Review article

Muscle Cooling and Performance: A Review

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ABSTRACT

Objectives: Skeletal muscle performance is determined by muscle temperature. This paper presents a review of the research literature to contribute to a better understanding of the physiological mechanisms of muscle fatigue and performance in cold exposure and in repetitive or sustained physical exertion in terms of isometric maximal force production, electromyographic activities, and gait ground reaction forces.

Materials and Methods: The PubMed and MEDLINE databases were searched for relevant articles in English. The titles and abstracts of all identified studies were initially screened by the first author to determine whether they could be included. Relevant articles were considered for full text analysis. The reference lists of the relevant studies were also checked.

Results: The review showed that different cooling methods have been used in the research settings. Current applications are reported of cold exposure to assess muscle strength through maximum voluntary contraction and functional activities, manual work of the upper limbs, gait and balance, fall risks, and mobility of the lower limbs. The review also showed that neuromuscular functions are impaired at 0° to 25°C of cold water immersion for 10 to 40 min where loss of strength and fatigue occurred in the limb muscles. Although some of the findings in previous studies about isometric force production in cooled muscles and joints are controversial, this review found that impeded strength is relatively well-established.

Conclusions: Cooling in cold water at certain temperatures can influence our maximum muscle performance but may not impact daily activities.

Keywords: Peripheral cooling, Isometric muscle strength, Fatigue, Electromyography, Gait ground reaction forces.

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INTRODUCTION

The functional properties and performance of skeletal muscles are determined by temperature[1,2]. Changes in body temperature influence muscular force generation, contraction and even relaxation activities. Both hypothermia and hyperthermia may impair muscle functions, including contractile and locomotion abilities. Since 1868, many studies have focused on the influence of temperature on muscle function and performance[3]. It is evident that there is an optimal muscle temperature range for the best performance. Many scientific studies support the assumption that prolonged or repeated cold exposure and physical exertion can induce fatigue, shivering and vasoconstriction responses, and impair neuromuscular functions. The temperature of large muscles tends to be higher in a thermo-neutral environment for a short-term maximum power output[4]. Low temperature reduces tissue temperature, which will influence the maximal loco-motor speed through the neuromuscular transmission system of both afferent and efferent impulses[5]. This may be slowed by cooling of the nerves[6]. It is important to explore more details about the effects of temperature on muscle force development and relaxation because temperature changes may constrain performance[1]. Much evidence and many reports exist about the effects of decreased muscle temperature on muscle contractile properties, indicating mostly that muscle contraction force and rate of force development are impaired at low muscle temperature[7-9].

Homeostasis is usually maintained throughout the body by thermoregulation processes. Sometimes it is not possible to keep the limb muscle temperature close to or within the optimal range without altering the core temperature even in moderately cold conditions[7,10]. Within the homeostatic range, the human body core temperature is relatively well protected even though skin and peripheral muscle temperatures may change under different severe temperature exposures[4]. To maintain thermal balance, there are mainly two human physiological responses elicited by cold exposure: shivering and peripheral vasoconstriction. Shivering increases metabolic heat production while peripheral vasoconstriction improves the thermal insulation of the body and retards the rate of heat loss[11]. The interaction between the two can be used as a model to investigate the thermoregulatory processes that influence physical performance and the muscle fatigue[2].

Cold and heat affect the mechanical contractile properties of muscles. Contractile properties such as muscular strength, power and endurance are important in understanding the effects of cooling or heating on performance[2,7]. Peripheral muscles can experience large thermal variation from as high as 41°C to as low as 23°C depending upon activity level, clothing, time and environment throughout the day[7,12]. Immersing limbs in cold water results in a relatively higher rate of heat loss compared to air cooling[4]. Previous studies have scrutinized human work capacity in extreme cold environments, focusing on the systemic effects of extreme cooling on survival after accidental cold water immersion[13]. Long exposure to cold occurs in sports, professional and recreational activities, which is why it is essential to explore the human capacity to perform work and sports in cold environments. Some sports require long exposures to cold and/or wet weather conditions with a risk for hypothermia. These circumstances make it even more difficult to avoid peripheral cooling[13].

This literature review explores studies of human performance using non-invasive methods to measure muscular activities, strength and gait in the cold. It also describes the cooling methods used in the study of maximum muscular performance, muscle electrical activity and ground reaction forces (GRFs) during gait, with a focus on state-of-the-art knowledge and future research needs.

