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Warm Up I

Potential Mechanisms and the Effects of Passive Warm Up on Exercise Performance

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Abstract

Despite limited scientific evidence supporting their effectiveness, warm-up routines prior to exercise are a well-accepted practice. The majority of the effects of warm up have been attributed to temperature-related mechanisms (e.g. decreased stiffness, increased nerve-conduction rate, altered force-velocity relationship, increased anaerobic energy provision and increased thermoregulatory strain), although non-temperature-related mechanisms have also been proposed (e.g. effects of acidaemia, elevation of baseline oxygen consumption (VO_2) and increased postactivation potentiation). It has also been hypothesised that warm up may have a number of psychological effects (e.g. increased preparedness). Warm-up techniques can be broadly classified into two major categories: passive warm up or active warm up. Passive warm up involves raising muscle or core temperature by some external means, while active warm up utilises exercise. Passive heating allows one to obtain the increase in muscle or core temperature achieved by active warm up without depleting energy substrates. Passive warm up, although not practical for most athletes, also allows one to test the hypothesis that many of the performance changes associated with active warm up can be largely attributed to temperature-related mechanisms.

Warm up is a widely accepted practice preceding nearly every athletic event. However, while warm up is considered essential for optimum performance by many coaches and athletes, there is surprisingly little scientific evidence supporting its effectiveness. Summarising the findings of the many studies that have investigated the physiological responses to warm up is difficult. Many of the earlier studies were poorly controlled, contained few study participants and often omitted statistical analyses. Moreover, 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.

Warm-up techniques can be broadly classified into two major categories: passive warm up or active warm up. Passive warm up involves raising muscle temperature (T_m) or core temperature (T_c) by some external means. Various methods including hot showers or baths, saunas, diathermy and heating pads have been used. Passive heating allows one to obtain the increase in T_m or T_c achieved by active warm up, without depleting energy substrates. Although not practical for most athletes, passive warm up also allows one to test the hypothesis that many of the performance changes associated with active warm up can be largely attributed to temperature-related mechanisms. Active warm up involves exercise and is likely to induce greater metabolic and cardiovascular changes than passive warm up. Typical examples of active warm up include jogging, calisthenics, cycling and swimming.

This review attempts to summarise and draw conclusions from the many disparate studies that have investigated mechanisms by which warm up may affect performance, and changes in performance following passive warm up. While warm up is also believed to have a role in injury prevention, this is beyond the scope of this paper (see Shellock and Prentice[1]).

1. Warm-Up Mechanisms

Table I. Possible effects of warm up

Temperature related	
	Decreased resistance of muscles and joints
	Greater release of oxygen from haemoglobin and myoglobin
	Speeding of metabolic reactions
	Increased nerve conduction rate
	Increased thermoregulatory strain
Non-temperature related	
	Increased blood flow to muscles
	Elevation of baseline oxygen consumption
	Postactivation potentiation
	Psychological effects and increased preparedness

Warm up has been proposed to affect performance via a variety of mechanisms (table I). As suggested by the name, the majority of the effects of warm up have been attributed to temperature-related mechanisms. However, it has also been suggested that the physiological and performance changes following active warm up may actually be due to a residual metabolic acidaemia and that warm up could therefore be termed ‘acid up’.[2] It has also been suggested that warm up may serve to elevate baseline oxygen consumption ($\dot{V}O_2$), resulting in a decrease in the initial oxygen deficit and thereby preserve more of the anaerobic capacity for later in the task.[3] Limited evidence suggests that under certain circumstances, warm up may cause postactivation potentiation, resulting in increased neuromuscular activation.[4,5] It has also been hypothesised that warm up may have a number of psychological effects.[6]

1.1 Temperature Effects Associated with Warm Up

In 1945, Asmussen and Boje[7] concluded that “…a higher temperature in the working organism facilitates the performance of work”. Since then, the effects of warm up have largely been attributed to temperature-related mechanisms. Specifically, it has been proposed that an increase in temperature may improve performance via a decrease in the viscous resistance of muscles, a speeding of rate-limiting oxidative reactions and/or an increase in oxygen delivery to muscles. However, increased thermoregulatory strain has the potential to adversely affect certain types of performance.

While the majority of the effects of warm up have been attributed to temperature-related mechanisms, many studies have not measured temperature changes as a result of warm up. In those studies that have measured temperature changes, it is often difficult to compare results as either rectal temperature (T_r) or T_m have been recorded. Furthermore, the T_m recorded in different studies may not be comparable if taken at different muscle depths (figure 1[8,9]).

Exercising muscles generate considerable heat and T_m is directly proportional to the relative work rate.[8] With the onset of moderate-intensity exercise (80–100% of the lactate threshold), T_m rises rapidly from resting levels (~35°C) and within 3–5 minutes exceeds T_r and reaches a relative equilibrium after approximately 10–20 minutes of exercise (figure 1). In commonly-observed ambient conditions (10–30°C), T_r is independent of ambient temperature and begins to rise once T_m exceeds T_r. Skin temperatures (T_s) typically drop during the first 10 minutes of moderate-intensity exercise in commonly observed ambient conditions (10–30°C).

1.1.1 Decreased Viscous Resistance

An increase in T_m may affect performance via a decrease in the viscous resistance of muscles and joints. Mild warming has been reported to reduce the passive resistance of the human metacarpal joint by 20%.[14] Similar changes in passive resistance of the knee have been reported following short-wave diathermy.[15] Increasing temperature has also been reported to decrease the stiffness of muscle fibres during contraction.[16] However, Buchthal et al.[16] also reported that, despite the small increase in dynamic shortening, there was very little extra tension developed. This suggests that the temperature effect on muscle elastic properties is quite small. Further research is required to quantify the effects of temperature-related changes in viscous resistance on performance.

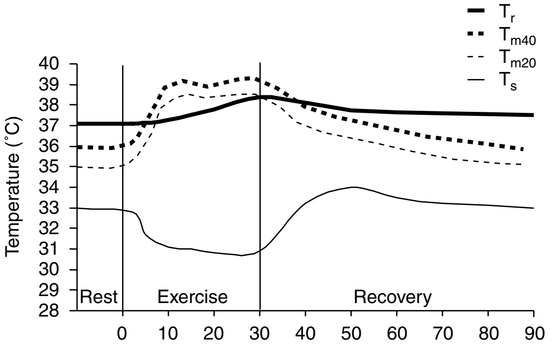

Fig. 1. Temperature measured at rest, during moderate exercise and during recovery for the rectal (T_r), skin (T_s) and muscle at a probe depth of approximately 20mm (T_{m20}) and 40mm (T_{m40}), in commonly-observed ambient conditions (10–30°C).[7-13]

1.1.2 Increased Oxygen Delivery to Muscles

It has also been suggested that performance changes following warm up may result from increased oxygen delivery to the muscles via a rightward shift in the oxyhaemoglobin dissociation curve and vasodilation of muscle blood vessels.[17] According to Barcroft and King,[18] haemoglobin at an oxygen tension of 30mm Hg gives up almost twice as much oxygen at 41°C as at 36°C and the oxygen dissociates from haemoglobin about twice as rapidly (figure 2). A corresponding effect of temperature on the dissociation curve for myoglobin has been demonstrated,[19] although the temperature effect is somewhat smaller. Furthermore, an elevated temperature also stimulates vasodilation of blood vessels and increases muscle blood flow.[20] However, while an increase in temperature should increase oxygen delivery to the muscles, this will only enhance aerobic energy production if $\dot{V}O_2$ kinetics are limited by oxygen delivery.

