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Warm Up II

Performance Changes Following Active Warm Up and How to Structure the Warm Up

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Abstract

While warm up is considered to be essential for optimum performance, there is little scientific evidence supporting its effectiveness in many situations. As a result, warm-up procedures are usually based on the trial and error experience of the athlete or coach, rather than on scientific study. Summarising the findings of the many warm-up studies conducted over the years is difficult. Many of the earlier studies were poorly controlled, contained few study participants and often omitted statistical analyses. Furthermore, over the years, warm up protocols consisting of different types (e.g. active, passive, specific) and structures (e.g. varied intensity, duration and recovery) have been used. Finally, while many studies have investigated the physiological responses to warm up, relatively few studies have reported changes in performance following warm up. The first part of this review critically analyses reported changes in performance following various active warm-up protocols.

While there is a scarcity of well-controlled studies with large subject numbers and appropriate statistical analyses, a number of conclusions can be drawn regarding the effects of active warm up on performance. Active warm up tends to result in slightly larger improvements in short-term performance (<10 seconds) than those achieved by passive heating alone. However, short-term performance may be impaired if the warm-up protocol is too intense or does not allow sufficient recovery, and results in a decreased availability of high-energy phosphates before commencing the task. Active warm up appears to improve both long-term (≥5 minutes) and intermediate performance (>10 seconds, but <5 minutes) if it allows the athlete to begin the subsequent task in a relatively non-fatigued state, but with an elevated baseline oxygen consumption ($\dot{V}O_2$). While active warm up has been reported to improve endurance performance, it may have a detrimental effect on endurance performance if it causes a significant increase in thermoregulatory strain. The addition of a brief, task-specific burst of activity has been reported to provide further ergogenic benefits for some tasks. By manipulating intensity, duration and recovery, many different warm-up protocols may be able to achieve similar physiological and performance changes. Finally, passive warm-up techniques may be important to supplement or maintain temperature increases produced by an active warm up, especially if there is an unavoidable delay between the warm up and the task and/or the weather is cold. Further research is required to investigate the role of warm up in different environmental conditions, especially for endurance events where a critical core temperature may limit performance.

Warm up is a widely accepted practice preceding nearly every athletic event. However, while warm up is considered to be essential for optimum performance by many coaches and athletes, there is little scientific evidence supporting its effectiveness. Furthermore, the limited research that has been conducted has provided conflicting results. As a result, warm-up procedures are usually based on the trial and error experience of the athlete or coach, rather than on scientific study.

Summarising the findings of the many studies that have investigated the physiological and performance responses to active warm up is difficult. Many of the earlier studies were poorly controlled, contained few study participants and often omitted statistical analyses. Furthermore, active warm-up procedures have differed in their duration, intensity, recovery periods, mode of exercise and whether the warm up was continuous or intermittent in nature. Finally, while many studies have investigated the physiological responses to warm up, relatively few studies have reported changes in performance following warm up.

This review attempts to summarise and draw conclusions from the many disparate studies that have investigated changes in performance following active warm up and how to structure the warm up.

1. Active Warm Up

Warm-up techniques can be broadly classified into two major categories: (i) passive warm up; or (ii) active warm up. Passive warm up involves raising muscle temperature (T_m) or core temperature (T_c) by some external means (e.g. hot showers or baths, saunas, diathermy and heating pads). Active warm up involves exercise and is likely to induce greater metabolic and cardiovascular changes than passive warm up. Active warm up is probably the most widely used warm-up technique. Consequently, many researchers have investigated the effects of active warm up on various performance measures. Typical examples of active warm up include jogging, calisthenics, cycling and swimming. Many of the proposed benefits of active warm up have been attributed to the increased T_m and T_c achieved via active movements of the major muscle groups.[1] However, active warm up may also provide additional ergogenic benefits to those achieved via temperature increases.[2,3] For convenience, performance measures in the following section have been divided into three major categories: (i) short-term – maximal effort for ≤10 seconds; (ii) intermediate – maximal effort for >10 seconds, but <5 minutes; and (iii) long-term – fatiguing effort for ≥5 minutes.

1.1 Short-Term Performance

An increase in T_m following active warm up has the potential to improve short-term performance in many ways. An increase in T_m has been reported to decrease the stiffness of muscles and joints,[4,5] increase the transmission rate of nerve impulses,[6] change the force-velocity relationship[7-9] and to increase glycogenolysis, glycolysis and high-energy phosphate degradation.[10,11] Active warm up may also have additional effects on decreasing muscle stiffness by 'breaking' the stable bonds between actin and myosin filaments.[12] However, despite these positive effects, it is likely to be important that the warm up is not too intense or followed by an inadequate recovery period.

As short-term performance is related to the ability to breakdown high-energy phosphate stores,[13] an intense warm up that decreases the availability of high-energy phosphates has the potential to impair short-term performance. While the majority of studies have reported that active warm up improves short-term performance,[2,14-20] a few studies have reported either no significant effect[14,21,22] or impaired performance[19,23] following active warm up (table I).

Improvements in vertical-jump performance, similar to those reported following passive heating of the thigh (9.6% or 3.1% per °C[8]), have been reported following 3–5 minutes of moderate-intensity jogging (7.2–7.8%; $p < 0.05$[15,18]). Although these authors did not report changes in T_m, it has previously been reported that within 3–5 minutes of the onset of moderate-intensity exercise, T_m rises ~2°C.[24] It can therefore, be estimated that the improvement in vertical-jump performance following active warm up was >3.5% per °C.[15,18] This is consistent with the results of other studies that have reported similar improvements in vertical-jump performance following active warm up (4.2–4.4% per °C[25,26]) and suggests that active warm up improves vertical-jump height via mechanisms in addition to an increase in T_m. In the only study not to report a significant improvement in vertical-jump performance, the warm up was of a very low intensity and consisted of only three practice jumps.[22] Thus, it appears that a moderate-intensity active warm up is able to improve vertical-jump performance and that this is largely attributable to an increase in T_m.

