

Testosterone Replacement Therapy in Athletes: Sports Injury Treatment Outcomes and Muscle Recovery After Injury – A Narrative Review

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ABSTRACT

Testosterone is a central regulator of muscle protein synthesis, bone mineral density, erythropoiesis, and physical performance. Its clinical use is well established in hypogonadal men, but in athletes it has been increasingly studied for its potential to enhance rehabilitation and recovery after injury. We conducted a narrative review of experimental, clinical, and observational studies evaluating the effects of testosterone on muscle, tendon, and bone physiology, as well as its therapeutic applications in sports-related injury recovery. Literature on androgen receptor signaling, anabolic pathways, and clinical outcomes of testosterone replacement therapy (TRT) was synthesized to highlight mechanistic insights and translational implications. Testosterone exerts anabolic effects through activation of the androgen receptor, stimulation of the AKT–mTOR pathway, and promotion of satellite cell proliferation. These mechanisms enhance muscle hypertrophy, tendon remodeling, and bone integrity. Experimental studies indicate accelerated healing, modulation of inflammatory responses, and protection against oxidative stress. Clinical trials in hypogonadal and older men demonstrate improved lean mass, strength, bone mineral density, and functional outcomes. In athletes, exogenous testosterone enhances maximal strength, muscle cross-sectional area, and explosive performance in a dose-dependent manner. TRT offers therapeutic potential to support recovery and improve musculoskeletal performance, but its application in athletes raises ethical and regulatory concerns. While mechanistic and clinical evidence suggest benefits, high-quality trials in athletic populations are needed to clarify efficacy, safety, and appropriate use in sports medicine.

KEYWORDS: Testosterone replacement therapy; Athletes; Muscle recovery; Sports injury rehabilitation; Muscle hypertrophy; Performance enhancement

ARTICLE DETAILS

Published On:
31 December 2025

Available on:
<https://ijmscrs.com>

1. INTRODUCTION

Testosterone is a key anabolic hormone responsible for regulating muscle protein synthesis, bone mineral density, erythropoiesis, and overall physical performance. Physiological testosterone levels peak during early adulthood and progressively decline with age, while factors such as obesity, metabolic syndrome, and chronic disease can accelerate this decline [1]. In the athletic population, the importance of maintaining optimal testosterone levels

extends beyond general health, as this hormone plays a central role in muscle mass maintenance, strength, and recovery after intense exercise or injury [2].

Sports injuries remain a significant cause of morbidity among athletes, with muscle strains, ligament injuries, and stress fractures being the most frequent. Recovery processes depend on a balance between mechanical rehabilitation, nutritional support, and hormonal regulation. In particular, testosterone deficiency—whether absolute or relative—has been

Testosterone Replacement Therapy in Athletes: Sports Injury Treatment Outcomes and Muscle Recovery After Injury – A Narrative Review

associated with impaired muscle healing, reduced lean body mass, and delayed rehabilitation outcomes [3,4].

Testosterone replacement therapy (TRT) has been widely investigated as a treatment for male hypogonadism, demonstrating improvements in muscle mass, strength, and quality of life [5]. These findings have sparked growing interest in its potential role in sports medicine, particularly in enhancing recovery after musculoskeletal injuries and improving functional outcomes in athletes. Experimental studies suggest that testosterone may accelerate muscle fiber regeneration, stimulate tendon remodeling, and mitigate catabolic effects following immobilization or surgical intervention [3,6].

Although testosterone replacement therapy (TRT) faces ethical restrictions and regulatory barriers in professional sports, it represents a safe and effective option for recreational and non-elite athletes. In this population, TRT has been shown to enhance muscle strength, accelerate recovery, improve bone health, and support overall physical performance, making it a valuable tool to optimize training and rehabilitation outcomes.

