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REVIEW

THE COMPARATIVE EFFECTS OF ECCENTRIC AND CONCENTRIC CONTRACTIONS AND VARIOUS LOAD-INTENSITIES ON IMPROVING MUSCLE TENDON MECHANICAL PROPERTIES. A NARRATIVE REVIEW

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ABSTRACT

Muscle tendons are anatomical structures that transfer force between muscle and bones, providing protection to the muscle in the presence of excessive stress by delaying transmission of mechanical energy to the muscle fibers. This acts as an energy buffer during tasks that produce high levels of force, particularly in lengthened positions. This paper examined the current literature investigating the comparative effects of eccentric and concentric contractions, as well as various load-intensities on improving muscle tendon mechanical properties. Fifteen studies were examined which consisted of randomized controlled trials and blinded studies, specific to the areas of sports medicine, clinical rehabilitation, biomechanics and clinical orthopaedics and trauma. The examined literature demonstrated that tendon mechanical properties can be positively influenced by both types of contractions, with eccentric contractions being favourable within the initial stages of tendon rehabilitation. In addition, the amount of external load applied to the tendon has a strong correlation to the rate of tissue turnover, with heavier loads producing significantly greater tendon adaptations compared to lighter loads. This is related to heavier loads disrupting the cellular environment of the tissue, thus increasing the anabolic responses within the collagen fibers. The findings provide a practical opportunity for coaches and practitioners, in which implementing heavy resistance training using both types of contractions with load intensities between 70-85%1RM, can significantly improve the mechanical properties of the tendon, therefore enhancing sport performance and decreasing injury risk.

KEYWORDS

Concentric, eccentric, mechanical properties, muscle tendons, resistance training

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INTRODUCTION

Muscle tendons are anatomical structures that are made up of 60-80% type 1 collagen, with 55-70% of the tendon being wet weight, and 30% being dry weight[1-3]. These structures are white in colour and belong to a group of dense connective tissues that are composed of closely packed collagen, which are arranged parallel and have a well-ordered extracellular matrix[3-5]. The tendon structure is layered and assembled into bundles (tertiary, secondary and primary) which further progress into a tendon fibre and tendon fibril *(Fig. 1)*. The collagen fibrils are 100 to 500 nanometers in diameter which are arranged as a triple helix, with the amino acids that make up this structure including hydroxyproline, proline and glycine, with glycine found within every third amino acid *(Fig. 2)*[6,7]. This arrangement is then assembled into periodic striated fibrils, forming the foundation of the collagen fibre[7]. With regards to tendon blood supply, it's considered hypovascular, meaning it has a limited blood supply therefore relying heavily on the diffusion of fluid to receive nutrition[8]. As a result, this will reduce the rate of recovery from damage that is caused by mechanical stress (e.g. resistance training), making the tendon more susceptible to injury if the appropriate measures are not implemented. The function of the tendon is to transfer force between muscle and bones, providing protection from excessive stress to the muscle by delaying transmission of mechanical energy to the muscle fibres, acting as an energy buffer during tasks that produce high levels of force, particularly in lengthened positions[9]. Furthermore, the tendon consists of many mechanical properties that contribute to its function, these include stiffness, viscoelasticity and elasticity, all of which result in the tendon increasing its integrity during various strain levels[9,10]. The stiffness component allows the tendon to resist large levels of force, with viscoelasticity containing both viscous and elastic properties, enabling responses to various levels of strain. During lower strain rates, the viscoelastic properties make the tendon more deformable, with higher strain rates making the tendon less deformable[10]. This suggests that at lower strain rates, the tendon may absorb mechanical energy better but may have inadequate ability to carry mechanical loads. However, at higher strain rates, the tendon increases its stiffness and can efficiently transmit load between muscles and bones[10]. Moreover, the tendon is also highly elastic, suggesting it can rapidly expand and recoil, thus assisting in force production[9]. This has been observed during the phenomenon known as the stretch shortening cycle, which is the stress reflex response that contributes to increasing force production, torque and mechanical work[9,11].

Resistance training has been continuously shown to improve the stiffness and integrity of the tendon, particularly when training in longer muscle lengths. This is due to tendons increasing their tensile strength and stiffness when the muscle is under tension at longer muscle lengths, rather than shorter muscle lengths[4].

