NEUROMUSCULAR PERFORMANCE LIMITATIONS IN COLD

Juha Oksa

ABSTRACT

This review will focus on the effects of cooling on muscular performance and its variables, functional properties of the muscles and some neural aspects of muscle function. The changes are described in terms of different cold exposures with varying intensity, therefore also looking at the dose dependent relationship between cooling and performance decrement. In addition, relationship between rewarming exercise and performance enhancement is described. Future research needs are addressed. *(Int J Circumpolar Health 2002; 61: 154-162)*

Keywords: neuromuscular performance, cold, muscle temperature, stretch reflex, EMG

When humans are exposed to cold ambient temperatures cooling may occur, thus resulting in subnormal body temperatures. It is well verified that a subnormal body temperature has an adverse effect on neuromuscular performance (7, 13, 23, 24, 45, 47, 49, 61). Decreased performance capacity increases the relative strain of the muscles and may cause fatigue earlier than in thermoneutral conditions. The following literature review will focus on the effects of cooling on muscular performance and its variables, functional properties of the muscles and some neural aspects of muscle function.

EXPOSURE

The exposures used to cause cooling of the body vary to a great deal in terms of length (from minutes to couple of hours), substance used (water or air) and area of exposure (local or whole body). The studies cited in this review have mainly used whole body cold air exposure but local cold water exposures have been used as well. However, the common nominator of the exposures (regardless of the

Oulu Regional Institute of Occupational Health, Laboratory of Physiology, Oulu, Finland

specific features of the exposure) is that they cause decreased muscle temperature, which can be considered as the most important factor in determining the outcome of muscular performance (7, 48, 49). In relation to thermoneutral muscle temperature, the magnitude of the decrease in muscle temperature in the studies cited here varies approximately between 1 - 7 °C.

The duration of the exercises cited in this review varies from less than a second to several minutes, their specific type being usually mentioned in the text. Roughly, muscular performance can be divided into isometric and dynamic exercises.

ISOMETRIC EXERCISE

In human studies maximal isometric force level has been found to be relatively stable within the muscle temperature range from 27 to 40°C (17). Within that temperature range Bergh and Ekblom (7) found a decrease of 2% MVC (maximal voluntary contraction) per degree of change in muscle temperature, very small decrease or no effect on MVC was observed by Clarke et al. (19) and Bundschuh and Clarke (15) and an increase in MVC was found by McGown (39). On the other hand, literature quite uniformly reports that with muscle temperatures below 27°C isometric MVC decreases, the decrement being within the range from 11 to 19 % (2, 14, 20, 22, 33, 50).

During sustained isometric exercises cooling, on the contrary, seems to have a beneficial effect (15, 18, 19, 54). When muscle temperature is below normal but higher than 27 °C the endurance time is increased and the rate of fatigue is slower (18, 54).

DYNAMIC EXERCISE

In general, the ability to perform dynamic exercises is more readily disturbed by cooling than isometric exercise. The decrement in performance is usually expressed as absolute decrease (%) or related to decrease in muscle temperature ($\% \cdot {}^{\circ}C^{-1}$ decrease in muscle temperature). The dynamic exercise types most often used are bicycling and jumping (1, 7, 9, 13, 21, 28, 49, 61). Other exercise types have been used less often. These include sprinting, isokinetic leg or manual arm performance (8, 29, 31). Quite uniformly literature, however, reports decreases in dynamic performances regardless of the exercise type, the decrement in general being approximately of the order of 2 - 10 % · °C^{-1} decrease in muscle temperature (9, 61). However, even bigger values have been reported. Bergh and Ekblom (8) found that cooling produced a 55 % decrement in maximal working time while muscle temperature was decreased by 3.4 °C, corresponding to a 16 % · °C^{-1} decrease in muscle temperature. Also, it has been found that during a drop jump exercise the highest decrease in performance was 17 % · °C^{-1} (49). The latter implies that exercise type, which is very fast and efficiently utilises the elastic properties of the working muscles is especially susceptible to cooling.

