The Mechanisms of Tendon Weakness and Strengthening Techniques: A Systematic Literature Review

Mekanisme Kelemahan Tendon dan Teknik Penguatan: Tinjauan Literatur Sistematis

Review Article

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Abstract.

Background Tendon weakness contributes to musculoskeletal injuries, especially in athletes and active individuals. Understanding tendon damage mechanisms and strengthening strategies is important for prevention and rehabilitation.

Objectives This systematic review aims to evaluate factors causing tendon laxity as well as strengthening strategies through mechanical loading, exercise, and nutrition.

Methods Following PRISMA guidelines, a literature search was conducted across databases from Scopus, PubMed, WOS, and ScienceDirect.

Results Results suggest that excessive mechanical strain, poor tendon adaptation, and muscle-tendon imbalance contribute to tendon weakening and increase the risk of injury. Eccentric training, isometric loading, and personalized tendon loading are effective in increasing tendon endurance. Collagen supplementation with vitamin C also supports tendon adaptation.

Conclusion However, variability in study methodology and limitations of long-term analysis hinder standardized protocols. An approach that combines mechanical loading, targeted training, and optimal nutrition is necessary to improve tendon health. Further research is needed to refine the intervention protocol and evaluate its long-term impact.

Keywords: tendon weakness, tendon strengthening, musculoskeletal injuries, injury prevention.

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INTRODUCTION

Tendons are connective tissue that have an important role in connecting muscles to bones and enabling efficient movement in daily activities and sports. Tendon health and strength determine athlete performance and the prevention of musculoskeletal injuries, especially for those who are physically active [1]. Tendons also have the ability to adapt to mechanical loads, but many people experience a decrease in tendon strength which can cause chronic pain or even tears due to repetitive loads that are not well managed [2]. Tendon injuries can interfere with an athlete's performance and daily activities, require a long recovery time, and impact a person's productivity and quality of life [3]. This problem is receiving increasing attention in the medical and sports fields due to the increasing prevalence of tendinopathy, especially among athletes and workers involved in heavy physical activity [4].

Several factors can cause tendon weakness, including lack of sufficient mechanical stimulation, incorrect training patterns, and lack of attention to nutritional aspects. Research shows that tendons require a certain mechanical load to stimulate collagen synthesis and increase tissue strength, but excessive or uncontrolled loads can actually cause tissue degeneration [5]. In addition, internal factors such as age, genetic factors, and metabolic conditions such as diabetes mellitus can also inhibit the tendon regeneration process and increase the risk of injury [6]; [7]. Therefore, understanding the mechanisms of tendon adaptation as well as implementing appropriate intervention strategies is essential to prevent and rehabilitate tendon injuries.

In physical training, various methods have been developed to strengthen tendons, such as eccentric, isometric, and heavy slow resistance training (HSRT), which have been proven to increase

tendon resistance to mechanical stress [1]; [8]. This approach is based on the principle that tendons require a certain load that can stimulate tissue changes without causing excessive microinjury. Recent research also shows the importance of a combination of low and high load training to optimize tendon adaptation and prevent degeneration due to load imbalance [9] ; [10]. Eccentric training has been shown to be effective in reducing pain in tendinopathy and increasing tendon thickness and strength [11]. Meanwhile, isometric exercises can help reduce acute pain and significantly increase tendon strength [12]. Therefore, choosing the right exercise method is very important to strengthen tendons and prevent injury.

Apart from biomechanical factors, nutrition also plays an important role in maintaining tendon health, especially in providing essential amino acids and micronutrients that support collagen synthesis. Research shows that consuming high-quality protein, vitamin C, and gelatin can increase collagen synthesis and accelerate tendon recovery after mechanical stress [13];[14]. Deficiencies in micronutrients such as vitamin D and magnesium can also increase the risk of tendon degeneration and hinder the healing process after injury [15]; [16]. Therefore, a proper nutritional approach, combined with appropriate exercise, can be an effective strategy in strengthening tendons and preventing tendinopathy.

With advances in technology and a deeper understanding of tendon biomechanics and physiology, recent research has begun to investigate the role of molecular factors in tendon adaptation. Research on genetic expression and molecular responses to exercise suggests that regulation of growth factors such as TGF-β and IGF-1 can influence the regenerative ability of tendons [17]; [1]. Advances in stem cell therapy and biomaterials are also opening up new opportunities in regenerative approaches to address more complex tendon defects [18]; [19]. Therefore, a deeper understanding of the molecular aspects of tendons may be the basis for the development of more effective therapeutic strategies in the future.