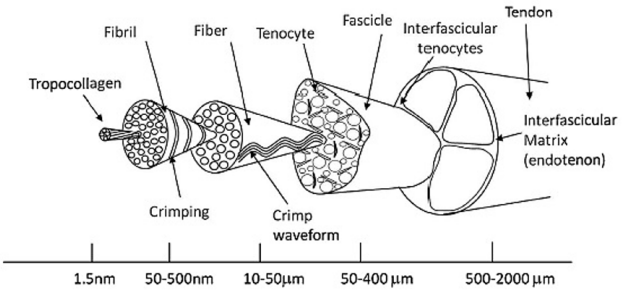


Figure 1. *The structural make-up of the tendon.*

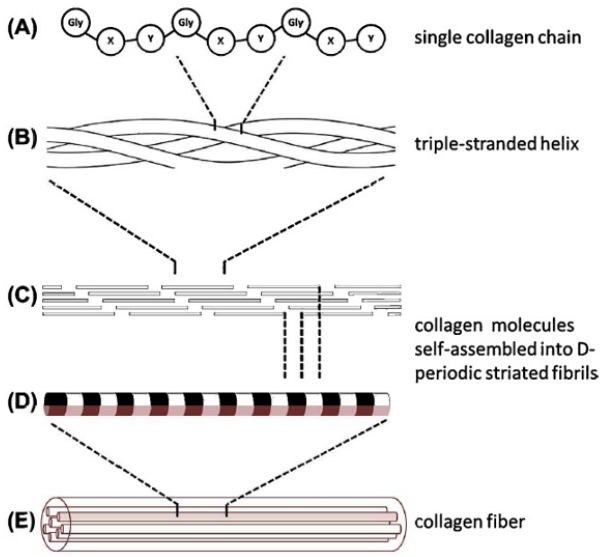


Figure 2. *The anatomical arrangement of the tendon fibre with its corresponding single collagen chain, triple stranded helix and periodic striated fibril.*

However, it's now a matter of understanding which stimulus and contraction type provides the most optimal outcome in relation to tendon adaptation. With regards to contraction type, many studies have stated that eccentric contractions are the most optimal for increasing tendon mechanical properties and treating tendinopathies[12-14]. However, there is growing evidence showing that both eccentric and concentric contractions produce similar long term tendon outcomes, particularly during rehabilitation and resistance training programs[15,16]. These results were mostly observed within the rotator cuff, patella and Achilles tendons. In addition, the amount of load also seems to be a factor when looking at these concepts, particularly as tendons respond to elevated levels of stress and strain[4,17]. Some sources have stated that low load stimuluses did not produce changes to tendon stiffness[18], with many other studies demonstrating that heavier loads are the most optimal method for increasing tendon mechanical properties[19-23].

Muscle tendon injuries in general are said to account for up to 30-50% of all injuries that occur in sport[15,23,24]. This has been associated with tendons undertaking a lot of stress and strain from various external stimuli, with their limited blood supply and lack of growth factors contributing to their reduced adaptation rate compared to other tissue

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structures[24,25]. Furthermore, tendon injuries have been suggested to occur based on the type and frequency of the applied load. Tendinosis refers to degeneration of the tendon from excessive overuse with minimal recovery time, tendinitis refers to inflammation of the tendon that occurs from sudden overload, with chronic tendinopathy considered to be present for more than 12 weeks which create structural changes to the tendon[7,26]. Although sources have provided distinct types of tendon injuries, much of the literature uses the term tendinopathy as a blanket term for tendon injuries. It has been stated that minimal physical stress (<1%) may cause maladaptive responses due to insufficient type 1 collagen mRNA expression, with excessive stress overexpressing various inflammatory markers, further damaging the tissue[16]. Moreover, it's been stated that tendon stiffness may reduce between 24-36 hours after exercise, which is due to elevations in protein degradation and synthesis, which then returns to baseline between 48-72 hours[27]. Indeed, if another stimulus is placed on the same tendon, the risk of tendon injury significantly increases due to excessive damage to the tissue. This highlights the importance of load management and progressive overload strategies to ensure optimal tendon recovery and adaptation[27-29].

Based on these factors, enhancing tendon mechanical properties will improve its load tolerance capacity, therefore reducing the risk of tendinopathies. This has become a topic of interest amongst coaches and practitioners, with regards to which training modality is the most optimal for improving tendon mechanical properties. These queries are based on the performance enhancing capacity of the muscle tendon, as well as reducing the risk of tendinopathies. This review examined the current literature to determine how eccentric and concentric contractions, as well as various load-intensities can influence the mechanical properties of the tendon.

METHODS

This review of the literature examined 15 articles containing the effectiveness of different resistance training loads on muscle tendon mechanical properties during eccentric and concentric contractions.

A search for "muscle tendons" was implemented within the databases of PubMed, Research Gate, Google Scholar, Wiley, and the Google search engine. Additional key words also included were "resistance training", "eccentric contractions", "concentric contractions" "strength training", "tendon stiffness", "tendon strength", "tendon cross sectional area", "tendinopathies" and "tendon injuries".

When exploring the databases, the primary focus was to obtain journal articles that have been published in the areas of sports medicine, clinical rehabilitation, biomechanics and clinical orthopaedics and trauma. However, the search was further limited to randomized control trials, and blinded studies.

