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REVIEW ARTICLE

Warm-Up Strategies for Sport and Exercise: Mechanisms and Applications

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Abstract It is widely accepted that warming-up prior to exercise is vital for the attainment of optimum performance. Both passive and active warm-up can evoke temperature, metabolic, neural and psychology-related effects, including increased anaerobic metabolism, elevated oxygen uptake kinetics and post-activation potentiation. Passive warm-up can increase body temperature without depleting energy substrate stores, as occurs during the physical activity associated with active warm-up. While the use of passive warm-up alone is not commonplace, the idea of utilizing passive warming techniques to maintain elevated core and muscle temperature throughout the transition phase (the period between completion of the warm-up and the start of the event) is gaining in popularity. Active warm-up induces greater metabolic changes, leading to increased preparedness for a subsequent exercise task. Until recently, only modest scientific evidence was available supporting the effectiveness of pre-competition warm-ups, with early studies often containing relatively few participants and focusing mostly on physiological rather than performance-related changes. External issues faced by athletes pre-competition, including access to equipment and the length of the transition/marshalling phase, have also frequently been overlooked. Consequently, warm-up strategies have continued to develop largely on a trial-and-error basis, utilizing coach and athlete experiences rather than scientific evidence. However, over the past decade or so, new research has emerged, providing greater insight into how and why warm-up influences subsequent performance. This review identifies potential physiological mechanisms underpinning warm-ups and how they can affect subsequent exercise performance, and provides recommendations for warm-up strategy design for specific individual and team sports.

Key Points

Passive and active warm-ups markedly influence subsequent exercise performance via increases in adenosine triphosphate turnover, muscle cross-bridge cycling rate and oxygen uptake kinetics, which enhance muscular function.

An active warm-up, consisting of a brief (< 15 min) aerobic portion and completion of 4–5 activation sprints/race-pace efforts, post-activation potentiation exercises or small-sided games, elicits improvements in performance.

Passive heat maintenance techniques can preserve the beneficial temperature effects induced via active warm-up during lengthy transition phases.

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1 Introduction

Warming-up prior to a competitive exercise bout is a widely accepted practice in the modern sporting environment, with athletes and coaches alike believing that warming-up is essential for attaining optimal performance. However, until quite recently, this belief was not well supported by empirical evidence, with coaches often resorting to a trial-and-error approach to design their athletes' warm-up strategies. In light of this, extensive research has been conducted over the past decade to determine the key warm-up elements for specific exercise tasks. A large number of physiological and neural mechanisms have been examined to ascertain their contributions to performance and responses to different warm-up strategies. Purported mechanisms include increased muscle metabolism [1], elevated oxygen uptake (VO_2) kinetics [2] and post-activation potentiation (PAP) [3]. Technological advances over the past decade have also facilitated the emergence of new types of warm-up strategies [4, 5]. With the last major review published over 10 years ago [6, 7], prior to several of these advances, it is timely to provide an update on recent developments in the area.

Compiling this review involved identifying articles via systematic searches (search completed 30 April 2014) of the EBSCO, Medline and SPORTDiscus databases, as well as inspection of the reference lists of the selected articles. Studies that examined passive and active warm-up strategies specifically are discussed, but we have excluded those investigating stretching-only strategies (see Smith [8]). For the final section of this review, studies regarding sport-specific strategies were sourced from publications between 2003 and 2014. Studies investigating tasks common to the competitive environment (e.g. a 100 m swimming time-trial) and those with a well-defined endpoint (e.g. a 4 min cycling time-trial) were included, but studies using 'time to exhaustion' tasks were not. From this analysis, recommendations are provided for warm-up strategies across several individual and team-based sports, taking into consideration the differences in competition structure and environment.

2 Mechanisms of Warm-Up

One of the main outcomes associated with warming-up is an increase in body temperature. Increases in muscle temperature (T_{muscle}) are reportedly accompanied by increases in muscle metabolism [1] and muscle fibre conduction velocity (MFCV) [9]. Elevation of VO_2 kinetics [10] and increases in muscle contractile performance following prior contractile activity [3] have also been reported. In addition, visualization and preparatory arousal techniques have been shown to enhance subsequent exercise performance [11]. For ease of reference, we have defined short-term/sprint performance as <1 min in duration, sustained high-intensity performance as >1–5 min in duration and long-term (endurance) performance as >5 min in duration.

2.1 Temperature Mechanisms

Performance improvements in exercise tasks preceded by a warm-up are generally attributed to temperature-related mechanisms. The early pioneers of warm-up research, Asmussen and Bøje [12], determined that 'organisms facilitate work more effectively at higher temperatures'. More recently, a strong association between power output and T_{muscle} has been established, with a 1 °C increase in T_{muscle} being shown to enhance subsequent exercise performance by 2–5 %, depending on the type and velocity of contraction(s) [13–15], with the magnitude of the T_{muscle} response being positively related to movement velocity [14]. In addition, changes in T_{muscle} are directly related to changes in the relative work rate, with T_{muscle} rising rapidly from baseline (~35–37 °C) at the onset of moderate-intensity exercise, before reaching a relative equilibrium after ~10–20 min [16, 17].

2.1.1 Increased Muscle Metabolism

Accelerated muscle glycogen degradation at higher ambient temperatures was first shown in the early 1970s [18, 19]. The passive elevation of T_{muscle} (e.g. via water-perfused cuffs) has been linked with faster adenosine triphosphate (ATP) turnover, primarily via augmentation in the rate of creatinine phosphate (PCr) utilization and H^+ accumulation, as well as increases in anaerobic glycolysis and muscle glycogenolysis [20–22]. Increases in subsequent exercise power production are considered the primary outcome of these changes [21, 23]. Specifically, passive warming of T_{muscle} can increase anaerobic ATP turnover within the first 2 min of heavy exercise, with no further changes in turnover rate after this period [1]. However, several studies investigating this shift towards greater anaerobic metabolism have yielded variable results, partly due to researchers failing to take muscle biopsy samples during the initial phase of the exercise task (<2 min) and instead procuring samples only upon exercise completion some 4+ min later [1]. An increase in the muscle cross-bridge cycling rate is one possible explanation for this higher reported turnover rate, with a temperature-dependent relationship existing between muscle fibre cross-bridge cycling and the force produced during the power stroke in cycling [24]. Given that passive elevation of T_{muscle} can increase muscle glycogen availability in the short term (~2 min), it is likely that both sprint and sustained high-intensity events could benefit from this intervention.

2.1.2 Increased Muscle Fibre Performance

There is much debate about which muscle fibre types are most affected by changes in temperature. Greater PCr utilization in type I fibres has been shown during low-cadence cycle exercise [≤60 revolutions per minute (rpm)] but not in type II fibres following prior passive warming [1]. However, at these low velocities, type II fibres are likely operating towards the lower part of the power–velocity curve, where a rightward shift would have a minimal effect on their power production capabilities. At a high cadence (~160–180 rpm), however, elevating T_{muscle} results in greater PCr and ATP utilization and maximal power outputs in type II, but not in other fibre types [22]. It seems that the function of both type I and type II muscle fibres is affected by elevations in T_{muscle} if contraction frequency is taken into account, with a velocity-dependent effect reported, i.e. type II fibres are more likely to benefit from increased T_{muscle} when the contraction frequency of the exercise task is high, and vice versa for type I fibres.

2.1.3 Increased Muscle Fibre Conduction Velocity

Elevations in T_{muscle} can positively alter the force–velocity relationship and concomitantly the power–velocity relationship [25–27], leading to higher power outputs in exercise tasks [25], with a ~3 °C augmentation in T_{muscle} being reported to elicit a measurable increase in both MFCV and power [21]. Following passive muscle warming, evidence for an improvement in MFCV has been observed, via a reduction in the time to reach peak twitch and an increase in the rate of force development [21, 28]. The MFCV in muscles both actively and passively involved in the warm-up has also been reported to increase (~5 % in the hand and ~8.5 % in the leg) following a moderate-intensity running-based warm-up [9]. Similarly, different types of active warm-up modalities, running- or back squat-based, produced ~12 % increases in MFCV [29]. Release of calcium from the sarcoplasmic reticulum during fibre membrane depolarization [30], membrane hyperpolarization as a result of increased Na^+/K^+ pumping activity [31], muscle fibre swelling [32] and/or faster activation of muscle fibres [21] are all plausible explanations for MFCV enhancement. Thus, post-warm-up improvements in neuromuscular performance can, in part, be attributed to alterations in muscle fibre conduction properties. In addition, strength- and power-demanding sports, such as sprinting and jumping, typically require a fast rate of force development to attain the highest possible peak power output within a short timeframe [33, 34]. It is also evident that during rapid cyclical movements, muscles must relax quickly. The muscle relaxation rate depends on the force level recorded from the time when a muscle starts to relax; thus, this is the chosen point of reference [27]. The speed of muscle relaxation can decrease at lower temperatures (22–25 °C). It has been established that maximal rates of force development (peak power) and relaxation have a temperature-dependent relationship with peak power output and peak relaxation rate reported at higher temperatures (25–37 °C) [27]. Temperature dependency is likely related to one of the underlying processes of muscle relaxation, such as calcium removal from the myoplasm, calcium dissociation from troponin and/or the cross-bridge detachment rate [25, 27, 35].