DOSE RESPONSE RELATIONSHIP

There are reports that the more the temperature of the working muscle tissue is decreased the more the amount and rate of deterioration of muscular performance increase (7, 17, 28, 48, 49). Bergh and Ekblom (7) reported that maximal dynamic strength, power output, jumping and running performance was positively related to change in muscle temperature. The changes in the above parameters were 4 - 6 % per 1degree decrease in thigh muscle temperature which ranged between 30 - 39 °C. Similar results were obtained when subjects were exposed to 27°C, 20°C, 15°C and 10°C air for 60 minutes wearing shorts and jogging shoes (49). After the exposures the subjects performed maximal rebound jump (drop jump) and the flight time of the jump (corresponding to the height of the jump) was measured. During the exposures the muscle temperature from calf (m. gastrocnemius medialis) was measured from the depth of 3 cm. Table 1 summarises the relationship between muscle temperature and decrease in the flight time

Table 1. The relationship between decrease in muscle temperature (Tm) and flight time (tf) after 60-min exposure to 4 different ambient temperatures. Decrease in muscular performance per degree Celsius is expressed as % · °C^{-1}.

Ambient temperature	27 °C	20 °C	15 °C	10 °C
Tm (°C)	32.9±0.5	32.0±0.8	31.0±0.4*	29.5±0.7**
tf (ms)	468±8	401±8***	394±10***	354±14***
% · °C^{-1}		17.0	8.4	7.6

Significant difference in relation to 27 °C is denoted by * $p<0.05$, ** $p<0.01$ and *** $p<0.001$, n=8 (49).

Table II. The relationship between increase in muscle temperature (Tm) and flight time (tf) after cooling and rewarming exercise (1, 2, 3, 4 and 5 walk).

	10 °C	1 walk	2 walk	3 walk	4 walk	5 walk
Tm (°C)	29.5±0.7	30.5±1.0	32.5±1.3	33.0±1.2*	33.4±1.5*	33.8±0.7*
tf (ms)	354±14	381±13	398±7	434±11*	464±21*	447±11*

Significant difference in relation to 27 °C is denoted by * $p<0.05$, n=8, except at 4th walk, n=7 and 5th walk, n=3 (48).

of the jump.

It has been reported that passive rewarming returns muscle force back to thermoneutral level during a three hour recovery period (50). However, with active rewarming exercise the decreased performance can be restored much faster. In the study of Oksa et al. (48) eight subjects were allowed to do rewarming exercise after being cooled at 10° for 60 minutes (see Table I). After cooling they performed a rebound jump and then walked on a treadmill for 5 minutes with the velocity of 5 km · h^{-1}, then performed another rebound jump and walked again. This cycle was repeated until thermoneutral flight time of the jump was gained (Table II).

Based on literature and tables I and II it can be concluded that there exists a dose dependent relationship between muscle temperature and decrease or increase in muscular performance.

THE COMPONENTS OF PERFORMANCE

Cooling affects all the components of muscular performance: endurance, force, power, velocity and co-ordination.

Endurance during bicycling (determined as maximal working time) has been reported to decrease 55 % (7) and 38 % (13).

The decrement in maximal muscle force (expressed as force, torque or instantaneous power) has been reported to vary between 20 - 52 % (1, 8, 49), the highest values being reported during drop jump exercise and the lowest during bicycling. The ability to maintain predetermined submaximal force level is not very much affected by cooling in distal muscles. However, shivering during cooling reduces the capability of proximal muscles to maintain accurately the required force level (40).

Both metabolic and mechanical powers are decreased due to cooling (28). Bergh (9) found that anaerobic power

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decreased 4 - 6 % per 1degree decrease in muscle temperature. The mechanical power have been reported to decrease during bicycling 17 % (61) and during jumping 24 % (28).