In the clinical and sports rehabilitation context, a multidisciplinary approach combining physical exercise, therapeutic modalities, and nutritional strategies is essential in the prevention and management of tendon disorders. Coaches, physiotherapists and health professionals must have a good understanding of the basic concepts of biomechanics and principles of tissue adaptation to design programs that suit each individual's needs [20]; [21]. With a comprehensive, scientific evidence-based approach, the risk of tendon injury can be reduced, and athletic performance can be maximized.

Based on the previous explanation, this study aims to analyze the factors that influence tendon weakness and identify effective strategies to increase tendon strength through an evidence-based scientific approach. By exploring various aspects of biomechanics, nutrition, and rehabilitative interventions, this research is expected to make significant contributions to the fields of sports science and medicine, as well as help improve the quality of life for individuals prone to tendon disorders.

METHOD

Research Design

This study followed Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure complete and transparent reporting. The PICO method (Population, Intervention, Comparison, Results) was used in this research to identify relevant articles and extract significant data from academic sources, including books and scientific journals that have gone through a peer review process. The primary focus of this review is the academic literature regarding tendon laxity, tendon adaptation mechanisms, and tendon strengthening techniques, particularly in the context of rehabilitation and athletic performance.

Search and Selection Strategy

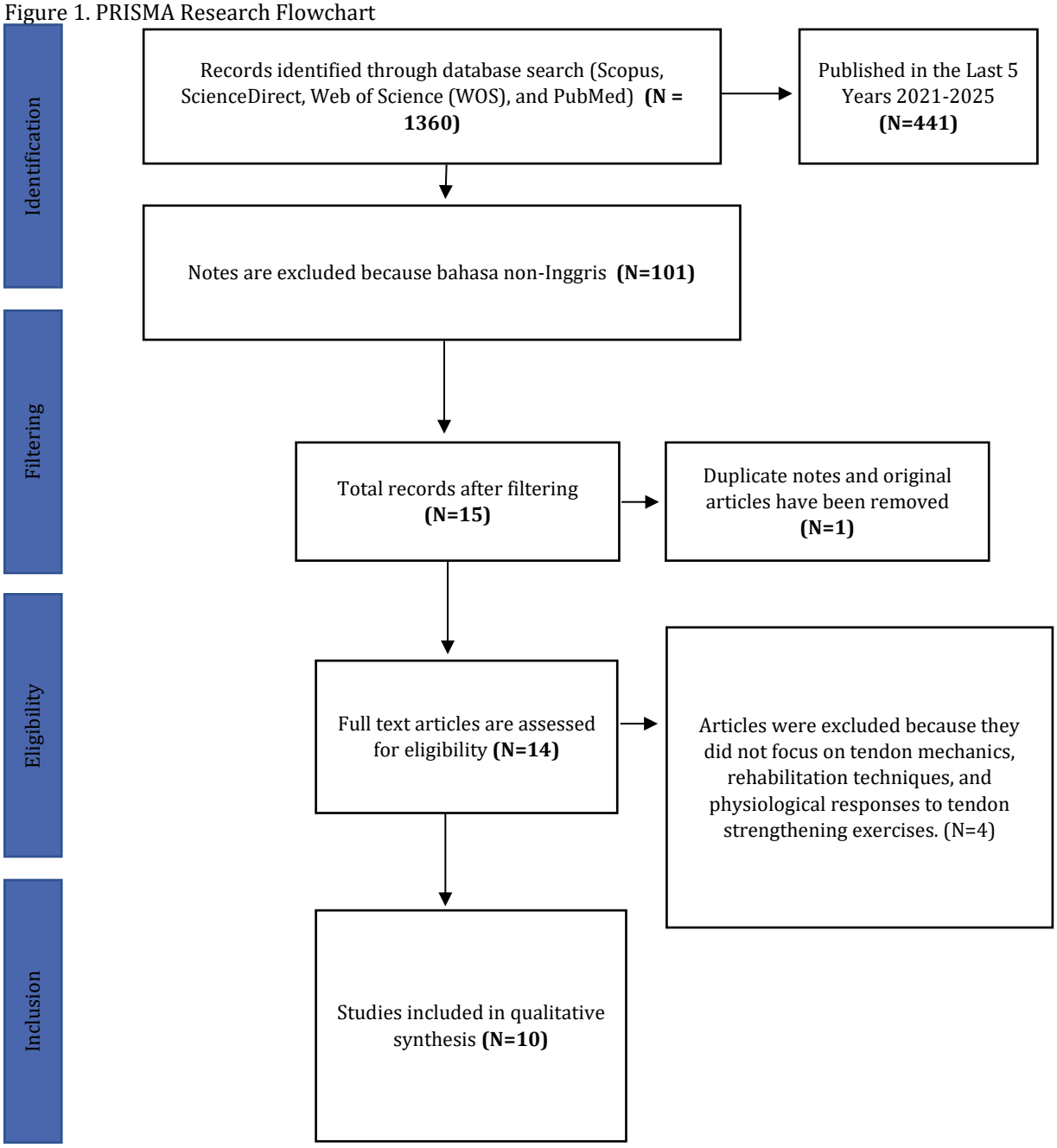
Databases used in this study included Scopus, ScienceDirect, Web of Science (WOS), and PubMed, as shown in Figure 1. Keywords used in the search included: tendon strength, tendon rehabilitation, tendon adaptation, tendon strengthening techniques, and injury prevention. Inclusion criteria for this study included journal articles published in scientific journals that discussed tendon mechanics,