Active warm up has also been reported to significantly improve 27–55m swim time,[14,20] 55m run time[16] and peak power on a cycle ergometer.[2,17,19] While not all of these warm-up protocols were well described, it appears in general that they consisted of ~3–5 minutes of exercise at a moderate intensity. Once again, there is evidence to suggest that improvements in power output following active warm up are slightly greater than those achieved by an increase in T_m alone (2.7% vs 2.3% per °C[2]). In the relatively few studies where active warm up has been reported not to significantly improve short-term performance, it appears that the warm up was either too easy (to sufficiently raise T_m) or too intense (resulting in decreased availability of high-energy phosphates).

It is not surprising that short-term performance was not improved by a low-intensity warm up consisting of calisthenics or a few practice trials.[14,22] In contrast, Hawley et al.[21] argued that cycle peak power was not improved in their study as the untrained participants were becoming fatigued during the warm up (8-minute incremental test). In the two studies reporting a significant decrease in short-term performance following warm up, it appears that the warm up was either too intense and/or there was insufficient recovery between the active warm up and the subsequent task.[19,23] For example, both of these studies used an intensive warm up with no rest between the warm up and the subsequent task. Thus, it appears that a moderate-intensity active warm up is also able to improve short-term swim, run and cycle performance and that once again, this improvement is largely attributable to an increase in T_m.

In summary, it appears that a 3–5 minute warm up of moderate intensity is likely to significantly improve short-term performance in a range of tasks. This improvement appears to be largely, although not entirely, attributable to an increase in T_m. Active warm up does not appear to improve short-term performance when it is of low intensity (e.g. calis-

Table I. Physiological and performance changes in short-term performance following active, general warm up

Study	Subjects	Warm up					Performance task		
		mode	duration (min)	intensity	rest (min)	phys. changes	mode	phys. changes	performance changes[a]
de Vries[14]	13 T males	N	NA	NA		NA	Swim (91m)	NA	Speed: $A_2 > A_1 = N$; $p < 0.05$
		A_1 calisthenics	NR	NA	'Brief'				
		A_2 swim	457m	'Moderate'					
Dolan et al.[2]	4 UT males	N	NA	NA	NA	NA	Cycle	NA	Peak power: $A > N$; $p < 0.01$
		A cycle	NR	~55% $\dot{V}O_{2max}$	6				
Goodwin[15]	10 T males	N	NA	NA	?	T_t: $A = N$; $p < 0.05$	Vertical jump	NA	Height: $A > N$; $p < 0.05$
		A jog	5	65% HR_{max}					
Grodjinovsky and Magel[16]	13 UT males	N	NA	NA	?	NA	Sprint (55m)	NA	Speed: $A_1 = A_2 > N$; $p < 0.05$
		A_1 jog	5	NR					
		A_2 jog + sprint	5+	NR					
Hawley et al.[21]	24 UT males	N	NA	NA	NA	NA	Cycle (30 sec sprint)	NA	Peak power: $A = N$; $p > 0.05$
		A cycle	8	'Moderate'	5				
Margaria et al.[23]	4 UT (sex NR)	N	NA	NA	NA	NA	Run (up stairs)	NA	Speed: $N > A_1 > A_2$
		A_1 stepping	3–9	15/min	0				
		A_2 stepping	3–9	30/min	0				
McKenna et al.[17]	8 UT males	N	NA	NA	NA	NA	Cycle (10 sec sprint)	NA	Peak power/work: $A > N$; $p < 0.05$
	6 UT females	A cycle	5	100–150W	2				
Pacheco[18]	10 MT males	N	NA	NA	NR	NA	Vertical jump	NA	Height: $A_3 > A_2 > A_1 > N$; $p < 0.05$
		A_1 knee bends	3	Low					
		A_2 stretching	3	Low					
		A_3 jog on spot	3	Moderate					
Pyke[22]	45 UT males (5/group)	N	NA	NA	NR	NA	Run (55m)	NA	Speed: $N = A_{1,2,3,4}$; $p > 0.01$
		A_1 2 or 3 × task	NA	Max. effort					
		A_2 2 or 3 × task	NA	75% max. effort			Vertical jump	NA	Height: $N = A_{1,2,3,4}$; $p > 0.01$
		A_3 calisthenics	NA	Low					
		A_4 stretching	NA	Low					

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Table I. Contd

Study	Subjects	Warm up					Performance task		
		mode	duration (min)	intensity	rest (min)	phys. changes	mode	phys. changes	performance changes[a]
Sargeant and Dolan[19]	5 UT males	N	NA	NA	0	NA	Cycle (20 sec sprint)	NA	Peak power: $A_1 > A_2 > N > A_3 > A_4$
		A_1 cycle	6	39% $\dot{V}O_{2max}$					
		A_2 cycle	6	56% $\dot{V}O_{2max}$					
		A_3 cycle	6	74% $\dot{V}O_{2max}$					
		A_4 cycle	6	80% $\dot{V}O_{2max}$					
Thompson[20]	34 UT males	N	NA	NA	5	NA	Swim (27m)	NA	Speed: $A_2 > A_1 = N$; $p < 0.01$
		A_1 calisthenics	NA	NR					
		A_2 swim	110m	Moderate					

a The absence of a p-value indicates that statistical analyses were not performed.

