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MELATONIN: A POTENTIAL ATHLETIC PERFORMANCE MODULATOR

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Abstract: Melatonin secreted by the pineal gland plays a crucial role in human biological activities. The rhythm of melatonin is closely related to athletic performance. In recent years, some studies have elucidated the relationship between melatonin and athletic function, but the potential enhancing effects of melatonin on improving athletic performance have not been widely noted. This article narratively reviews the impact of melatonin on different physical qualities, different types of athletic performance and their rhythmicity, and the potential mechanisms by which melatonin affects athletic performance, and then sorts out the role of melatonin in optimizing athletic performance.
Keywords: Melatonin; Athletic performance; Physical qualities

1 INTRODUCTION

Human physical performance is not constant across the day. Strength, power, reaction capacity, body temperature, and aspects of endurance show time-of-day variation, with many neuromuscular measures tending to peak in the late afternoon or early evening [1]. These rhythms matter in exercise physiology because performance emerges from dynamic interactions among circadian timing, substrate availability, mitochondrial ATP production, thermoregulation, and central nervous system state [1,2]. Against this background, melatonin is of particular interest. Although classically regarded as a hormonal signal of biological night and a regulator of sleep-circadian timing, melatonin is also relevant to oxidative stress, inflammation, mitochondrial protection, and glucolipid metabolism, all of which may influence exercise tolerance and recovery [2,3]. Thus, from both a chronobiological and mechanistic perspective, melatonin is a plausible modulator of athletic performance rather than merely a sleep-related molecule.

2 THE EFFECT OF MELATONIN ON STRENGTH QUALITY

Strength quality is the foundation of athletic performance. Processes like energy synthesis, utilization, and temperature changes can all influence skeletal muscle strength. The energy requirements in skeletal muscle cells of athletes are mainly derived from mitochondria. Melatonin maintains the integrity of mitochondria in muscles by preventing oxidative damage, thus ensuring the normal function and survival of myocytes [4-6], which thereby provides a better energy supply platform for the display of muscle strength quality. A series of studies have elaborated on the positive effects of melatonin on mitochondrial function and integrity [7,8], and it plays a central role in the processes of glycolipid catabolism and endocrine homeostasis [9,10]. For instance, melatonin can enhance the gene expression of glucose transporter protein type-4 (GLUT4), leading to an increase in glycogen content in rat skeletal muscles and glucose transport proteins on muscle cell membranes [11]. Furthermore, some studies have indicated that muscle strength is significantly influenced by temperature, with maximum strength typically appearing during the peak period of the diurnal temperature change curve [12]. The hypothermic effect of melatonin was reported in the last century [13,14], and this effect may help preserve strength performance in high-temperature environments [15]. This phenomenon could be related to the appropriate temperature promoting enzyme activity, which in turn plays a crucial role in facilitating energy generation, glycolipid catabolism, and endocrine function.