rehabilitation techniques, as well as physiological responses to tendon strengthening exercises. Reference management software (Mendeley) was used to organize citations, screen article titles and abstracts, and evaluate full-text articles based on inclusion and exclusion criteria. A total of 150 articles published between 2021 and 2025 were collected for further analysis.

Inclusion and Exclusion Criteria

Inclusion criteria for this systematic review included: journal articles that had gone through a peer review process with a focus on tendon rehabilitation and tendon strengthening techniques, studies that discussed tendon mechanics, the influence of exercise on tendon adaptation, as well as the role of nutrition in tendon health, and studies published between 2021 and 2025. Articles with full text available for review were also an important requirement. Conversely, articles were excluded if they were not published in a peer-reviewed scientific journal, did not focus on tendon rehabilitation, tendon strengthening exercises, or tendon adaptation mechanisms, were not available in full text form, did not have sufficient data on intervention outcomes, or were published in a language other than English. Only journals that meet all inclusion criteria will be considered for evaluation. The process of searching and selecting articles is explained in the flow diagram which can be seen in Figure 1.

Figure 1. PRISMA Research Flowchart



RESULTS AND DISCUSSION

Table 1 provides a summary of the methodological aspects of the studies conducted between 2021 and 2025. The results show that tendon strength and the tendon's adaptive response to strengthening exercises are strongly influenced by the type of exercise performed. Several studies reveal that eccentric training provides a significant positive effect on tendon resilience and reduction of pain due to tendinopathy [1]; [21]. In addition, heavy slow resistance training (HSRT) has been shown to increase tendon strength and the ability of tendon tissue to adapt to mechanical stress [9].

Further research also emphasizes the importance of isometric exercises in reducing acute tendon pain and increasing tendon strength capacity in the short term [12]. On the other hand, the study by [22] shows that nutritional integration, such as consuming high-quality protein and vitamin C, can speed up the tendon healing process and increase collagen synthesis which is vital for tendon strength.

However, several studies also reveal that internal factors such as age and metabolic conditions can slow down the tendon adaptation process and increase the risk of injury [6]; [23]. This suggests that although exercise and nutrition have a significant role, individual factors such as physical condition and age must also be taken into account in designing tendon rehabilitation interventions.