A = active warm up; $\mathbf{HR_{max}}$ = maximum heart rate; **MT** = moderately trained; **N** = no warm up; **NA** = not applicable; **NR** = not reported; **phys.** = physiological; **T** = trained; $\mathbf{T_t}$ = tympanic temperature; **UT** = untrained; $\mathbf{\dot{V}O_{2max}}$ = maximum oxygen consumption.

thenics), causes fatigue, or does not allow sufficient recovery prior to the short-term task. It is likely that performance decrements following an intense warm up are due to a decrease in the availability of high-energy phosphates and/or a build up of metabolites.

1.2 Intermediate Performance

Active warm up has the potential to improve intermediate performance via many of the same temperature-related mechanisms postulated to improve short-term performance (i.e. decreasing stiffness and altering the force-velocity relationship). In addition, active warm up may improve intermediate performance by decreasing the initial oxygen deficit, leaving more of the anaerobic capacity for later in the task. While it appears that prior exercise does not increase oxygen consumption ($\dot{V}O_2$) kinetics,[27,28] warm up may allow subsequent tasks to begin with an elevated baseline $\dot{V}O_2$. Consequently, less of the initial work will be completed anaerobically, leaving more of the anaerobic capacity for later in the task. This hypothesis is supported by the results of many studies that have reported a greater aerobic contribution[29-32] and/or a decreased oxygen deficit[31,33-35] when tasks are preceded by warm-up exercise. An elevated baseline $\dot{V}O_2$ may also indicate that the warm up was of sufficient intensity to significantly raise T_m and/or T_c. However, active warm up that raises temperature (T_m or T_c) or baseline $\dot{V}O_2$ may impair intermediate performance if the active warm up is too intense and causes fatigue.[36]

As a result of very different warm-up routines and performance tests, conflicting results have been reported for the effects of active warm up on intermediate performance (table II). It has been reported that following active warm up, intermediate performance increases,[14,16,32,33,37,38] is unchanged,[14,21,32,33,38-43] or is impaired.[38,39] There appear to be a number of explanations for these conflicting results.

In two of the studies reporting improved intermediate performance, the warm-up exercise caused the task to begin with an elevated $\dot{V}O_2$.[33,38] Consequently, there may have been an initial sparing of

Table II. Physiological and performance changes in intermediate performance following active, general warm up

Study	Subjects	Warm up					Performance test		
		mode	duration (min)	intensity	rest (min)	phys. changes	mode	phys. changes	performance changes[a]
Asmussen and Boje[37]	4 UT males	N	NA	NA	NA	T_r: ↑0.8°C	Cycle (956 kgm)	NA	Work: A > N
		A cycle	30	110W	NR				
Andzel[33]	12 UT males	N	NA	NA		$\dot{V}O_2$: $A_2 > A_1$	Run (1.6km)	NA	Speed: $A_2 > A_1 = N$; $p < 0.05$
		A_1 jog	~6	~120 beats/min	30 sec				
		A_2 jog	~6	~140 beats/min					
De Bruyn-Prevost and Lefebvre[38]	9 UT males and females	N	NA	NA	NA	HR: $A_{2,4} > A_{1,3}$	Cycle (350 or 400W)	HR: $A_1 = A_2 = A_4 > N = A_3$	Time to fatigue: $A_1 = A_3 = A_4 = N > A_2$; $p < 0.05$
		A_1 cycle	5	30% $\dot{V}O_{2max}$	0	$\dot{V}O_2$: $A_{2,4} > A_{1,3}$		$\dot{V}O_2$: $A_2 > A_1 = A_3 = A_4 = N$	
		A_2 cycle	5	75% $\dot{V}O_{2max}$	0	[La⁻]: $A_{2,4} > A_{1,3}$		[La⁻]: $A_1 = A_2 = A_3 = A_4 = N$	
		A_3 cycle	5	30% $\dot{V}O_{2max}$	5			$p < 0.05$	
		A_4 cycle	5	75% $\dot{V}O_{2max}$	5				
de Vries[14]	13 T males	N	NA	NA			Swim (91m)	NA	Speed: $A_2 > A_1 = N$; $p < 0.05$
		A_1 calisthenics	NR	NA	'Brief'	NA			
		A_2 swim	457m	Low					
Genovely and Stamford[39]	5 UT males	N	NA	NA		T_r: $A_2 > A_1 > N$	Cycle (40 sec)	Peak [La⁻]: $A_2 < A_1 = N$	Work: $A_2 < A_1 = N$; $p < 0.05$
		A_1 cycle	60	40% $\dot{V}O_{2max}$	10	[La⁻]: $A_2 > A_1 = N$		$p < 0.05$	
		A_2 cycle	60	68% $\dot{V}O_{2max}$		$p < 0.05$			
Grodjinovsky and Magel[16]	13 UT males	N	NA	NA			Run (402m)	NA	Speed: $A_1 = A_2 > N$; $p < 0.05$
		A_1 jog	5	NR	NR	NA			
		A_2 jog + sprint	5+	NR					
Hawley et al.[21]	24 UT males	N	NA	NA	NA	NA	Cycle (30 sec)	NA	Work: A = N; $p > 0.05$
		A cycle	8	Moderate	5				