2.1.4 Temperature Mechanisms Summary

In summary, passively or actively elevating T_{muscle} can markedly influence exercise performance. Increases in ATP turnover and cross-bridge cycling rate, as well as improvements in muscle fibre functionality and MFCV, appear as likely mechanisms. Athletes competing in sprint and sustained high-intensity events seem the most likely beneficiaries of elevations in body temperature due to increases in muscle glycogen availability and the rate of force development. However, caution should be exercised under conditions of high heat and/or humidity, as it is conceivable that prescribed warm-ups that are overly intense or prolonged might adversely affect thermal tolerance. Pre- and within-exercise cooling methods, such as cold water immersion [36–38], cooling vests [39, 40], ice slurry ingestion [41–43] or a combination of different strategies [44], might be introduced in these settings.

2.2 Metabolic Mechanisms

While elevating body temperature via either passive or active warm-up can improve subsequent exercise performance, such elevations are not the sole determinant of energy metabolism changes during exercise [45]. Active warm-up, in particular, can stimulate changes in the mechanisms underlying both anaerobic and aerobic metabolism. In a landmark study, Gerbino and colleagues [46] showed that 6 min of heavy-intensity (>lactate threshold, <critical power) but not moderate-intensity (<lactate threshold) exercise increased VO_2 kinetics during a subsequent heavy exercise bout. Importantly, this was one of the first studies to definitively show a 'speeding' of VO_2 kinetics following an exercise-based intervention. In

addition, the elevated VO_2 and associated aerobic metabolism might spare finite anaerobic stores during the initial stages of a subsequent exercise bout, thus preserving this energy for subsequent use [47].

2.2.1 Elevation of Oxygen Uptake Kinetics

Oxidative metabolism is the principal means by which humans generate energy for physical activity, the exception being sprint-based activities. It is well established that a bout of heavy-intensity priming exercise affects the time course of the pulmonary VO_2 response within a subsequent heavy-intensity exercise bout by speeding overall VO_2 kinetics [46, 48–51]. Initially it was believed that this speeding of VO_2 kinetics occurred via an enhancement of the primary VO_2 response to exercise [46, 52]. However, it has now been revealed that completion of a priming exercise bout elicits an increase in the amplitude of the primary VO_2 response and a reduction in the VO_2 slow component [49, 53, 54]. Together, these changes in metabolic function can improve exercise tolerance [48, 55] and mean power output [54]. However, there are other reports that priming exercise bout completion may impair [56] or have no influence [57] on subsequent exercise performance. Explanations for the large variation between studies include differences in the intensities of the priming and criterion bouts, and the length of time between the priming and criterion exercise bouts (here termed the 'transition phase').

Moderate-intensity (below the lactate threshold) priming bouts have a limited effect on the subsequent VO_2 response [53], yet priming bouts performed at a heavy intensity (from the lactate threshold up to critical power) can enhance subsequent exercise performance [46, 48–51]. Severe-intensity priming exercise (above critical power) has been linked to improved [53–55] as well as impaired subsequent performance [58], with impairments most likely attributable to the transition phase being too short, such that the blood lactate concentration (La^-) at the onset of the subsequent bout was >3 mmol/L [53]. Therefore, it is necessary to strike a balance between the potential benefits of priming exercise on VO_2 kinetics and the depletion of anaerobic stores, as well as the associated metabolic acidosis. This challenge was addressed in a comprehensive study conducted by Bailey and colleagues [53], in which both the intensity of the priming exercise bout and the duration of the transition phase were manipulated. A severe-intensity priming bout increased the time to exhaustion (15–30 %) when the transition phase was ≥9 min. This particular combination of priming bout intensity and transition phase duration appears to have optimized the balance between preserving the beneficial effects of the priming bout on VO_2 kinetics while still providing sufficient time for muscle homeostasis (e.g. muscle phosphocreatine and H^+ concentrations) to be restored.

Another study reported that a 6 min priming bout completed at a constant work rate of ~80 % of peak oxygen uptake (VO_{2peak}), followed by a 10 min transition phase, produced a mean La^- concentration of ~2.6 mmol/L [48]. Taking into consideration these findings, as well as others [53], it appears that a bout of priming exercise which elicits a degree of lactic acidosis (<3 mmol/L at the onset of the criterion bout) is capable of positively altering VO_2 kinetics. Furthermore, an individual's baseline VO_2 response may be elevated following completion of a priming exercise bout [47]. This outcome may lead to the initial sparing of an individual's finite anaerobic energy stores, preserving this energy for subsequent use (e.g. the final sprint to the line). However, this elevated baseline VO_2 returns to baseline if the transition duration exceeds 10 min [49], so the duration of the transition phase is important to consider.

The precise physiological mechanism(s) responsible for the effects of priming exercise on VO_2 kinetics are unclear. Altered O_2 delivery and extraction [46, 59–61], increased motor unit recruitment [49, 52, 53, 62], shifts in the oxyhaemoglobin curve [46], oxidative enzyme activity [63, 64], residual acidosis [48, 54, 65]—or a combination of these mechanisms [66–68]—have all been implicated in altering the VO_2 kinetic response. Overall, it appears that completion of a bout of heavy-intensity priming exercise can increase the amplitude of the primary VO_2 response and reduce the VO_2 slow component. Collectively, these effects may enhance subsequent exercise performance via increases in oxidative enzyme activity and/or motor unit recruitment, such that the 'strain' placed on each individual muscle fibre is reduced.

2.3 Neural Mechanisms

It has been postulated that following a pre-loading stimulus (i.e. active warm-up), fatigue and muscle potentiation coexist within skeletal muscle [69, 70], with the subsequent force that a muscle is capable of generating ultimately being dependent upon the net balance between these factors [70]. Although fatigue will impair performance, inclusion of muscle 'potentiation' exercises within an active warm-up might improve subsequent performance. At present, tasks that require maximum power output over a relatively short (<1 min) timespan [71, 72], such as jumping [73, 74] and sprinting [75, 76], can benefit following completion of a pre-loading stimulus.

2.3.1 Post-Activation Potentiation

The recent activity of skeletal muscle is known to have a significant effect upon a muscle's ability to generate subsequent force [71, 72, 77]. PAP is a phenomenon where muscular performance is acutely enhanced when preceded by maximal or near-maximal neuromuscular activation exercises [69, 71, 72]. It has been proposed that PAP may increase the rate of acceleration attained with loads between zero and peak isometric force, thus shifting the load (force)–velocity relationship upward and to the right (making it less concave) [3]. For example, 1 min after inducement of PAP (via a 6 s maximal voluntary contraction) the load–velocity relationship shifted significantly upward and the maximal power of the muscle (adductor pollicis) was increased [78]. Mechanisms through which PAP may improve subsequent physical performance include enhanced central output to motor neurons [69], increased reflex electrical activity in the spinal cord [79] and phosphorylation of myosin regulatory light chains [80, 81], which increase Ca^{2+} sensitivity of the myofilaments [82]. PAP may also increase the concentration of sarcoplasmic Ca^{2+}, which, in turn, can increase actin–myosin cross-bridge cycling [83]. Completion of PAP-inducing pre-loading can enhance performance in short-duration tasks, such as jumping [74, 75, 84, 85] and sprinting [76, 86, 87], with heavy-resistance exercises [>85 % of 1 repetition maximum (1RM)], such as bench presses [88], back squats [76, 89, 90] and Olympic lifts [91], traditionally used to induce the PAP response. However, the practicality of completing such exercises in a competition setting is limited. In more recent times, increases in power output of 2–5 % have been elicited via completion of more practical, ballistic-style, pre-loading activities, such as drop jumps [92, 93] and weighted jumps [94–96].