MATERIALS AND METHODS

Data sources and searches

Computerized searches were carried out to find articles published worldwide in the PubMED and

MEDLINE databases. Both medical subject heading (MeSH) terms and keywords were used including 'peripheral cooling', 'cooling', 'neuromuscular', 'isometric muscle strength', 'fatigue', 'electromyography', 'EMG', 'gait', 'ground reaction forces'. These keywords were used separately and in combination. Moreover, the reference lists of all retrieved studies and relevant review articles were manually checked for additional studies.

Study selection

Different study designs including randomized control trials, within subject trials, case trials and reviews met the inclusion criteria by search key words among the retrieved articles, with restrictions on the publications in English. The titles and abstracts of all identified studies were initially screened by the first author to determine whether they could be included. Relevant articles were considered for full text analysis. It was further investigated with the neuromuscular functions reported in potentially relevant studies as to whether isometric maximal muscle strength or performance and gait biomechanics, and ground reaction forces were altered by cooling.

RESULTS

Muscle cooling and maximum strength

The muscular functional rate slows down with almost any degree of cooling, thus considerably reducing the muscle force. Reduced muscle force production due to slowed nerve conduction velocity and enzymatic processes lowers local muscular endurance during dynamic muscular contraction[2]. Below a water temperature of 27°C, both the voluntary muscular contraction and force progression capabilities are affected. Most of these effects can occur without cooling the core body when the person is wearing sufficient clothing to maintain the core temperature while his or her limbs are exposed[14]. Several of the studies that investigated the cooling effect on human performance involved core cooling. The studies examined muscle fatigue under isometric conditions at different temperatures during voluntary sub-maximal sustained contractions. However, the effect of temperature on muscle function requires further study because the results were not entirely conclusive. De Ruiter et al.1 investigated the effect of temperature on the rates of isometric force development by immersing the human lower arm for 20 min in water baths of different temperatures. The results showed that the isometric force was reduced when the water bath was below 25°C. Although in water temperatures from 32°-22°C, muscle fatigue parameters decreased related to muscular force production. In numerous animal studies, rates of muscle force have also been shown to decrease at low temperatures[1].

In addition to affecting the force production, the cooling of limbs may also affect biochemical reactions at sarcomere level[4]. Studies have shown that cooling may hinder muscular performance[15] as a result of biochemical changes e.g. declined adenosine tri-phosphate (ATP) hydrolysis or availability and impaired calcium release and uptake in the muscle from the sarcoplasm due to impairment of sarcoplasmic reticulum ATPase. The slowing of calcium reuptake thus leads to force production without the required stimulation by prolonging the relaxation time[16,17]. Enzymatic activity, speed (such as time to twitch or voluntary contraction or relaxation of muscle contraction) and the rate of onset of fatigue have been studied. Studying these properties can help us understand the mechanisms of local muscle cooling on muscle performance2. Very few studies assessed the effect of cooling on the electrical activation and force generating capacity of a previously fatigued muscle. Cè et al.[18] showed that after fatigue and muscle cooling nerve conduction velocity decreased. The human subjects' longest isometric handgrip endurances were recorded at 40% of their maximum strength at 22°C. There was an optimal temperature for each individual subject, above or below which the endurance of isometric contraction dropped remarkably[19]. Evidence from previous research on human subjects showed that muscle cooling in water at 10°-12°C and intramuscular temperature at 28°C significantly increased the glycolysis from glycogen in both the red and white muscles, leading to a rapid accumulation of lactate during exercise[20]. The local vasoconstriction in tissues exposed to cold is likely to reduce the oxygen supply, impair the oxidative reactions and modify the metabolic pathways[21]. Through high intensity, dynamic and frequent work, fatigue developed earlier when the muscle temperature was lowered[22].

Earlier studies demonstrated that isometric force production starts to reduce due to peripheral muscle cooling at any temperature below 25°C[1, 23]. Davies et al.[23] reported that when cooled to 24°C, the maximum voluntary contraction (MVC) of the triceps muscle complex was reduced. Holewijn and Heus[7] also reported a reduced maximal grip power after 30 min of local cooling at 15°C. The study was performed to determine the effects of environmental cooling on force production in the thigh muscles and showed that the performance of quadriceps and hamstrings significantly dropped when the environmental temperatures were at or below 10°C for at least [40] minutes. In the meantime, the body lost a significant amount of heat as the environmental temperature decreased and warm-up time increased[24]. However, Abbiss et al.[25] studied cycling performance in hot (34°C) and cold (10°C) environments. The results showed that power output declined more during exercise in the heat than in the cold. Premature fatigue development could be stimulated at high temperatures in easily fatigued muscle fibers due to oxidative stress impaired exercise performance.