During the research analysis process, the aim was to investigate topics that primarily compare both eccentric and concentric contractions amongst younger and older adults, as well as load applications within the muscle tendon. The sample sizes across the studies consisted of 461 subjects between the ages of 18 to 75 years, including both male and female subjects. Since the data within this specific topic is limited, the inclusion criteria also incorporated studies looking at the comparisons between isometric contractions and eccentric contractions. This was due to these studies comparing both heavier and lighter loads on tendon mechanical properties, which is one of the main focuses of this narrative review. Furthermore, despite many studies having investigated tendon responses to external load, many studies that only assessed one type of contraction, load-intensity or training intervention were not included in the selection criteria, as they did not produce comparable results. Based on these factors, a reliable and reputable conclusion can be drawn regarding muscle tendon responses to eccentric and concentric contractions with various load-intensities.

DISCUSSION

Eccentric vs. concentric contractions

Muscle contraction types have become a special area of interest when addressing tendon strength and integrity, particularly from a rehabilitation and injury prevention perspective. With regards to resistance training, there is speculation as to whether eccentric contractions are better than concentric contractions for increasing tendon mechanical properties. The studies reviewed demonstrated that all contraction types have a positive influence on increasing tendon strength and integrity, however different contractions may be necessary within different time points. Moreover, studies comparing these contractions are limited in certain areas, particularly ones that are commonly injured in professional sport.

Contraction types - rotator cuff muscle tendons

Rotator cuff tendon injuries occur quite frequently in sport, however much of the literature is limited when comparing the effects of eccentric and concentric contractions. Macías-Hernández et al.[30] performed a study amongst 26 individuals aged 47-62 years old, who were suffering with moderate to severe shoulder pain, which was in the form of a partial rotator cuff tear. Their objective was to assess resistance training tolerance, whilst comparing the effects of eccentric and concentric contractions. The timeline of this study was 12 months, which initially included 20 physical therapy sessions which entailed both physical therapy and resistance training, 5 times per week for 4 weeks. After this period, the participants carried out the resistance training program in their own time for the remainder of the 12 months. With regards to the resistance training program, the intervention group performed a series of both eccentric exercises in both a supine and side lying position whilst holding a weight, emphasizing the eccentric

portions of the movement for 15-20 seconds for 3 sets of 8-12 reps. Furthermore, the control group performed similar exercises, however the emphasis was on both types of contractions. Their results showed that the eccentric group had significantly greater improvements in shoulder functional movement after 3 months compared to the control group. However, at the 12-month follow-up, both groups had the same outcome with regards to shoulder function. In addition, Wahba et al.[31] performed a similar study, looking at how both contractions affect shoulder function and pain in patients with rheumatoid arthritis and rotator cuff tendinopathies. In this study, 40 patients were chosen, 20 of whom were split into the eccentric group and 20 into the concentric group. They used both the shoulder pain and disability index, as well as the visual analogue scale (VAS) to assess shoulder pain and function. With regards to the intervention, the patients received a total of 12 sessions, at a consistency of 3 times a week. These sessions included the eccentric group performing banded exercises where they focused on gradually controlling the lengthening component of the movement, with the concentric group performing the same exercises with consistent motion. Furthermore, they also included a banded abduction exercise with the same cues based on their assigned group. All exercises were performed for 3 sets of 10 reps, with additional pectoralis static stretching for 3 sets of 30 seconds also implemented within the program. Their results showed that the eccentric group had better improvements in shoulder pain and function compared to the concentric group. However, there were no differences between the groups regarding changes in tendon characteristics, apart from the supraspinatus tendon which favoured the eccentric group.

Both the Macías-Hernández et al.[30] and Wahba et al.[31] demonstrated that eccentric contractions produce better outcomes than concentric contractions for pain and function within the rotator cuff. However, both studies were within a rehabilitation setting, which may have additional limitations with regards to load application. Both interventions implemented low load stimuli to the tissue structure, with only Macías-Hernández et al.[30] having some type or progressive overload during the program. Furthermore, the Wahba et al.[31] protocol was much shorter than Macías-Hernández et al.[30], which may have only provided a minimal effective dose to improve the patients pain and function. Since tendons take longer to adapt compared to other tissues, this may explain the lack of improvements observed in the tendon characteristics, alongside the minimal external load used. Nevertheless, these studies provide evidence that low load eccentric contractions can improve pain and function with limited equipment, within the initial stages of tendon rehabilitation.