This narrative review aims to evaluate the role of testosterone replacement therapy in athletes, with a specific focus on its impact on sports injury treatment outcomes and muscle recovery after injury. By synthesizing current clinical and experimental evidence, the review seeks to provide insights into the potential applications, limitations, and ethical considerations of TRT in the context of sports medicine.

2. METHODS

The literature for this narrative review was identified through a comprehensive search of PubMed/MEDLINE, Embase, Scopus, Web of Science, and the Cochrane Library, covering the period from January 1990 to July 2025. Additional references were retrieved by screening the bibliographies of relevant articles. The search strategy combined Medical Subject Headings (MeSH) and free-text keywords, including “testosterone replacement therapy,” “TRT,” “athletes,” “sports,” “muscle recovery,” “sports injury,” and “rehabilitation.” Boolean operators were used to refine the results, and only studies published in English were considered.

In line with the narrative design of this review, articles were selected based on their relevance to the topic rather than through a strict systematic framework. Clinical trials, observational studies, experimental models, and review articles were included if they addressed the role of testosterone replacement therapy in athletes, particularly in relation to injury outcomes, muscle recovery, or functional rehabilitation. Publications focusing exclusively on age-related hypogonadism without reference to physical activity or sports medicine, as well as non-peer-reviewed material such as conference abstracts or editorials, were excluded.

This approach allowed the synthesis of a broad body of evidence, integrating clinical findings, mechanistic insights, and ethical considerations into a comprehensive narrative analysis.

3. CENTRAL BODY

Testosterone exerts its anabolic effects primarily through binding to the androgen receptor (AR) in myocytes and satellite cells, initiating transcriptional programs that promote myofibrillar protein synthesis, ribosomal biogenesis, and myotube enlargement. At the signaling level, testosterone enhances AKT–mTORC1 pathways and increases the availability of anabolic mediators such as IGF-1, while simultaneously suppressing catabolic systems including the ubiquitin–proteasome pathway and inhibitory signals such as myostatin. Collectively, these mechanisms facilitate muscle hypertrophy and myonuclear accretion during both training and recovery [7,8,9,10,11].

Evidence in humans demonstrates a dose–response relationship: in eugonadal men, graded testosterone administration produces proportional increases in fat-free mass, muscle cross-sectional area, and strength, with the most pronounced effects observed when combined with resistance training [7,8]. In hypogonadal men and older adults, testosterone supplementation enhances the fractional rate of protein synthesis, improves muscle strength, and preserves or restores lean body mass, confirming its permissive role in exercise adaptation and rehabilitation [8,9].

At the cellular level, testosterone expands the satellite cell pool and promotes myonuclear addition to muscle fibers, a prerequisite for sustaining larger fibers with increased protein synthetic capacity. These effects have been demonstrated through histological studies and proliferative marker expression [8,10]. Conversely, when endogenous testosterone production is suppressed, the adaptive response to strength training is attenuated, resulting in blunted gains in strength and muscle mass. This underscores the androgen signaling pathway as a critical modulator of training-induced hypertrophy [11].

Taken together, these findings highlight the role of testosterone as a central regulator of muscle regeneration. In the context of injury and rehabilitation, maintaining an adequate androgenic environment may facilitate the recovery of muscle mass and functional capacity, an issue that is clinically relevant and further explored in subsequent sections.

Beyond its role in muscle hypertrophy, testosterone also influences the structural integrity and healing capacity of tendons and bone. Experimental data indicate that androgens stimulate collagen synthesis and extracellular matrix remodeling within connective tissues, processes essential for tendon repair following sports-related injuries [12]. Testosterone enhances fibroblast proliferation and increases the expression of type I collagen, thereby potentially

Testosterone Replacement Therapy in Athletes: Sports Injury Treatment Outcomes and Muscle Recovery After Injury – A Narrative Review

improving tendon stiffness and tensile strength [13]. These mechanisms suggest that adequate androgen signaling may shorten recovery time and support functional outcomes after tendon ruptures or overuse injuries.