The success of a pre-loading exercise in generating a PAP response depends on the balance between fatigue and potentiation [69]. This balance is affected by numerous factors, including training experience [75], the transition phase duration [97] and the intensity of the pre-loading activity [3]. The load to be moved in a pre-loading exercise bout is important to consider, with higher loads associated with a greater PAP response [98–100]. Henneman's size principle [101, 102] likewise suggests that higher rather than lower loading should more effectively increase activation of the motor units in type II muscle fibres, which has been confirmed in in vitro studies [103, 104]. However, higher loads are associated with a greater concomitant increase in fatigue, which may eliminate the potential for performance enhancement if a sufficient transition phase is not observed. According to a recent meta-analysis [105], exercises of moderate intensity (60–84 % 1RM) are ideal for eliciting a PAP response, in comparison with very high-intensity exercises (>85 % 1RM), independent of an athlete's training experience [106], perhaps due to increased contractile activity leading to increased muscle damage. However, athletes with >3 years of resistance training experience, where training adaptation may protect against muscle damage, appear more likely to respond optimally to pre-loading activities [105, 107]. In addition, muscle fibre type has been reported to influence the level of PAP response, with persons possessing a higher percentage of type II postulated to achieve a greater PAP response. In support of this, a positive correlation ($r = 0.63$, $P = 0.01$) between muscular strength (absolute and relative) and counter-movement jump (CMJ) peak potentiation has been reported 12 min after completion of a 3 repetition maximum (3RM) back squat stimulus [75]. The transition duration is also important to consider, because while potentiation of a muscle twitch is greatest immediately following a PAP stimulus [108–110], the same cannot be said for subsequent performance. Improvements in power output can occur after 5 min transitions [81], 8–12 min transitions [75, 89, 97] and even 18.5 min transitions [107], with a transition duration of 7–10 min deemed optimal for eliciting peak power outputs in experienced individuals [75, 105, 111]. Individual responses can vary, though [75, 97]; thus, coaches should determine each individual athlete's optimal transition duration to maximize their power-generating capabilities in a subsequent exercise task. Finally, although some researchers have reported no improvement or a negative impact on performance following PAP [112–114], this outcome may be partially explained by methodological differences between studies [3, 83].

In summary, several factors need to be considered when designing a PAP-inducing, pre-loading exercise bout, including an individual's training experience and the intensity at which the bout is completed. Exercises such as drop jumps completed as part of a pre-loading bout appear to induce a PAP response and yield substantial improvements in subsequent exercise tasks in which maximal power production is a key determinant.

2.4 Psychological Mechanisms

The warm-up period is recognized as an opportunity to mentally prepare for an upcoming event by providing time for athletes to concentrate on the task ahead. It is well recognized that many athletes complete some form of mental preparation prior to competition tasks [115]. Typical strategies include visualization, saying of cue words, attentional focus and preparatory arousal ('psyching-up') [11, 116]. These strategies are designed to narrow an individual's attention and build their self-confidence [116]. Athletes competing in various sports, such as water polo [117], football [118] and tennis [119], have shown improvements in task execution following use of prior mental rehearsal techniques. Bench press force production can also be enhanced by psyching-up [115]. It is known that elite athletes often use mental preparation tasks more regularly in both training and competition than recreational and novice athletes [120], with the use of mental performance strategies prior to competition deemed a distinguishing characteristic of successful Olympians [121]. Although the focus of this review is primarily on the physiological and performance aspects of warm-up, the information highlighted in this section is an important consideration for the real-world implications of effective warm-up strategies. Psychological feedback, including the athlete's and their coach's comfort with warm-up routines for future use, should be evaluated alongside physiological measures in future studies.

3 Passive Warm-Up Strategies and Exercise Performance

An increase in T_{muscle} of 1 °C can enhance subsequent exercise performance by 2–5 % [15]. Unlike active warm-up, passive warming permits an increase in core temperature (T_{core}) and/or T_{muscle} without depletion of energetic substrates. Much of the early research in this area has been laboratory based, with increases in body temperature achieved via external heating methods, such as hot showers/baths. These types of passive warm-ups are, however, not often practical in the field. However further investigations of passive warm-up strategies have been prompted, given that (1) T_{muscle} begins to decline immediately following exercise cessation; (2) appreciable declines occur as early as ~15–20 min post-exercise [122, 123]; and (3) there is often a lengthy period between the end of the warm-up and the start of competition (the transition phase).

3.1 Hot Showers, Baths, Heated Garments and Blizzard Survival Jackets

Passive elevation of T_{muscle} was first achieved via the use of hot showers (~47 °C), lasting 8–10 min, and/or baths, both of which were linked with improvements in the total work completed in a subsequent exercise bout [12] and swimming performances over 50, 200 and 400 m distances [124, 125]. Hot water immersion (~42.8 °C), combined with electric blankets applied to the lower body, also increased power output (by ~22 %) in a 6 s maximal cycle sprint task [21]. Recently, however, the way in which passive warm-up strategies are employed has changed, largely because of the timing constraints incurred during competition [4, 123]. It is not uncommon for competitive athletes to complete their active warm-up and then have to wait 10–40 min in a changing room, call room or marshalling area before their event begins [4, 123, 126–128]. This delay may reduce the beneficial effects of the pre-competition warm-up, given that T_{muscle} begins to decline immediately following exercise cessation, with a significant reduction occurring ~15–20 min after exercise termination [4, 123]. While it has been shown on several occasions that reducing the transition duration from ~40 to ~10 min improves subsequent performance [123, 126, 129], it is usually not possible to alter a competition schedule by such a large margin. In light of this, it has been postulated that the decline in body temperature during the transition phase could be offset by combining an athlete's sport-specific active warm-up with passive warming techniques. However, until recently, the feasibility of combining these two warm-up strategies was limited, with the notion of athletes showering in the last 10–20 min before competition often being impractical. The emergence of new methods of passive heat maintenance, such as heated athletic garments (e.g. Adidas Clima365, AG, Germany) and blizzard survival jackets (e.g. those produced by Blizzard Protection Systems Ltd, Bangor, UK), provide practical passive warming alternatives.

Heated athletic garments have battery-powered heat filaments sewn into the fabric fibres, allowing them to be used across a wide range of athletic activities. Combining an active cycle ergometer warm-up with application of additional passive heat maintenance via heated tracksuit pants worn during a 30 min transition phase yielded a substantial improvement in T_{muscle} maintenance (heated garment use resulted in a 1 °C higher T_{muscle} at a depth of 0.01 m and a 0.4 °C higher T_{muscle} at 0.03 m than when no additional heated was applied) within the transition, and ~9 % enhancement in both peak and relative power output during a sprint cycling task [4]. In another study conducted by the same group, T_{muscle} remained elevated during the transition and was greater immediately prior to the start of a sprint cycling task when heated tracksuit pants were worn during the transition phase (36.9 ± 0.3 °C) and during the active warm-up (37.0 ± 0.2 °C) compared to control (36.6 ± 0.3 °C) [130]. However, wearing heated tracksuit pants during the active warm-up as well as during the transition phase did not provide additional performance benefit [130]. The wearing of blizzard survival jackets has also been shown to elicit a 65 % increase in tympanic temperature and improve performance in a 20 m sled sprinting task [129]. Furthermore, an active warm-up followed by application of a blizzard survival jacket during a 15 min transition phase produced faster repeat-sprint performance (6.96 ± 0.14 s versus control 7.01 ± 0.16 s) in elite rugby players [5]. The reduction in T_{core} during the transition was minimized when the blizzard jackets were worn (−0.19 ± 0.08 °C) versus control (−0.55 ± 0.10 °C) [5]. As a result, participants began the subsequent criterion testing bout with an elevated T_{core}.

In summary, although the use of passive warm-up alone is not commonplace, the idea of using it to maintain an elevated body temperature throughout the transition phase is gaining traction. Passive heat maintenance via the wearing of heated tracksuit pants or blizzard survival jackets appears to be an effective method for attenuating the decline in T_{muscle} and/or T_{core} during lengthy transition phases, and subsequently improving exercise performance. Furthermore, it is likely that passive warming techniques may be applied to other situations in which it is difficult to maintain T_{core} via metabolic heat production alone, such as between repeated exercise bouts (e.g. multiple races within a swimming meet) separated by periods of low to moderate activity. Further research is required to determine the optimum use of such devices, including garment temperature, the length of time for which the garment(s) should be worn, when in the competition timeline the garment(s) should be used, and the specific placement of the passive heat source on the body for individual sports.

4 Active Warm-Up Strategies and Exercise Performance

Active warm-up is the most widely chosen warm-up strategy for pre-competition preparation. The effectiveness of an active warm-up strategy is determined largely by its composition, including the intensity and duration of the physical tasks completed, as well as the length of the transition phase. For each of the three individual sports we reviewed, we have confined our discussion to the effects of active warm-up on single exercise tasks (e.g. an 800 m running time-trial). For team sports, we have focused on reviewing studies that examined the effects of active warm-up on actual game play, simulated game play or relevant sport-specific performance tests (e.g. repeat-sprint tasks for team sports).