Using an isolated dog gastrocnemius muscle, it has been demonstrated that convective oxygen delivery does not limit $\dot{V}O_2$ kinetics during transitions from rest to ~60% maximum oxygen consumption ($\dot{V}O_{2max}$).[21,22] However, convective oxygen delivery may contribute to $\dot{V}O_2$ kinetics during transitions from rest to $\dot{V}O_{2max}$.[23] Despite this, neither active warm up[24,25] nor passive heating of the thighs (to ~40°C)[26] has been reported to speed $\dot{V}O_2$ kinetics during exercise halfway between the lactate threshold and $\dot{V}O_{2max}$, in healthy, young adults. There is however, evidence that active warm up can speed $\dot{V}O_2$ kinetics in the elderly,[27] possibly via an improved rate of oxygen utilisation by the muscle.[28]

There appears to be two possible explanations for these findings. First, in individuals with adequate muscle perfusion and/or oxygen delivery, greater convective oxygen delivery may not affect $\dot{V}O_2$ kinetics during transitions to exercise less than $\dot{V}O_{2max}$. Secondly, the increases in blood flow typically achieved by warm up (active or passive) may not be sufficient to significantly speed $\dot{V}O_2$ kinetics. With their isolated dog gastrocnemius *in situ* model, Grassi et al.[23] were able to increase muscle blood

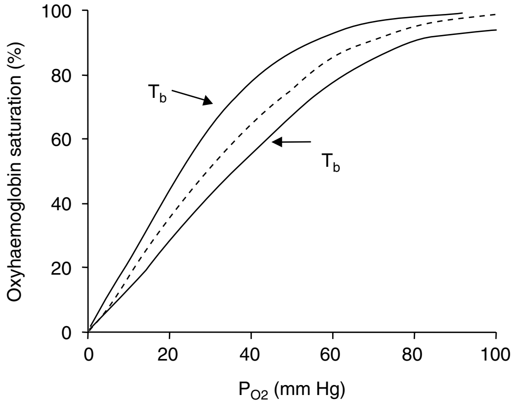

Fig. 2. The effect of changing blood temperature (T_b) on the shape of the oxyhaemoglobin dissociation curve. P_{O2} = oxygen partial pressure.

flow ($\dot{Q}_m$) to ~100 mL/100g/min. This is much greater than the increase in $\dot{Q}_m$ reported with moderate exercise (~20 mL/100g/min) and the increase in $\dot{Q}_m$ due to the reactive hyperaemia that occurs in the first few minutes following the completion of moderate exercise (~40 mL/100g/min).[29] Therefore, while convective oxygen delivery does represent a theoretical limitation to $\dot{V}O_2$ kinetics and aerobic energy production, it has not been demonstrated that temperature changes in response to warm up (active or passive) are able to sufficiently increase $\dot{Q}_m$ to speed $\dot{V}O_2$ kinetics in healthy, young adults.

1.1.3 Speeding of Rate-Limiting Oxidative Reactions

An elevated T_m, as a result of warm up, has been proposed to enhance aerobic energy production by accelerating the rate-limiting reactions associated with oxidative phosphorylation.[26] Increased T_m elevates oxygen consumption ($\dot{Q}O_2$) of isolated mitochondria by a Q_{10} effect[1] and by decreasing the ratio between adenosine diphosphate (ADP) production and mitochondrial $\dot{V}O_2$ (ADP : O ratio).[30] One of the principle limiting factors for muscle $\dot{V}O_2$ kinetics appears to reside in an inertia of oxidative metabolism.[21-23] Thus, if increasing T_m does speed rate-limiting oxidative reactions, this should be accompanied by a speeding of $\dot{V}O_2$ kinetics. As a result, less of the initial work will be completed anaerobically and performance may be improved by leaving more of the anaerobic capacity for later in the task.

However, neither prior moderate- or high-intensity exercise,[24] nor passive heating of the thighs (to ~38°C)[26] has been reported to significantly speed $\dot{V}O_2$ kinetics in healthy, young adults. Furthermore, a Q_{10} effect of only ~1.2 can be calculated from the data of Koga et al.,[26] for the effect of increasing T_m on the primary component of the $\dot{V}O_2$ response. This indicates a very small positive thermal dependence and is much less than the value reported for most skeletal muscle enzymatic reactions (Q_{10} = 2.0–3.0).[31] One possible explanation for these findings is that oxidative phosphorylation has been reported to become uncoupled only above ~40°C.[30] While Burnley et al.[24] did not measure T_m, previous studies have reported a T_m of ~39.0°C in response to exercise of similar intensity.[7,8] It is therefore possible that these previous studies were unable to sufficiently raise T_m to significantly affect oxidative phosphorylation and therefore, $\dot{V}O_2$ kinetics. While further research is necessary, it appears unlikely that the increase in T_m achieved by current warm-up procedures improves performance via a speeding of rate-limiting oxidative reactions.

1.1.4 Increased Anaerobic Metabolism

The acceleration of muscle glycogen breakdown in humans exercising at high ambient temperatures was first described by Fink et al.[32] Subsequent research has demonstrated that an increase in T_m *per se* has little effect on resting muscle metabolism, but increases muscle glycogenolysis, glycolysis and high-energy phosphate (ATP and phosphocreatine) degradation during exercise[33] (figure 3). Exercise in the heat appears to increase muscle glycogen breakdown by augmenting the secretion of epinephrine and by increased muscle temperature *per se*.[34] However, while the critical role of muscle glycogen availability for endurance exercise performance has been well established,[35] fatigue during exercise in hot environments occurs in the presence of adequate muscle glycogen stores.[36] The more rapid muscle glycogen breakdown following an increase in T_m is therefore, unlikely to adversely affect long-term performance. However, an increase in anaerobic metabolism may benefit short-term and intermediate performance.

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[1] $Q_{10} = (R_2/R_1)^{[10/(T_2-T_1)]}$; R_1 and R_2 are rate processes at temperatures T_2 and T_1 and $T_2 > T_1$. $Q_{10} > 1.0$ indicates a positive thermal dependence.

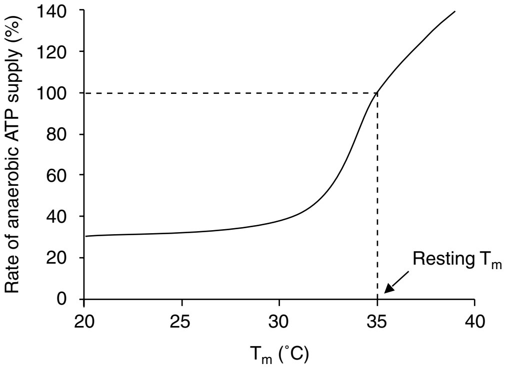

Fig. 3. Anaerobic adenosine triphosphate (ATP) supply during exercise at different muscle temperatures (T_m). Rates are expressed as a percentage of normal (100%).[33,37]

1.1.5 Increased Nerve Conduction Rate

An increase in T_m may also contribute to improved performance by augmenting the function of the nervous system. Karvonen[38] has demonstrated that increased T_m improves central nervous system function and increases the transmission speed of nervous impulses. Improved nervous system function may be especially important for tasks that demand high levels of complex body movements or require rapid reactions to a variety of stimuli.[39] Further research is required to investigate the effects of temperature-induced increases in nervous system function on performance.

1.1.6 Increased Thermoregulatory Strain

Increases in thermoregulatory strain following warm up are likely to reflect changes in both body temperature *per se* and hydration status. Exercising muscle generates considerable heat and causes T_m to rise in proportion to the relative workload.[8] There is however, a limit to how much heat the body can store. Ultimately, long-term performance in uncompensable hot environments appears to be limited by a critical core temperature.[40,41] Increasing the body temperature before vigorous exercise may decrease heat-storage capacity via a decrease in the temperature range before an upper critical T_r can be reached.[42] Pre-cooling has been reported to have the opposite effect of delaying the attainment of an upper critical T_r and increasing run time to exhaustion in dogs[40] and in trained runners.[43] In addition, decreases in hydration status, as a result of warm up, may also have a negative influence on the ability of the body to control its internal temperature.[44] Warm up therefore, has the potential to decrease long-term performance via a decrease in heat-storage capacity and impaired thermoregulation mechanisms.

1.2 Metabolic Effects of Active Warm Up

Oxygen delivery to the muscles may also be affected by a number of metabolic changes that occur in response to active warm up. For example, reduced oxygen tension,[45] increased potassium (K^+) concentration[46] and increased hydrogen ion (H^+) concentration[47] have all been reported to cause vasodilation and to increase muscle blood flow. Increases in [H^+], pCO_2 and 2,3-diphosphoglycerate in response to warm up may also increase oxygen delivery to the muscles via a rightward shift in the oxyhaemoglobin dissociation curve.[48] However, once again, it has not been demonstrated that metabolic changes in response to active warm up are able to sufficiently increase $\dot{Q}_m$ to speed $\dot{V}O_2$ kinetics in healthy, young adults.