Several experiments have been performed in human and rat[26] models showing that muscle properties, including voluntary isomeric maximal force were altered by decreasing temperature. Oksa et al.[27] showed that maximal dynamic muscle performance reduced at a lowered room air temperature (10°-5°C). Ranatunga et al.[28] also observed that maximum voluntary tension was relatively stable at or below the muscle temperature of 25°C, however reduced by about 30% when muscles cooled to 12°-15°C. It was expected that the electromechanical response time of the muscle will be longer at low muscle temperatures due to the impaired contractile properties[8]. Drinkwater and Behm reported that the rate of isometric plantar flexor twitch and tension force reduced around 50% during cooling at 22°C[16]. By contrast, Meigal et al.[29] reported that exposure to cold air (10°C) for 30 min did not impair MVC during isometric elbow flexion. Sargeant reported that maximal contraction force and peak power were increased after warming of the leg in 44°C water[9].

MUSCLE COOLING AND ELECTROMYOGRAPHY

Electromyography (EMG) is widely used to understand muscle mechanics, physiology, neurophysiology and motor control mechanisms during human locomotion[30]. There is generally a positive linear relationship between EMG amplitudes and muscle voluntary force[31]. Temperature may have a modulating effect on input and output motor control mechanisms and thus may affect electrical responses. Some authors have reported the effects of cooling on EMG during isometric and sub-maximal exercise. Petrofsky and Lind[32] and Bigland-Ritchie et al.[33] investigated the effect of cooling on EMG frequency of the working muscles focusing on isometric and sub-maximal exercises; they reported increased amplitude of the surface electromyogram but decreased center frequency of the EMG power spectra with decreasing muscle temperature from 40° to 10°C water immersion[32]. 'However, the relationship between force production and EMG activity remained same during cooling in the particular study by Holewijn and Heus[7]. Asmussen et al.[34] focused on the agonist muscle and Oksa et al.[15] found that during the shortening phase, the EMG activity of the agonist decreased while the activity of the antagonist increased. After cooling and during the shortening phase of the jumps, the EMG activity of the triceps surae muscle complex decreased. Alterations in the motor unit by recruiting more fibers could be responsible for the prolonged muscle contraction and decreased force production[15].

Fatigued muscular EMG during isometric contraction has been shown to increase the amplitude[32]. In the cooled muscles and during concentric contractions[35], the level of co-activation (i.e. increased EMG amplitude of flexor and extensor muscles) and the amplitude of EMG may be affected by many other factors. Cooling may modify the shape of the action potential and cooled skin and muscle may act as a low pass filter[36]. Rissanen et al.[14] observed that cooling increased the co-activation level of lower leg muscles at the beginning of exercise. Potential reasons for these differences may include experimental factors such as specific instructions given to subjects, different cooling durations and temperatures, different body positions.

Results from a recent study by Halder et al.[37] showed that lower leg muscle strength decreased during ankle dorsiflexion (DF), muscle electrical activity (EMG) increased in planter flexion (PF) due to leg immersion in cold water at 10°C for 20 min. However, the EMG amplitude of the lateral gastrocnemius muscle decreased in planter flexion when walking on a slippery icy surface in a climate chamber at -10°C compared to that on a non-slippery surface in a room temperature environment, and increased with inclination when walking upwards on both surfaces[38]. The effect of cold water temperatures close to 0°C (like ice water) on muscle performance could be different[39]. A possible reason why the PF MVC was not affected was due to a much larger volume of the PF muscle than the DF muscle. The temperature drop of these large muscles might be less affected by the method of cooling in the study. However, the surface skin temperature did decrease significantly. Invasive techniques are required to register the muscle temperature to get more stable and reliable data. Another reason why the MVC was not affected was that the PF was also performed by the large and deep soleus muscle. The soleus muscle is known to be rich in blood volume, which may resist superficial cooling effects. Cè et al.[18] claimed that muscle tissue cooling decreased nerve conduction velocity and receptor firing rate at low temperatures. Especially when combined with fatigue, muscle cooling changed the sarcolemma propagation properties thus altering the force production. Oksa et al.[40] argued that cooling induced excitability of the motor neuron and depressed muscle spindle activity, thus changing muscle activation agonist and antagonist EMG patterns in the shortening phases. Agonist and antagonist muscles play a momentous role during the production of maximal isometric force[15]. Previous studies on the EMG amplitude of fatigued and cooled muscles reported an increased amplitude during isometric and sub-maximal exercise because more fibers were recruited to produce the same force. However, the center frequency of the EMG power spectra decreased with decreasing muscle temperature from 40° to 10°C water cooling.[32,33,36]