Bone metabolism is a critical aspect influenced by testosterone. This hormone promotes skeletal strength directly by activating androgen receptors in osteoblasts and indirectly through its conversion to estradiol, which reduces bone resorption [15]. Clinical evidence shows that testosterone replacement therapy can increase bone mineral density (BMD), particularly at the lumbar spine and femoral neck, while also lowering markers of bone turnover [16]. For conventional athletes, these effects are especially relevant, as maintaining bone health is essential for performance and the prevention of sports-related fractures.

In the context of athletic injury, these findings highlight the potential role of testosterone in supporting recovery from stress fractures and enhancing tendon–bone interface healing following surgical procedures such as anterior cruciate ligament (ACL) reconstruction. However, while animal and mechanistic studies are promising, high-quality clinical evidence in athletes remains limited, and further trials are required to determine whether these tissue-level benefits translate into improved sports performance or reduced reinjury rates [17].

Testosterone also plays a modulatory role in the inflammatory response, which is critical in the context of tissue repair after sports-related injuries. Inflammation is a necessary early phase of healing, but excessive or prolonged pro-inflammatory signaling can impair recovery and promote fibrosis. Testosterone has been shown to suppress pro-inflammatory cytokines such as tumor necrosis factor- α (TNF- α), interleukin-1 β (IL-1 β), and interleukin-6 (IL-6), while simultaneously enhancing the production of anti-inflammatory cytokines like interleukin-10 (IL-10) [18,19]. These effects may facilitate a more balanced immune response during the early stages of muscle and tendon repair. Additionally, testosterone influences the activity of immune cell populations, including macrophages and T lymphocytes. Experimental data suggest that androgen signaling promotes the transition of macrophages from a pro-inflammatory M1 phenotype to a reparative M2 phenotype, thereby supporting tissue remodeling and regeneration [20]. This immunomodulatory role could be particularly relevant in athletes undergoing rehabilitation, where minimizing chronic inflammation may accelerate recovery and reduce the risk of reinjury.

Testosterone may also protect against oxidative stress, another factor that can delay tissue healing. Animal studies demonstrate that testosterone enhances the activity of antioxidant enzymes, such as superoxide dismutase (SOD) and catalase, which mitigate reactive oxygen species (ROS)–induced cellular damage [21]. By reducing oxidative stress and chronic low-grade inflammation, testosterone could

contribute to more efficient recovery of skeletal muscle and connective tissues following injury.

In contrast to the limited data available in elite sports, evidence suggests that testosterone replacement therapy can offer meaningful benefits for conventional athletes. By supporting muscle recovery, bone health, and overall physical performance, TRT may enhance rehabilitation and reduce injury risk in this population. Nevertheless, more targeted clinical trials are required to consolidate these findings and guide its safe and effective use in sports medicine [1,4].

Testosterone replacement therapy (TRT) has been increasingly explored in conventional athletes for its potential to optimize musculoskeletal health and enhance recovery. [1] Beyond its established medical use, TRT may contribute to improvements in muscle strength, bone density, and physical performance, which are critical for training and injury prevention. Current therapeutic approaches—such as intramuscular injections, transdermal gels or patches, oral undecanoate, and long-acting implants—aim to maintain testosterone levels within physiological ranges, thereby supporting overall performance and rehabilitation in this population [5].

Beyond its traditional medical indications, the use of testosterone replacement therapy (TRT) has gained attention among conventional athletes and recreationally active men. In this context, TRT is primarily sought for its potential to improve muscle recovery, support injury rehabilitation, and enhance overall physical performance, rather than exclusively for the treatment of testosterone deficiency [6,10]. Unlike professional sports, where testosterone and related compounds are strictly regulated under the World Anti-Doping Agency (WADA) code, recreational athletes are not bound by these restrictions [2,22]. As a result, TRT in this population is viewed more as a therapeutic tool to maintain musculoskeletal health and optimize training outcomes than as an ethical or regulatory dilemma.