It has also been suggested that the residual metabolic acidaemia from a warm-up bout (~80% $\dot{V}O_{2max}$) leads to improved muscle perfusion during exercise and speeds $\dot{V}O_2$ kinetics.[2] However, the results of more recent studies suggest that the overall speeding of $\dot{V}O_2$ kinetics previously reported[2] is primarily related to a reduced amplitude of the $\dot{V}O_2$ slow component and not to a measurable speeding of the $\dot{V}O_2$ kinetics.[24,49] It could be argued that the active warm up in these studies may not have caused sufficient metabolic acidaemia to increase $\dot{Q}_m$ to an extent that would increase $\dot{V}O_2$ kinetics. However, it has previously been shown that if the warm-up intensity is too high (~75% $\dot{V}O_{2max}$), the subsequent metabolic acidaemia is associated with impaired supramaximal performance and a reduction in the accumulated oxygen deficit.[50] This was attributed to an accumulation of H^+ and subsequent inhibition of anaerobic glycolysis[51] and/or interference with muscle contractile processes.[52] Thus, even if the greater metabolic acidaemia associated with a more intense warm up is able to speed $\dot{V}O_2$ kinetics, it is unlikely to benefit performance.

1.3 Elevation of Baseline Oxygen Consumption

While it appears that warm up 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 (figure 4). As the anaerobic capacity appears to be a well-defined entity,[53,54] initial sparing of the anaerobic capacity should increase time to exhaustion and improve performance in tasks that require a significant anaerobic contribution.

The 'mobilisation' hypothesis is supported by the results of many studies that have reported a greater aerobic contribution[17,55-57] and/or a decreased oxygen deficit[3,17,58,59] when tasks are preceded by active warm up. Furthermore, the blunted blood lactate increase following active warm up, in response to a standard workload (4 minutes at $\dot{V}O_{2max}$) provides further support for an attenuation of anaerobic energy production following warm up.[56] However, an elevated $\dot{V}O_2$ is only likely to result in the initial sparing of the anaerobic capacity if the period between warm up and the criterion task does not allow $\dot{V}O_2$ to return to rest. While $\dot{V}O_2$ recovery kinetics will depend on many factors, following a moderate to heavy warm up $\dot{V}O_2$ is likely to return very close to its resting value within ~5 minutes.[60] This may explain why it has previously been reported that there is no initial sparing of the anaerobic capacity when there is a 5-minute interval between a moderate-intensity warm up and a 2-minute all-out performance.[50]

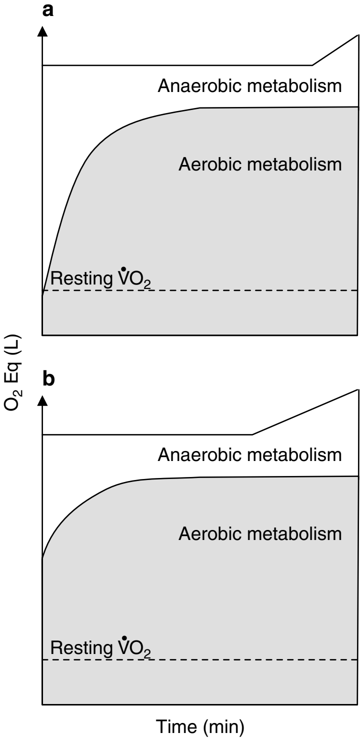

Fig. 4. Schematic representation of the aerobic and anaerobic contribution to an all-out task with (**a**) and without (**b**) prior warm up. **O_2 Eq** = oxygen equivalents; **$\dot{V}O_2$** = oxygen consumption.

1.4 Postactivation Potentiation

The performance of skeletal muscle is affected by its contractile history. While fatigue will impair performance, postactivation potentiation acts to improve performance.[61] Postactivation potentiation is the transient increase in muscle contractile performance following previous 'conditioning' contractile activity.[62] It is therefore, possible that active warm up of high intensity, especially if it includes a sprint component or maximum voluntary contractions (MVCs) may improve certain types of performance by increasing muscle contractile performance. In support of this, power output of both the upper and lower extremities has been reported to increase following MVCs.[4,5] Increased potentiation has also been reported following maximal dynamic knee extensions.[63] This potentiation has been attributed to phosphorylation of myosin regulatory light chains[64] and/or elevation of Ca^{2+} in the cytosol.[65]

Not all studies have reported a significant increase in muscle force following a MVC.[63] However, these authors allowed only a 15-second recovery interval between the 10-second MVC and the dynamic knee extensions. With only a 15-second recovery interval, it is likely that there was still some residual fatigue from the MVC, prior to the dynamic contraction. This is supported by the significant decline in torque (16.3%) during the 10-second MVC.[63] Previous studies reporting a significant increase in dynamic performance following MVCs have used longer recovery intervals of 3–5 minutes.[4,5] While it is likely that some of the postactivation potentiation would have been diminished by this longer recovery interval,[66] the greater reduction in residual fatigue may have more than compensated for the diminished postactivation potentiation. Thus, with an appropriate rest period, it appears that active warm up that includes maximal to near-maximal voluntary contractions may be able to increase twitch potentiation and improve subsequent strength and power performance (figure 5).

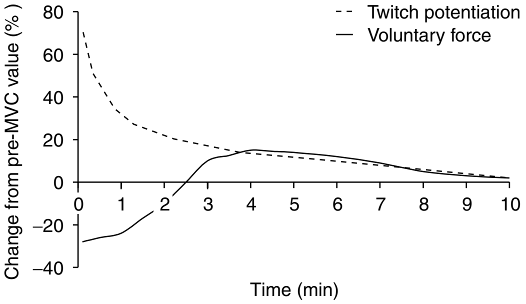

Fig. 5. Schematic representation of changes in twitch potentiation and maximal voluntary force following a maximal voluntary contraction (MVC).[4,61,66]

1.5 Breaking of Actin-Myosin Bonds

Part of the explanation for the stiffness of resting muscle may involve the development of stable bonds between actin and myosin filaments. With inactivity, the number of bonds increases and hence the stiffness of muscle increases.[67] However, with physical activity many of the bonds are broken, and muscle stiffness decreases.[68,69] Therefore, one of the benefits of an active warm up may be to minimise muscle stiffness by moving the required muscle groups through their range of motion.[70] As a result, the warm up may disturb actin-myosin bonds and thereby reduce the passive stiffness of muscle. This may contribute to an increased rate of force development and an increase in power during short-duration tasks. While warm up can decrease muscle stiffness, there is a rapid increase in stiffness, which then becomes more gradual, once the warm up is completed.[71]

1.6 Psychological Effects

Although warm up has been shown to result in a number of physiological changes, it is possible that psychological mechanisms contribute to reported improvements in performance. Massey et al.[6] reported no improvement in time to complete 100 cycle revolutions when subjects were hypnotised to ‘forget’ that they warmed up. However, the warm up used in this study was quite moderate (mostly running and jogging in place). Active warm up of similar duration and intensity is not usually associated with improved performance – even in the absence of hypnotism.[72,73] It has, however, been reported that athletes who ‘imagined’ a warm up had an enhanced physiological performance.[74] Therefore, while it is possible that there is a psychological component to warm up, this remains to be confirmed by further studies, especially studies using warm-up routines that have previously been shown to improve performance.

Warm up may also provide valuable time for athletes to mentally prepare for their event. In this respect, warm up can possibly be considered part of a pre-performance routine, assisting the athlete to obtain an appropriate activation state. Qualitative analysis has concluded that the use of pre-performance routines was a distinguishing characteristic of successful Olympians.[75] Furthermore, it has been suggested that warm up may benefit performance by providing time to concentrate.[1] Thus, increased preparedness is an additional possible psychological benefit of warm up.