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Table II. Contd

Study	Subjects	Warm up					Performance test		
		mode	duration (min)	intensity	rest (min)	phys. changes	mode	phys. changes	performance changes[a]
Massey et al.[40]	14 UT males	N	NA	NA	NA	NA	Cycle (100 revs)	NA	Time: A = N; $p > 0.05$
		A walk/jog	10	Moderate	5				
Mathews and Snyder[41]	50 UT males	N	NA	NA	NA	NA	Run (402m)	NA	Time: A = N; $p > 0.05$
		A walk/jog	NR	Moderate	5–10				
Mitchell and Huston[42]	10 T males	N	NA	NA	NA	$[La^-]$: $A_2 > A_1 = N$	Swim (tethered)	$[La^-]$: $A_2 = A_1 = N$	Time: $A_1 = A_2 = N$; $p > 0.05$
		A_1 swim	360m	70% $\dot{V}O_{2max}$	5	$\dot{V}O_2$: $A_2 > A_1$		$\dot{V}O_2$: $A_2 = A_1 = N$	
		A_2 swim	4 × 46m	110% $\dot{V}O_{2max}$	5	HR: $A_2 > A_1$; $p < 0.05$		HR: $A_2 = A_1 > N$; $p < 0.05$	
Skubic and Hodgkins[43]	8 UT females	N	NA	NA	NA	T_b: $A_3 > A_2 = A_1 > N$	Cycle (160m)		Time: $A_1 = A_2 = N$; $p > 0.05$
		A_1 calisthenics	12 jumps	Low	0	HR: $A_3 > A_2 > A_1 > N$		NA	
		A_2 cycle	8 revs	Moderate	0	$p < 0.05$			
Stewart and Sleivert[32]	9 MT males	N	NA	NA	NA	NA	Run (13 km/h 20% grade)		Time: $A_2 = A_1 > N = A_3$; $p < 0.05$
		A_1 jog	15	60% $\dot{V}O_{2max}$	5			NA	
		A_2 jog	15	70% $\dot{V}O_{2max}$	5				
		A_3 jog	15	80% $\dot{V}O_{2max}$	5				

a The absence of a p-value indicates that statistical analyses were not performed.

A = active warm up; **HR** = heart rate; **$[La^-]$** = blood lactate concentration; **MT** = moderately trained; **N** = no warm up; **NA** = not applicable; **NR** = not reported; **phys.** = physiological; **revs** = revolutions; **T** = trained; **T_b** = body temperature; **T_r** = rectal temperature; **UT** = untrained; **$\dot{V}O_2$** = oxygen consumption; **$\dot{V}O_{2max}$** = maximum oxygen consumption; ↑ = increase.

the anaerobic capacity, leaving more for later in the task. While other studies reporting improved intermediate performance following warm up did not measure $\dot{V}O_2$, it is likely that the warm up (moderate intensity for ≥5 minutes) and the brief recovery period were sufficient to result in an elevated baseline $\dot{V}O_2$ immediately prior to the intermediate performance task.[14,16,37] Although a 5-minute recovery period was used in one study,[32] the warm up involved 'heavy' exercise (15 minutes at 70% maximum oxygen consumption [$\dot{V}O_{2max}$]) which has been reported to significantly elevate $\dot{V}O_2$ above baseline following 6 minutes of recovery.[27] Therefore, while other mechanisms are likely to be involved (i.e. decreased stiffness and an altered force-velocity relationship), it appears that in those studies reporting improved intermediate performance, the active warm up probably caused the subsequent task to begin with an elevated baseline $\dot{V}O_2$.

In contrast, in many of the studies that did not report a significant increase in intermediate performance, the active warm up was unlikely to have caused the subsequent task to begin with an elevated $\dot{V}O_2$. This was because the warm up was of low intensity (≤40% $\dot{V}O_{2max}$[33,38-41]) and/or the recovery period was too long (5–10 minutes[38-41]). In some instances, especially where there was a significant decrease in intermediate performance, an additional possibility is that study participants were becoming fatigued during the warm up.[21,32,38,39] Thus, for active warm up to improve intermediate performance it appears important that the warm up is structured so that study participants begin the subsequent task sufficiently recovered, but with an elevated $\dot{V}O_2$.

1.3 Long-Term Performance

Active warm up is unlikely to improve long-term performance by the same temperature-related mechanisms postulated to improve short-term performance (i.e. decreased stiffness and an improved force-velocity relationship). However, similar to intermediate performance, long-term performance may be improved by elevating baseline $\dot{V}O_2$ prior to the task. Unlike intermediate performance, long-term performance is more likely to be impaired if the warm up depletes muscle glycogen stores[44] and/or increases thermoregulatory strain.[45,46]

Conflicting results have been reported for the effects of an active warm up on long-term performance (table III). Long-term performance has been reported to improve,[16,20,47] remain unchanged[16,48-50] or be impaired[49,51] following an active warm up. Once again, a comparison of the results is made difficult by the use of different warm-up routines, different performance tasks (running, cycling, swimming and bench stepping) and different performance times (5–70 minutes).

Similar to the results reported for intermediate performance, elevation of baseline $\dot{V}O_2$ is a possible mechanism contributing to the improved long-term performance in some studies.[16,48-50] While none of these studies measured $\dot{V}O_2$, two reported a significantly elevated heart rate prior to the long-term performance task.[48,50] Furthermore, the warm-up routines used in the other two studies[16,47] are similar to those previously reported to significantly increase $\dot{V}O_2$.[30,38] Therefore, while other mechanisms may be involved, it appears that in the majority of studies reporting improved long-term performance (5–25 minutes), the active warm up probably allowed the subsequent task to begin with an elevated $\dot{V}O_2$.