Contraction types - patella tendon

When looking at the patella tendon, studies have thoroughly addressed the effects of both eccentric and concentric contractions on the mechanical properties amongst various age groups. Quinlan et al.[32] performed a study amongst 37 males, 20 of which were between the ages of 18-35, and 17 elderly males between the ages of 65-73. Their objective was to compare the differences of eccentric and concentric resistance training on tendon adaptations and to establish a time course of these changes. The intervention went for 8 weeks, which included 3 sessions a week, performing 4 sets of 15 reps at 60% 1 rep maximum (RM), with both groups executing the reps based on their assigned group. During the protocol, the first 4 weeks of the program were executed as a bilateral movement on a leg press machine, with week 5 onwards altered to a unilateral movement on the same machine. Muscle activation levels were measured using electromyography (EMG), with magnetic resonance imaging (MRI) and ultrasound implemented to assess the structure of the patella tendon. Their results showed that positive tendon adaptations occurred within the first 4 weeks, but then plateaued in young males, but continued to increase in the older males. Furthermore, they stated that the patella tendon responds equally to both eccentric and concentric contractions at submaximal loads, with both groups increasing the tendons Youngs modulus and maximal voluntary contraction capacity at various knee joint angles. They concluded that moderate intensity exercise can produce tendon adaptations during both eccentric and concentric contractions, with younger individuals adapting faster than older individuals. Crossland et al.[33] performed a similar study to that of Quinlan et al.[32], looking at the molecular changes within the patella tendon during eccentric and concentric contractions. However, in addition to MRI, they also performed tendon biopsies in week 4 and week 8, looking at fractional synthesis rate of tendon protein synthesis and gene expression. Their results showed that overall tendon protein synthesis did not differ between the groups, with most of the adaptations occurring within the first 4 weeks of the intervention. However, eccentric contractions produced greater gene expression, facilitating tendon remodelling at lower metabolic costs with higher strain levels. In addition, proximal tendon cross sectional area (CSA) significantly increased in the younger groups, with no change seen in the elderly groups.

Both Quinlan et al.[32] and Crossland et al.[33] demonstrated that patella tendon adaptations can occur in younger and older individuals with submaximal loads, when performing both eccentric and concentric contractions. However, only the Crossland et al.[33] study showed increases in proximal patella tendon CSA in the younger subjects, with the authors suggesting it may be related to lower proximal baseline levels due to insufficient habitual loading compared to the older individuals. Furthermore, reductions in collagen and gene expression may potentially be related to slower adaptation rates, which was seen more in the elderly subjects. However, only the Quinlan et al.[32] study showed an initial lower patella tendon stiffness in the

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older individuals, therefore creating a larger potential for long term tissue turnover. Moreover, the submaximal load used in both studies may only provide a minimal effective dose in responsive tendons, thus potentially explaining the plateau in the younger groups in both studies after 4 weeks. Nevertheless, both studies demonstrated that patella tendon adaptations can occur with both types of contractions, with younger individuals having faster responses compared to older individuals.

Studies have also looked at the effect of eccentric and concentric contractions with heavier loads and how it may influence tendon adaptations. Kubo et al.[34] conducted a study assessing patella tendon stiffness and blood flow when comparing eccentric and concentric contractions. 17 trained 20-year-old males were assigned to either the training group, or the control group. They measured patella tendon CSA at 50% of the patella tendons length, as well as blood saturation levels. The training group performed 5 sets of 10 reps at 80% 1RM on a leg extension machine, with one leg being concentrically focused, and the other being eccentrically focused, which were performed 3 times a week for 12 weeks. Their results showed that tendon stiffness increased by 55.8% in the concentric leg, but not within the eccentric leg, which they were surprised to see. Furthermore, they saw no increase in patella tendon CSA, with both contractions showing increases in oxygen saturation, but not in blood volume. In addition, Malliaras et al.[35] performed a similar study to that of Kubo et al.[34], specifically in relation to exercise selection, the study duration and load-intensity. However in this study, 38 males between the age of 18-35 were split into 4 groups which included a control group, who performed no training, a concentric only group, who performed 4 sets of 7-8 reps at 80% concentric 1 RM, a standard eccentric group who performed 4 sets of 12-15 reps at 80% concentric 1 RM, and a high load eccentric group, who performed 4 sets of 7-8 reps at 80% eccentric 1 RM. Knee extensor torque, patella CSA and length were measured using dynamometry and ultrasound, with patella tendon force calculated using the equilibrium equation. Their results showed that patella tendon stiffness, Youngs modulus and 5 RM significantly increased in all exercise groups compared to controls. The concentric group showed the highest reduction in elongation and strain, with the higher eccentric load group producing superior results (84-87%) compared to the standard load eccentric group (59%) in relation to the modulus. They concluded that patella tendon modulus responds to loading at or above 80% of a concentric 1RM, with intensity and contraction types affecting the tendon modulus, with muscle strength responding more to load-intensity.

