

Effects of Cold Acclimation on Human Physical Fitness in Cold Environment

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Abstract. The systematic impact of cold environments on human physiological functions has become a significant research area in sports medicine and physiology. As exposure to cold increases, the body's nerve conduction rate decreases, affecting muscle contraction efficiency. These physiological changes can directly impair motor coordination and reduce muscle explosive power output. Additionally, in cold environments, the body's core temperature drops, leading to cognitive decline, fainting, and even death as the core temperature continues to drop. However, cold acclimation serves as an adaptive mechanism that can effectively enhance the body's tolerance to cold environments, thereby improving physical fitness levels. This article primarily discusses the role of cold acclimation in enhancing human physical fitness. It concludes that the formation of cold acclimation not only has a significant impact on the health intervention of type 2 diabetes patients at the genetic level but also affects body composition, cardiorespiratory endurance, muscle strength, and muscle endurance. Furthermore, it promotes changes in the autonomic nervous system, thereby reducing the harm caused by cold stress.

Keywords: cold acclimation, physical fitness, cold environment

1. Introduction

Engaging in physical activities at low temperatures can lead to multiple risks. Research indicates that cold environments increase the likelihood of hypothermia (core temperature $\leq 35^{\circ}\text{C}$) and frostbite, especially in individuals with inadequate protective measures. Hypothermia can cause neurological issues such as confusion, speech disorders, and abnormal behavior; frostbite typically affects exposed or peripheral areas, such as the tip of the nose and extremities, because the tissue freezing point (approximately -2.2°C) is lower than that of pure water, and the contraction of peripheral blood vessels further accelerates the local temperature drop [1].

Furthermore, the negative effects of low temperatures on the musculoskeletal system are also significant. Studies show that a brief cold exposure can increase sympathetic nervous system tension; however, prolonged exposure to cold can impair the function of motor and sensory nerves. If cold injuries occur, the nerve conduction rate decreases, affecting muscle contraction efficiency [2]. Research on knee biomechanics has found that cold exposure significantly reduces the force generation rate of the knee flexors. EMG analysis indicates that the neural drive patterns of the medial and lateral femoral muscles change, potentially leading to the hamstring muscles being

unable to effectively counteract rapid knee extension movements, thereby increasing the risk of anterior cruciate ligament (ACL) injury. These findings suggest that cold environments not only weaken athletic performance but may also trigger potential sports injuries [3].

Globally, cold regions are widely distributed. With the increasing frequency of outdoor activities, polar exploration, and winter rescue operations, people are more frequently exposed to cold environments. Cold environments significantly impact human physiological functions in multiple ways, reducing athletic performance, impairing cognitive judgment, and significantly increasing health risks. In response to the numerous challenges posed by cold environments, cold acclimatization has gained attention as an adaptive mechanism. This discovery provides crucial theoretical support for individuals who are frequently exposed to cold environments, such as polar researchers and border guards, helping them develop more scientific protection and training strategies.

2. Adaptation mechanism of cold acclimation

2.1. Definition of cold suit

Cold acclimation is a physiological compensation mechanism developed by the body through repeated exposure to cold environments, which can lead to morphological and/or physiological changes. This mechanism can reduce the harm caused by cold stress on the human body. Once established, it does not require additional methods to maintain its effectiveness, and even in non-cold environments, cold acclimatization can continue to provide benefits for several months [4].

2.2. Physiological mechanism of cold acclimation

Cold acclimation can be categorized into genetic and acquired types. Acquired cold acclimatization can occur in both natural and artificially created cold environments. Based on the method of cold acclimation, it can be divided into four types: metabolic, insulative, hypothermic and a combination of the latter (insulative hypothermic) [5]. Slim individuals primarily rely on metabolic reactions to combat the cold, while those with a heavier build rely on insulative reactions.