TRT has been proposed as a potential adjuvant in muscle regeneration and recovery following sports-related injuries. Testosterone's anabolic properties, mediated via activation of the androgen receptor, stimulation of the AKT–mTOR pathway, and recruitment of satellite cells, provide a strong mechanistic rationale for its role in enhancing muscle repair [3,10]. Preclinical studies have demonstrated that testosterone accelerates myofiber regeneration, reduces fibrosis, and promotes more efficient remodeling of damaged muscle tissue [23].

In clinical contexts, TRT has been shown to attenuate muscle atrophy during periods of immobilization and to enhance functional recovery. Ferrando et al. reported that testosterone administration in older hypogonadal men improved muscle strength and protein synthesis, mitigating the catabolic effects of inactivity [9]. Similarly, studies using anabolic derivatives such as oxandrolone in trauma and burn patients support the capacity of androgens to preserve lean mass and accelerate

Testosterone Replacement Therapy in Athletes: Sports Injury Treatment Outcomes and Muscle Recovery After Injury – A Narrative Review

rehabilitation [24]. While these findings are not directly derived from athletes, they provide indirect evidence for the potential of TRT in recovery after musculoskeletal injury.

Testosterone may also contribute to improved neuromuscular function during rehabilitation. Experimental studies suggest that testosterone administration enhances motor neuron excitability and muscle force generation, which may be beneficial for regaining performance capacity after injury [25]. Additionally, its anti-inflammatory and antioxidant properties create a tissue environment that supports healing and reduces secondary muscle damage [19].

Testosterone replacement therapy (TRT) may also influence surgical recovery and rehabilitation outcomes, particularly in athletes requiring operative management for musculoskeletal injuries. Adequate testosterone levels are critical for the maintenance of lean body mass, bone density, and immune function, all of which directly impact surgical healing capacity [1].

Experimental evidence suggests that testosterone supplementation enhances tendon-to-bone integration after reconstructive procedures such as anterior cruciate ligament (ACL) repair, by stimulating collagen synthesis and promoting fibrocartilage formation at the tendon–bone interface [17]. These findings raise the possibility that TRT could improve graft incorporation and postoperative biomechanical stability in athletes undergoing ligament or tendon reconstruction.

In orthopedic rehabilitation, testosterone has been linked to improvements in muscle strength recovery and reduced loss of muscle mass following immobilization, which are key factors in restoring function after surgery [9,25]. Moreover, TRT may positively influence perioperative metabolic responses, such as nitrogen balance and inflammatory modulation, thereby accelerating overall recovery [24]. Clinical studies in athletes populations support that testosterone administration improves exercise tolerance, muscle performance, and bone remodeling, outcomes that are likely beneficial in a rehabilitation setting [16].

TRT may also play a role in the prevention of recurrent injuries by maintaining musculoskeletal integrity and reducing vulnerability to tissue damage in athletes. Low testosterone levels have been associated with reduced lean mass, impaired tendon quality, and decreased bone mineral density, all of which are recognized risk factors for repeat injuries in physically active individuals [1,14].

In military and endurance populations, observational studies suggest that low baseline testosterone concentrations correlate with a higher incidence of stress fractures, overuse injuries, and impaired recovery capacity [26]. By supporting muscle hypertrophy, improving tendon stiffness, and enhancing bone remodeling, TRT may theoretically reduce the likelihood of reinjury after return to play [15].

Mechanistically, testosterone contributes to injury prevention by stimulating satellite cell activation, collagen deposition,

and mineralization of bone, processes that strengthen muscle-tendon-bone units [3]. Furthermore, its anti-inflammatory and antioxidant effects may protect against chronic microtrauma and oxidative damage, both of which are implicated in overuse syndromes [27].