Individual muscular characteristics and morphologic structures could be the factors contributing to the performance of different types of muscles. Type 1 muscle, like the tibialis anterior (TA), has 70% slow oxidative non-fatigue fibers, whereas type 2 (gastrocnemius), has fast oxidative glycolytic or fast glycolytic fibers. Type 2 fibers due to their metabolic properties are more fatigable, and it is generally accepted that EMG amplitudes increase during fatigue[41]. It is possible that the cooling, as performed in one study, exerted stress on fast fibers thus resulting in higher EMG amplitudes in the gastrocnemius muscle but not in the non-fatigable fibers of the TA muscle[37]. The decrease in DF isometric strength was attributed in part to failure of excitation-contraction coupling and the effects on sarcolemma propagation properties as suggested by the low-frequency fatigue[18]. Previous studies have revealed that the gastrocnemius muscle for PF was more prone to fatigue after a prolonged level of running[42]. Another observation, made by Swanson and Caldwell[43] was that the EMG amplitude of the gastrocnemius and other PF muscles during the support phases was greater.

MUSCLE COOLING AND GAIT GROUND REACTION FORCE

Force platforms are used to measure the force, power and velocity of human performance derived from ground reaction force data during gait and countermovement jumping[44]. Walking performance over a force plate floor describes the human sensory motor system and measures the gait biomechanics[45]. Oksa et al.[15] measured the agonist and antagonist muscle pair of the lower leg to determine the duration of the stretch and shortening phases during the stretch-shortening cycle using reaction force and EMG between the exposures at 27° and 10°C. Hori et al.[44] tested the reliability of a ground reaction force plate to measure performance during countermovement jumping and confirmed that it is reliable for the measurements of the peak power, force and velocity of jumping. Mäkinen et al.[46] compared general cold exposure from 25°C to 10°C for 90 min and found that induced cold thermal sensation, thermal discomfort and increased muscle tone were associated with postural sway. Eils et al.[39] used icy cold water (0°C) immersion for 10 min aimed at reducing cutaneous information of the plantar surface of the right foot to record reaction forces, EMG and three-dimensional movement during walking before and after immersion. Stel et al.[47] in their study also experimented with ice water for 20 min cooling to get hypothermic anesthesia in the feet to determine the role of mechanoreceptor activity for postural control on a force platform. Currently, the required coefficient of friction (RCOF) has been used in many papers, representing the minimum friction needed at the foot or shoe and floor interface to avoid slips and falls. RCOF is the ratio of Fy (longitudinal or antero-posterior force) over Fz (vertical force) and is used to assess slip risk. Slip incidents may occur when the available coefficient of friction is smaller than the RCOF[45]. Some investigations dealt only with the role of local cooling in skeletal muscle performance, but cooling effects on neuromuscular function during gait have yet to be established.