1.7 Summary of Potential Warm-Up Mechanisms

The majority of the effects of warm up have been attributed to temperature-related and non-temperature-related physiological mechanisms. However, psychological mechanisms have also been proposed (e.g. increased preparedness). Proposed non-temperature-related mechanisms include increased oxygen delivery and speeded $\dot{V}O_2$ kinetics, elevation of baseline $\dot{V}O_2$ and increased postactivation potentiation. While warm up does not appear to speed $\dot{V}O_2$ kinetics in healthy, young adults, warm up may allow subsequent tasks to begin with an elevated $\dot{V}O_2$, if the recovery period between warm up and exercise is brief. An initial sparing of the anaerobic capacity should increase time to exhaustion and improve performance in tasks that require a significant anaerobic contribution. An increase in postactivation potentiation following warm up also has the potential to improve performance, especially in strength and power tasks. Proposed temperature-related mechanisms include decreased stiffness, increased nerve-conduction rate, altered force-velocity relationship, increased anaerobic energy provision and increased thermoregulatory strain. Decreases in muscle and joint stiffness and increases in nerve conduction rate following an increase in temperature have the potential to improve performance, especially strength and power tasks. Increased thermoregulatory strain has the potential to adversely affect long-term performance.

2. Passive Warm up and Performance

The majority of the effects of warm up have been attributed to temperature-related mechanisms.[7] Although not practical for most athletes, the use of a passive warm up allows one to test this hypothesis. Furthermore, passive heating allows one to obtain the increase in T_m or T_c achieved by active warm up, without depleting energy substrates. Passive warm up involves raising T_m or T_c by some external means. Various methods including hot showers or baths, saunas, diathermy and heating pads have been used. 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; (iii) long-term – fatiguing effort for ≥5 minutes.

2.1 Short-Term Performance

2.1.1 Isometric Force

Research has generally reported either no effect[76-79] or only a minor effect[80,81] of increasing T_m above normal (~35°C), on maximal isometric force (F_0) [figure 6; table II]. It should be noted, however, that these studies all had small sample sizes (~4 subjects) and consequently often did not conduct statistical analyses to support their findings. Furthermore, in both studies reporting an increase in F_0 (0.8–2.1% per °C), the increase in T_m was achieved with active exercise.[80,81] Active warm up has been shown to result in greater improvements in dynamic performance than passive warm up, despite similar changes in T_m.[82] Therefore, the ‘small’ increase in F_0 may have been due to mechanisms in addition to an increase in T_m. While some of the effects of temperature on muscle contractile properties depend on fibre composition, temperature-dependent changes in F_0 appear to be identical for both fast- and slow-twitch fibres.[83,84]

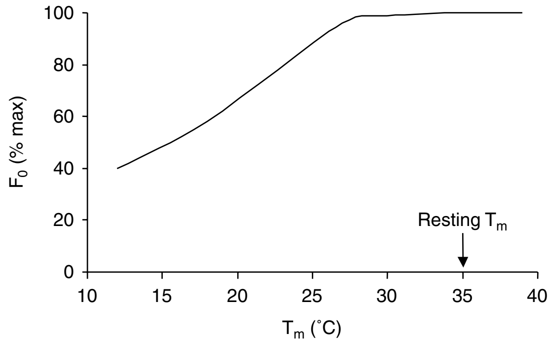

Fig. 6. Changes in maximum isometric force (F_0) as a function of changes in muscle temperature (T_m).[77-79]

While better designed studies, with greater sample sizes, are needed, it appears that there is very little effect of increasing T_m above normal on F_0. Thus, small temperature-related increases in joint resistance, muscle resistance and/or nerve-conduction rate appear to allow very little extra tension to be developed. These physiological changes are more likely to increase dynamic contractile properties.

2.1.2 Dynamic Force

The relationship between dynamic force and velocity of contraction for a muscle group can be described by the formula of a rectangular hyperbola. While F_0 does not appear to be significantly altered by an increase in T_m above normal, all other parameters of the force-velocity diagram have been reported to increase with increased T_m[76,78,79] (figure 7). Davies and Young[78] reported that increasing T_m by 3.1°C (from 36.8–39.9°C), decreased electrically-evoked time to peak tension (TPT) [7.7% per °C] and half-relaxation time ($RT_{1/2}$) [7.2% per °C] in the triceps surae muscle. The thermal dependence of both TPT and $RT_{1/2}$ decreases with increasing temperature.[31] Furthermore, like maximal isometric force, TPT has been reported to have a similar thermal dependence in both major muscle-fibre types.[83,84]

Changes in T_m, within the physiological range (22.5–38.0°C), have also been reported to affect both maximum velocity of shortening (V_{max}: 2.6% per °C) and maximal power (5.1% per °C) on a handgrip dynamometer.[76] Interestingly, similar values for change in V_{max} with increased T_m can also be derived from the data of Asmussen et al.[85] and have been reported in isolated cat muscle (unpublished observation). As with maximal isometric force, TPT and $RT_{1/2}$, the thermal dependence of V_{max} tends to decrease with increasing temperature.[31] However, in contrast to these previous measures, V_{max} has been reported to have a greater thermal dependence in fast-, than in slow-twitch fibres.[31] These results suggest that if the above changes for isolated muscles could be fully utilised during short-term athletic performance (e.g. running, jumping, cycling), a passive warm up may

Table II. Physiological and performance changes in short-term performance following heating or cooling

Study	Subjects	Intervention					Performance task		
		mode	duration (min)	temperature (°C)	rest (min)	phys. changes (°C)	mode	phys. changes	performance changes[a]
Asmussen and Boje[7]	5 MT males	N room temp	NA	NA	NR	NA	Isometric		F_0: ↑0.8% per °C; TPT: ↑3–5% per °C
		C_1 cold water	NR	NR	NR	$T_m = 32.7$		NA	
		H_1 exercise	NR	NA	NR	$T_m = 37.7$	Vertical jump		Height: ↑22 mm/°C
Bergh and Ekblom[81]	4 MT males	N room temp	NA	NA	NA	NA	Isometric		F_0: ↑2.1% per °C
		C_1 cold water	20	NR	NR	$T_m = 30–32$			
		C_2 cold water	20	NR	NR	$T_m = 33–35$	Vertical jump	NA	Height: ↑4.2% per °C
		H_1 exercise	20	NR	NR	$T_m = 36–37$			
		H_2 exercise	20	NR	NR	$T_m = 38–39$	Cycle		Peak power: ↑5.1% per °C
Binkhorst et al.[76]	4 UT males	C_1 cold water	30	18	0	$T_m = 23–25$	Isometric (hand grip)		F_0: $C_1 = N = H_1 = H_2$; $p > 0.05$
		N room temp	30	20–22	0	$T_m = 32–34$			V_0: ↑2.6% per °C
		H_1 hot water	30	25	0	$T_m = 28–29$		NA	Peak power: ↑5.1% per °C
		H_2 hot water	30	39	0	$T_m = 37–38$			
Clarke et al.[77]	4 MT males	C_1 cold water	30	2	0	$T_m = 18$	Isometric (hand grip)		F_0: $C_1 < C_2 < C_3 < C_4 = N = H_1 = H_2$
		C_2 cold water	30	10	0	$T_m = 23$			
		C_3 cold water	30	18	0	$T_m = 25$			
		C_4 cold water	30	14	0	$T_m = 27$		NA	
		N room temp	30	26	0	$T_m = 30$			
		H_1 hot water	30	34	0	$T_m = 35$			
		H_2 hot water	30	42	0	$T_m = 39$			
Davies and Young[78]	5 UT males	N room temp	NA	NA	NA	$T_r = 36.7$	Isometric (leg)		F_0: H = N > C; TPT: H > N > C; $p < 0.05$
		C_1 cold water	30–45	0	0	$T_r = 28.4$	Vertical jump	NA	Height: H = N > C; ↑2.4 cm/°C
		H_1 hot water	30–45	46	0	$T_r = 39.9$	Cycle		Peak power: H = N > C; $p < 0.05$
Ranatunga et al.[79]	4 UT males	N room temp	NA	NA	NA	$T_s \sim 25$	Isometric (finger)		F_0: H > N > C; TPT: H > N > C; $p < 0.05$
		C_1 cold water	5–15	25	NR	$T_s \sim 15$		NA	
		H_1 hot water	5–15	39	NR	$T_s \sim 35$			

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

C = cooling; $\mathbf{F_0}$ = isometric force; **H** = heating; **MT** = moderately trained; **N** = no treatment; **NA** = not applicable; **NR** = variable not reported; **phys.** = physiological; $\mathbf{T_m}$ = muscle temperature; **TPT** = time to peak tension; $\mathbf{T_r}$ = rectal temperature; $\mathbf{T_s}$ = skin temperature; **UT** = untrained; $\mathbf{V_0}$ = maximal velocity; ↑ = increase.