Both Kubo et al.[34] and Malliaras et al.[35] demonstrated that heavier loads when performing an isolation isolation exercise produce optimal tendon adaptations. However, although these studies performed a similar protocol, Kubo et al.[34] showed that only the concentric contractions increased tendon stiffness, with Malliaras et al.[35] showing that all contractions increased tendon adaptations, with higher load eccentric contractions having better results within the modulus. This may be due to the load applied to the tendon, as eccentric 1 RM increases the load by up to 40% that of a concentric 1 RM[36]. Therefore, the higher load eccentric group in the Malliaras et al.[35] study would have been under more stress than the subjects within the Kubo et al.[34] eccentric group, leading to greater improvements within the tendon modulus. Nevertheless, both studies showed that both eccentric and concentric contractions improve tendon mechanical properties, particularly at higher loads.

Contraction types - Achilles tendon

When it comes to the Achilles tendon, studies have analysed the adaptation response from both eccentric and concentric contractions within various age groups. However, the data comparing both types of contractions in the Achilles tendon is quite limited. Morrissey et al.[37] conducted a six-week study amongst 38 individuals aged 20-22, aiming to compare the effects of both eccentric and concentric contractions within the Achilles tendon. Ultrasound was used to assess tendon CSA, with dynamometry used to assess peak torque. The training intervention included an eccentric group of 6 males and 13 females, with the concentric group consisting of 8 males and 11 females, both of which performed 3 sets of 15 reps at bodyweight, which was based off the protocol from a study by Alfredson et al.[38]. Their results showed that the eccentric group demonstrated reduced tendon stiffness, indicating a more compliant tendon response under load, whereas the concentric group showed no significant changes. However, they stated that if the tendon is stiffer at the onset of training, the greater the reduction in stiffness, and that eccentric exercise may provide therapeutic effects to Achilles tendinopathy.

In addition, Mafi et al.[39] performed a 12-week study amongst 44 participants (24 men and 20 women) aged 48 years old with severe Achilles tendon pain who were referred as candidates for surgery. Ultrasound was used to diagnose the damaged area, with the VAS used to measure pain intensity. The exercise intervention included patients being split into an eccentric and concentric group performing their exercises 2 times a day, 7 days a week and consisted of 3 sets of 15 reps. The eccentric group included bodyweight heel lowering with both a bent knee, which targets mainly the soleus, and a straight knee, which targets mainly the gastrocnemius[40]. The exercises then progressed into loaded eccentric contractions with either a backpack or a pin loaded machine. The concentric group performed 6 additional bodyweight exercises for 3 sets of 15-20 reps, which included resistance band plantar flexion whilst sitting upright, heel raise variations, as well as various jumping exercises. Their results showed that 82% of patients were satisfied and returned to their previous

activity level after the eccentric training, compared to 36% that of the concentric group, concluding that eccentric training produces significantly better results compared to concentric contractions, particularly for patients with Achilles tendinopathy.

Morrissey et al.[37] and Mafi et al.[39] showed that eccentric contractions had better results than concentric contractions, while performing high rep bodyweight exercises. However, the Mafi et al.[39] study included external load within the eccentric group, compared to the concentric group. Since eccentric contractions have been suggested to place higher strain on tendons, these results were always going to be better when performing bodyweight exercises. However, based on the previous studies in this paper, it's evident that external load placed on the tendon will dictate its adaptation potential. Therefore, since many of the exercises were bodyweight, it's of no surprise that the concentric groups in both the Morrissey et al.[37] and Mafi et al.[39] studies didn't see significant improvements. Indeed, although the Mafi et al.[39] study chose their subjects based on radiographic images, their conclusion was based on subjective responses from the participants, rather than an objective view of the structural changes to the tendon that could've been obtained with an image-based measure, such as ultrasound or MRI.

When comparing isolated eccentric training and heavy resistance training, Beyer et al.[41] conducted a 12-week study evaluating the effectiveness of eccentric training and heavy slow resistance training (HSR) on 58 individuals (32 men, 15 women) between the ages of 18-60 with Achilles tendinopathy. They also implemented a follow up protocol at 52 weeks post intervention. The measurements in this study included the Victorian Institute of Sports

Assessment–Achilles (VISA-A) to assess the symptoms, function and overall pain levels, with ultrasound used to analyse the structure of the injured Achilles tendon. The participants were randomly assigned to either the eccentric group, or the HSR group. The eccentric group performed staircase unilateral heal drop downs, emphasizing the eccentric contraction on the affected limb, which included 3 sets of 15 reps. Much like the Mafi et al.[39] study, the eccentric group performed the exercises in both a bent and straight knee, as well as implementing the same exercise frequency of 7 days a week. The HSR group performed the program 3 times a week, with all exercises being bilateral. These included seated calf raises with a bent knee, seated calf press on the leg press machine, and standing calf raises on a smith machine using a disc. Furthermore, the protocol included 3-4 sets of each exercise, which were based on RM zones and progressively overloaded as the weeks progressed (15 RM in week 1, 12 RM in week 2-3, 10 RM in week 4-5, 8 RM in week 6-8, 6 RM in week 9-12). Their results showed that both eccentric and HSR training protocols produced similar outcomes, with HSR producing favourable results for patients with mid portion Achilles tendinopathy. This was particularly evident with patient satisfaction at 12 weeks (HSR 100%, ECC 80%), however not as significant at 52 weeks (HSR 96%, EC 76%).