In contrast, in many of the studies that did not report a significant increase in long-term performance, the warm-up protocol appears unlikely to have elevated $\dot{V}O_2$ immediately prior to the task.[16,48,50] Once again, it appears that this was due to the warm up being of low intensity and/or being followed by a long recovery period. It is also possible that in some instances long-term performance was not improved because untrained study participants were becoming fatigued during the warm up. For example, identical warm-up procedures produced a significant increase in time to fatigue (at 95% maximum heart rate [HR_{max}]) in moderately-trained females,[48] but no significant change in time to fatigue (at 95% HR_{max}) in untrained females.[49] Similarly, active warm up improved bench-stepping endurance when followed by 30 or 60 seconds recovery, but not when fol-

Table III. Physiological and performance changes in long-term performance following active, general warm up

Study	Subjects	Warm up					Performance test		
		mode	duration (min)	intensity (beats/min)	rest	phys. changes	mode	phys. changes	performance changes[a]
Andzel[48]	20 MT females	N	NA	NA	NA	HR: $A_1 = A_2 > A_3 = A_4 = N$;	Run (95% HR_{max})	NA	time to fatigue:
		A_1 jog	~6	~140	30 sec				A1 = A2 > A3 = A4 = N; $p < 0.05$
		A_2 jog	~6	~140	60 sec				
		A_3 jog	~6	~140	90 sec	$p < 0.05$			
		A_4 jog	~6	~140	120 sec				
Andzel and Busuttil[49]	8 UT females	N	NA	NA	NA	HR: $A_1 > A_2 > N$	Run (95% HR_{max})	First 30 sec	Time to fatigue: $N = A_1 > A_2$; $p < 0.05$
		A_1 jog	~6	~140	30 sec	$\dot{V}O_2$: $A_1 = A_2 > N$		$\dot{V}O_2$: $A_1 > A_2 > N$	
		A_2 jog	~6	~140	90 sec	$p < 0.05$		HR: $A_1 > A_2 > N$	
Andzel and Gutin[50]	12 UT females	N	NA	NA	NA	HR: $A_3 = A_2 = A_1 > N$; $p < 0.05$	Stepping (bench)	NA	No. of steps: $A_3 = A_2 > A_1 = N$; $p < 0.05$
		A_1 jog	~5	~140	0 sec				
		A_2 jog	~5	~140	30 sec				
		A_3 jog	~5	~140	60 sec				
Atkinson et al.[47]	8 T males	A_1 cycle	5	Self-select	NR	$T_r = 38.0°C$	Cycle (16.1km)	NA	Speed: $A_2 > A_1$; $p < 0.05$
		A_2 cycle	25	60% PPO					
Gregson et al.[51]	6 T males	N	NA	NA	10 min	$T_r = 38.0°C$	Interval run (30 sec: 30 sec)	Heat storage	Time to fatigue: $N > A$; $p < 0.05$
		A jog	~20	70% max. effort	10 min			$N > A$; $p < 0.05$	
Gregson et al.[52]	6 T males	N	NA	NA	10 min	NA	Run (70% $\dot{V}O_{2max}$)	Heat storage	Time to fatigue: $N > A$; $p < 0.05$
		A jog	~20	70% max. effort	10 min			$N > A$; $p < 0.05$	
Grodjinovsky and Magel[16]	13 UT males	N	NA	NA	NA	NA	Run (1.6km)	NA	Speed: $A_2 > A_1 = N$; $p < 0.05$
		A_1 jog	5	NR	5 min				
		A_2 jog + sprint	5+	NR					
Thompson[20]	26 UT males	N	NA	NA	NR	NA	Swim (5 min)	NA	No. of laps: $A > N$; $p < 0.05$
		A swim	2.5	75% max. effort					

a The absence of a p-value indicates that statistical analyses were not performed.

A = active warm up; **HR** = heart rate; **HR_{max}** = maximum heart rate; **MT** = moderately trained; **N** = no warm up; **NA** = not applicable; **NR** = not reported; **phys.** = physiological changes; **PPO** = peak power output (from graded exercise test); **T** = trained; **T_r** = rectal temperature; **UT** = untrained; **$\dot{V}O_2$** = oxygen consumption; **$\dot{V}O_{2max}$** = maximum oxygen consumption.

lowed by no recovery.[50] Thus, as with intermediate performance, warm up appears more likely to improve performance if it allows the individual to commence the task with an elevated $\dot{V}O_2$, but sufficiently recovered from the warm up.

Three studies have reported impaired long-term performance following warm up.[49,51,52] The first of these studies recruited untrained females ($\dot{V}O_{2max}$ = 35.9 mL/kg/min) and it appeared that the warm up (~6 minutes at 140 beats/min with 90 seconds recovery) may have fatigued the study participants.[49] In the second study, intermittent running (30 seconds at 90% $\dot{V}O_{2max}$: 30 seconds recovery) was impaired (72.0 vs 51.8 minutes; $p < 0.05$) when preceded by an active warm up that raised T_r to 38.0°C.[51] In a similar study by the same authors, time to exhaustion at 70% of $\dot{V}O_{2max}$ was impaired (62.0 vs 47.8 minutes; $p < 0.05$) when preceded by an identical warm up.[52] The decrease in run time in both studies was associated with a decrease in heat-storage capacity and the earlier attainment of a high rectal temperature (T_r). Interestingly, passive warming to the same T_r produced a greater decrement in performance. Therefore, while there is limited research, it is probably important that warm up prior to long-term exercise is not fatiguing and does not significantly raise T_r.

1.4 Summary of Active Warm Up

Active warm up has the potential to improve short-term, intermediate and long-term performance. Improvements in short-term performance appear to be largely, although not entirely, attributable to an increase in T_m. Possible mechanisms include decreased stiffness of muscles and joints, increased transmission rate of nerve impulses, an altered force-velocity relationship and increased glycogenolysis, glycolysis and high-energy phosphate degradation. An additional non-temperature-related mechanism may be decreased muscle stiffness by 'breaking' the stable bonds between actin and myosin filaments. However, short-term performance may be impaired if the warm-up protocol decreases the availability of high-energy phosphates as a result of being too intense or not allowing sufficient recovery before commencing the task.