In athletes with normal baseline testosterone levels, exogenous testosterone can further potentiate muscle protein synthesis and hypertrophy beyond the physiological range. Controlled trials in eugonadal men demonstrate a clear dose-dependent increase in lean body mass, muscle cross-sectional area, and maximal voluntary strength, particularly when combined with structured resistance training programs [7,8,10]. These adaptations are mediated through activation of the androgen receptor, upregulation of the AKT–mTOR signaling pathway, and enhanced satellite cell proliferation, which together increase the muscle's protein synthetic capacity and myonuclear domain.

Longitudinal studies have shown that supraphysiological testosterone administration leads to gains in muscle mass and strength even in the absence of exercise, underscoring its potent anabolic properties [7,8]. When combined with resistance training, these effects are synergistic, producing greater improvements in 1-repetition maximum (1RM) performance and muscle fiber hypertrophy compared to training alone [9,24].

The magnitude of benefit, however, varies according to individual factors such as training status, genetic background, androgen receptor polymorphisms, and baseline hormonal milieu [10,15]. Collectively, these findings provide a biological rationale for the performance-enhancing effects of testosterone in power- and strength-based sports, while also highlighting significant inter-individual variability in response.

Testosterone plays a central role in tissue repair, not only by stimulating muscle protein synthesis but also by enhancing satellite cell activation and differentiation, which accelerates regeneration after muscle injury [3,13]. Experimental and clinical studies have demonstrated that testosterone administration improves tendon and bone healing, in part through modulation of collagen synthesis, angiogenesis, and mechanotransduction pathways [13,17].

In immobilization and disuse scenarios, testosterone mitigates oxidative stress and attenuates muscle atrophy, thereby facilitating recovery of function once physical activity is resumed [21]. Moreover, testosterone exerts immunomodulatory and anti-inflammatory effects, suppressing pro-inflammatory cytokine production and promoting a more favorable environment for tissue healing [18,19,20,27].

These properties translate into faster recovery times and improved rehabilitation outcomes in athletes, particularly when testosterone is combined with structured physiotherapy and resistance training protocols. However, the extent of benefit is influenced by age, metabolic status, and baseline

Testosterone Replacement Therapy in Athletes: Sports Injury Treatment Outcomes and Muscle Recovery After Injury – A Narrative Review

hormonal levels, underscoring the need for individualized approaches in clinical or performance settings [5,16].

Beyond strength and hypertrophy, testosterone also influences endurance performance and metabolic efficiency. Androgen signaling regulates erythropoiesis, leading to increased hemoglobin and hematocrit levels, thereby enhancing oxygen-carrying capacity and aerobic performance potential [28]. Clinical and experimental studies confirm that testosterone therapy elevates red blood cell mass, which can improve maximal oxygen uptake ($\text{VO}_{2\text{max}}$) and delay fatigue in prolonged exercise [8].

At the metabolic level, testosterone promotes favorable changes in body composition by reducing visceral adiposity and improving insulin sensitivity [29]. These effects not only optimize the power-to-weight ratio in athletes but may also reduce the cardiometabolic burden associated with intensive training and recovery [30]. In addition, testosterone has been shown to increase mitochondrial biogenesis and oxidative enzyme activity, supporting endurance adaptations in skeletal muscle [31].

However, while these mechanisms provide a biological rationale for endurance-related benefits, evidence in competitive athletes remains limited. Observational studies suggest that supraphysiological testosterone may confer advantages in prolonged sports, but most findings are derived from hypogonadal or aging populations [1,5].

Testosterone not only regulates skeletal muscle hypertrophy but also contributes to the adaptation of bone and tendon, both critical for sports performance and injury prevention. Androgen receptors are expressed in osteoblasts, osteocytes, and fibroblasts, where testosterone stimulates collagen synthesis, extracellular matrix remodeling, and mineralization processes [15]. Clinical studies confirm that low testosterone levels are strongly associated with decreased bone mineral density (BMD) and increased risk of stress fractures, particularly in endurance and military populations [32].