Velocity of movements is also deteriorated due to cooling. With decreasing muscle temperature (from 38.3 to 31.4°C) the velocity of the flywheel during cycling decreased 32 % (4.7 % · °C^{-1}, 8). Sargeant (61) demonstrated that the decrease in muscular performance is dependent on muscle contraction velocity. Bicycling at faster velocities, 144 rpm, decreased muscular performance more than bicycling with 54 rpm.This finding was confirmed for the upper body muscles in another study (45) where cooling-induced decrement in ball throwing exercise was higher with light balls (0.3 - 0.6 kg, faster movement) than with heavier balls (2.0 - 3.0 kg, slower movement).

Cooling also affects the relationship between force production and velocity. Force-velocity curve is shifted to the left (8, 11), which means that with a given force the velocity of movements or muscle contraction decreases after cooling. A similar shift is seen also in force-time curve. In a given time less force is produced after cooling (17).

There are only few studies concerning the co-ordination of the muscle contraction after cooling. Oksa et al. (45,49) have reported the so called "braking effect" of the muscles due to cooling. During the concentric phase of the muscle contraction the activity of the antagonist muscle is significantly increased when cooling occurs and at the same time the activity of the agonist decreases significantly. These two changes increase the level of co-contraction of the agonist - antagonist muscle pair and are one reason for the decreased muscular performance. Similarly, Bawa et al. (3) found that during light exercise after cooling (extension of the elbow) co-contraction of the antagonist muscle (*m. biceps brachii*) occurs simultaneously with the agonist muscle (*m. triceps brachii*), whereas in thermoneutrality only the agonist is active.

CONTRIBUTING FACTORS

There are individual differences in physical characteristics, which may modify the thermal responses to cooling and protect against loss of performance. First, subcutaneous fat acts as a thermal insulator slowing the rate of cooling (46).

Second, with increasing body size the surface area - body mass ratio decreases thus decreasing the area for heat loss and along with the increase in body size the body heat content also increases. Due to these factors increased body size slows the rate of cooling (16).Third, a fit person is able to produce more heat, therefore maintaining thermal balance more effectively than an unfit person (34). All these factors may help to maintain performance in cold environment.

THE FUNCTIONAL PROPERTIES OF SKELETAL MUSCLE

In addition to decreased muscular performance cooling has also a profound effect on functional properties of skeletal muscle (27). It has been well verified that the rate of tension development in the beginning of muscle contraction i.e. the time to maximum force level (twitch or tetanic tension) is temperature dependent (e.g. 6, 55).The temperature sensitivity (Q10) of the rate of tension development in humans has been shown to be approximately 1.5 (55).

A similar temperature dependence has been found also for the rate of relaxation at the end of muscle contraction (64). It is generally described as half relaxation time i.e. the time from the maximum tension to 50 % of the maximum tension. The Q10 of the rate of relaxation in humans has been reported to be approximately between 1.7 - 2.3 (55, 64)

The velocity of muscle contraction itself, shortening and lengthening, is also slower in a given time when muscle tissue is cooled (27).Therefore, the power production of the muscle during shortening is less and power absorption during lengthening is more thus leading to a less powerful contraction of a muscle.

The biochemical reasons underlying the increased time to peak tension, half relaxation time and velocity of muscle contraction have been related to decreased ATP-hydrolysis (28), slowed Ca2+ release and uptake from the sarcoplasmic reticulum (36) and decreased calcium sensitivity of the actomyosin (63). These changes may also cause impaired cross-bridge formation and breakdown or decreased force per cross-bridge (63).There are only few studies concerning the effects of cooling on elasticity and stiffness of the muscles. It has been shown that the stiffness (i.e. the ratio between force and length changes) of the muscle-tendon enti-

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ty does not significantly change due to cooling (1), which is unexpected because at lower temperatures the stiffness of tendons and joints has been reported to increase (32, 56).

Asmussen et al. (1) studied the effect of cooling on the capacity of the muscles to utilise their elastic properties by comparing the jump height of static and countermovement jump. It was found that the "gain" in height i.e. the increase in the countermovement jump height in relation to the height of the static jump increased after cooling. Simultaneously the EMG-activity of the working muscles during countermovement jump increased. These results led to the conclusion that the utilisation of elastic components of the muscle are enhanced after cooling (1).