People who live long-term in cold regions, such as the Arctic and temperate zones, primarily adopt a metabolic cold acclimation. They increase heat production through shivering and non-shivering thermogenesis, raising the average skin temperature while maintaining a stable core temperature. The characteristic of an insulative cold acclimation is that the skin temperature remains low when exposed to a cold environment, but the metabolic rate and core temperature remain constant. This type of adaptation reduces heat loss by causing strong contraction of skin blood vessels, increasing hair growth on the skin, and adding more fat layers. In contrast, hypothermic cold acclimation involves lowering the body's core temperature, while combination acclimation results in a decrease in both the average skin temperature and the core temperature.

It is worth noting that cold acclimation has potential value in health interventions for specific populations. For instance, in obese patients with type II diabetes, the combination of cold therapy and exercise training can enhance peripheral insulin sensitivity. This effect may be linked to the regulation of skeletal muscle gene expression, particularly those involved in neuromuscular signaling and tissue remodeling pathways, rather than directly affecting glucose metabolism pathways [6]. This finding offers new insights into non-drug interventions for metabolic diseases.

3. The components of physical fitness

Physical fitness refers to the physical ability of an individual to not only handle daily tasks but also enjoy leisure activities and cope with stress and sudden changes. Physical fitness is categorized into health-related fitness and athletic fitness. Health-related fitness is primarily for everyday use, focusing on maintaining a healthy body and a high-quality life. It includes cardiorespiratory endurance, muscle strength and endurance, flexibility, body composition, and neuromuscular relaxation. Athletic fitness, on the other hand, aims to win medals and honors in sports competitions. In addition to the five elements of health-related fitness, it also includes agility, balance, speed, explosive power, and coordination. Since athletic fitness is less common in daily life, this section will focus on the elements of health-related fitness.

3.1. Body composition

Body composition mainly refers to the relative proportion of lean body weight and body fat. The non-fat weight in the body is called lean body weight, which includes muscle, bone, viscera, blood and skin weight. The percentage of body fat weight in the total weight is called body fat percentage.

3.2. Cardiopulmonary endurance

Cardiopulmonary endurance is the ability of the heart, lungs, and circulatory system to effectively supply muscles with enough oxygen and nutrients and to remove waste from the muscles. It is the body's cardiopulmonary system's ability to supply cells throughout the body with oxygen, and it represents the endurance of large muscles in prolonged exercise.

Cardiovascular endurance involves the heart's pumping ability and the respiratory system's gas exchange. The heart pumps blood throughout the body, ensuring that oxygen and nutrients are delivered to all tissues and cells while removing carbon dioxide and waste products from the cells. The respiratory system takes in oxygen, which enters the alveoli and then diffuses into the blood vessels. Simultaneously, carbon dioxide from the blood also diffuses into the alveoli and is expelled from the body during exhalation. Additionally, the ability of cells to utilize oxygen is crucial. The mitochondria in cells consume oxygen, glucose, and fat for respiration, producing ATP, which provides energy for the body. If cells cannot effectively use oxygen to oxidize glucose and fat to produce energy for bodily activities, the heart's pumping ability and the respiratory system's efficient oxygen supply to cells are rendered useless.

3.3. Muscle strength and endurance

Muscle strength and muscle endurance refer to the ability of the muscular system to function effectively. Muscle strength is the maximum force a muscle or muscle group can produce during a single contraction, or the maximum resistance it can overcome. Many factors influence muscle strength, including the cross-sectional area of the muscles, their initial length, the recruitment and contraction speed of motor units, and the type of muscle fibers, all of which affect muscle power. Muscle endurance is the number of repetitions a muscle or muscle group can perform under a specific resistance.