The physiological structural aspects of skeletal muscle (such as muscle fiber size, muscle fiber type, and mass) are directly related to muscle strength. Aging and other factors leading to a decline in skeletal muscle mass result in weakened muscle strength [16-20]. Multiple studies have demonstrated the beneficial efficacy of melatonin in the treatment of sarcopenia [21,22]. Obayashi et al. conducted a study involving 760 elderly individuals to investigate the relationship between melatonin secretion and grip strength as well as quadriceps strength. The findings revealed a positive correlation between melatonin secretion and muscle strength [23]. Together with evidence that melatonin influences skeletal muscle cell proliferation and differentiation [24], these findings suggest that melatonin may affect muscle strength by modulating muscle fiber structure. In another study on melatonin levels and sarcopenia, participants' morning urine levels of 6-sulphatoxymelatonin (aMT6s) were negatively correlated with muscle loss, this means that the higher the melatonin level in the morning urine, the less the decline in muscle mass [25]. Because larger muscles with more muscle fibers can generate greater force than smaller muscles [26], appropriate melatonin levels may help preserve muscle mass and maintain muscle strength. Therefore, appropriate levels of melatonin can prevent the decline in muscle mass and maintain muscle strength. Additionally, recent research has found that the administration of melatonin can also enhance muscle tension after exercise [11]. During training, the supplementation of melatonin has been shown to improve women's muscle strength and reduce serum levels of the free radical byproduct malondialdehyde (MDA) [27]. These studies have confirmed the correlation between melatonin and muscle strength, but there is currently no in-depth exploration of the specific mechanisms. It's worth noting that some studies have indicated that melatonin has no effect on muscle strength. For instance, a study involving 81 women found no significant effect of melatonin intake on their muscle strength [28]. Moreover, according to a survey, when men ingested melatonin during the day, there's no significant difference in cortisol levels, maximum jumping ability, or maximum strength between the melatonin group and the placebo group [29], suggesting that some external environmental factors might need to be considered. Overall, the majority of studies support the notion that melatonin has a beneficial effect on muscle strength.

Previous studies have demonstrated that skeletal muscle strength exhibits diurnal rhythm variations [30-32], although the peak times of muscle strength for different muscle groups vary throughout the day, most are concentrated around 19:00 [31,33]. Recently, Douglas et al. reviewed the daily variation of human muscle strength based on nearly 20 years of relevant research. The findings indicated that muscle strength exhibits temporal variation, and peaks between 16:00 and 20:00 [1]. Meanwhile, studies have shown that it is better to perform muscle strength exercises in the evening [31], which parallels the time of the trough of melatonin concentration in the human body. Based on this inference, athletes might consider anticipating the occurrence of their optimal strength quality based on their internal melatonin rhythm and concentration, thereby, they can strategically plan their training sessions accordingly, which could yield better results. Nevertheless, whether the rhythmic changes in muscle strength are directly related to the secretion rhythm of melatonin is currently under-researched and cannot be fully confirmed.

3 THE EFFECT OF MELATONIN ON SPEED QUALITY

Speed quality plays a crucial role in athletes' physical performance, and studies have indicated that melatonin has a significant effect on athletes' alertness, reaction time, movement speed, and other relevant variables that directly impact speed quality.

Research conducted as early as 1997 demonstrated that melatonin affects alertness and **reaction time** [34]. The mechanism may involve inhibition of the central nervous system through modulation of the sleep–wake system [35-37]. Atkinson et al. (2.5 mg) and Dollins et al. (10-80 mg) investigated the effects of daytime melatonin consumption on short-term performance and found that melatonin intake significantly decreased alertness [38,39]. Several other studies have demonstrated that excessively high concentrations of melatonin decrease human alertness [40], and there is evidence suggesting that high melatonin concentrations induce somnolence by suppressing the central nervous system [41,42]. The findings suggested that the effect of melatonin on alertness might be closely related to its dosage. In addition to dose, the greater the complexity of the task and the greater the mental concentration required, the greater and longer the decrease in alertness [43]. It is possible that the melatonin dose is too high and enhances the drowsiness of the body [41]. In addition to dose, the more complex the task and the higher the level of mental concentration required, the more pronounced and prolonged the decrease in alertness exhibited [43]. Other studies have shown that too much melatonin reduces the body's alertness and the presence of increased drowsiness through suppression of the central nervous system [40,42]. It is hypothesized that the effect of melatonin on alertness may be closely related to the amount of melatonin dosage. Notably, there were opposite results in patients with chronic insomnia. Compared to a placebo, insomnia patients who took melatonin showed a more significant increase in alertness [44]. Paryab et al. found that athletes deprived of sleep who took 6 mg of melatonin had a positive effect on their reaction time [45]. The above experiments show that melatonin affects the alertness and responsiveness of the human body, which are related to the dosage and the individual's physical state.