4.1 Running

Competitive runners competing across all distances ranging from sprint events (100–400 m) to middle-distance (800–1500 m) and long-distance (>1500 m) events typically complete some form of active warm-up prior to competition. For the current review, ten papers met the selection criteria, of which eight demonstrated improved running performance following an active warm-up (Table 1). Only one study investigated if active warm-up induced biomechanical changes, with shoulder lean, hip flexion and forward lean deemed to have improved [87]. However, in the same study, performance times for 36.6 m sprint sled pulls did not improve following an active warm-up involving sled pulls with different mass loadings [87]. In another study, a set of 5 × 40 m efforts completed at near-race-pace intensity (90–95 % $\dot{V}O_{2\max}$) resulted in faster 50–60 m split times in a subsequent 60 m sprint than when only a single near-race-pace effort was completed [131]. All of the studies utilized a sprint-oriented (<400 m) test, except for one study in which 800 m running performance was investigated. In that study, athletes completed an active warm-up involving ‘jogging’, mobility drills and strides with or without a 200 m effort at 800 m race pace, prior to a 20 min transition period [128]. Subsequent performance in an 800 m time-trial was ~1 % faster when a race-pace effort was included, with pacing differences in the latter part of the effort. It appears that completion of at least one race-pace effort (of at least 25 % of the distance to be raced) is necessary to sufficiently prime runners for a middle-distance event, while completion of multiple near-race-pace efforts can improve sprint performance.

The most common active warm-up strategy we investigated involved completion of several repetitions of a back squat. One study reported similar performance times following no warm-up or a warm-up of 3 × 3 back squats (90/100 % 1RM) [132], while the remaining four studies required participants to complete one set at between 60 % and 90 % 1RM, resulting in superior sprint performance over 20, 30 and 40 m distances in comparison to when no back squats were completed [76, 133–135]. Another popular active warm-up strategy involves the use of drop jumps. A brief active warm-up entailing 5 min of ‘jogging’, dynamic stretches and three drop jumps improved (by 5 %) 20 m sprint performance in comparison to when no drop jumps were completed [93]. These findings were confirmed by another study, where completion of 2 × 5 drop jumps from a height of 0.75 m elicited faster 50 m sprint times (by ~2 %) [136]. In addition, these researchers investigated the optimal transition duration after which sprint performance should commence, with a transition phase of 15 min found to elicit the best performances [136]. The remaining nine studies utilized transition durations of 1 min [93, 133], 4 min [76, 87, 132, 134] and 10 min [131, 135], with only one study extending the transition phase to 20 min [128]. Given that the marshalling time in competitive running events, particularly track events, can last between 10 and 20 min [128], arguably a focus for future studies should be to employ more competition-realistic timelines.

In terms of recommendations, it appears that completion of at least one race-pace effort for middle-distance races and a set of at least five near-race-pace efforts for sprint races results in subsequent faster running performance. For sprint events, performing a set of heavy-resistance exercises, such as back squats, may also enhance performance, though the feasibility of completing such exercises in the competition environment is questionable. Finally, much of

Table 1 Performance, physiological and biomechanical changes following active warm-up in running

References	Participants	Warm-up		Post warm-up measures				
		Volume	Intensity	Changes	Transition (min)	Criterion test	Performance results	Physiological/biomechanical results
Byrne et al. [93]	29 T (M)	WU_1: 5 min	'Jog'	NS	1	20 m	Overall time: WU_2 (2.2 %) < WU_1*	–
		WU_2: same as WU_1 + 10 dynamic stretches					WU_3 (5 %) < WU_1*	
		WU_3: same as WU_2 + 3 drop jumps					WU_3 (2.9 %) < WU_2*	
Smith et al. [87]	24 T: 12 M, 12 F	WU_1: 4 min cycle	50–70 % HR_{max}	–	4 ('slow' walk)	36.6 m	Overall time: similar	Shoulder lean: WU_4 + WU_3 > WU_2; WU_4 + WU_3 > WU_1*;
		36.6 m	Max sprint					
		18.3 m	Max sprint					
		WU_2: same as WU_1 + 18.3 m	Sled sprint 10 % BM					Hip flexion: WU_4 + WU_3 > WU_2 + WU_1*;
		WU_3: same as WU_1 + 18.3 m	Sled sprint 20 % BM					
		WU_4: same as WU_1 + 18.3 m	Sled sprint 30 % BM					Forward lean: WU_4 + WU_3 > WU_2 + WU_1*
Ingham et al. [128]	11 T: 7 M, 4 F national/international level	WU_1: 10 min	'Jog'	La^-: WU_2 > WU_1*	20	800 m	Overall time: WU_2 < WU_1*; split time (400–500; 700–800): WU_2 < WU_1	La^-: similar
		Mobility drills						Total VO_2: WU_2 > WU_1*;
		6 × 50 m strides	RP					
		WU_2: 10 min	'Jog'					Peak VO_2: WU_2 > WU_1;
		Mobility drills						
		2 × 50 m strides	RP					Mean VO_2 response time: similar
		200 m	RP					
Lim et al. [132]	12 T (M)	WU_1: 0		NS	4	30 m	Overall time: similar	–
		WU_2: 3 (3 × 3 s) IKE	Max (2 min rest/set)					
		WU_3: 3 (3 × 3 s) IS	100 % 1RM					
		WU_4: 3 (3 × 3 s) BS	90 % 1RM					

Table 1 continued

References	Participants	Warm-up		Post warm-up measures				
		Volume	Intensity	Changes	Transition (min)	Criterion test	Performance results	Physiological/biomechanical results
Watterdale [131]	5 T (M)	WU_1: 0		NS	10	60 m	Overall time: similar	–
		WU_2: 10 min	'Jog'				Final 10 m: $WU_3 < WU_2$	
		7 min	Mobility drills					
		5 × 40–50 m	90–95 % VO_{2max}					
		WU_3: 10 min	'Jog'					
		1 × 40–50 m	90–95 % VO_{2max}					
Bomfim Lima et al. [136]	10 T (M)	WU_1: 0		NS	T_1: 5	50 m	Overall time: $WU_2 + T_2$ (2.4 %) $< WU_1 + T_2$*; $WU_2 + T_3$ (2.7 %) $< WU_1 + T_2$*	–
		WU_2: 2 × 5 drop	15 s rest/ jumps		T_2: 10			
		jumps (0.75 m)	3 min rest/ sets		T_3: 15			
Ronnestad and Ellefsen [133]	9 T (M)	WU_1: 7 min	'Jogging'	–	1	40 m	Overall time: $WU_3 < WU_1$*; $WU_1 + WU_2$: similar	–
		3–4 × 40 m	'Sub-maximal'					
		15 × BhS	BW					
		WU_2: same as WU_1 + 15 × BhS	With WBV (30 Hz)					
		WU_3: same as WU_1 + 15 × BhS	With WBV (50 Hz)					
Rahimi [134]	12 T (M)	WU_1: 0		NS	4	40 m	Overall time: WU_2 (1.1 %), WU_3 (1.8 %), WU_4 (3 %) $< WU_1$* $WU_4 < WU_2$*	–
		WU_2: 2 × 4 BS	60 % 1RM					
		WU_3: 2 × 4 BS	70 % 1RM					
		WU_4: 2 × 4 BS	85 % 1RM					
McBride et al. [76]	15 T (M)	WU_1: 5 min cycle	70 rpm	–	4 ('slow' walk)	40 m	Overall time: $WU_2 < WU_3$; WU_2 (−0.9 %) $< WU_1$*; 0–10 m: WU_2 (−1.4 %) $< WU_1$	–
		WU_2: 5 min cycle	70 rpm					
		4 min walk	'slow'					
		3 × BS	90 % 1RM					
		WU_3: 5 min cycle	70 rpm					
		4 min walk	'slow'					
		3 × CMJ	30 % 1RM (BS)					

Table 1 continued

References	Participants	Warm-up		Post warm-up measures				
		Volume	Intensity	Changes	Transition (min)	Criterion test	Performance results	Physiological/biomechanical results
Matthews et al. [135]	20 T (M)	WU_1: 20 m WU_2: 20 m 5 × BS	Max sprint Max sprint 5RM	NS	10	20 m	Overall time: WU_2 (0.1 s) < WU_1*	–

1RM 1 repetition maximum, *5RM* 5 repetition maximum, *BhS* back half-squat, *BM* body mass, *BS* back squat, *BW* body weight, *CMJ* counter-movement jump, *F* female, *HR* heart rate, HR_{max} maximum heart rate (bpm), *IKE* isometric knee extension, *IS* isometric squat, *M* male, *m* metre, *max* maximal, *min* minute, *NS* not stated, La^- blood lactate concentration (mmol/L), *RP* race pace, *rpm* revolutions per minute, *s* second, *T* trained runners, VO_2 oxygen uptake, VO_{2max} maximal oxygen uptake, *WBV* whole-body vibration, *WU* warm-up intervention

* $P < 0.05$

the existing research has been conducted in sprint performance, so less is known about optimal warm-up strategies for middle- and long-distance running events.