Warm up also appears to improve long-term and intermediate performance if it allows the athlete to begin the subsequent task in a relatively non-fatigued state, but with an elevated baseline $\dot{V}O_2$. While it appears that warm-up exercise does not increase $\dot{V}O_2$ kinetics, warm up may allow subsequent tasks to begin with an elevated baseline $\dot{V}O_2$. Consequently, less of the initial work will be completed anaerobically, leaving more of the anaerobic capacity for later in the task. Long-term performance may be impaired if the warm up depletes muscle glycogen stores and/or increases thermoregulatory strain.

2. How to Structure a Warm Up

The structure of the warm up will depend on many factors, including the task to be undertaken, the physical capabilities of the athlete, the environmental conditions and also any constraints imposed by the organisation of the event. From section 1, it also appears that different physiological responses to warm up may be required to optimise performance for different tasks. Furthermore, the athlete's physical capabilities are likely to influence the physiological and performance responses to the warm up. Due to a more efficient thermoregulatory system,[53] well-conditioned athletes may require a longer and/or more intense warm up to sufficiently increase T_r or T_m. An athlete's physical capabilities will also influence whether the warm up has a fatiguing effect. It should also be noted that by manipulating intensity, duration and recovery, many different warm-up protocols may be able to achieve similar physiological and performance changes. For some tasks, the addition of task-specific bursts of activity may provide an additional ergogenic benefit. Finally, passive warm-up techniques may be important to supplement or maintain temperature increases produced by an active warm up, especially if there is an unavoidable delay between the warm up and the task, and/or the weather is cold.

2.1 Warm-Up Intensity

Short-term performance appears to largely depend on T_m[7-9] and the availability of high-energy phosphates.[13] To improve short-term performance, it would therefore appear to be important to structure a warm up that is of sufficient intensity to increase T_m, but does not significantly decrease the availability of high-energy phosphates immediately prior to the task.

In general, low-intensity warm up (e.g. calisthenics) has not been reported to improve short-term performance.[14,22] As changes in T_m have been reported to be related to exercise intensity,[24] the increase in T_m in these studies may not have been sufficient to have an ergogenic effect on short-term performance. While a greater warm-up intensity will cause a greater increase in T_m, increasing the workload intensity above ~60% $\dot{V}O_{2max}$ has also been shown to increasingly deplete high-energy phosphate concentration.[54] Consequently, at workloads greater than ~60% $\dot{V}O_{2max}$, an inverse relationship between warm-up intensity and subsequent short-term performance has been reported.[19,55] Thus, when there is no recovery period following the warm up, it appears that a warm-up intensity of ~40–60% $\dot{V}O_2$ is sufficient to raise T_m, limit high-energy phosphate degradation and improve short-term performance (figure 1).

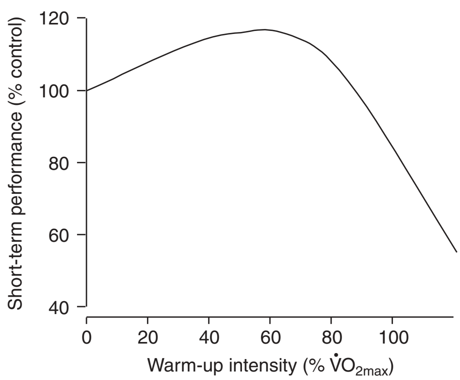

Fig. 1. Changes in short-term performance (expressed as a percentage of a control performance without a warm up) immediately following warm up performed at different intensities of maximum oxygen consumption ($\dot{V}O_{2max}$).[14,19,22,55]

As discussed in sections 1.2 and 1.3, to improve intermediate and long-term performance it appears important that the warm up increases baseline $\dot{V}O_2$. Elevation of baseline $\dot{V}O_2$ will increase with increasing exercise intensity up to $\dot{V}O_{2max}$.[56] However, once again, there is a trade-off. While a more intense warm up will further increase the baseline $\dot{V}O_2$, if the warm up is too intense (and the subsequent recovery too brief), performance may be impaired due to a decrease in high-energy phosphate stores and/or an accumulation of H^+. Research suggests that for moderately-trained athletes, a warm-up intensity of ~70% $\dot{V}O_{2max}$ is likely to be optimal for intermediate performance (figure 2).[32,36] However, a slightly lower intensity may be optimal for untrained study participants.[38] It is likely that similar recommendations can be made for long-term performance. The only exception may be for longer aerobic events (>30 minutes), where a critical T_r may be an important limiting factor and the optimal warm-up intensity may be one which does not significantly raise pre-exercise T_r.

2.2 Duration of Warm Up

To maximise short-term performance, it appears important that the warm up is of sufficient duration to maximise the increase in T_m, while causing minimal fatigue. With the onset of exercise, T_m rises rapidly within the first 3–5 minutes and reaches a relative plateau after 10–20 minutes of exercise.[24] Furthermore, exercise intensities below ~60% $\dot{V}O_{2max}$ have been shown to cause minimal depletion of high-energy phosphates.[54] Therefore, a warm up performed at <60% $\dot{V}O_{2max}$ for 10–20 minutes is likely to cause minimal phosphate depletion, maximise the increase in T_m and significantly improve short-term performance. Recent results from our laboratory have shown that the duration of warm up does affect both T_m and subsequent short-term performance. Peak power on a cycle ergometer was significantly greater following a 20-minute warm up at 40% $\dot{V}O_{2max}$, but not significantly greater following a 4-minute warm up at 40% $\dot{V}O_{2max}$ (unpublished observation).