3.4. Flexibility

Flexibility refers to the body's ability to move through its maximum range of motion. It is closely linked to joint mobility, with the length of ligaments, tendons, and muscles in the joints determining the range of motion for each part. The quality of flexibility directly impacts an individual's performance during physical activities, and a lack of proper flexibility can lead to issues, such as arthritis, hunchback, and lower back pain. Overall, five main factors influence an individual's flexibility. Firstly, the amount of exercise. People who exercise less, especially those who sit for long periods, may experience increased viscosity between joint tissues due to lack of regular movement, which limits their range of motion. Secondly, body temperature. An increase in body temperature can reduce the adhesion between muscles and joint capsules, enhancing their extensibility. Unwarming up can reduce flexibility by 10% to 20% compared to warming up. Lastly, individual differences. Factors like age, gender, and genetics can all affect flexibility. Age-wise, flexibility tends to decline gradually from birth. Generally, the most effective time to improve flexibility is between the ages of 13 and 19, after which it tends to decline more significantly. Gender-wise, there are differences in muscle mass, bone size, and the flexibility of ball-and-socket joints between males and females. Therefore, there are also differences in flexibility between men and women. Genetics can affect the structure and proportions of the skeleton, such as scoliosis, X-shaped legs and O-shaped legs, which are all related to genetics.

3.5. Neuromuscular relaxation

Neuromuscular relaxation involves reducing or eliminating unnecessary muscle tension and psychological stress. It can also be seen as reducing psychological stress to promote muscle relaxation. Research indicates that chronic stress can affect skeletal muscles and even lead to diseases. Chronic stress is defined as a prolonged state of internal imbalance or abnormal homeostasis caused by real or perceived threats, where the body cannot restore normal internal balance through various behavioral and physiological adaptive responses. Excessive cortisol secretion and circadian rhythm disorders associated with chronic stress, along with systemic low-grade inflammatory damage, can cause fat degeneration in metabolically active organs, affecting their structure and function. Under the combined effects of chronic stress and related inflammation, skeletal muscle fat degeneration, or intramuscular fat infiltration, occurs. This intramuscular fat infiltration, which exists in the form of lipids within muscle cells, alters the orientation of muscle fibers, reduces muscle strength, and increases the risk of decreased exercise capacity [7].

4. Effects of cold acclimation on various elements of human physical fitness in cold environment

4.1. Effects on body composition

The development of cold acclimation can increase the amount of brown fat in the human body. Brown fat tissue is a heat-producing tissue that primarily functions to maintain body temperature through non-shivering thermogenesis in cold environments, thereby consuming excess energy and maintaining energy balance. J Clin et al.'s study demonstrated that after ten days of repeated intermittent cold exposure, adults experienced a significant increase in their brown fat content, with a 37% increase in detectable brown fat volume. Moreover, the activity of brown fat was similar between males and females, with negligible gender differences. These brown fat tissues enable the

body to perform non-shivering thermogenesis in cold conditions. In acute cold exposure, the increase in non-shivering thermogenesis was 11% in individuals who had not developed cold acclimation, compared to 18% in those who had [8]. The development of cold acclimation increases both the amount and volume of brown fat, reducing shivering and thus lowering the harm of cold stress, significantly enhancing the body's adaptability to cold environments.