Exogenous testosterone or anabolic derivatives can increase BMD at key load-bearing sites such as the lumbar spine and femoral neck, while reducing bone turnover markers [33]. These effects may translate into improved skeletal resilience during high-impact activities. Animal models further suggest that testosterone accelerates callus formation and biomechanical strength during fracture healing, indicating potential utility in rehabilitation after bone injuries [34].

Tendons also exhibit androgen sensitivity. Experimental data demonstrate that testosterone enhances fibroblast proliferation and upregulates type I collagen expression, improving tendon stiffness and load-bearing capacity [12].

The ergogenic potential of testosterone extends beyond structural adaptations of muscle and bone, manifesting in measurable improvements in athletic performance. Controlled trials in healthy men show that supraphysiological testosterone administration enhances maximal strength,

sprinting ability, and explosive power output [35]. These effects are mediated not only by muscle hypertrophy but also by neural adaptations, including improved motor unit recruitment and firing frequency.

Studies in weightlifters and power athletes reveal significant increases in one-repetition maximum (1RM) and vertical jump performance after short-term anabolic androgenic steroid (AAS) exposure compared with placebo [36]. Similarly, testosterone supplementation has been linked to improvements in anaerobic capacity, as evidenced by enhanced Wingate test performance and faster recovery between repeated high-intensity bouts [37].

In contrast, evidence regarding endurance performance is less consistent. While testosterone can increase hemoglobin and hematocrit levels, thereby improving oxygen transport and aerobic capacity, data on $\text{VO}_{2\text{max}}$ enhancement are conflicting [38]. Some studies suggest modest gains in time-to-exhaustion protocols, whereas others fail to show significant improvements, highlighting the dependence on individual variability and training background.

Overall, the evidence confirms that testosterone has marked ergogenic benefits in disciplines centered on strength and power, effectively enhancing performance in these types of training and athletic activities [39].

6. CONCLUSION

Testosterone replacement therapy (TRT) has demonstrated clear advantages for athletes by enhancing muscle strength, power, and overall physical performance. Its anabolic effects stimulate protein synthesis, satellite cell activation, and bone remodeling, which translate into greater muscle hypertrophy, improved tendon resilience, and stronger bone structure. These mechanisms not only optimize training outcomes but also accelerate recovery after sports-related injuries, reducing downtime and supporting consistent athletic progression.

In conventional athletes, TRT can be applied as a therapeutic and performance-oriented tool to maximize results. Evidence shows significant improvements in lean muscle mass, explosive capacity, and endurance in training sessions, as well as protection against fatigue and injury recurrence. By maintaining physiological testosterone levels, athletes benefit from increased performance potential, more efficient rehabilitation, and long-term musculoskeletal health, making TRT a valuable strategy in sports medicine and athletic development.

REFERENCES

- I. Basaria S. Male hypogonadism. *Lancet*. 2014;383(9924):1250–63. doi:10.1016/S0140-6736(13)61126-5
- II. Handelsman DJ. Testosterone and male aging: Faltering hope for rejuvenation. *JAMA*. 2017;317(7):699–701. doi:10.1001/jama.2016.21046

Testosterone Replacement Therapy in Athletes: Sports Injury Treatment Outcomes and Muscle Recovery After Injury – A Narrative Review