4.2 Cycling

Cyclists competing in events on the road and the track in both sprint and endurance-focused events typically complete a warm-up either on a portable ergometer or on the competition surface itself. Much of the research conducted into endurance cycling performance has utilized time to exhaustion testing as the criterion task, with participants required to 'pace' themselves according to their VO_2 or heart rate (HR). In this review, however, we chose to examine only studies in which the criterion task sought to simulate a competitive event with a clearly defined end-point. In keeping with these criteria, a total of five studies were chosen for review (Table 2). Each of these studies investigated the influence of warm-up on sprint events lasting 6–60 s in duration. In terms of warm-up duration and intensity, reducing the duration and the intensity of the initial aerobic portion (from 20 to 15 min) and the number of activation sprints completed (1 vs 4) resulted in higher peak power outputs during a 30 s Wingate test [137]. In this example, it appears that the change in warm-up structure likely reduced fatigue, providing a better balance between fatigue and performance potentiation.

Two groups have examined the influence of PAP-inducing exercises on sprint cycling performance. The addition of 4 × 4 dynamic contractions (four pedal revolutions against heavy resistance) to an existing warm-up involving a 15 min aerobic effort [60–70 % of maximum heart rate (HR_{max})] and a single 6 s sprint resulted in a faster time to maximal velocity and higher peak power output during a subsequent 6 s sprint [138]. Additionally, participants reached maximal velocity quickest after only a 4 min transition, whereas the highest mean power output was recorded after a 16 min transition phase. In support of these findings, the completion of 2 × 5 deadlifts enhanced peak power output within the first 5 and 10 s of a 30 s sprint bout [139] following a 10 min transition phase. It appears that short-duration (5–10 s) sprint performance (peak power and mean power output) can be enhanced following completion of a minimum of two sets of 4–5 repetitions of a dynamic heavy-resistance exercise prior to a 10–16 min transition phase.

The composition of an active warm-up strategy also appears to depend on the duration of the criterion task. In two studies conducted by the same research group [140, 141], the same three active warm-up strategies were examined. Each strategy involved participants completing a total of 5 min of cycling at 40 % of their peak aerobic power, followed by 1 min at either 40, 80 or 110 % of peak aerobic power, with a 10 min transition phase then being observed. Participants performed either a 60 s maximal sprint [140] or a 30 s maximal sprint [141]. In both studies, La^- was increased by the active warm-ups and remained elevated up until the time-trial start in the 110 % condition (∼4 mmol) versus the 80 % (∼2 mmol) and 40 % (∼1 mmol) conditions. While there was no difference in mean power output during the 60 s effort [140], mean power output during the 30 s sprint was highest following the 40 % condition compared with the 80 and 110 % conditions [141], suggesting that residual acidosis has a greater effect on performance in shorter (i.e. 30 s) rather than longer (i.e. 60 s) sprint events.

In summary, for cycling, it appears that longer, higher-intensity aerobic warm-up strategies do not translate into better sprint cycling performance in comparison with relatively shorter, lower-intensity aerobic efforts followed by a few activation sprint efforts. Addition of several sets of dynamic heavy-resistance exercises towards the end of an active warm-up should promote sprint cycling performance but might only be practical in a training session. The duration of the criterion task is also important to consider, as 'pure' (i.e. $\leq$30 s) sprint events might be more sensitive to fatigue induced by a prior active warm-up than longer events (i.e. 30–60 s). Finally, there is a lack of studies examining the influence of active warm-up on simulated endurance competition events (e.g. a 4000 m individual pursuit). Future research should seek to rectify this issue.

4.3 Swimming

Pool-based warm-ups are the most commonly utilized type of active warm-up strategy for swimmers competing at all levels, with many coaches believing that these are superior to dry-land-based warm-ups as they assist swimmers in gaining a 'feel for the water' [142]. Of the nine studies in the review, four [123, 126, 143, 144] demonstrated improvements in performance following completion of an active pool or dry-land-based warm-up, while the remaining five studies [145–149] reported no improvements in swimming performance following active warm-up completion (Table 3). Three studies directly compared the influence of a pool-based warm-up on sprint swimming performance, with varying results. Significantly faster (100 m freestyle [144]) or similar (50 m freestyle [145, 146]) performances were recorded following a 1000 m pool-based warm-up compared with no warm-up. The improved performance occurred [144] following completion of a set of short-duration (25 m) race-pace efforts within the 1000 m warm-up, while in the remaining two studies [145, 146], swimmers were simply requested to complete 1000 m at a 'freely' chosen exercise intensity. In addition, swimmers who completed a set of race-pace efforts produced faster 50 m split times [144]. Completion of at least one set of race-pace efforts during the pool warm-up appears necessary to sufficiently prime swimmers for an upcoming sprint swim event.

In terms of total pool warm-up volume, three studies specifically compared the influence of short (91.4 m) and long-duration (457.2–1200 m) pool warm-ups on subsequent sprint (45.7 m) swimming performance. Two of these studies [147, 149] reported that the total volume had no influence on subsequent performance, while the remaining study reported faster sprint swimming times following a pool warm-up of ∼1200 m in volume in comparison with a 91.4 m warm-up or no warm-up [143]. It appears that the significantly higher HR reported following the longer-duration warm-up may have positively influenced subsequent sprint performance by elevating cardiac output prior to the start and potentially speeding VO_2 kinetics. It could also be speculated that the shorter warm-up and the no-warm-up conditions may not have altered T_{muscle} significantly from baseline. Individual differences were observed, however, with 19 % of participants swimming faster after a short-duration warm-up and 37 % swimming faster after no warm-up at all. It seems that the total pool warm-up volume can influence subsequent performance; however, individual responses can vary substantially. In terms of dry-land-based warm-ups, three research groups reported that either upper body vibration [147], an exercise routine including skipping and vertical jumps [149] or heavy-resistance exercises (87 % 1RM back squats) [148] yielded swimming performances similar to those produced following a pool-based warm-up. These findings indicate that for athletes unable to access a pool, variations of a dry-land-based warm-up may be a feasible alternative. It appears that the performance of these exercises induces a PAP response, which most likely underpins subsequent improvements in short-duration events, such as sprint swimming.

In swimming, the duration of the transition phase is of particular importance because competitive swimmers are routinely required to report to the marshalling area ∼15–20 min prior to the start of their race [123, 126], effectively preventing them from completing additional active warm-up activities during this time. Prior to this, swimmers must complete their pool warm-up, change into their race swimsuit and receive any final communications from their coach. Thus, transition phases of 30–45 min are not uncommon [123, 126]. Only limited research has been conducted to quantify the impact of the transition duration on subsequent swimming performance. Reducing the transition duration from 45 to 10 min was associated with improvements (∼1.4 %) in 200 m swimming performance [126], but this paradigm does not reflect the competition reality (a ∼15–20 min marshalling period). Similarly, a

Table 2 Performance, physiological and biomechanical changes following active warm-up in cycling

References	Participants	Warm-up		Post warm-up measures					
		Volume	Intensity	Changes	Transition (min)	Criterion test	Performance results	Physiological results	Biomechanical results
Munro [138]	6 T: 4 M, 2 F	WU_1: 5 min 5 min 5 min 30 s 6 s 1.5 min WU_2: same as $WU_1 + 4 \times 4$ pedal strokes WU_3: same as $WU_1 + 4 \times 4$ (5 s IC)	60 % HR_{max} 65 % HR_{max} 70 % HR_{max} 'Acceleration' Max sprint Easy Max sprints, 2 min rest/set 2 min rest/set	NS	T_1: 4 T_2: 8 T_3: 16	6 s	Time required to reach max velocity: $WU_2 + T_1 < WU_1 + WU_3$*	–	Optimal cadence, mean PO: $WU_3 + T_3 > WU_2 + WU_3$*
Thatcher et al. [139]	10 T (M)	WU_1: 0 WU_2: 5 min 1 × 5 DL 1 × 5 DL	 60 W 50 % 1RM 85 % 1RM	La^-, VO_2: $WU_2 > WU_1$*	T_1: 5 T_2: 10 T_3: 20 T_4: 30	30 s (5 s, 10 s, 30 s splits)	–	La^-: $WU_2 + T_2 > WU_1 + T_2$ *; VO_2: $WU_2 + T_1 > WU_1 + T_1$*	PPO: $WU_1 + T_2 > WU_2 + T_2$ for 5 s, 10 s splits*
Wittekind et al. [141]	8 T (M)	WU_1: 6 min WU_2: 5 min 1 min WU_3: 5 min 1 min	40 % PaP 40 % PaP 80 % PaP 40 % PaP 110 % PaP	La^-: WU_3 $(\sim 4) > WU_2$ $(\sim 2) > WU_1$ (1)*	10	30 s	–	HHb: similar	Mean PO: $WU_1 > WU_2 > WU_3$*
Wittekind and Beneke [140]	11 T (M)	WU_1: 6 min WU_2: 5 min 1 min WU_3: 5 min 1 min	40 % PaP 40 % PaP 80 % PaP 40 % PaP 110 % PaP	La^-: WU_3 $(\sim 4) > WU_2$ $(\sim 2) > WU_1$ (~ 1)*	10	1 min	–	La^-: $WU_1 + WU_2 > WU_3$*; VO_2: $WU_3 > WU_2 > WU_1$*	Mean PO: similar
Tomaras and MacIntosh [137]	10 T (M)	WU_1: 20 min 1 × 4 WU_2: 15 min 1 × 1	60–95 % HR_{max} Max sprints, 8 min rest 60–70 % HR_{max} Max sprint	HR_{max}: $WU_1 > WU_2$; LA^-: $WU_1 > WU_2$*	12.5	30 s Wingate test	–	T_{skin}: similar	PPO: $WU_2 > WU_1$*; PATT: $WU_2 > WU_1$*