4.2. Effects on cardiopulmonary endurance, muscle strength and muscle endurance

In cold environments, the blood vessels in the human body constrict due to cold stimulation, leading to reduced blood flow and slower blood flow velocity. This reduces the efficiency of blood circulation and decreases the oxygen supply to skeletal muscles compared to warm conditions. With less oxygen being taken up by skeletal muscles, the tricarboxylic acid cycle cannot produce enough energy to support prolonged skeletal muscle activity. A study on the cold resistance training of young people in northern China used the Cold Vessel Index, which reflects the local blood vessels' response to cold stimulation, to monitor changes in the blood vessels of new recruits before and after cold resistance training. The data showed that the Cold Vessel Reaction Index of new recruits before cold resistance training was 9.39 ± 1.23 , and it increased to 11.05 ± 1.53 after training, similar to that of veterans (11.58 ± 1.33). This indicates that after cold acclimation, the dilation amplitude of blood vessels increases and lasts longer, leading to an increase in blood flow [9]. The increase in blood flow results in more oxygen being delivered to organs and skeletal muscles within a given time, thereby enhancing aerobic exercise capacity. Additionally, studies have shown that cold acclimation can increase the basal $[Ca^{2+}]_i$ in mouse muscle fibers by 50%, the taut $[Ca^{2+}]_i$ by 40%, and the sarcoplasmic reticulum (SR) Ca^{2+} leakage by four times, while the SR Ca^{2+} pump rate decreases. The increase in SR Ca^{2+} leakage is fundamental. The primary cause of the increase in $[Ca^{2+}]_i$ (about 70%) is the elevated levels of SERCA1 protein expression. Meanwhile, the increase in mitochondrial content enhances the body's oxidative metabolic capacity, better maintaining ATP supply and thus enhancing resistance to fatigue. Despite the increased ATP consumption due to SR Ca^{2+} leakage, the beneficial effects of mitochondria still dominate [10].

4.3. Effects on flexibility

Few studies have explored the effects of cold habit formation on body flexibility. It is known that muscles and ligaments in cold environments become stiff when stimulated by cold, reducing joint mobility and thus affecting flexibility.

4.4. Effects on neuromuscular relaxation

Cold acclimation enhances an individual's adaptability to cold conditions by optimizing autonomic nervous system regulation. Specifically, acute cold exposure activates the sympathetic nervous system (low-frequency power increases, norepinephrine increases, and blood pressure rises), accompanied by a slight activation of the parasympathetic nervous system (RMSSD increases). After cold acclimation, the sympathetic response is reduced (norepinephrine increases but less significantly, and blood pressure rises but less significantly), while parasympathetic activity is significantly enhanced (high-frequency power increases) [10]. Cold acclimation maintains higher skin temperature by reducing vasoconstriction, thereby lowering the metabolic heat production required, which is the insulating type of cold acclimation. This shift in autonomic nervous system

balance can reduce the cold stress response, maintain energy metabolism homeostasis, and thus minimize the damage caused by low temperatures.

5. Conclusion

In summary, the impact of cold environments on human physiological functions is complex and multifaceted. When the human body is exposed to low temperatures, these conditions can inhibit multiple systems, including the nervous system, muscles, and joints. In the nervous system, low temperatures slow down nerve conduction, affecting the precise transmission of nerve signals. In the muscle system, cold reduces the efficiency of muscle contraction and weakens force output due to the reduced nerve conduction rate. These factors collectively significantly affect the body's normal functions and metabolic processes. Cold acclimation provides an effective way for the human body to cope with cold environments. After undergoing cold acclimation training, the body can improve neuromuscular coordination, making nerve signal transmission and muscle contraction more efficient and precise. Additionally, the stability of the autonomic nervous system is enhanced, helping to maintain the body's internal stability in cold conditions. In terms of physical functions, cold acclimation can alter body composition, increase brown fat tissue, and enhance muscle strength and endurance, thereby improving the body's adaptability to cold exposure and ultimately enhancing physical fitness in cold conditions. However, current research on the effects of cold acclimation on athletic performance remains limited. On one hand, the number of related studies is relatively small, making it difficult to form a comprehensive understanding. On the other hand, the theoretical framework of the system is well-established; on the other hand, research into its mechanisms of action remains insufficient. Many key aspects and potential mechanisms are still unclear, which hinders a full understanding of the specific impacts and factors influencing human health through cold suits. Therefore, future research could focus more on the specific effects and mechanisms of cold suits on physical fitness. By integrating multidisciplinary approaches and advanced technologies, researchers can delve into the physiological and molecular mechanisms behind the effects of cold suits. This not only aids in developing personalized training strategies but also helps assess the potential applications of cold suits in extreme environment operations, sports medicine rehabilitation, and chronic disease management, promoting the dual development and deep integration of theoretical research and practical applications.

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