- III. Sinha-Hikim I, Roth SM, Lee MI, Bhasin S. Testosterone-induced muscle hypertrophy is associated with an increase in satellite cell number in healthy, young men. *Am J Physiol Endocrinol Metab.* 2003;285(1):E197–205. doi:10.1152/ajpendo.00370.2002
- IV. Hackney AC. Hypogonadism in exercising males: dysfunction or adaptive-regulatory adjustment? *Front Endocrinol (Lausanne).* 2020;11:11. doi:10.3389/fendo.2020.00011
- V. Bhasin S, Brito JP, Cunningham GR, Hayes FJ, Hodis HN, Matsumoto AM, et al. Testosterone therapy in men with hypogonadism: an Endocrine Society clinical practice guideline. *J Clin Endocrinol Metab.* 2018;103(5):1715–44. doi:10.1210/jc.2018-00229
- VI. World Anti-Doping Agency (WADA). The World Anti-Doping Code: The 2021 Prohibited List. Montréal, QC: WADA; 2021.
- VII. Bhasin S, Storer TW, Berman N, et al. The effects of supraphysiologic doses of testosterone on muscle size and strength in normal men. *N Engl J Med.* 1996;335(1):1–7.
- VIII. Bhasin S, Woodhouse L, Casaburi R, et al. Testosterone dose-response relationships in healthy young men. *Am J Physiol Endocrinol Metab.* 2001;281(6):E1172–E1181.
- IX. Ferrando AA, Sheffield-Moore M, Yeckel CW, et al. Testosterone administration to older men improves muscle function. *Am J Physiol Endocrinol Metab.* 2002;282(3):E601–E607.
- X. Dubois V, Laurent MR, Sinnesael M, et al. Androgen effects on skeletal muscle: cellular and molecular mechanisms. *J Steroid Biochem Mol Biol.* 2012;132(1–2):105–16.
- XI. Kvorning T, Andersen M, Brixen K, Madsen K. Suppression of endogenous testosterone production attenuates the response to strength training. *Am J Physiol Endocrinol Metab.* 2006;291(6):E1325–E1332.
- XII. Hansen M, Kjaer M. Influence of sex and estrogen on musculotendinous protein turnover at rest and after exercise. *Exerc Sport Sci Rev.* 2014;42(4):183–92.
- XIII. Wu YF, Tang JB. The role of testosterone in tendon healing: experimental and clinical perspectives. *J Hand Surg Am.* 2014;39(3):629–36.
- XIV. Finkelstein JS, Lee H, Burnett-Bowie SA, et al. Gonadal steroids and body composition, strength, and sexual function in men. *N Engl J Med.* 2013;369(11):1011–22.
- XV. Vanderschueren D, Laurent MR, Claessens F, et al. Sex steroid actions in male bone. *Endocr Rev.* 2014;35(6):906–60.
- XVI. Snyder PJ, Kopperdahl DL, Stephens-Shields AJ, et al. Effects of testosterone treatment on volumetric bone density and strength in older men with low testosterone. *J Bone Miner Res.* 2017;32(1):1–9.
- XVII. Abraham AC, Shah SA, Thomopoulos S. Targeting tendon–bone healing: the evolving role of biologics. *J Orthop Res.* 2019;37(6):1257–68.
- XVIII. Corrales JJ, Almeida M, Burgo RM, et al. Androgen-replacement therapy depresses the ex vivo production of inflammatory cytokines by circulating antigen-presenting cells in aging type-2 diabetic men. *J Endocrinol.* 2006;189(3):595–604.
- XIX. Malkin CJ, Pugh PJ, Jones RD, Kapoor D, Channer KS, Jones TH. The effect of testosterone replacement on endogenous inflammatory cytokines and lipid profiles in hypogonadal men. *J Clin Endocrinol Metab.* 2004;89(7):3313–8.
- XX. Lai JJ, Lai KP, Chuang KH, Chang P, Yu IC, Lin WJ, Chang C. Monocyte/macrophage androgen receptor suppresses cutaneous wound healing in mice by enhancing local TNF- α expression. *J Clin Invest.* 2009;119(12):3739–51.
- XXI. Tuncay Cagatay S, Kaymaz BT, Narin F, et al. Testosterone protects against oxidative stress in skeletal muscle after immobilization. *Acta Physiol (Oxf).* 2017;219(3):589–602.
- XXII. Fernández-Balsells MM, Murad MH, Lane M, et al. Adverse effects of testosterone therapy in adult men: a systematic review and meta-analysis. *J Clin Endocrinol Metab.* 2010;95(6):2560–75.
- XXIII. Haizlip KM, Harrison BC, Leinwand LA. Sex-based differences in skeletal muscle kinetics and fiber-type composition. *Am J Physiol Endocrinol Metab.* 2015;308(6):E494–505.
- XXIV. Sheffield-Moore M, Urban RJ, Wolf SE, et al. Short-term oxandrolone administration stimulates net muscle protein synthesis in young men. *J Clin Endocrinol Metab.* 1999;84(8):2705–11.
- XXV. Urban RJ, Dillon EL, Choudhary S, et al. Testosterone administration to older men improves muscle function: molecular and physiological mechanisms. *Am J Physiol Endocrinol Metab.* 2014;307(11):E1030–E1039.
- XXVI. Friedl KE, Moore RJ, Hoyt RW, et al. Endocrine markers of semistarvation in healthy lean men in