1RM 1 repetition maximum, *DL* deadlift, *F* female, *HHb* deoxyhaemoglobin, *HR* heart rate (bpm), HR_{max} maximum heart rate, *IC* isometric contraction, *M* male, *m* metre, *max* maximal, *min* minute, *NS* not stated, La^- blood lactate concentration (mmol/L), *PaP* peak aerobic power, *PATT* peak active twitch torque, *PO* power output, *PPO* peak power output, *s* second, *T* trained cyclists, T_{skin} skin temperature, VO_2 oxygen uptake, *W* watts, *WU* warm-up intervention

* $P < 0.05$

Table 3 Performance, physiological and biomechanical changes following active warm-up in swimming

References	Participants	Warm-up			Post warm-up measures					
		Volume (m)	Intensity	Dry-land	Changes	Transition (min)	Criterion test	Performance results	Physiological results	Biomechanical results
Neiva et al. [144]	20 T: 10 M, 10 F	WU_1: 0		–	NS	10	100 m free	Overall, 50 m split time: $WU_2 < WU_1$*	La^-, RPE: similar	1st 50 m SL, SI: $WU_2 > WU_1$*
		WU_2: 300	Easy							
		2 × 100	High SL							
		4 × 50	Drill							
		4 × 50	1st 25 m RP							
		100	Easy							
Al-Nawaiseh et al. [149]	13 T: 9 M, 4 F	WU_1: 365.8	On 6 min	WU_3: 1 min skip, 10 VJ, 365.8 m easy swim, 5 × push offs, 45.7 m kick/swim, 5 × push offs	HR: $WU_2 > WU_1$, WU_3	5	45.7 m free	Overall time: similar	HR: similar	–
		4 × 91.4 drill/swim	On 1.40 min							
		4 × 45.7 kick/swim	On 1 min							
		4 × 22.8	1 RP/1 easy							
		WU_2: 45.7	90 % max							
		45.7	100 % max							
West et al. [123]	8 T: 4 M, 4 F	WU_1: 400	HR 40–60 bpm < HR_{max}	–	T_{core} $WU_1 > WU_2$; La^-: similar	T_1: 20	200 m free	Overall time: WU_1 (∼1.5 %)	T_{core}, HR, RPE: similar;	SR: similar
		200 pull				T_2: 45		< WU_2*	La^-: $WU_1 > WU_2$*	
		200 kick								
		200 drill								
		200 IM								
		4 × 50 free	RP							
		200 free	Easy							
Neiva et al. [145]	10 T (M)	WU_1: 0		–	NS	10	50 m free	Overall time: similar	La^-, RPE: similar	–
		WU_2: 1000	'Freely'							
Neiva et al. [146]	7 T (F)	WU_1: 0		–	NS	10	50 m free	Overall time: similar	La^-, RPE: similar	SR, SL, SI: similar
		WU_2: 1000	'Freely'							

Table 3 continued

References	Participants	Warm-up			Post warm-up measures					
		Volume (m)	Intensity	Dry-land	Changes	Transition (min)	Criterion test	Performance results	Physiological results	Biomechanical results
Balilionis et al. [143]	16 T: 8 M, 8 F	WU_1: 0 WU_2: 45.7 45.7 WU_3: ~1200	 40 % max 90 % max Freely	–	HR: $WU_3 > WU_1$*; RPE: $WU_3 > WU_1$, WU_2*	3	45.7 m free	Overall time: $WU_3 < WU_2$*	HR: $WU_2 < WU_3$	Dive distance, SC, SR: similar
Kilduff et al. [148]	9 T: 7 M, 2 F	WU_1: 300 6 × 100 pull/kick 10 × 50 100	Easy RP Easy	WU_2: 3 × 87 % 1RM BS	NS	8	15 m start free	15 m start time: similar	–	PHF: $WU_1 < WU_2$*; PVF: $WU_1 < WU_2$*
Nepocatych et al. [147]	10 Mast: 4 M, 6 F	WU_1: <400 45.7 m WU_2: 45.7 45.7	 90 % VO_{2max} 40 % VO_{2max} 90 % VO_{2max}	WU_2: 5 × 1 min UBV (22 Hz) WU_3: 5 × 1 min UBV (22 Hz)	HR: $WU_1 >$ WU2*	3	45.7 m free	Overall time: similar	HR: $WU_1 > WU_2$, WU_3; RPE: similar	–
Zochowski et al. [126]	10 T: 5 M, 5 F	WU_1: 300 6 × 100 pull/kick 10 × 50 100	Easy RP Easy	–	HR: $WU_1 > WU_2$*	T_1: 10 T_2: 45	200 m back/free/breast	Overall time: WU_2 (~1.4 %) < WU_1*	HR: $WU_1 > WU_2$*; La^-, RPE: similar	–

1RM 1 repetition maximum, *back* backstroke, *bpm* beats per minute, *breast* breaststroke, *BS* back squat, *F* female, *free* freestyle, *HR* heart rate, HR_{max} maximum heart rate (bpm), *Hz* hertz, *IM* individual medley, La^- blood lactate concentration (mmol/L), *M* male, *m* metre, *Mast* masters swimmers, *max* maximal, *min* minute, *NS* not stated, *PHF* peak horizontal force, *PVF* peak vertical force, *RP* race pace, *RPE* rate of perceived exertion, *SC* stroke count, *SI* stroke index, *SL* stroke length, *SR* stroke rate, *T* trained swimmers, T_{core} core temperature, *UBV* upper body vibration, *VJ* vertical jump, VO_2 oxygen uptake, *WU* warm-up intervention

* $P < 0.05$

transition phase of 20 min yielded performance superior (∼1.5 %) to that of a 45 min transition [123]. The participants' T_{core} remained elevated during the 20 min transition, suggesting that improved maintenance of T_{core} may enhance subsequent exercise performance [123]. In future studies, researchers should ensure that the study format accounts for the lengthy transition phases experienced by competitive swimmers and should identify effective methods for improving T_{core} maintenance.

From the studies reviewed, several recommendations can be made. Swimmers should complete between ∼500 and 1200 m and include at least one set of short-duration race-pace efforts towards the end of their pool warm-up. Swimmers could also incorporate dry-land activities or even passive heat maintenance devices, such as heated athletic garments (as have been trialled in cycling studies) to maintain an elevated body temperature during lengthy transition phases. Finally, much research has been conducted on the influence of warm-up on short-duration (50–100 m) freestyle swimming events, but evidence is lacking for events lasting 200 m or more in freestyle and in other strokes (e.g. breaststroke).