When examining these studies, Beyer et al.[41] was the only protocol that used a strength-based program programming that included progressive overload. The principle of progressive overload ensures that tissues can continue to adapt to higher loads, which can be achieved by manipulating both intensity and rep ranges[42-44]. The Morrissey et al.[37] and Mafi et al.[39] studies mainly incorporate bodyweight movements very frequently, whereas Beyer et al.[41] had a reduction in training frequency and a progressive overload structured resistance training program. Although the Morrissey et al.[37] and Mafi et al.[39] studies showed positive impacts with eccentric based training compared to concentric training, Beyer et al.[41] was able to demonstrate that training frequency can be much less if enough external load is placed on the tendon using both eccentric and concentric contractions, thus facilitating optimal tissue adaptation.

Based on the studies reviewed, it is evident that both types of contractions can produce favourable adaptations within the muscle tendon. However, the timing of the application and the overall load may be an important factor.

Heavier loads vs. lighter loads

When it comes to resistance training programs, training load has been shown to be one of the main drivers of tissue adaptation, especially training intensity. With regards to application, training stimulus is generally based on the 1 RM percentage, thus giving a numerical indication of the external stimulus placed on the tissue. With reference to muscle tendons, the conversation around heavier loads and lighter loads has become a topic of interest, especially when aiming to accelerate the response time of increasing tendon stiffness and integrity. Based on the studies reviewed, it is evident that tendons have a better response to heavier loads compared to lighter loads and produce greater tendon adaptations. Furthermore, the studies reviewed comparing these load applications were limited and were specific to the patella and Achilles tendon.

Training load – patella tendon

When looking at the patella tendon, Kongsgaard et al.[45] performed a 12-week study examining the patella tendon response to both heavy and lighter loads amongst 12 healthy 24-year-old men. The measurements included maximal voluntary contraction (MVC) tests unilaterally using the leg extension machine, with all portions of the patella analysed using MRI, with the tendon mechanical properties assessed using ultrasound. The resistance training program consisted of knee extensions 3 times a week, performing heavy loads on one leg, and lighter loads on the other. The protocol included the heavy leg performing 10 reps at 70% 1 RM, with the light leg performing 36 reps with the load equalling the amount of work that was performed by the heavy leg, in which the

absolute load between the legs were equal. Furthermore, from the 36 total sessions, a new 1 RM was established at the 10th, 20th and 30th training session, with the same load percentages and rep ranges. Their results showed that the lighter leg showed a 7% increase in patella CSA, but only within the proximal portion, whereas the heavy leg showed a 6% increase in the proximal portion and 4% increase in the distal portion, with no changes to the middle portion of the tendon. Furthermore, tendon stiffness and Youngs modulus did not change in the lighter group, with the heavy group showing a significant increase in tendon stiffness and marginal increases in the Youngs modulus. They concluded that increasing tendon stiffness may provide a clinical relevance, as it will decrease stress and strain during tensile loading, in which heavy resistance training can facilitate these adaptations.

In addition, Grosset et al.[46] conducted a 12-week study comparing the effect of low intensity and high intensity training on tendon mechanical properties, amongst 20 healthy elderly participants. Patella tendon stiffness, CSA and Youngs modulus were measured using a combination of both ultrasound and MRI, with dynamometry used to assess isometric knee extension force. The training intervention included 3 sessions a week, with the exercises including the seated leg press, leg extension, calf rotator and gluteal conditioner. The participants were randomly assigned to either the low intensity group (40% 1 RM), or the high intensity group (80% 1 RM), both of which performed 8-11 reps. Moreover, 1 RM was measured every second week, applying progressive overload due to the physiological adaptations occurring during the program. When normalising the data, tendon length and CSA was normalised by converting it to Youngs modulus. Their results showed that when analysed at 100% MVC, patella tendon stiffness increased by 57.7% in the higher intensity group, with no change seen in the lighter intensity group. When looking at Youngs modulus at 100% MVC, the higher intensity group showed a 57.9% increase, with the lighter intensity group only showing a 2% increase. Furthermore, when analysed within the linear range of 60-100% MVC, the higher intensity group had a 58.9% increase in Youngs modulus, with the lighter intensity group only showing a 5.5% increase. They concluded that compared to high intensity resistance training, low intensity resistance training does not promote beneficial tendon adaptations in the elderly, in which high intensity resistance training is recommended for increasing overall tendon stiffness and integrity.

