques, which may be due to the existing lack of warm-up specificity.

6 Future Research

Some limitations were found in the literature that researched the topic covered in this review. In fact, it appears that investigations of warm-up effects on swimming performance were not performed for a few years, resulting in a lack of research and resulting restrictions. The particular swimming pool environment, with a high temperature and humidity, and the complexity of warm-up procedures could explain why there are few studies on this topic.

Some methodological issues can be observed in the literature and should be overcome in future research. For instance, the control group or control condition in the study design sometimes did not exist, and a standard warm-up was compared with other variations of it. This methodological issue may be relevant to the analysis of the results obtained and should be considered in the possible conclusions. Additionally, the small sample sizes used in some of the studies increased the effects of chance and enhanced the ambiguity of the results.

Passive warm-up and dry-land exercises should be deepened as alternative and/or complementary practice for an active warm-up. Additionally, most of the studies focused on freestyle swimming, and a study on the warm-up effects on different techniques and swimming distances should be developed. There is a gap in the research on the influence of the different subject's ages, gender, and training status for selecting the proper warm-up. Once some of these broader issues are clarified, we can evaluate the structure and specificity of warm-up practices.

7 Conclusions

Warm-up is commonly accepted as fundamental, and any priming practices are usually considered to optimize performance. Specifically in swimming, and despite some contradictory results, research tends to suggest that warm-up, more particularly the active type, has a positive effect on the swimmer's performance, especially for distances above 200 m. Additionally, the literature proposes that in-water activities are the most useful activities, but when it is not possible to do in-water warm-up, dry-land exercises can be performed as an alternative.

Dry-land warm-up should include all body segments. Strength exercises with few repetitions and high-load intensities, vibration stimulation, or the use of calisthenics are hypothesized to better prepare the swimmer for racing. Although there are some doubts about using these methods, some studies found promising results, with no differences in performance compared with in-water warm-up. Weight and vibration exercises are not practical to perform before a swimming event, but calisthenics can be used. Further investigation is needed to reach a consensus about the use of alternative methods of warming up and define its ideal structure in terms of the type, duration, volume, specific and/or general tasks, and recovery period. Moreover, little is known about dry-land exercise for maintaining the effects of the in-water warm-up during the waiting time before the swimming race. Additionally, the use of stretching exercises is common among swimmers as a complement to the in-water warm-up, but the effects are not known and could even impair performance. Dynamic stretches are not detrimental to performance, and a daily routine could be replicated in warm-up procedures to prevent possible injuries.

The in-water warm-up should last for 15–25 min, and short, intensive, and specific tasks can be performed in some parts of the warm-up; there are favorable effects after short distances of progressive swimming up to the race-pace velocity. However, one should be cautious because high-intensity swimming during warm-up can be overvalued and may not be essential to performance optimization. Moreover, some studies presented standard warm-ups with exclusive lower/upper limb exercises that may achieve better activation for each body part. A swimming race is performed using the whole body and splitting stimulation of the body may not be the best way to increase the swimmer's preparedness. The use of technical drills during warm-up could increase the swimming efficiency in the first meters by the longer distance per stroke achieved [37]. The recovery period after warming up should be balanced so that it is sufficient for energy replenishment and so that swimmers can benefit from the proposed effects of warm-up (Table 2).

Because there is a latency period between the in-water warm-up and the swimming race, passive warm-up should be considered. Despite the lack of concrete evidence, these practices could be used to maintain elevated core and muscle temperatures, which are beneficial for swimmers. Little is known about the best passive practices to implement, but passive exercise could be any method that does not elevate the temperature above 39 °C, which would otherwise impair performance.

Scientists have recently started to study the effects of warm-up on swimming performance, but numerous doubts remain. Not much is known about the structure and components of warm-up even though it is still thought to influence performance in a sport where a tenth of a second could determine success or failure. The results highlight that the volume, intensity and recovery, and specific exercises of active warm-up are complementary variables. Any change carried out in one of these characteristics leads to variations in the others, which can influence the results.

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