Cooling also slows nerve and muscle conduction velocity, which may result in a slower and weaker muscle contraction (10, 25, 51). The decrease in conduction velocity has been reported to have a Q10 of approximately 1.4 (37). The absolute decrease in nerve conduction velocity has been reported to vary between 1.1 - 2.4 m · s^{-1}/°C (25).

The motor unit recruitment pattern is also affected by cooling. At a given submaximal work level after cooling more and faster motor units are being recruited in order to maintain the given work level (27, 58-60). On the other hand, the greater decrease of fast maximal exercise in comparison to slower exercise (61) after cooling would imply that fast motor units are first dropped out during maximal exercise after cooling.

ELECTRICAL ACTIVITY OF SKELETAL MUSCLE

Cooling clearly has a modulating input on electromyographical (EMG) activity of the muscles (30, 57). The two conventionally used parameters to describe muscular activity are the amplitude and frequency of EMG. It is reported rather uniformly that cooling decreases the frequency of EMG (54, 65, 66) and that the decrement seems to depend rather linearly on the level of cooling (53). For example, a 30 min exposure of the forearm to 10°C water in relation 40°C water decreased the center frequency of EMG power spectra from approximately 180 Hz to 100 Hz (53). The effect of cooling seems to be similar regardless of the exercise type (dynamic or isometric) or cooling procedure (water or air) (43, 53, 65). The decrement in frequency of EMG has been connected with simultaneous decrease in nerve conduction velocity (43).

The amplitude of EMG does not seem to be as uniformly affected by cooling as the frequency. There are studies reporting decreased amplitude of the EMG due to cooling (4, 43, 53, 66) while others report increased amplitude (62, 65, 67). Different exercise types, cooling procedures and measuring techniques may explain the difference.

PERIPHERAL FORCE REGULATION

Force production is regulated peripherally and/or centrally. Peripheral regulation is mainly conducted through reflex pathways, the stretch reflex (T-reflex) playing a major role. Stretch reflex is a monosynaptic, ipsilateral spinal reflex which is activated by stretching the muscle spindles (during the stretch phase of stretch-shortening cycle, tapping the tendon or causing a flexion of a joint), which in turn facilitates the following contraction of the agonist muscle and inhibits the contraction of the antagonist muscle (38). The stretch reflex depends upon both alpha-motoneuron excitability and muscle spindle (gammamotoneuron) sensitivity (12). Many studies concerning the effects of cooling on stretch reflex have shown that cooling suppresses stretch reflex amplitude (e.g. 25, 35, 42, 47). There is evidence that the suppressed T-reflex amplitude is due to decreased activity of the muscle spindles and thus decreased gammamotoneuron excitability (5, 26, 41) and these changes may lead to a decreased force production of a muscle (35, 47, 52). On the other hand, it also has been shown that during low-intensity repetitive work in cold (when forearm muscle strain is higher in relation to same work in thermoneutral condition), stretch reflex responses are enhanced. This probably indicates that the increased strain of the working muscles are met by increasing the reflex activity, therefore, in cold recruiting more muscle fibres in order to maintain the given work level (44).

CONCLUSIONS AND RESEARCH NEEDS

It is evident that cooling deteriorates muscular performance, its components, functional properties of the muscle and neural functioning. The amount of deterioration is dependent on the amount of cooling i.e. how much muscle temperature

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is lowered. There seems to be no "threshold" in muscle temperature after which performance starts to decrease. Rather the decrement starts immediately when muscle temperature decreases. The effects of cooling on short term muscle functioning are rather well understood, but long term functioning (hours or days) has received little or no attention. Therefore, the long term functioning of a muscle in cold environment should be studied more, especially because there is reason to believe that cold is a risk factor for the development of musculoskeletal disorders in cold work.

Juha Oksa

Aapistie 1, 90220 Oulu

Finland

email: juha.oksa@TTL.fi