Table 1. Summary of Tendon Weakness Mechanisms and Strengthening Strategies

Author	Characteristics of the sample	Method	Conclusion
[24]	97 untrained middle-aged men	Randomized controlled trial (RCT); participants underwent 12 weeks of resistance training supplementation with collagen peptides, whey protein, or placebo	Collagen peptides increased fat-free mass and decreased fat mass more significantly than placebo, with effects similar to those of whey protein
[25]	34 handball players (12-14 years old)	Functional high load training (2x/week) for the experimental group, while controls followed regular training	This exercise decreases patellar tendon pain without changing tendon stiffness; all players in the experimental group remained pain free
[25]	Adolescent basketball players (13-15 years) measured tendon strain, micromorphology, and pain	The intervention group (INT) with high load training showed a decrease in strain and an increase in tendon stiffness, while the control group (CON) had an increase in strain. At INT, 100% of athletes are symptom-free	High-load tendon training is effective in preventing high strains and micromorphological damage in juvenile patellar tendons
[26]	39 men (20-55 years) with chronic Achilles tendinopathy	A 12-week controlled clinical trial, comparing high-load training, eccentric training, and passive therapy	Only high-load training increases tendon stiffness and cross-sectional area, as well as muscle strength, and is therefore recommended for Achilles tendinopathy rehabilitation
[27]	10 recreational athletes with chronic Achilles tendinopathy	A 4-stage rehabilitation program based on isometrics and progressive loading, evaluated over 12 months	The program effectively improves tendon function and is worthy of further trials.
[28]	Of 44 adolescent athletes (12-17 years), 14 experienced patellar tendon pain, 23 remained asymptomatic.	Longitudinal study with measurements of tendon mechanical properties via ultrasound and inverse dynamics over one season	High tendon strain increases the risk of tendinopathy 2.3-fold. Inadequate tendon adaptation to increased muscle strength can lead to tendon injury
[29]	41 patients with Achilles tendinopathy	Intervention study with high load training and Alfredson for 12 weeks, measuring asymmetry of tendon mechanical and functional properties	Diseased tendons are different from healthy ones, but training does not affect the asymmetry much. Reduction of asymmetry is not always associated with improved tendon health
[30]	28 elite handball athletes (15 girls, 13 boys) average age 14-16 years	Longitudinal study with measurements of muscle strength and tendon mechanical properties using dynamometry and ultrasonography over the course of one season	Female athletes had lower muscle strength and tendon stiffness than males, but high tendon strain rates (~40%) occurred in both groups. Specific tendon training is necessary to prevent injury
[31]	22 male volleyball athletes, divided	Measurement of muscle strength and tendon mechanical properties	Personalized exercise programs reduced muscle-tendon imbalances and may help

	into intervention (n = 10) and control (n = 12) groups	over the course of a season. The intervention group performed exercises with adjusted loads to stimulate tendon adaptation	prevent injury, while the control group experienced increased tendon strains
[32]	26 male teenage handball athletes	The intervention group followed personalized muscle strength training, 3x/week for 31 weeks	Personalized muscle strength training reduces muscle-tendon imbalance and the risk of tendon injury

Tendon health is a key factor in athletic performance, injury prevention, and rehabilitation. Because the mechanical properties of tendons involve stiffness and stretch, tendons are greatly influenced by various factors such as training load, muscle strength, and tendon adaptation. Understanding the mechanisms that cause tendon weakness as well as strategies to strengthen them is critical. Tendon laxity is often related to repetitive strain, which can lead to injuries such as tendinopathy, which is characterized by collagen degeneration and microtears in the tendon [6];[9]. Excessive use or inappropriate loads, especially in young athletes, can cause an imbalance between muscle strength and tendon stiffness, thereby increasing their susceptibility to injury [1];[21]. Therefore, it is important to explore the mechanisms of tendon weakness and effective strengthening techniques to support rehabilitation and injury prevention.

Research shows that tendon weakness can result from inadequate adaptation to mechanical loads during exercise or training. Tendons undergo a process called mechanotransduction, namely the conversion of mechanical forces received during exercise into biological signals that regulate tendon remodeling [33]; [8]. If the mechanical load is too great or occurs too frequently, the tendon cannot adapt properly, which causes weakening of the tendon structure and increases the risk of injury. Research also shows that prolonged tendon strain, especially in high-load sports, can cause tendon degeneration, such as thickening, neovascularization, and changes in collagen structure [34]; [2]. Therefore, it is critical to understand how different loading patterns affect tendon strength as well as identify effective methods to promote healthy tendon adaptation.

The role of exercise in tendon strengthening is critical, with different types of exercise having different effects on tendon properties. Eccentric exercise has been widely recommended for tendinopathy rehabilitation because it has been shown to increase tendon strength and accelerate healing of damaged tendons by stimulating collagen synthesis [1]; [8]. Eccentric loading creates microtrauma in the tendon, which then triggers the healing process through inflammatory pathways and collagen remodeling. This approach has been shown to reduce tendon pain and improve tendon function in athletes experiencing conditions such as Achilles tendinopathy [35]. Although eccentric training is effective, this approach is not universally applicable, as different types of tendons and injuries require specific, individualized rehabilitation protocols.