Additionally, melatonin also has an important effect on **movement speed**. Jasper et al. conducted an experiment to test handwriting speed on nine subjects and found that handwriting speed decreased at 22:00 when melatonin began to be secreted [46]. It suggests that melatonin might have an effect on handwriting speed. Moreover, it has been shown that movement speed is related to the anaerobic metabolic capacity of muscles. Beck et al. conducted a study to investigate the effects of melatonin supplementation on anaerobic metabolism in swimming rats [47]. The results indicated that rats receiving melatonin intervention exhibited an extended duration of anaerobic metabolism compared to the control group [47]. Therefore, melatonin likely influences movement speed by affecting the muscle's anaerobic metabolic capacity.

Moreover, among the variables affecting movement speed, flexibility has a consistent circadian rhythm with melatonin secretion [48]. In the last century, Gifford et al. demonstrated that flexibility usually peaks in the afternoon or evening of the day [49]. Flexibility was also found to be greater at night than during the day in the seated forward flexion test conducted by Guariglia et al. with 25 subjects [50]. These results suggest that the changes in flexibility coincide with the rhythm of melatonin secretion, although there are still no studies demonstrating a direct correlation between melatonin levels and body flexibility.

In summary, speed qualities might be influenced by the effects of melatonin on related variables such as alertness, reaction time, movement speed, and flexibility. The peak performance of speed qualities might coincide with the peak time of these motion variables. Further research about melatonin and speed qualities has significant potential value in refining the study of the relationship between melatonin and athletic performance.

4 THE EFFECT OF MELATONIN ON ENDURANCE QUALITIES

Melatonin is a potent antioxidant that modifies the metabolic utilization of carbohydrates (CHO) and lipids [51], and it also has a cooling effect [52,53], all of which have a significant impact on the endurance qualities of the body. By supplementing with exogenous melatonin, athletes can reduce the production of reactive oxygen species (ROS) in the muscles, delay muscle fatigue, and enhance endurance qualities [54,55].

4.1 Effect of Melatonin on Anaerobic Endurance

The concept of "anaerobic endurance" refers to the body's ability to repeatedly perform short, intermittent, intense bursts of exercise or sustained bouts of high-intensity exercise at the highest possible level [56,57]. It refers to the ability to maintain the highest possible power output during activities lasting from approximately 30 seconds to several minutes and to recover effectively between repeated bouts of such efforts [58]. But this concept is still controversial [59], and lacks a gold standard for anaerobic endurance testing [58,60]. Researchers have proposed the simultaneous use of two variables, maximum anaerobic performance (which refers to the maximum value of a given variable attained in the series) and performance index (which is the ratio of the mean performance to the maximum one), from a series of interval exercises to evaluate anaerobic endurance [57,61]. Maximum anaerobic performance refers to the highest level of work that can be accomplished utilizing anaerobic energy pathways before fatigue sets in, also known as "anaerobic capacity"， which is the basis of anaerobic endurance [62].