When examining the studies comparing heavier loads and lighter loads in the patella tendon, both Kongsgaard et al.[45] and Grosset et al.[46] demonstrated that heavier loads produce better results than lighter loads in relation to tendon mechanical properties. However, Kongsgaard et al.[45] only produced marginal increases in Youngs modulus, compared to Grosset et al.[46]. This is potentially related the Grosset et al.[46] study having higher loads and lower rep ranges, as well as implementing more exercises. As a result, this may produce better collagen synthesis rates, therefore enhancing tendon mechanical properties.

Training load – Achilles tendon

When addressing load applications within the Achilles tendon, Arampatzis et al.[47] conducted a 14-week study amongst 21 healthy males aged between 23-42, investigating whether the magnitude of mechanical load influences tendon adaptation rate. The measurements included seated dynamometry, where they performed plantar flexion and assessed maximal isometric voluntary contractions. In addition, ultrasound was used to assess medial gastrocnemius activity at rest, 50% and 100% MVC, with MRI used to assess Achilles tendon CSA. The exercise intervention included 4 sessions a week, with the experimental group performing 5 sets of isometric contractions during plantar flexion, with the starting position being at 85% dorsiflexion, full knee extension at 180 degrees, and 140 degrees of hip flexion. The participants were assigned one leg which was considered low strain magnitude (55% MVC), with the other being high strain magnitude (90% MVC). The low strain magnitude leg performed 7 reps of 3 seconds loading and 3 seconds relaxation, with the high strain magnitude leg performing 4 reps of the same protocol. Both groups performed 5 sets each, with the low strain magnitude leg performing more reps in order to meet the same volume of work as the higher strain magnitude leg. Their results showed that the high strain leg had better tendon aponeurosis stiffness, moment ratio, modulus and maximal stress results compared to the low strain magnitude leg. Furthermore, the high strain leg also had favourable increases in tendon CSA, compared to the lower strain leg. They concluded that Achilles tendon adaptations occur mainly during higher strain magnitudes, with lower strain magnitudes not providing enough stimulus to create an optimal adaptation.

Arampatzis et al.[48] conducted a subsequent study, examining the effects of controlled modulation of strain magnitude and strain frequency applied to the Achilles tendon, and how this effects plasticity of the tendon mechanical properties. They used a very similar intervention to their pervious study, with the aim to make a direct comparison of their results. However, the subjects included 11 healthy 24-year-old males with no history of regular resistance exercise. With regards to the protocol in this study, the higher strain leg performed 12 reps of 1 second on and 1 second relaxation, with the lower strain leg performing 20 reps of the same duration, which again was so that both legs achieve the same volume of work. Their results once again showed that the higher strain leg displayed significant increases in stiffness and elastic modulus compared to the lower strain leg, with only a marginal and non-statistically significant difference in CSA, in favour of the higher strain leg. However, the ratio of exercise execution was lower compared to the previous

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study, which therefore did not produce a superior result in comparison to their previous study. Moreover, the authors did state why this could be the case, however, it may potentially be related to the amount of time under tension placed on the tendon. Nevertheless, much like their previous study, they concluded that heavier strain magnitudes produce superior tendon adaptations compared to lighter strain magnitudes. In addition, Merza et al.[49] performed a similar protocol to the Arampatzis et al.[47,48] studies amongst 16 participants, looking at how load intensity and isomeric contraction duration influence the Achilles tendon volume and stiffness. The protocol included 3 maximal voluntary isometric contraction (MVIC) interventions over a 3-week period. These included contraction durations between 2 to 8 secs and intensities between 35% and 75% MVIC. Their results showed that MVIC at 75% for 8 secs had a significant reduction Achilles tendon volume by 60%, compared to the MVIC at 75% for 2 secs and MVIC at 35% for 8 secs groups. They stated that load-induced fluid flow may be a remodelling signal for tendon cells, as this may generate shear forces and stimulate tenoycyte mechanotransduction and signalling. They concluded that the load applied to the tendon must be heavy and sustained for long durations to maximise fluid reduction and facilitate tendon adaptation via mechanotransduction pathways.