Recent study observed that lower leg cooling has some effects on muscular performance. Halder et al.[37] found no significant results on GRF during gait after cooling on a dry and level walkway, however, cooling had a significant outcome on ankle MVC force. This might be explained by the fact that the task and forces were not sufficiently demanding when walking on the walkway with the force plate. Fast gait speed or running would have a high impact on the force plate. It appears that the non-max performances of the muscles were not much affected by the cooling, which requires further research. The method of cooling might have also cooled the nerve of the entire lower legs, neuromuscular junctions (end plates), calcium ion flow, and contractile protein, which could have slowed nerve conduction velocity[2,6,8,32]. A few investigators also described increased joint stiffness[9] due to the increased viscosity of the joints' synovial fluid[48] after exposure in cold water. This might alter postural control and force production through joints too, consequently hampering the EMG amplitude. Sekihara et al.[49] pointed out that cooling tends to increase the muscle stiffness and to resist high velocity movements. However, some authors disagree that muscle cooling has an effect on force production[50-52] and performance[53,54]. Hopkins and Adolph[55] observed that 30 min of ice bag cooling on ankle and knee joints has no effect on motor function and biomechanics. This appears to be the result of the type of measurement used, the location of ice immersion (muscles or joints), and the time when (during or following ice application) the motor output measurement was taken. Miniello et al.[56] also concluded that there was no impairment of ankle stabilization following landing from a jump after immersion of the entire lower leg in cold water. However, Kinzey et al.[57] showed decline in vertical impulse during a single leg vertical jump following immersion of the ankle under cold water. These authors concluded that a decrease in nerve conduction velocity was a primary contributor to the decrease in vertical impulse. Since the average peak vertical ground reaction force was not significantly changed, the time component was primarily responsible for the non-significant decrease in vertical impulse. In other words, either the extra time necessary to produce force following cooling or the muscle contraction time is slower[8,57].

Eils et al.[39] and Stel et al.[47] studied gait by immersing feet into ice water and found gait changes on the force plate, where the timing of the first and second peaks were modified and delayed by braking and accelerating forces. As this study used ice water, the cutaneous sensation might have been reduced and affected the RCOF due to cautious gait and heel strikes[46]. But Stel et al.[47] reported that the anterior-posterior and lateral torque responses to the vibratory stimulation were higher with cooled feet. This increase disappeared after about 2 min. It is well documented that 0°C temperature might also alter plantar sensation by stimulating the mechanoreceptors of the skin[48,49]. Reduced plantar sensitivity may cause changes in the muscle recruitment strategy while responding to afferent sensory signals and put extra loads on the joints during walking. Due to the decreased plantar sensitivity, changes could be expected in the EMG amplitude when performing external work.

FUTURE PERSPECTIVES

The results of this review suggest some directions for future studies about muscular performance in the cold using human subjects. The number of human performance laboratories has considerably increased in response to the demands of research and practice in sports medicine, ergonomics, occupational health and safety, and rehabilitation. It is worth focusing on the implications of these research findings, and further research needs where muscle cooling is an obstacle for better performance. Solutions and strategies are required to meet the challenges and improve people's work capacities when they are exposed to cold environments in the workplace, sports and during exercise. Data comparisons and quantitative descriptions of locomotor muscle activities and patterns can become more effective by using kinesiology electromyography. More research is needed to explore EMG activities and the GRFs of gait muscles in relation to temperature.

It is evident that cooling can be a determinant of muscle force production. However, it is still controversial whether or not cooling induces muscle fatigue. Further studies are needed that compare fatigue muscle characteristics induced by repetitive movements with those after cooling. In the clinical application of cooling to prevent injury, the findings from the literature suggest that during rehabilitation or treatment of muscular injuries, muscle performance may be affected immediately after cooling.

From a research methodology point of view in most of the previous studies, muscle temperature was not directly measured, which should be considered to improve reliability. It is difficult to keep the muscle or skin constantly cooled under clinical conditions. Further studies are needed to measure muscle temperature changes, to study different degrees of muscle cooling, to explore its effects on muscle performance, fatigue during sports, exercise, and work in cold environments (e.g. brisk walking, jogging, jumping and walking on slippery and inclined surfaces). Sport and work performance may decline due to local cooling in cold environment. The literature review indicates that muscular physiological regulatory process can be disturbed to some extent in lower degrees of cooling (below 25°C), whether it is artificial cooling or outdoor exposure in winter. Ground reaction forces may be affected by cooling during high velocity human movement.

CONCLUSION

The purpose of this review was to update the knowledge about the effects of cooling on muscular function and human performance. Different cooling mechanisms and methods have been used in research settings. With the advances in research, effective cooling can be incorporated into clinical practice that can have positive effects on treatment and performance. The present review shows that when neuromuscular functions are impaired, strength is reduced and fatigue may occur in limb muscles when exposed to cold water at 0° to 25°C for 10 to 40 min. Although some of the findings in previous studies about isometric force production in cooled muscles and joints are controversial, this review found that impeded strength is relatively well-established. The maximum

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muscle strength required for sports and vigorous activities are impacted by cooling, but the strength required for less physically demanding activities may not be affected.

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