There is limited recent research specifically addressing the effects of melatonin on anaerobic endurance. However, melatonin has been widely studied for its broader effects on anaerobic exercise performance rather than anaerobic endurance) [63], with findings indicating both potential benefits and drawbacks. Existing studies on the effects of melatonin supplementation on anaerobic exercise performance mainly fall into three categories: acute supplementation before exercise, supplementation before bedtime the day before exercise testing, and long-term melatonin supplementation. **Firstly,** existing studies on acute single-dose melatonin supplementation before exercise have yielded conflicting results. For example, acute melatonin supplementation (6 mg) taken 30 minutes before exercise can enhance anaerobic power, e.g., the Wingate test (30-second all-out cycling) [64], relative peak, anaerobic, and mean power [65]. However, Ghattassi et al. reported that taking 5 mg of melatonin at 7:30 AM significantly impaired some measures of short-term maximal performance (medicine-ball throw and handgrip strength) tested 30 minutes later (at 8:00 AM) [66]. **Additionally**, the positive effect was observed in tests conducted the day after melatonin supplementation on the previous day. Mahdi et al. (2025) demonstrated that acute nighttime melatonin supplementation (6 mg) enhances next-day high-intensity exercise performance (5 m shuttle test (5mSRT)) and post-exercise recovery in trained males [67]. Moreover, supplementing with 10 mg of melatonin the previous day improved anaerobic performance metrics the following day, e.g., increased peak and mean power of the Running-Based Anaerobic Sprint Test (RAST), decreased total time and fatigue index [68], improved short-term maximal performances (HG and SJ) (handgrip strength (HG) and squat jump (SJ)), reaction-time, as well as peak and mean Wingate anaerobic test (WanT) powers, and decreased fatigue index and RPE scores [69]. **Thirdly,** there is only one report on the effects of long-term melatonin supplementation on anaerobic endurance. Farjallah et al. found that when 20 soccer players took a 5-mg dose of melatonin at 7:00 p.m. each day after their training session during six consecutive days of high-intensity training, it helped improve their performance on the repeated sprint ability (RSA) test conducted on the seventh day [70,71]. In summary, the effects of melatonin on anaerobic endurance are closely related to the type of exercise and the timing of melatonin ingestion relative to exercise.

From an energy metabolism perspective, anaerobic endurance primarily relies on the phosphagen (adenosine triphosphate (ATP), creatine phosphate (CP)) and glycolysis systems [72], e.g., during maximal-intensity exercise, such as sprinting, when power output reaches 900 W, approximately 300% of VO_2 max, and the ATP utilization rate is approximately 3.7 mmol ATP kg^{-1} s^{-1}, the exercise can be sustained for less than 2 s if stored ATP is the only energy source [2]. However, the concentration of intramuscular ATP stores (~ 5 mmol per kg of wet muscle) is very low and not enough to support prolonged, high-intensity muscle contraction. Therefore, in conditions of high-intensity and sustained contractile activity, anaerobic glycolysis serves as the primary source of energy to fulfill the rapid ATP requirements [73,74]. At exercise intensities approaching or exceeding ~100% VO_2 max, ATP production undergoes a marked shift toward anaerobic pathways. For instance, during a maximal 6-second sprint (peak intensity ~300% VO_2 max), the rapid hydrolysis of phosphocreatine (PCr) and a sharp increase in anaerobic glycolysis together provide approximately 50% of the ATP, while oxidative phosphorylation contributes less than 10%. This demonstrates that to meet the extreme power demands of such efforts, the body relies predominantly on immediate and short-term anaerobic systems [75]. A similar reliance on anaerobic metabolism is observed during 30-second all-out exercise, where glycolysis is estimated to supply between 65% and 75% of the required ATP [75].

The glycolytic capacity is not limited by glycogen availability, as the amount of glycogen utilized during anaerobic glycolysis is trivial relative to the total available substrate pool in the muscle cell [76]. Therefore, phosphofructokinase (PFK), the rate-limiting enzyme of glycolysis, which catalyzes the conversion of fructose-6-phosphate to fructose-1,6-bisphosphate, is one of the key factors affecting anaerobic endurance [77]. During intense muscle contractions, the demand and synthesis of ATP increase rapidly, leading to enhanced glycolytic flux. However, acidosis (a glycolytic product) can impair PFK activity, reducing glycolytic efficiency and ATP production [78,79]. The primary glycolytic product that plays a significant role in this inhibition is hydrogen ions (H^+), which accumulate as a result of high glycolytic flux. Since H^+ ions compete with other allosteric regulators of PFK, PFK is inhibited by high H^+ levels [80]. Within non-mitochondrial energy catabolism, the glyceraldehyde-3-phosphate dehydrogenase (GAPDH) reaction is the foremost H^+-liberating step. Its release of H^+ further intensifies as pH decreases, while ATP hydrolysis, the second most significant contributor of H^+ release, shows a decrease in H^+ release as pH decreases [81]. Furthermore, lactate, a key glycolytic product, acts as a feedback inhibitor by directly suppressing the phosphorylation of PFK tyrosine residues in skeletal muscle, thereby reducing PFK activity [82]. High lactate levels are associated with muscle fatigue, as observed in elite and sub-elite 400-meter sprinters, where increased lactate concentration correlates with decreased anaerobic power and muscle performance [83]. Additionally, during sustained anaerobic exercise, glycolytic products can inhibit body functions through several other mechanisms, e.g., hydrogen (H+) and phosphate (Pi), as metabolic byproducts of intense contractile activity, can reduce muscle tension and overall performance by inhibiting force and power of the cross-bridge while reducing myofibrillar Ca^{2+} sensitivity, and Pi further exacerbates contractile impairment by directly inhibiting sarcoplasmic reticulum Ca^{2+} release [84,85].