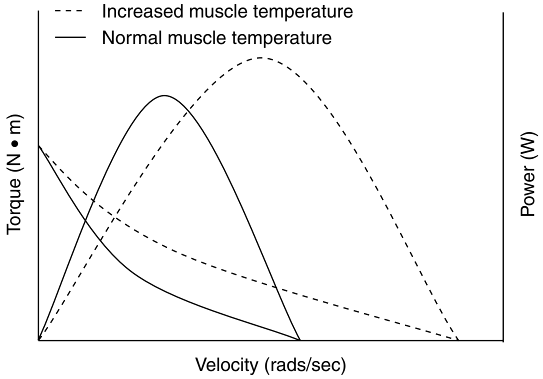

Fig. 7. Idealised effect of an increase in muscle temperature on the torque- and power-velocity relationships. Note there is an increase in maximum velocity and maximum power, but no change in isometric torque (velocity = 0 rads/sec).

increase power output by ~5.0% per °C change in T_m.

Consistent with the previously mentioned results for simple muscle contractions, an increase in T_m (from 27–40°C) has been reported to increase maximum isokinetic torque (4.7–4.9% per °C)[81] and vertical jump height (4.2–4.4% per °C)[80,81] [table II]. Vertical jump performance was affected in direct proportion to the change in peak torque. While these changes are similar in magnitude to those predicted from simple muscle contractions, variations in T_m were obtained by immersing the subject in cold water or by active exercise. It has been reported that active warm up results in a slightly greater increase in peak power output than passive warm up (2.7 vs 2.3% per °C).[86] It is therefore, likely that some of the improvement in performance can be attributed to the active warm up, rather than the increase in T_m alone. Slightly smaller increases in vertical jump height (3.1% per °C) and vertical-jump power (3.6% per °C) have been reported following passive heating alone (increased T_m from 36.3–39.9°C).[78] These smaller than predicted changes in vertical-jump power may be related to the previously reported decrease in the thermal dependence of V_{max} with increasing temperature.[31]

Changes in peak power, following an increase in T_m, have also been reported for cycle ergometry (1.2–10.0% per °C)[78,81,86,87] [table II]. However, changes appear to be dependent on the velocity of contraction. Peak power has been reported to increase by 2.0% per °C rise in T_m at a cycle cadence of 54 revs/min and 10% per °C at 140 revs/min.[87] This suggests that temperature-related changes in the force-velocity relationship may be greater at faster contraction velocities.

2.1.3 Summary of Short-Term Performance

Despite a scarcity of well-controlled studies, with appropriate statistical analyses, it appears that passive warming has little effect on maximum isometric force, but can improve dynamic force. However, changes in the force-velocity relationship, following an increase in T_m, may not be fully utilised during dynamic short-term performance. Furthermore, the results suggest that passive warm up has a greater ergogenic effect at greater contraction velocities. While passive warm up is not practical for most athletes, it may have an important role in maintaining an elevated T_m between the warm up and short-term performance (e.g. sprinting, jumping). It appears particularly important that muscles are not allowed to cool below their normal physiological range before commencing short-term exercise.

2.2 Intermediate Performance

Three studies have reported that a passive warm up can improve intermediate performance[7,10,88] (table III). Asmussen and Boje[7] observed, in two subjects, that passive heating (a 10-minute hot shower at 47°C) raised T_r by 0.5–0.6°C and improved performance (time to complete 956 or 9860 kg/m of work) by ~6%. They also reported a strong relationship between increases in T_m and performance time and largely attributed the performance improvement to an increase in T_m, rather than T_r. Passive heating (hot showers or diathermy for 15–18 minutes) has also been reported to improve swimming performance over both 50m (0–2%; n = 3) and 200–400m (1.3–3.9%; n = 3).[10] However, these authors reported that when they allowed T_m to return to normal, but T_r to remain elevated, performance remained improved. Thus, in contrast to Asmussen and Boje,[7] they concluded that the beneficial effects of passive warm up on intermediate performance could mostly be attributed to an increase in T_r, rather than T_m. A statistically significant improvement (1%; n = 10; $p < 0.05$) in 40-yard (36.6m) swim performance has also been reported following an 8-minute hot shower (increased T_r to 38°C).[88] In addition, two other studies have reported a relationship between improved intermediate performance and T_m when the increase in T_m was achieved by active exercise.[7,81] The limited re-

Table III. Physiological and performance changes in intermediate performance following heating or cooling

Study	Subjects	Warm up					Performance task		
		mode	duration (min)	intensity	rest (min)	phys. changes (°C)	mode	phys. changes	performance changes[a]
Asmussen and Boje[7]	4 UT males	N room temp	NA	NA	NR	NA	Cycle (956 kg/m)	NA	Time: H_2 < N (~5.8%)
		H_1 heating pads	10	110W	NR	T_r = ↑0.8			H_1 < N (~5.5%)
		H_2 exercise	30	NA	NR	T_r = ↑1.5			
Bergh and Ekblom[81]	4 MT males	N room temp	NA	NA	NA	NA	Cycle (20 revs)	NA	Sprint time: ↓with ↑T_m
		C_1 cold water	20	NR	NR	T_m = 30–32			
		C_2 cold water	20	NR	NR	T_m = 33–35			Average speed: ↑4.7% per °C
		H_1 exercise	20	NR	NR	T_m = 36–37			
		H_2 exercise	20	NR	NR	T_m = 38–39			Peak velocity: ↑4.7% per °C
Carlile[88]	10 T males and females	N shower	0.5	'Luke warm'	NR	NA	Swim (40yd [36.6m])	NA	Speed: H > N (~1.0%; $p < 0.01$)
		H shower	8.0	'Hot'	NR	NA			
Muido[10]	3 UT males	N room temp	NA	NA	NA	NA	Swim (50m)	NA	Speed: H_1 > N (0.0–2.0%)
		H_1 hot bath		40–43°C	NA	T_r = ↑1.0–1.6			H_2 > N (0.6–2.2%)
		H_2 exercise		'Jog'	10	T_r = ↑0.4–0.9	Swim (400m)		Speed: H_3 > N (1.4–2.6%)
		H_3 exercise		180W	10	T_r = ↑~0.6			H_1 > N (2.1–3.9%)

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

C = cooling; **H** = heating; **MT** = moderately trained; **N** = no treatment; **NA** = not applicable; **NR** = variable not reported; **phys.** = physiological; **T** = trained; **T_m** = muscle temperature; **T_r** = rectal temperature; **UT** = untrained; ↑ = increase; ↓ = decrease.

search to date suggests that passive warm up can improve intermediate performance.

When discussing the effects of passive warm up on intermediate performance, it may also be important to consider the effects of contraction frequency. It has been reported that increasing T_m decreased net mechanical efficiency when cycling at 60 revs/min, but increased net mechanical efficiency when cycling at 120 revs/min.[89] Thus, the contraction frequency may determine whether or not passive warming has an ergogenic effect.

Further research is required to determine the relative contributions of an increase in T_m or T_r to improved intermediate performance. However, performance improvements are likely to be attributable to a decrease in joint and muscle resistance and/or an increase in nerve conduction rate.

2.3 Long-Term Performance

Very few studies have investigated the effects of passive warm up on long-term performance (table IV). This is possibly because an excessive body-heat load is well acknowledged as one of the limiting physiological factors for long-term performance.[40,41] Therefore, increasing the body temperature before vigorous exercise may decrease long-term performance via a decrease in heat-storage capacity[42] and/or impaired thermoregulation mechanisms.[44] In support of this, passive warm up has been reported to decrease intermittent (30 seconds at 90% $\dot{V}O_{2max}$: 30 seconds passive rest) run time to exhaustion (38.5 + 11.1 minutes vs 72.0 + 17.2 minutes; $p < 0.05$) in moderate ambient conditions (21.7°C and 36.7% RH).[90] In a similar study by the same authors, time to exhaustion at 70% of $\dot{V}O_{2max}$ was also impaired (62.0 vs 39.6 minutes; $p < 0.05$) when preceded by a warm up that raised T_r to 38.0°C.[91] The decrease in run time in both studies was associated with a decrease in heat-storage capacity and the earlier attainment of a high T_r. At the onset of exhaustion, there were no significant differences in $\dot{V}O_2$, plasma volume changes, total sweat loss or T_s. Pre-cooling has been reported to have the opposite effect, increasing heat-storage capacity and increasing run time to exhaustion in dogs[40] and in trained runners.[43] Passive warm up therefore, has the potential to decrease long-term performance via a decrease in heat-storage capacity and therefore, a decrease in the temperature range before an upper critical T_r can be reached.