Recent studies have also examined the benefits of isometric exercises in tendon rehabilitation. Isometric exercises involve muscle contraction without movement in the joint and have shown positive results in strengthening tendons, especially in the early stages of rehabilitation. For example, a study by [12] found that isometric exercises can reduce tendon pain and stiffness. This approach helps reduce tendon tension by placing a controlled load on the tendon without excessive movement. Additionally, isometric exercises are particularly beneficial for individuals with chronic tendinopathy who have previously been unable to tolerate dynamic exercises. Therefore, combining isometric and eccentric exercises may provide a more comprehensive approach to tendon strengthening and rehabilitation.

Adapted tendon loading has emerged as an effective approach to optimize tendon adaptation and prevent injury. Research shows that exercise programs designed to load tendons within the effective strain range (usually 4.5-6.5%) can significantly reduce musculotendinous imbalances and tendon strain that are often trigger factors for tendinopathy [30]. By adjusting training intensity according to individual capacity, personalized loading ensures the tendon receives the proper stimulus for adaptation without exceeding its structural limits. This approach helps reduce the risk of overuse injuries, especially in young athletes who are still developing their tendons [1]. Additionally, personalized programs allow for ongoing monitoring and adjustment, so tendon strength can increase gradually without harming tendon health.

In addition to tailored loading, functional exercises designed to target specific tendon properties have also been shown to be effective in increasing tendon resilience. Functional exercises mimic specific movements in a sport and ensure the tendon is exposed to the types of stress it will encounter during athletic activity. Research by [30] showed that the integration of functional training, such as jumping

and sprinting, in rehabilitation programs can increase tendon strength and reduce the risk of tendon injury in athletes. These exercises not only increase tendon strength, but also contribute to improving overall athletic performance by improving coordination and interaction between muscles and tendons. Therefore, functional loading should be an important part of any tendon strengthening program, especially for athletes involved in high-intensity sports.

The role of tendon microstructure in injury prevention and rehabilitation is critical. Tendons adapt to mechanical loading through changes in their microstructure, which include collagen fiber alignment, cross-sectional area (CSA), and the formation of new blood vessels (neovascularization) [36]. Although these changes are necessary for tendon adaptation, excessive loading or inappropriate stretching can cause pathological changes in the tendon structure, such as collagen fiber irregularities and increased vascularity, which commonly occur in tendinopathy [2]. Ultrasound imaging has been shown to be effective in assessing these microstructural changes as well as monitoring tendon recovery over time [37]. By integrating imaging techniques into clinical practice, practitioners can more effectively tailor rehabilitation strategies and track tendon recovery progress, thereby ensuring optimal outcomes for athletes.

The mechanisms underlying tendon weakness and strengthening techniques are complex and involve various factors. Tendon weakness is often caused by excessive tension, inadequate adaptation, or inappropriate loading, which can lead to injuries such as tendinopathy. However, with the implementation of appropriate rehabilitation strategies, such as eccentric and isometric exercises, adapted tendon loading, and functional training, tendons can be strengthened and injuries can be prevented. Further research needs to focus on developing loading strategies and rehabilitation protocols that suit different tendon types, particularly in the context of specific sport demands and diverse athlete profiles.

CONCLUSION

This systematic review emphasizes the complexity of the mechanisms of tendon laxity, involving factors such as overuse, muscle-tendon imbalance, and suboptimal recovery, all of which contribute to the development of tendinopathy. This research also reveals the effectiveness of targeted strengthening techniques, such as progressive loading, eccentric and isometric exercises, in increasing tendon strength, stiffness and endurance. Additionally, nutritional interventions, such as collagen supplementation, show promising results in improving tendon structure and recovery. Although exercise-based interventions provide significant benefits, further research is needed to determine the optimal loading dose and its long-term impact, taking into account individual factors such as age, gender, and tendon strength. Future research is expected to explore intervention protocols that include exercise, nutrition, as well as the use of the latest technology to monitor tendon structural adaptations. By addressing these deficiencies, athletes and active individuals can increase tendon resilience, reduce the risk of injury, and maintain their long-term musculoskeletal health.

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AUTHOR CONTRIBUTION STATEMENT

The writing of this article involved roles in devising the research concept and design, reviewing and analyzing relevant literature, and drafting the overall manuscript

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There is no conflict of interest

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