Relevant research has found that prolonged anaerobic exercise, such as acute sprint-interval/repeated-sprint exercise/sprint-interval exercise, produced mitochondrial damage, including ultrastructural disturbance with accompanying swelling-like morphological shifts and altered cristae metrics [86], and inhibited mitochondrial respiration [87]. Melatonin supplementation can alleviate exercise-induced cellular damage [88], reduce oxidative stress and inflammatory signaling [3,89], and attenuate mitochondrial autophagy and damage in the other research [90,91]. Therefore, this research indicates that melatonin can mitigate compensatory glycolysis and lactic acid accumulation triggered by mitochondrial damage in non-cancer contexts by restoring mitochondrial function, thereby indirectly alleviating cytoplasmic acidification [90,91]. Furthermore, melatonin supplementation has been shown to significantly reduce post-exercise blood lactate in humans and animals [65,92-94], although this remains somewhat ambiguous [53,68,69]. Moreover, melatonin treatment upregulated the expression of Sirtuin 1 (SIRT1) [95], a histone deacetylase known to promote cell survival and positively regulate AMPK activation. AMPK phosphorylated PFK-2 at Ser466 [96], which activated the kinase domain, leading to increased fructose 2,6-bisphosphate and increased the activity of phosphofructokinase-1 (PFK-1) and enhanced glycolysis independent of mitochondria [97-99]. Accordingly, based on the above findings, melatonin supplementation is beneficial for enhancing anaerobic endurance.

4.2 Effect of Melatonin on Aerobic Endurance

Aerobic endurance (often called cardiorespiratory endurance) is the capacity to sustain whole-body exercise for prolonged periods through efficient oxygen utilisation and energy conversion, where ATP demand is met predominantly by oxidative metabolism [100]. Recent studies indicate that aerobic endurance performance is closely associated with four physiological pillars, including maximal oxygen uptake ($\dot{V}O_2$max), submaximal exercise economy/efficiency, the fractional utilisation of $\dot{V}O_2$max that can be sustained (often indexed by lactate/ventilatory thresholds or critical power/critical speed), and physiological resilience [101,102]. The main methods of evaluating aerobic endurance performance include the $\dot{V}O_2$max, lactate thresholds (LTs), and the exercise capacity at the highest constant exercise intensity that can be maintained for a longer period of time without a continuous rise in blood lactate concentrations (bLa) [103], such as the maximum distance that a person can walk in 6 min or the exercise time to volitional exhaustion during submaximal cycling at 75% of maximal power output [104,105].