Following on from these studies, Radovanovic et al.[50] performed a 12-week clinical trial amongst 39 males aged between 20-55 who were diagnosed with Achilles tendinopathy. They investigated the effects of high-load exercise on tendon mechanical properties and morphological adaptations via dynamometry, EMG, ultrasound and MRI. Furthermore, clinical adaptation and pain scores via VISA-A and numerical rating scale were also implemented, as well as measuring both drop jump and countermovement jump heights and intratendinous vascularity. The participants were split into a passive therapy group which consisted of 12 manual therapy sessions and no exercise, an eccentric loading group, and a high loading isometric group. The eccentric loading group program was based on the Alfredson et al.[38] study, which included performing the heal eccentric heal drop exercise, 3 sets of 15 reps with both a bent knee and a straight knee. The high loading group performed a similar protocol to that of Arampatzis et al.[47], with the isometric application including 3 secs of 90-degree high isometric loading, followed by 3 seconds of rest for 5 sets. Their primary findings showed improvements in tendon MVC (7.2%), stiffness (20.1%), CSA (8.98%), and a decrease in strain (-12.4%) within the high loading isometric group, with no changes within the other groups. In addition, the passive group displayed decreases in tendon stiffness (-7.7%), with countermovement and drop jumps heights decreasing in all groups. Moreover, all groups showed a decrease in pain scores, with no changes seen in the modulus. They concluded that higher loading induces significant mechanical and morphological adaptations, improving tendon mechanical properties and thus protecting the tendon from strain induced injuries.

When comparing the studies addressing load applications within the Achilles tendon, it is evident that heavier loads placed on the Achilles tendon creates a better adaptive response compared to lighter loads. However, many of these studies performed these exercises with isometric contractions rather than isotonic contractions, aside from the Radovanovic et al.[50] study, which implemented bodyweight eccentric exercises. These studies may have been more reliable if they were compared with heavy isotonic exercises, as force distribution between these contractions differ between exercises. However, since these studies all produced a similar result, heavier loads may produce favourable responses compared to lighter loads for increasing mechanical properties within the Achilles tendon.

Based on the studies reviewed regarding the effect of heavier loads and lighter loads on tendon mechanical properties, it seems as though heavier loads provide a better result in terms of improving tendon mechanical properties, which are consistent with the findings in recent additional reviews[51,52].

Practical applications

With regards to practical applications, coaches and practitioners should implement the most appropriate loading strategies to enhance tendon mechanical properties. Based on the presented studies, performing both eccentric and concentric contractions with intensities between 70-80%1 RM seem to be effective at increasing tendon adaptations. Furthermore, when working within these intensity zones, it's recommended to perform reps between 5-7 as this will provide a sufficient level of volume without training to failure. However, since tendons respond to heavier loads, this author recommends implementing additional intensities between 80-85% 1 RM, with rep ranges between 3-5, particularly within late-stage rehabilitation or a high-performance setting. This will provide the most optimal intensity for improving neuromuscular characteristics, muscle and tendon strength, as well as tolerance to higher loads. Moreover, since tendon stiffness has been shown to temporarily reduce from exercise, not to mention the tendon being hypovascular, low frequency resistance training should be encouraged. This author recommends implementing heavy resistance training 2-3 days a week within a tendon rehabilitation program, with 3-4 days a week being more toward late-stage rehabilitation or a high-performance setting. The application of lower frequency and higher intensities will enable the tendon to enhance its structural integrity, as well as regain its stiffness and adapt to previous loads, to which an additional stimulus can be applied without negatively impacting the tendon structure. This concept also highlights the principle of emphasizing

training quality, rather than quantity, as performing less sessions with higher intensities and better exercises can produce superior adaptations than more sessions with lower intensities. Therefore, applying progressive overload principles within the recommended load percentages is advised, which should be implemented within the mid-later stages of a tendon rehabilitation program, or when the individual's pain is approximately a 2-3/10.

In relation to exercise selection, both multi-joint and isolation exercises may prove to be beneficial for enhancing tendon mechanical properties. If an individual is presenting with isolated tendon pain, performing an isolation exercise may be a viable option to target that specific tendon. In the initial stages of tendinopathy rehabilitation, eccentric focused exercises may produce favourable adaptations and can be executed with minimal equipment. However, if equipment specific to isolating a muscle group is available, this will most likely produce a better outcome in relation to tendon mechanical properties. Moreover, within a general setting, compound and multiple-joint exercises may prove to be the most optimal for strengthening multiple tendons in a larger range of muscle groups, especially during late-stage tendon rehabilitation. Regardless of the exercise selection, the most important factor is the amount of load that is placed on the tendon, as this will determine the rate of tissue turnover and overall load tolerance capacity.

CONCLUSION

Through the preceding analysis of the literature, it is evident that both types of contractions produce similar adaptations within the mechanical properties of the tendon. Based on these factors, heavier loads seem to produce more favourable outcomes than lighter loads, which should be a point of interest when applying exercise interventions in both a rehabilitation and high-performance setting.

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