A number of studies have also reported decreases in isometric endurance performance following passive warm up.[37,77,92,93] Sedgewick and Whalen[93] reported a nonsignificant, 2% decrease in the number of isometric handgrip contractions until fatigue (7 minutes 20 seconds vs 7 minutes 31 seconds) following 10 minutes of diathermy (T_m = 40.7–41.1°C). A 5.8% decrease in impulse (force × time) has also been reported for 180 isometric handgrip contractions (6 minutes) following 8 minutes immersion in hot water (48.0°C), compared with immersion in cold water (10.0°C).[92] It is possible that Sedgewick and Whalen[93] did not find a significant difference between conditions as a consequence of their use of a less reliable ‘time to fatigue’ test.[94]

The relationship between T_m and isometric endurance appears to be best described by a curvilinear relationship (figure 8). Clarke et al.[77] reported that time to fatigue for isometric handgrip endurance, following immersion in seven different water baths (T_m = 18.0–38.5°C), was optimal at a T_m of ~27°C. The decrease in isometric endurance did not appear to be associated with a reduction in the ability of muscles to exert maximum tension when T_m >27°C (figure 8). Rather, the authors hypothesised that the reduction in the duration of contractions when T_m >27°C was due to a more rapid accumulation of metabolites (as indicated by the hyperaemic response; figure 8). This hypothesis is supported by subsequent research reporting that the decreased endurance time during repeated isometric contractions in heated muscle is accompanied by enhanced ATP utilisation, increased rate of phosphocreatine breakdown and accelerated glycolysis.[40]

While there have been only a few studies, it appears that passive warm up does not improve, and may have a detrimental effect, on endurance performance in commonly observed ambient conditions. The detrimental effects of passive warm up on endurance performance appear to be due to a decrease in heat storage capacity and/or impaired thermoregulatory mechanisms resulting in the earlier attainment of a high T_r, and/or a more rapid accumulation of metabolites.

2.4 Summary of Passive Warm Up and Performance

While there is a scarcity of well-controlled studies, with large subject numbers and appropriate sta-

Table IV. Physiological and performance changes in long-term performance following passive, general warm up

Study	Subjects	Warm up					Performance task		
		mode	duration (min)	intensity (°C)	rest (min)	phys. changes (°C)	mode	phys. changes	performance changes[a]
Clarke et al.[77]	4 MT males	C_1 cold water	30	2	0	$T_m = 18$	Isometric (grip ⅓MVC)	NA	ttf: $C_4 > C_3 = N > C_2 = H_1 > C_1 = H_2$
		C_2 cold water	30	10	0	$T_m = 23$			
		C_3 cold water	30	14	0	$T_m = 25$			
		C_4 cold water	30	18	0	$T_m = 27$			
		N room temp	30	26	0	$T_m = 30$			
		H_1 hot water	30	34	0	$T_m = 35$			
		H_2 hot water	30	42	0	$T_m = 39$			
Edwards et al.[37]	10 UT males	C_1 cold water	30	12	NR	$T_m = 22.5$	Isometric (knee extension – ⅔ MVC)	↑Glycolysis and ATP use in heated muscle	ttf: $C_2 > N > C_1 > H$
		C_2 cold water	30	26		$T_m = 32.6$			
		N room temp	30	NA		$T_m = 35.1$			
		H hot water	30	44		$T_m = 38.6$			
Gregson et al.[90]	6 MT males	N room temp	30	NA	10	NA	Run (30 sec at 70% $\dot{V}O_{2max}$: 30 sec rest)	↓Heat-storage capacity	ttf: $N > A > H$; $p < 0.05$
		H hot water	~30	NA	10	$T_r = 38$		$T_r = A = h = N$	
		A active	~20	70% $\dot{V}O_{2max}$	10	$T_r = 38$			
Gregson et al.[91]	6 MT males	N room temp	30	NA	10	NA	Run (70% $\dot{V}O_{2max}$)	↓Heat-storage capacity	ttf: $N > A = H$; $p < 0.05$
		H hot water	~30	NA	10	$T_r = 38$		$T_r = A = h = N$	
		A active	~20	70% $\dot{V}O_{2max}$	10	$T_r = 38$			
Grose[92]	12 UT males	C cold water	8	10	30 sec	NA	Isometric (grip × 180)		Total work: $C > H$; $p < 0.05$
		H hot water	8	48	30 sec				
Sedgwick and Whalen[93]	6 UT males	N room temp	NA	NA	NA	T_m: $H > N$ (2–4°C)	Isometric (grip)		ttf: $N = H$
		H diathermy	10	NR	30 sec				

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

A = active; **ATP** = adenosine triphosphate; **MT** = moderately trained; **MVC** = maximal voluntary contraction; **N** = no treatment; **NA** = not applicable; **NR** = not reported; **T_m** = muscle temperature; **T_r** = rectal temperature; **ttf** = time to fatigue; **UT** = untrained; **$\dot{V}O_{2max}$** = maximum oxygen consumption.

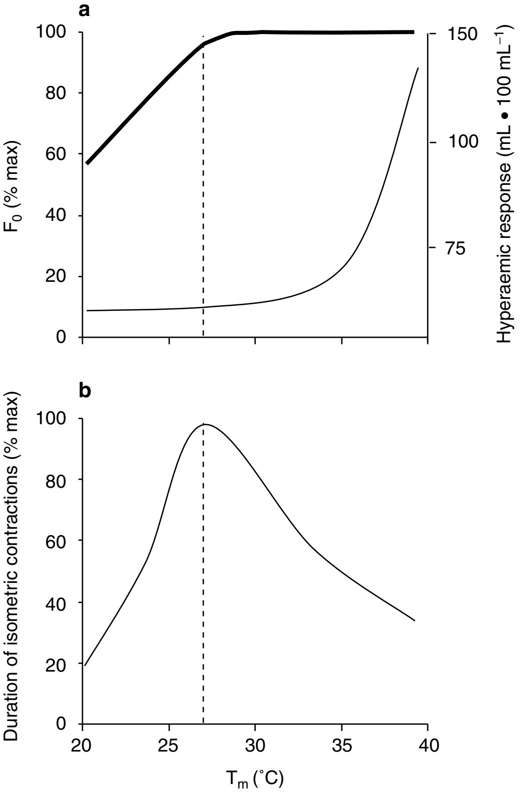

Fig. 8. Changes in maximum isometric force (F_0) [thick line] and hyperaemic response (thin line) as a function of changes in muscle temperature (T_m) [**a**]. Change in duration of isometric contractions as a function of changes in T_m (**b**).[77]

tistical analyses, a number of conclusions can be drawn regarding the effects of passive warm up on performance. It appears that passive warm up does not improve isometric force, but may improve short-duration (<10 seconds) dynamic force. However, changes in the force-velocity relationship, following an increase in T_m, may not be fully utilised during dynamic short-term performance (e.g. vertical jumping and sprint cycling). Furthermore, passive warm up appears to have a greater ergogenic effect on dynamic short-term performance at faster contraction velocities. While the mechanisms remain to be fully elucidated, it also appears that passive warm up can improve intermediate performance (~10 seconds to 5 minutes). Passive warm up does not improve, and may have a detrimental effect on, long-term performance (>5 minutes).

3. Conclusions

While it has been hypothesised that warm up may have a number of psychological effects, the majority of the effects of warm up have been attributed to temperature-related mechanisms (e.g. decreased stiffness, increased nerve-conduction rate, altered force-velocity relationship and increased lactic energy provision). However, other mechanisms have also been proposed (e.g. effects of acidaemia, mobilisation of the aerobic system and increased postactivation potentiation). Despite the above-mentioned mechanisms, it appears that passive warm up does not improve isometric force, but may improve short-duration (<10 seconds) dynamic force. However, improvements in dynamic short-term performance (e.g. vertical jumping and sprint cycling) tend to be less than those reported for isolated muscles. While the mechanisms remain to be fully elucidated, it also appears that passive warm up can improve intermediate performance (~10 seconds to 5 minutes). Passive warm up does not improve, and may have a detrimental effect on, long-term performance (>5 minutes), possibly via an increase in thermoregulatory strain.