4.4 Football, Rugby and Repeat-Sprint Performance

Athletes competing in field-based team sports, such as football and rugby, typically complete an active warm-up compromising running and mobility exercises, as well as sport-specific drills with or without the ball prior to a competitive match [150]. These pre-match warm-ups on average last ∼30 min, with a ∼12 min transition between the end of the warm-up and the start of the match [5, 127]. A 10–15 min break between the first and second halves is also common [5, 127]. Fourteen studies feature in the review, with nine examining the influence of different pre-match warm-up strategies on performance (Table 4), while the remaining five investigated the efficacy of various re-warm-up strategies completed during the half-time break (Table 5). Five studies demonstrated that a non-sport-specific pre-match warm-up consisting of heavy-resistance exercises, such as back squats [97, 151], back half-squats [152], front squats [151, 153] and leg press exercises [150], enhanced subsequent CMJ, repeat-sprint and reactive agility performance. However, sport-specific warm-ups, including activities such as small-sided games (SSGs), provide additional ergogenic benefits over a generic conditioning warm-up strategy by priming neural pathways and increasing neuromuscular activation [154]. SSGs are designed to simulate the skill and physical/physiological demands of a particular sport by incorporating activities and movement patterns specific to competitive team-sport tasks, such as passing, shooting and ball control activities [155]. The current evidence surrounding SSGs is equivocal, however, with reports of both improvements in CMJ, repeat-sprint and reactive agility performance following 3 × 2 min (2 min rest between) SSGs compared with a standard team-sport active warm-up (mobility drills, sprints and ball drills) [150], and no improvements in reactive agility, vertical jump or sprint performance [156]. A limitation of the latter study [156], however, was that the prescribed warm-up strategy was 22 min in duration, longer than previous recommendations [7], and included static stretching, which is known to impair subsequent performance [157]. An over-long warm-up may needlessly deplete energy stores and decrease heat storage capacity [158], resulting in impaired performance. This theory is supported by work demonstrating that shorter-duration (12/16 min) warm-ups [150, 159] including SSGs produce better performance than longer-duration (22/23 min) warm-ups involving SSGs [156].

The intensity of the pre-match warm-up strategy is also important. An active warm-up completed at an intensity just above the anaerobic threshold was more effective than a warm-up performed below the anaerobic threshold [160]. While transition phases of 3 min [152, 153], 6 min [153] and 8 min [97] have resulted in improved subsequent CMJ and repeat-sprint performance, this finding is not consistent with similar improvements in 20 m sprint and vertical jump performance reported following transition phases ranging from 4 to 9 min in the same study [161]. Although these results are informative, in the competition environment, transition phases of ∼12 min in duration are the norm, with some sports stipulating that pre-match warm-ups must be concluded no later than 10 min prior to match start [162]. Thus, use of other activities, including passive heat maintenance strategies, is of interest in future research.

A number of studies have identified a decline in player work rate [163–165] within the initial phase of the second half in comparison with the corresponding phase in the first half. Several reasons for this have been postulated, but, of pertinence here, sub-optimal preparation as a consequence of no re-warm-up completion during the half-time break [122, 163, 166] may be a contributing factor. Compounding this issue is the fact that at the elite level, in particular, there is limited time during the half-time break for re-warm-up activities to be undertaken with practitioners (e.g. sport scientists, coaches), suggesting that only a ∼3 min window is available [127]. In the only study that investigated a 3 min re-warm-up strategy, players were required to play a two versus two SSG or complete a 5 repetition maximum (5RM) leg press or no re-warm-up at all, with subsequent performance in a repeat sprint, CMJ and football-specific criterion task all shown to be superior following completion of either of the two re-warm-up

Table 4 Performance, physiological and biomechanical changes following active warm-up in football and rugby, and effects upon repeat-sprint performance

References	Participants	Warm-up: Volume	Warm-up: Intensity	Post warm-up measures: Changes	Transition (min)	Criterion test	Performance results	Physiological results	Biomechanical results
Anderson et al. [160]	11 T (M)	WU_1: 0		HR, La^-, RPE: $WU_3 + WU_4 > WU_1 + WU_2$*;	5	RST: 15 × 20 m	Overall time: $WU_4 < WU_1 + WU_2 + WU_3$	–	–
		WU_2: 10 min running	Half the difference between AT and La^-T	T_{core}: WU4 > WU_1, WU_2, WU_3*					
		WU_3: 10 min running	50 % of AT and La^-T						
		WU_4: 10 min running	> AT						
Pringle et al. [159]	28 T (M)	WU_1: 22 min of static stretching, mobility drills, ball drills, SSGs	–	HR: $WU_2 > WU_1$; RPE: similar	5	40 m	Sprint time: $WU_2 < WU_1$*;	–	–
		WU_2: 16 min of mobility drills, ball drills, sprint drills, SSGs				VJ	10, 20 m split time, VJ: similar		
Zois et al. [150]	10 T (M)	WU_1: 3 × 2 min SSGs	3 vs 3 (2 min rest) 70–85 % HR_{max}	T_{core}: $WU_3 > WU_1 > WU_2$;	4	RST: 15 × 20 m sprints	CMJ: $WU_1 > WU_2 > WU_3$; sprint time: $WU_2 < WU_1 < WU_3$;	–	–
		WU_2: 5 min	'Jog'	HR, La^-: $WU_1 > WU_3 > WU_1$					
		5RM leg press				CMJ			
		WU_3: 23 min of strides, mobility drills, ball drills and 40 m sprints				RA	RA: $WU_2 > WU_1 > WU_3$		
Needham et al. [153]	20 T (M)	WU_1: 5 min	'Jog'	–	T_1: 0	CMJ	CMJ: $WU_3 + T_2/T_3 > WU_2 + WU_1$, $WU_3 + T_2/T_3 > WU_3 + T_1$; sprint time: $WU_3 + T_1/T_2/T_3 < WU_2 + T_1/T_2/T_3 < WU_1 + T_1/T_2/T_3$*	–	–
		10 min static stretching			T_2: 3	10 + 20 m max sprint			
		WU_2: 5 min	'Jog'		T_3: 6				
		10 min dynamic stretching							
		WU_3: same as WU_2 + 8 × FS	20 % BM						
Till and Cooke [161]	12 T (M)	WU_1: 5 min	'Jog'	–	T_1: 4	20 m	10, 20 m time, VJ height: similar	–	–
		WU_2: 5 min	'Jog'		T_2: 5	VJ			
		5RM DL			T_3: 6				
		WU_3: 5 min, 1 × 5 TJ	'Jog'		T_4: 7				
		WU_4: 5 min, 3 × 3 s IC KE	'Jog'		T_5: 8				
					T_6: 9				

Table 4 continued

References	Participants	Warm-up		Post warm-up measures					
		Volume	Intensity	Changes	Transition (min)	Criterion test	Performance results	Physiological results	Biomechanical results
Gabbett et al. [156]	14 T: 6 M, 8 F	WU_1: 7 min mobility exercises, static stretching, 15 min ball drills and SSGs	–	NS	0	RA 20 m sprint CoD speed VJ	RA, 20 m sprint, CoD speed, VJ: similar	–	–
		WU_2: same as WU_1 + 15 min skipping, acceleration runs, CoD running, 20 m sprints							
Kilduff et al. [97]	20 T (M)	WU_1: 5 min rowing, mobility exercises		NS	T_1: 0.25	CMJ	Jump height: $WU_1 + T_3 > T_1, T_2, T_4–T_7$*	–	CMJ PPO, peak rate of force development: $WU_1 + T_3 > T_1, T_2, T_4–T_7$*
		3 × 3 BS	87 % 1RM		T_2: 4 T_3: 8 T_4: 12 T_5: 16 T_6: 20 T_7: 24				
Yetter and Moir [99]	10 T (M)	WU_1: 5 min cycling	300 kp	NS	4	RST: 3 × 40 m (3 min rest)	0–10 m time: $WU_3 < WU_1$*; 30–40 m time: $WU_3 < WU_1 + WU_2$*	–	–
		WU_2: 5 min cycling	300 kp						
		5, 4, 3 × BS	30, 50, 70 % 1RM						
		WU_3: same as WU_2 except FS	Same as WU_2						
Chatzopoulos et al. [152]	15 T (M)	WU_1: 3 × 30 m	100 % VO_{2max}	NS	T_1: 3	RST: 3 × 30 m	Overall time: $T_1 < T_2$;	–	–
		10 × BhS	90 % 1RM		T_2: 5		Initial 10 m time: $T_1 < T_2$		

1RM 1 repetition maximum, *5RM* 5 repetition maximum, *AT* anaerobic threshold, *BhS* back half-squat, *BM* body mass, *BS* back squat, *CMJ* counter-movement jump, *CoD* change of direction, *DL* deadlift, *F* female, *FS* front squat, *HR* heart rate, HR_{max} maximum heart rate (bpm), *Hz* hertz, *IC* isometric contraction, *KE* knee extension, *kp* kilo pound, La^- lactate concentration (mmol/L), La^-T lactate threshold, *M* male, *m* metre, *max* maximal, *min* minute, *NS* not stated, *PPO* peak power output, *RA* repeat agility, *RPE* rate of perceived exertion, *RST* repeat-sprint test, *s* second, *SSG* small-sided game, *T* trained team-sport athletes, T_{core} core temperature, *TJ* tuck jump, *VJ* vertical jump, VO_2 oxygen uptake, *WU* warm-up intervention

* $P < 0.05$

Table 5 Performance, physiological and biomechanical changes following active half-time re-warm-up in football and rugby, and effects upon repeat-sprint performance