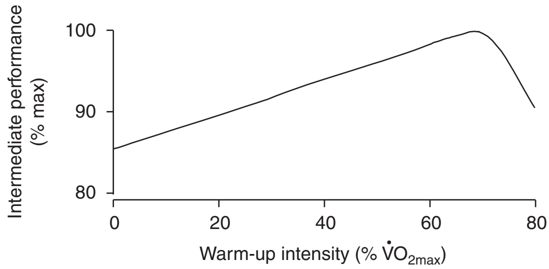

Fig. 2. Changes in intermediate performance (expressed as a percentage of maximum performance) following warm up performed at different intensities of maximum oxygen consumption ($\dot{V}O_{2max}$).[32,36]

The optimal duration of the warm up will also depend on its intensity. If there is no recovery period following a moderate to high-intensity warm up, there appears to be a rapid exponential decline in subsequent short-term performance with increasing warm-up duration,[19,55] with little additional impairment of short-term performance by increasing the duration of the warm up beyond 3 minutes (figure 3).[23] It is likely that this exponential decline in subsequent short-term performance is related to the exponential decline of high-energy phosphate stores in the active muscle that reaches a plateau following 3–6 minutes.[57] Thus, if there is limited or no recovery following a high-intensity warm up, the warm up prior to a short-term task should be as brief as possible so as to minimise the performance impairment.

To maximise intermediate and long-term performance, it appears important that the warm up is of sufficient duration to elevate baseline $\dot{V}O_2$, while causing minimal fatigue. For warm up of 'moderate' to 'heavy' intensity, $\dot{V}O_2$ will reach a steady state within 5–10 minutes.[56] Interestingly, this matches an earlier observation that a warm up of ≥10 minutes at 60–80% $\dot{V}O_{2max}$ tends to enhance performance.[58] There is unlikely to be any additional elevation of baseline $\dot{V}O_2$ or ergogenic effect on intermediate or long-term performance by increasing the duration of the warm up beyond 10 minutes. While a 25-minute warm up has been reported to improve long-term performance,[47] a warm up in excess of 10 minutes has the potential to impair long-term performance by decreasing muscle glycogen content[29] or decreasing heat-storage capacity.[51]

2.3 Recovery Duration

The recovery interval following the warm up is also likely to affect performance. Depending on the intensity and duration of the warm up, short-term performance is likely to be improved if the recovery interval allows phosphocreatine (PCr) stores to be significantly restored. The resynthesis of PCr stores is a very rapid process and is largely complete within ~5 minutes of exercise.[59,60] The near complete resynthesis of PCr stores may explain why peak cycle power was reported to be maximised when the recovery duration following a 6-minute warm up at 87% $\dot{V}O_{2max}$ was extended from 3 to 6 minutes.[19] While a longer recovery period (up to 20 minutes) may be necessary for the complete resynthesis of PCr stores,[60] for optimal short-term performance it is also likely to be important that the recovery duration does not allow T_m to drop significantly. Depending on the intensity and duration of the warm up, and the environmental conditions, T_m is likely to significantly drop following ~15–20 minutes recovery.[24] Therefore, a recovery interval of more than 5 minutes, but less than 15–20 minutes is likely to provide the greatest ergogenic effect on short-term performance.

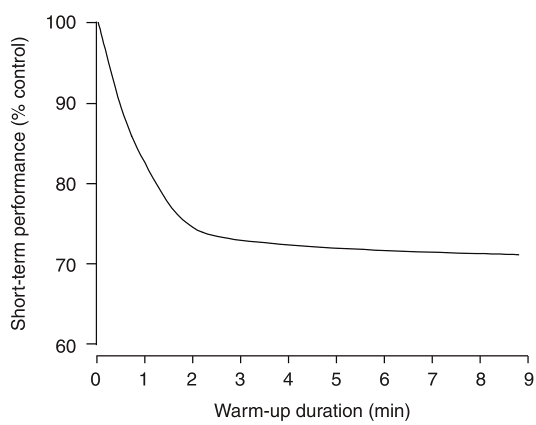

Fig. 3. Changes in short-term performance (expressed as a percentage of a control performance without a warm up) immediately following high-intensity warm up performed for different durations.[19,23,55]

To improve intermediate and long-term performance, it appears important that the recovery duration does not allow $\dot{V}O_2$ to return to baseline. While $\dot{V}O_2$ recovery kinetics are influenced by exercise intensity, following a 'moderate' to 'heavy' warm up, $\dot{V}O_2$ will return very close to baseline within ~5 minutes.[56] In support of this, pre-exercise $\dot{V}O_2$ has been reported not to be significantly elevated above baseline 5 minutes following a 5-minute warm up at 75% $\dot{V}O_{2max}$.[38] Furthermore, intermediate and long-term performance have typically not been reported to improve when the recovery duration is ≥5 minutes.[16,33,38-41,48,50] Thus, while warm-up intensity and duration are important, to improve long-term and intermediate performance, it is probably also important that the recovery period allows sufficient recovery, but is less than ~5 minutes.

2.4 Specificity of the Warm Up

While a number of studies have investigated the influence of warm-up intensity, duration and recovery interval on performance, few studies have investigated the effects of a task-specific warm up on performance. In one of the few studies to investigate the effect of a specific warm up on short-term performance, Pyke[22] reported that three maximal practice jumps did not improve vertical-jump performance. Such a warm up would not be expected to increase T_m and would most likely only improve performance via an increase in postactivation potentiation.[61,62] While little study detail was provided, it is likely that three maximal practice jumps do not increase postactivation potentiation. Alternatively, there may have been insufficient time for study participants to recover from the practice jumps. It has previously been reported that a 15-second recovery interval between a maximal voluntary contraction and dynamic knee contraction does not significantly increase muscle force despite an increase in postactivation potentiation, possibly as a result of residual fatigue.[63] Further research is therefore required to establish the effects of a task-specific warm up on short-term performance.