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References

1. Shellock FG, Prentice WE. Warming-up and stretching for improved physical performance and prevention of sports-related injuries. Sports Med 1985; 2: 267-78
2. Gerbino A, Ward S, Whipp B. Effects of prior exercise on pulmonary gas-exchange kinetics during high-intensity exercise in humans. J Appl Physiol 1996; 80 (1): 99-107
3. Andzel WD. One mile run performance as a function of prior exercise. Sports Med Phys Fitness 1982; 22: 80-4
4. Gullich A, Schmidtbleicher D. MVC-induced short-term potentiation of explosive force. New Stud Athletics 1996; 11 (4): 67-81
5. Young WB, Jenner A, Griffiths K. Acute enhancement of power performance from heavy load squats. J Strength Cond Res 1998; 12: 82-4
6. Massey BH, Johnson WR, Kramer GF. Effect of warm-up exercise upon muscular performance using hypnosis to control the psychological variable. Res Q Exerc Sport 1961; 32: 63-71
7. Asmussen E, Boje O. Body temperature and capacity for work. Acta Physiol Scand 1945; 10: 1-22
8. Saltin B, Gagge AP, Stolwijk JAJ. Muscle temperature during submaximal exercise in man. J Appl Physiol 1968; 25: 679-88
9. Sargeant AJ. Effect of muscle temperature on leg extension force and short-term power output in humans. Eur J Appl Physiol 1987; 56: 693-8
10. Muido L. The influence of body temperature on performance in swimming. Acta Physiol Scand 1946; 12: 102-9

11. Fisher M, Paolone V, Rosene J, et al. The effect of submaximal exercise on recovery hemodynamics and thermoregulation in men and women. Res Q Exerc Sport 1999; 70 (4): 361-8
12. Matthews DK. Physiological responses during exercise and recovery in a football uniform. J Appl Physiol 1969; 26: 611
13. Price MJ, Campbell IG. Thermoregulatory responses of paraplegic and able-bodied athletes at rest and during prolonged upper body exercise and passive recovery. Eur J Appl Physiol 1997; 76: 552-60
14. Wright V, Johns RJ. Quantitative and qualitative analysis of joint stiffness in normal subjects and in patients with connective tissue disease. Ann Rheum Dis 1961; 20: 36-46
15. Wright V. Stiffness: a review of it's measurement and physiological importance. Physiotherapy 1973; 59: 59-111
16. Buchthal F, Kaiser E, Knappeis GG. Elasticity, viscosity and plasticity in the cross striated muscle fibre. Acta Physiol Scand 1944; 8: 16-37
17. McCutcheon LJ, Geor RJ, Hinchcliff KW. Effects of prior exercise on muscle metabolism during sprint exercise in humans. J Appl Physiol 1999; 87 (5): 1914-22
18. Barcroft J, King WOR. The effect of temperature on the dissociation curve of blood. J Physiol 1909; 39: 374-84
19. Theorell H. The effect of temperature on myoglobin. Biochem Z 1934; 73: 268
20. Barcroft H, Edholm OG. The effect of temperature on blood flow and deep temperature in the human forearm. J Physiol 1943; 102: 5-12
21. Grassi B, Gladden LB, Samaja M, et al. Faster adjustment of O2 delivery does not affect V̇O2 on-kinetics in isolated in situ canine muscle. J Appl Physiol 1998; 85 (4): 1394-403
22. Grassi B, Gladden LB, Stary CM, et al. Peripheral O2 diffusion does not affect V̇O2 on-kinetics in isolated in situ canine muscle. J Appl Physiol 1998; 85 (4): 1404-12
23. Grassi B, Hogan MC, Kelley KM, et al. Role of convective O2 delivery in determining V̇O2 on-kinetics in canine muscle contracting at peak V̇O2. J Appl Physiol 2000; 89: 1293-301
24. Burnley M, Jones AM, Carter H, et al. Effects of prior exercise on phase II pulmonary oxygen uptake kinetics during exercise. J Appl Physiol 2000; 89: 1387-96
25. Koppo K, Bouckaert J. The effect of prior high-intensity cycling exercise on the V̇O2 kinetics during high-intensity cycling exercise is situated at the additional slow component. Int J Sports Med 2001; 22: 21-6
26. Koga S, Shiojiri T, Kondo N, et al. Effect of increased muscle temperature on oxygen uptake kinetics during exercise. J Appl Physiol 1997; 83 (4): 1333-8
27. Scheuermann BW, Bell C, Peterson DH, et al. Oxygen uptake kinetics for moderate exercise are speeded in older humans by prior heavy exercise. J Appl Physiol 2002; 92: 609-15
28. Bell C, Paterson DH, Kowalchuk JM, et al. Detrminants of oxygen uptake kinetics in older humans following single-limb endurance exercise training. Exp Physiol 2001; 86 (5): 659-65
29. Barcroft H, Dornhorst AC. The blood flow through the human calf during rhythmic exercise. J Physiol 1949; 109: 402-11
30. Brooks GA, Hittelman KJ, Fauklner JA, et al. Temperature, skeletal muscle functions, and oxygen debt. Am J Physiol 1971; 220 (4): 1053-9
31. Bennett AF. Thermal dependence of muscle function. Am J Physiol 1984; 247: R217-29
32. Fink WJ, Costill DL, Van Handel PJ. Leg muscle metabolism during exercise in the heat and cold. Eur J Appl Physiol 1975; 34: 183-90
33. Febbraio MA, Carey MF, Snow RJ, et al. Influence of elevated muscle temperature on metabolism during intense, dynamic exercise. Am J Physiol 1996; 271 (40): R1251-5
34. Febbraio MA. Does muscle function and metabolism affect exercise performance in the heat? Exerc Sport Sci Rev 2000; 28 (4): 171-6
35. Bergstrom J, Hermansen L, Hultman E, et al. Diet, muscle, glycogen and physical performance. Acta Physiol Scand 1967; 71: 140-50
36. Febbraio MA. Temperature, muscle metabolism and performance. In: Lamb DL, Murray R, editors. Perspectives in exercise science and sports medicine. Carmel (IN): Cooper Publishing Group, 1999: 315-53
37. Edwards RHT, Harris RC, Hultman E, et al. Effect of temperature on muscle energy metabolism and endurance during successive isometric contractions, sustained to fatigue, of the quadriceps muscle in man. J Physiol 1972; 220: 335-52
38. Karvonen J. Importance of warm up and cool down on exercise performance. In: Karvonen J, Lemon PWR, Iliev I, editors. Medicine and sports training and coaching. Basel: Karger, 1992: 190-213
39. Ross A, Leveritt M. Long-term metabolic and skeletal muscle adaptations to short-sprint training: implications for sprint training and tapering. Sports Med 2001; 31: 1063-82
40. Kozlowski S, Brzezinska Z, Kruk B, et al. Exercise hyperthermia as a factor limiting physical performance: temperature effect on muscle metabolism. J Appl Physiol 1985; 59 (3): 766-73
41. Romer LM, Barrington JP, Jeukendrup AE. Effects of oral creatine supplementation on high intensity, intermittent exercise performance in competitive squash players. Int J Sports Med 2001; 22: 546-52
42. Nadel ER. Prolonged exercise and high and low ambient temperatures. Can J Sport Sci 1987; 12 (3 Suppl. 1): 140S-2S
43. Lee DT, Haymes EM. Exercise duration and thermoregulatory responses after whole body precooling. J Appl Physiol 1995; 79 (6): 1971-6
44. Fortney S, Wenger C, Bove J, et al. Effect of hyperosmolality on control of blood flow and sweating. J Appl Physiol 1984; 57: 1688-95
45. McComas AJ. Skeletal muscle: form and function. Champaign (IL): Human Kinetics, 1996: 213
46. Kiens B, Saltin B, Wallye L, et al. Temporal relationship between blood flow changes and release of ions and metabolites from muscle upon single weak contractions. Acta Physiol Scand 1989; 213: 235-54
47. Guyton AC. Textbook of medical physiology. Philadelphia (PA): W.B. Saunders, 1986: 235
48. Boning D, Hollnagel C, Boecker A, et al. Bohr shift by lactic acid and the supply of O2 to skeletal muscle. Respir Physiol 1991; 85: 231-43
49. Burnley M, Doust JH, Carter H, et al. Effects of prior exercise and recovery duration on oxygen uptake kinetics during heavy exercise in humans. Exp Physiol 2001; 86 (3): 417-25
50. Bishop D, Bonetti D, Dawson B. The influence of three different warm up intensities on sprint kayak performance in trained athletes. Med Sci Sports Exerc 2001; 33 (6): 1026-32
51. Hermansen L. Muscle fatigue during maximal exercise of short duration. In: di Prampero PE, Poortmans J, editors. Physiological chemistry of exercise and training. medicine and sport science. Basel: Karger, 1981: 45-52
52. Fabiato A, Fabiato F. Effects of pH on the myofilaments and the sarcoplasmic reticulum of skinned cells from the cardiac and skeletal muscles. J Physiol (Lond) 1978; 276: 233-55
53. Bishop D, Bonetti D, Dawson B. The influence of pacing strategy on V̇O2 and kayak ergometer performance. Med Sci Sports Exerc 2002; 34 (6): 1041-7
54. Gastin PB, Costill DL, Lawson DL, et al. Accumulated oxygen deficit during supramaximal all-out and constant intensity exercise. Med Sci Sports Exerc 1995; 27 (2): 255-63
55. Gollnick PD, Armstrong RB, Sembrowich WL, et al. Glycogen depletion pattern in human skeletal muscle fibres after heavy exercise. J Appl Physiol 1973; 34 (5): 615-8
56. Ingjer F, Stromme SB. Effects of active, passive or no warm-up on the physiological response to heavy exercise. Eur J Appl Physiol 1979; 40: 273-82
57. Stewart IB, Sleivert GG. The effect of warm-up intensity on range of motion and anaerobic performance. JOSPT 1998; 27 (2): 154-61