Reference	Participants	Warm-up: Volume	Warm-up: Intensity	Post warm-up measures: Changes	Transition (min)	Criterion test	Performance results	Physiological results	Biomechanical results
Edholm et al. [169]	22 T (M)	Re-WU_1: 0		HR: Re-WU_2 > Re-WU_1*	15 (2 × 45 min simulated game play)	RST: 2 × 10 m sprints	Sprint time: Re-WU_2 < Re-WU_1*; CMJ: Re-WU_2 > Re-WU_1*; ball possession: Re-WU_2 > Re-WU_1	HR: Re-WU_2 > Re-WU_1*	–
		Re-WU_2: 7 min	'Jogging' 70 % HR_{max} + 'light' calisthenics			2 × CMJ			
Lovell et al. [168]	10 T (M)	Re-WU_1: 0		T_{muscle}: Re-WU_2 > Re-WU_1 + Re-WU_3*; HR, VO_2: Re-WU_2 > Re-WU_3 > Re-WU_1*	15 (2 × 45 min simulated game play)	RST: 3 × 10 m sprints	Sprint time: Re-WU_2, Re-WU_3 < Re-WU_1*, Re-WU_2 < Re-WU_3; CMJ: Re-WU_2, Re-WU_3 > Re-WU_1*	–	–
		Re-WU_2: 5 min	IAE (de/acceleration, forward/backward + CoD running)			CMJ			
		Re-WU_3: 3 × 1 min	WBV (40 Hz), 1 min rest/set						
Zois et al. [167]	8 T (M)	Re-WU_1: 0		RPE: similar Re-WU_2 + Re-WU_3 > Re-WU_1	15 (2 × 26 min intermittent running)	CMJ	RSA: Re-WU_3 > Re-WU_2 > Re-WU_1; LSPT: Re-WU_2 > Re-WU_3 > Re-WU_1	RPE: Re-WU_3 > Re-WU_2 > Re-WU_1	CMJ $velocity_{peak}$: Re-WU_3 > Re-WU_2 > Re-WU_1
		Re-WU_2: 3 min SSG	2 vs 2			RSA			
		Re-WU_3: 5RM leg press				LSPT			
Lovell et al. [166]	7 T (M)	Re-WU_1: 0		HR: Re-WU_2 + Re-WU_3 > Re-WU_1*	15 (2 × 16.5 min intermittent running)	RST: 40 × 15 s (10 s rest)	Total distance covered in RST: Re-WU_2 + Re-WU_3 > Re-WU_1*	T_{core}: Re-WU_2 > Re-WU_3 + Re-WU_1*	–
		Re-WU_2: 7 min cycle	70 % HR_{max}						
		Re-WU_3: 7 min RSA drill	70 % HR_{max}						
Mohr et al. [122]	25 T (M)	Re-WU_1: 0			15 (2 × 45 min game play)	RST: 3 × 30 m (25 s rest)	Sprint time: Re-WU_2 < Re-WU_1	HR: similar	–
		Re-WU_2: 7 min running	HR: 70 % HR_{max} ~135 bpm					T_{muscle} (~2 °C), T_{core} (~1 °C): Re-WU_2 > Re-WU_1*	

5RM 5 repetition maximum, *bpm* beats per minute, *CMJ* counter-movement jump, *CoD* change of direction, *HR* heart rate, HR_{max} maximum heart rate (bpm), *Hz* hertz, *IAE* intermittent agility exercise, *LSPT* Loughborough soccer passing test, *M* male, *m* metres, *min* minute, *Re-WU* re-warm-up intervention, *RPE* rate of perceived exertion, *RSA* repeat-sprint ability, *RST* repeat-sprint test, *s* second, *SSG* small-sided game, *T* trained team-sport athletes, T_{core} core temperature, T_{muscle} muscle temperature, $velocity_{peak}$ peak velocity, *WBV* whole-body vibration, *WU* warm-up intervention

* $P < 0.05$

strategies [167]. Regarding longer re-warm-up strategies, completion of a 5 min repeat-sprint drill enhanced repeat-sprint and CMJ performance in comparison with no re-warm-up [168], while a 7 min repeat-sprint drill or cycle exercise prompted an increase in the distance covered within the second half [166]. Improvement in second-half performance was also correlated with better T_{core} maintenance resulting from completion of either of the two active re-warm-up strategies [166].

Finally, a 7 min half-time re-warm-up strategy involving continuous running at 70 % HR_{max} improved [169] and maintained repeat-sprint performance [122] in comparison with no activity. Ball possession in the second half was also greater following a continuous sub-maximal re-warm-up [169], while the decline in T_{core} and T_{muscle} was attenuated during a 15 min half-time break (0.97 ± 0.1 and 2.17 ± 0.1 °C higher than control, respectively) [122] with this re-warm-up strategy. It appears that completion of an active re-warm-up during the half-time break can enhance subsequent performance, and although only a small time-frame has been identified (~3 min) for a re-warm-up to be completed, it is known that steady-state moderate-intensity exercise increases T_{muscle} at a rate of 0.15–0.38 °C per minute [45, 170]. Thus, players may still be able to partially offset the 1.5 °C to 2.0 °C reduction shown to occur in T_{muscle}/T_{core} during a 15 min half-time break [122] or substitution periods.

In summary, the inclusion of SSGs in a pre-match warm-up strategy for sports such as football and rugby may enhance subsequent performance but only if the duration of the warm-up strategy is ≤16 min. The pre-match warm-up should also be completed as close to match start as possible, with passive heat maintenance strategies considered if the transition duration exceeds 10 min. Completion of a 3–7 min half-time re-warm-up strategy involving activities such as SSG, repeat-sprint drills or continuous running can also enhance second-half and repeat-sprint performance by minimizing the decline in T_{core}/T_{muscle} during the half-time break.

5 Future Directions

Although completion of a pre-event warm-up is common practice in sports, several questions remain unanswered. Much research has investigated the influence of warm-up completion on sprint and sustained high-intensity performance, with few studies on endurance performance. In addition, researchers should expand study designs beyond simply comparing one warm-up intervention strategy, either passive or active, with a control strategy in which no warm-up is performed, given that these days it is virtually standard for athletes to complete some form of pre-event warm-up. Studies in which multiple warm-up strategies are examined and then compared for their efficacy are needed to provide more meaningful information. Access to equipment and transition/marshalling period length have been overlooked, and future studies should replicate competition conditions as closely as possible for external validity. Finally, within cycling and rugby, passive heat maintenance strategies, such as heated athletic garments, have been shown to assist in maintaining some of the beneficial temperature effects induced by an active warm-up throughout lengthy transition phases. It would be pertinent to examine the influence of passive heat maintenance in sports such as athletics and swimming, where the transition phase also extends beyond ~10–15 min.

6 Conclusions

Despite a previous scarcity of well-controlled studies and minimal empirical evidence supporting coaches' and athletes' belief that a pre-event warm-up is essential for optimal performance, extensive research over the past decade has provided substantial support for pre-competition warm-up completion. Passively or actively elevating T_{muscle} can markedly influence subsequent exercise performance via mechanisms such as increases in ATP turnover and muscle cross-bridge cycling rate, as well as improvements in muscle fibre functionality and conduction velocity. Athletes competing in sprint and sustained high-intensity events seem the most likely beneficiaries of elevations in body temperature due to increases in muscle glycogen availability and the rate of force development. A speeding of VO_2 kinetics following completion of a priming exercise bout may also enhance subsequent endurance performance, possibly via sparing of finite anaerobic stores and/or prompting an increase in motor unit recruitment, such that the 'strain' placed on each individual muscle fibre is reduced. The short-term contractile history of skeletal muscle has also been shown to have a significant effect upon a muscle's ability to generate force. Athletes seeking to harness the benefits of PAP should complete several sets of ballistic exercises, such as drop jumps or CMJs, while wearing a weighted vest, and should experiment with different transition durations to determine the optimal length.

The majority of the recent research supports the notion that a well-structured active warm-up elicits improvements in performance across a wide range of sports, while passive heat maintenance devices, such as heated athletic garments and blizzard survival jackets, can preserve the beneficial temperature effects induced via an active warm-up during lengthy transition phases. The initial aerobic portion of an active warm-up should be shortened to <15 min, and a few (e.g. 1–5) activation sprints/race-pace efforts or dynamic PAP-inducing exercises should be completed to elicit improvements in subsequent sprint and sustained high-intensity events. Finally, for team sports, such as football or rugby, the addition of SSGs to the pre-match warm-up, as well as completion of a brief, sub-maximal active re-warm-up involving activities such as repeat-sprint drills or continuous running during the half-time break, elicits improvements in repeat-sprint and second-half performance.

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