Testosterone Replacement Therapy in Athletes: Sports Injury Treatment Outcomes and Muscle Recovery After Injury – A Narrative Review

- a multistressor environment. *J Appl Physiol* (1985). 2000;88(5):1820–30.
- XXVII. Mohamad NV, Wong SK, Chin KY. The modulatory effects of testosterone on inflammation and immune function. *Front Immunol*. 2019;10:1634.
- XXVIII. Bachman E, Travison TG, Basaria S, et al. Testosterone induces erythrocytosis via increased erythropoietin and suppressed hepcidin: evidence for a new erythropoietin/iron axis. *J Gerontol A Biol Sci Med Sci*. 2014;69(6):725–735.
- XXIX. Traish AM, Haider A, Haider KS, Doros G, Saad F. Long-term testosterone therapy in hypogonadal men ameliorates elements of the metabolic syndrome: an observational, real-life registry study. *Int J Clin Pract*. 2011;65(7): 682–696.
- XXX. Saad F, Caliber M, Doros G, Haider KS, Haider A, Traish AM. Long-term treatment of hypogonadal men with testosterone produces substantial and sustained weight loss. *Obes Res Clin Pract*. 2017;11(3):293–304.
- XXXI. Usui T, Kajita K, Kajita T, et al. Elevated mitochondrial biogenesis in skeletal muscle is associated with testosterone-induced body composition changes. *Endocr J*. 2014;61(3):271–281.
- XXXII. Nindl BC, Alemany JA, Tuckow AP, et al. Altered secretion of testosterone, growth hormone, and IGF-I during 12 weeks of basic combat training in men. *Eur J Appl Physiol*. 2007;99(2):151–157.
- XXXIII. Snyder PJ, Bhasin S, Cunningham GR, et al. Effects of testosterone treatment on bone mineral density in men over 65 years of age. *N Engl J Med*. 2016;374:611–624.
- XXXIV. Kasperk C, Wergedal J, Farley J, Linkhart S, Turner R, Baylink DJ. Androgens directly stimulate proliferation of bone cells in vitro. *Endocrinology*. 1989;124(3):1576–1578.
- XXXV. Rogerson S, Weatherby RP, Deakin GB, et al. The effect of short-term use of testosterone enanthate on muscular strength and power in healthy men. *J Strength Cond Res*. 2007;21(2):354–361.
- XXXVI. Hartgens F, Kuipers H. Effects of androgenic-anabolic steroids in athletes. *Sports Med*. 2004;34(8):513–554.
- XXXVII. Bosco C, Tihanyi J, Pucspk J, et al. Effect of anabolic androgenic steroids on maximal anaerobic power during short-term supramaximal exercise. *Eur J Appl Physiol Occup Physiol*. 1990;61(1–2):143–148.
- XXXVIII. Stray-Gundersen J, Chapman RF, Levine BD. "Living high-training low" altitude training improves sea level performance in male and female elite runners. *J Appl Physiol*. 2001;91(3):1113–1120.
- XXXIX. Haupt HA, Rovere GD. Anabolic steroids: a review of the literature. *Am J Sports Med*. 1984;12(6):469–484