58. Gutin B, Stewart K, Lewis S, et al. Oxygen consumption in the first stages of strenuous work as a function of prior exercise. Sports Med Phys Fitness 1976; 16: 60-5
59. di Prampero E, Davies CTM, Cerretelli P, et al. An analysis of O2 debt contracted in submaximal exercise. J Appl Physiol 1970; 29 (5): 547-51
60. Ozyener F, Rossiter HB, Ward SA, et al. Influence of exercise intensity on the on- and off-transient kinetics of pulmonary oxygen uptake in humans. J Physiol 2001; 533 (3): 891-902
61. Vandervoort AA, Quinlan J, McComas AJ. Twitch potentiation after voluntary contraction. Exp Neurol 1983; 81: 141-52
62. Sale DG. Postactivation potentiation: role in human performance. Exerc Sport Sci Rev 2002; 30 (3): 138-43
63. Gossen ER, Sale DG. Effect of postactivation potentiation on dynamic knee extension performance. Eur J Appl Physiol 2000; 83: 524-30
64. Moore RL, Stull JT. Myosin light chain phosphorylation in fast and slow skeletal muscles in situ. Am J Physiol 1984; 247: C462-71
65. Allen DG, Lee JA, Westerblad H. Intracellular calcium and tension during fatigue in isolated single muscle fibres from xenopus laevis. J Physiol 1989; 415: 433-58
66. Hamada T, Sale DG, MacDougall JD, et al. Postactivation potentiation, fibre type and twitch contraction time in human knee extensor muscles. J Appl Physiol 2000; 88: 2131-7
67. Enoka RM. Acute adaptations. In: Enoka RM, editor. Neuromechanical basis of kinesiology. 2nd ed. Champaign (IL): Human Kinetics, 1994: 271-302
68. Proske V, Morgan DL, Gregory JE. Thixotropy in skeletal muscle spindles: a review. Prog Neurobiol 1993; 41: 705-21
69. Wiegner AW. Mechanism of thixotropic behaviour at relaxed joints in the rat. J Appl Physiol 1987; 62: 1615-21
70. Wiktorsson-Muller M, Oberg B, Ekstrand J, et al. Effects of warming up, massage, and stretching on range of motion and muscle strength in the lower extremity. Am J Sports Med 1983; 11 (4): 249-52
71. Lakie M, Robson LG. Thixotropic changes in human muscle stiffness and the effects of fatigue. Q J Exp Physiol 1988; 73: 487-500
72. De Vries HA. Effects of various warm-up procedures on 100-yard times of competitive swimmers. Res Q Exerc Sport 1959; 30: 11-22
73. Pyke FS. The effect of preliminary activity on maximal motor performance. Res Q Exerc Sport 1968; 39 (4): 1069-76
74. Malareki I. Investigation of physiological justification of so-called ‘warming up’. Acta Physiol Pol 1954; 5: 543-6
75. Orlick T, Partington J. The sport psychology consultant: analysis of critical components as viewed by Canadian Olympic athletes. Sport Psychol 1987; 2: 105-30
76. Binkhorst RA, Hoofd L, Vissers ACA. Temperature and force-velocity relationship of human muscles. J Appl Physiol 1977; 42 (4): 471-5
77. Clarke RSJ, Hellon RF, Lind AR. The duration of sustained contractions of the human forearm at different muscle temperatures. J Physiol 1958; 143: 454-73
78. Davies CTM, Young K. Effect of temperature on the contractile properties and muscle power of triceps surae in humans. J Appl Physiol 1983; 55 (1): 191-5
79. Ranatunga KW, Sharpe B, Turnbull B. Contractions of human skeletal muscle at different temperatures. J Physiol 1987; 390: 383-95
80. Asmussen E, Bonde-Petersen F, Jorgensen K. Mechano-elastic properties of human muscles at different temperatures. Acta Physiol Scand 1976; 96: 83-93
81. Bergh U, Ekblom B. Influence of muscle temperature on maximal muscle strength and power output in human skeletal muscles. Acta Physiol Scand 1979; 107: 33-7
82. O’Brien B, Payne W, Gastin P, et al. A comparison of active and passive warm ups on energy system contribution and performance in moderate heat. Aust J Sci Med Sport 1997; 29 (4): 106-9
83. Petrofsky JS, Lind AR. The influence of temperature on the isometric characteristics of fast and slow muscle of the cat. Pflugers Arch 1981; 389: 149-54
84. Ranatunga KW. Influence of temperature on isometric tension development in mouse fast- and slow-twitch skeletal muscles. Exp Neurol 1980; 70: 211-8
85. Asmussen EO, Hansen O, Lammert O. The relation between isometric and dynamic muscle strength in man [communication 20]. Copenhagen: National Association for Infant Paralysis, 1965
86. Dolan P, Greig C, Sargeant AJ. Effect of active and passive warm-up on maximal short-term power output of human muscle. J Physiol 1985; 365: P74
87. Sargeant AJ. Effect of muscle temperature on maximal short-term power output in man. J Physiol 1983; 341: 35P
88. Carlile F. Effect of preliminary passive warming on swimming performance. Res Q Exerc Sport 1956; 27 (2): 143-51
89. Ferguson RA, Ball D, Sargeant AJ. Effect of muscle temperature on rate of oxygen uptake during exercise in humans at different contraction frequencies. J Exp Biol 2002; 205: 981-7
90. Gregson W, Batterham A, Drust B, et al. The effects of pre-warming on the metabolic and thermoregulatory responses to prolonged intermittent exercise in moderate ambient temperatures. J Sports Sci 2002; 20 (1): 49-50
91. Gregson WA, Drust B, Batterham A, et al. The effects of pre-warming on the metabolic and thermoregulatory responses to prolonged submaximal exercise in moderate ambient temperature. Eur J Appl Physiol 2002; 86: 526-33
92. Grose JE. Depression of muscle fatigue curves by heat and cold. Res Q Exerc Sport 1958; 29: 19-31
93. Sedgwick AW, Whalen HR. Effect of passive warm-up on muscular strength and endurance. Res Q Exerc Sport 1964; 35 (1): 45-59
94. McLellan TM, Cheung SS, Jacobs I. Variability of time to exhaustion during submaximal exercise. Can J Appl Physiol 1995; 20 (1): 39-51

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