There are also few studies that have investigated the influence of a task-specific warm up on intermediate or long-term performance. Grodjinovsky and Magel[16] reported that a 'vigorous' warm up (a 5-minute jog plus 161m run at near maximum speed) resulted in greater improvements in 1-mile (1.6km) run time than a 'regular' warm up (5-minute jog) in untrained males. Similarly, it has been reported that a task-specific warm up (continuous warm up at ~65% $\dot{V}O_{2max}$ plus five, 10-second sprints at ~200% $\dot{V}O_{2max}$, separated by 50 seconds of recovery at ~55% $\dot{V}O_{2max}$) resulted in significantly greater kayak ergometer performance than a continuous warm up performed at ~65% $\dot{V}O_{2max}$.[64] Despite the improved performance, there was no significant difference in $\dot{V}O_2$ or accumulated oxygen deficit between the two warm-up conditions. It was suggested that the large voluntary contractions required for the sprint component of the intermittent, high-intensity warm up might have improved performance via an increase in neuromuscular activation.

Two other studies, however, have reported no additional benefits to swim performance by including a high-intensity component (4 × 46m sprints with 1-minute rest intervals) compared with a low-intensity warm up.[42,65] However, neither of these two studies directly measured performance. Houmard et al.[65] reported only changes in stroke distance, while Mitchell and Huston[42] reported only tethered swim time to exhaustion. To date, only one study has reported a decrease in performance (time to fatigue at ~90% $\dot{V}O_{2max}$) following a specific warm up, when compared with a general, active warm up.[66] However, the warm up used was severe (30 seconds at 50% $\dot{V}O_{2max}$ alternated with 30 seconds at 100% $\dot{V}O_{2max}$ until fatigue) and was more than twice the duration (~19 minutes) of the criterion task. The blood lactate concentration following the specific warm up was 7.4 + 1.8 mmol/L, compared with 1.8 + 0.5 mmol/L following the general, active warm up. With such an intense warm up, it is likely that acidaemia may have limited subsequent performance. It has previously been shown that if the warm-up intensity is too high (~75% $\dot{V}O_{2max}$), the subsequent metabolic acidaemia (blood lactate concentration $[La^-]$ = 5.1 ±

1.4 mmol/L) is associated with impaired performance and a reduction in the accumulated oxygen deficit.[36] It therefore appears that a specific warm up may provide ergogenic benefits in addition to those provided by a general, active warm up. However, the task-specific bursts of activity should be brief enough so as not to cause significant fatigue.

2.5 Summary of How to Structure a Warm Up

To improve short-term performance, it appears important to structure a warm up that is of sufficient intensity and duration, when followed by an appropriate recovery period, to increase T_m, but allow resynthesis of high-energy phosphates immediately prior to the task. While the optimal warm up will depend on many factors, the research suggests that a warm-up performed at ~40–60% $\dot{V}O_{2max}$ for 5–10 minutes, followed by a 5-minute recovery will improve short-term performance. Further research is required to establish whether the addition of task-specific activities will have a further ergogenic effect on short-term performance.

To improve intermediate or long-term performance, it appears important to structure a warm up that is of sufficient intensity and duration, when followed by an appropriate recovery period, to elevate baseline $\dot{V}O_2$, but to not cause significant fatigue. It appears that a specific warm up can provide ergogenic benefits in addition to those provided by a general, active warm up; possibly by increasing neuromuscular activation. While the optimal warm up will depend on many factors, the research suggests a warm up performed at ~60–70% $\dot{V}O_{2max}$ for 5–10 minutes, followed by ≤5 minutes recovery will improve intermediate and long-term performance. The addition of brief, task-specific burst of activity should provide further ergogenic benefits.

3. Future Research

While warm up is a widely accepted practice preceding most physical activities, there are many areas that require further investigation. For example, further research is required to investigate the role of warm up in different environmental conditions, especially for endurance events performed in hot conditions, where a critical T_r may limit performance. The role of cooling strategies (such as the wearing of ice vests) to prevent a significant increase in T_r while warming up also requires further investigation. There is also a need for more research on the effects of warm up on intermittent-sprint performance. In addition to further performance-based studies, further research is required to elucidate the mechanisms responsible for changes in performance following warm up. Better controlled studies are required to examine the possible psychological effects of warm up. Further research investigating the relative contribution of increases in muscle or core temperature to performance changes following warm up are also needed. Finally, future studies need to develop their warm-up protocols on a sound physiological rationale, rather than merely replicating commonly used warm-up procedures.

4. Conclusions

While there is a scarcity of well controlled studies, with large subject numbers and appropriate statistical analyses, a number of conclusions can be drawn regarding the effects of warm up on performance. Active warm up tends to result in slightly larger improvements in short-term performance (<10 seconds) than those achieved by passive heating alone. However, short-term performance may be impaired if the warm-up protocol is too intense or does not allow sufficient recovery and results in a decreased availability of high-energy phosphates before commencing the task. Active warm up appears to improve both long-term and intermediate performance (>10 seconds, but <5 minutes) if it allows the athlete to begin the subsequent task in a relatively non-fatigued state, but with an elevated $\dot{V}O_2$. While passive warm up has been reported to improve intermediate performance, both active and passive warm up may have a detrimental effect on endurance performance if the warm up causes a significant increase in T_r. The addition of a brief, task-specific burst of activity should provide further ergogenic benefits for most tasks. By manipulating intensity, duration and recovery, many different warm-up protocols may be able to achieve similar physiological and performance changes. Finally, passive warm-up techniques may be important to supplement or maintain temperature increases produced by an active warm up, especially if there is an unavoidable delay between the warm up and the task and/or the weather is cold.

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