Recently, there has been an explosion of study in the field of exercise on the effects of melatonin on aerobic endurance. In athletes, there is direct evidence that the intake of 6 mg of exogenous melatonin half an hour before exercise can increase aerobic endurance by 19% [106]. Athletes that ingest melatonin during exercise exhibit a beneficial effect on endurance adaptation as well [106,107], their triglyceride levels decreased significantly, i.e., the level of lipid metabolism increased during exercise. However, one timing-dependent meta-analysis reports endurance benefits that are stronger with evening administration and with longer supplement-to-exercise intervals (>6 h), indicating that classic “30 min pre-race” or “during exercise” patterns may not be the most relevant for endurance effects [63]. For instance, next-day performance is better following nocturnal melatonin administration. Cheikh et al. found that after exhaustive late-evening exercise, a single 10 mg dose improved sleep quantity/quality and improved next-morning intermittent endurance-like performance (Yo-Yo IR1 distance +82 m) in teenage athletes [108]. Additionally, chronic supplementation may influence endurance indirectly through sleep/circadian alignment, reduced muscle damage/inflammation during heavy training, or improved rehab tolerance [88].

The energy source for aerobic endurance mainly depends on the aerobic oxidation of carbohydrate and lipid metabolism, the storage and metabolism of energy substances (glucose, lipids, etc.) are crucial. Melatonin contributes to the storage of energy substances within the body and improves myocyte energy utilization capacity [94,109]. In myocytes, glucose is transported to the sarcolemma and transverse tubules by GLUT4 [110]. As exercise duration increases, more energy and energy substrates (carbohydrates, free fatty acids (FFAs), triglycerides, etc.) need to be provided, and melatonin has been shown to increase GLUT4 expression, FAT/CD36, and other energy substrate utilization, improving aerobic endurance and metabolic recovery [11]. Melatonin alleviates impaired glucolipid metabolism by activating expression of the AMPK-activated protein kinase alpha (AMPKα)-peroxisome proliferator-activated receptor alpha (PPARα) pathway in guinea pigs with impaired glucolipid metabolism [111]. Further discoveries had been made in animal models, particularly in relation to the mechanisms by which melatonin affects energy metabolism. Melatonin has been found to enhance locomotor performance in rats [47,11,112]. Hepatic glycogen levels in melatonin-supplemented rats were higher than in other groups, while lactate levels were lower than in other groups [113,114]. This suggests that melatonin may have a protective effect on liver glycogen reserves, delaying exercise fatigue and improving endurance. The rats in the study exhibited improved results in physical performance, glucose tolerance, citrate synthase activity, liver glycogen and myogen content, and stronger expression of phosphatidylinositol 3-kinase (PI3K), mitogen-activated protein kinase (MAPK), adenosine-activated protein kinase (AMPK), and GLUT4 in the liver, indicating that melatonin alters aerobic metabolic adaptation [115]. Notably, when aerobic exercise was performed, the mitochondria of adult pinealectomized rats showed reduced aerobic oxidative capacity, increased oxidative stress, and altered energy metabolism compared to the control group, resulting in a decrease in their aerobic endurance [116]. Another study showed that pinealectomy in aged rats led to a significant decrease in insulin-stimulated glucose uptake in adipocytes, which altered the substrate utilization pattern of adipocytes and thus affected exercise tolerance, but pinealectomy in young rats had no significant effect [117], this may be related to the condition or status of the rat organism. Michurina et al. found in mice exposed to light for 14 consecutive days that melatonin-treated rats had higher hemoglobin levels in their blood at the end of the experiment, although there were no significant changes in physical endurance performance [118], which could be related to the influence of other extrinsic factors. In conclusion, glycogen preservation and increased expression of glucose and lipid transporters suggest that melatonin may help spare or replenish energy stores, reducing reliance on anaerobic glycolysis in some contexts.

5 CONCLUSION

Melatonin supplementation significantly affects strength, speed, and endurance qualities. Considering the benefits of melatonin supplementation—specifically its affordability and few side effects—investigating its impact on sports performance is highly pertinent. Notably, sports-related randomized controlled trials and reviews have used a wide range of doses, with some trained-athlete biomarker studies using approximately 5–100 mg. However, most supplementation trials have used doses around 3–10 mg, whereas higher doses may raise concerns regarding sedation and metabolic risk in some populations.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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