Neuromuscular Adaptations to Plyometric Training in the Triceps Surae Muscle-Tendon Unit and Implications to Tendon Loading: A Literature Review

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ABSTRACT

Background and Purpose: The current evidence-based rehabilitation approach for Achilles tendinopathy is heavy slow resistance loading. However, this approach at times fails to reduce symptoms and improve function for a significant number of patients. The purpose of this study was to review the literature related to the neuromuscular adaptations that occur at the triceps surae muscle tendon unit with plyometric loading and the implications these changes have in performance and tendon loading. Additional investigation was to determine whether further research on plyometric loading is warranted within injured populations. **Methods:** A literature search was performed for articles in the English language using the following MeSH terms, “plyometric”, “gastrocnemius”, “stretch shortening cycle”, “muscle-tendon unit”, “Achilles tendinopathy”, which were entered into the following databases, Google Scholar, PubMed, ScienceDirect, SAGE journals. Databases were searched in order to identify articles that examined the effects of plyometric-based training on the behavior of the triceps surae muscle tendon unit in healthy adults using EMG and/or dynamic ultrasound during plyometric exercise. **Results:** Plyometric training increased EMG activity and decreased fascicle muscle length during the braking phase of a plyometric activity. **Clinical Relevance:** Increased EMG activity during the braking phase allows for greater use of elastic energy stored within the tendon and helps to improve the function and performance of plyometric activities. Conclusion: Plyometric training creates neuromuscular adaptations that enhances elastic use of the Achilles tendon that may have implications for prevention and treatment of patients with Achilles tendinopathy. As this literature review did not include those with Achilles tendinopathy, the authors cannot generalize to patients with Achilles tendinopathy. The authors of the current study suggest more evidence needs to be gathered before this can be answered.

Key Words: Achilles tendon, jumping, stretch shortening cycle, tendinopathy

INTRODUCTION

Tendinopathy is characterized by Cook and Purdam as an overuse injury that can occur in both the upper and lower extremities that results in pain, decreased tolerance to exercise, and a decrease in function.[1] Overuse injuries, including tendinopathies, represent approximately 7% of all primary care physician visits in the United States.[2] Tendon injuries make up anywhere between 30% and 50% of all sports injuries and account for 50% of all injuries to elite endurance runners.[3–5] Given its injury prevalence in elite endurance runners, the Achilles tendon has been an area of focus in research to understand the influences and disruptions to this tendon.[6–16] The prevalence of Achilles tendinopathy in runners has been cited as anywhere between 11% and 30% depending on the number of miles run.[5,17] Although tendinopathy is common in sports, 1 out of 3 patients with Achilles tendinopathy are not active in sport.[17] Some epidemiological studies show that up to 6% of the sedentary population will suffer from tendinopathy.[3]

For the past several decades, a major component of the rehabilitation of Achilles tendinopathy has focused on tendon loading exercises. In 1998, Alfredson published a study that supported the idea that heavy-load slow eccentric training was effective in the treatment of mid-substance Achilles tendinosis.[18] This study laid the groundwork for subsequent research that examined the effect of eccentric exercises on the treatment of tendinopathy, particularly of the Achilles tendon.[8–12,15] The APTA’s 2010 and 2018 Clinical Practice Guidelines based on strong evidence, recommended eccentric loading and heavy slow resistance to decrease pain and increase function in patients with mid-substance Achilles tendinopathy.[6,7] Authors conducting mechanistic studies around the benefits of eccentric exercise have focused primarily on the structural changes that occur within the tendon such as matrix quality, collagen orientation, tendon thickness and tendon stiffness.[8,14,15]

Various authors suggest that structural degeneration does not always correlate proportionally with the clinical symptoms of tendinopathy.[1,19,20] Fredberg and Bolvig[21] revealed that 29% of Danish soccer players displayed abnormal ultrasonographic findings of the Achilles tendon during preseason testing despite the lack of symptoms. Further, post-season testing revealed that of the original 29% with abnormal ultrasonography findings, 36% were still asymptomatic and the tendons had normalized while another 18% remained asymptomatic with abnormal tendon structure following rehabilitation and participation in their sport, by the end of the season. Some authors have found that there is a subset of patients that either do not respond well to standard physical therapy interventions or those whose symptoms recur after discharge. One literature review cited that “several clinical studies investigating Achilles and patellar tendinopathy have verified a 40% to 60% good outcome after a home-based, twice daily, 12-week regime of mainly eccentric training.”[17] Authors have demonstrated that individuals with Achilles tendinopathy show a diminished ability to load the Achilles tendon elastically during the eccentric or braking phase of athletic movement.[22–24] Authors have also shown that there are neuromuscular deficiencies within the triceps surae muscle tendon unit in individuals with mid-substance Achilles tendinopathy.[22–24] One study by Baur et al[24] compared the EMG activity of the gastrocnemius in runners with Achilles tendinopathy and in controls during running. This study showed that runners with tendinopathy showed decreased muscle activity during the weight acceptance phase of running.[24] These authors also showed that the EMG activity on the asymptomatic side in runners with Achilles tendinopathy demonstrated a similar decrease in muscle activity, suggesting that this movement strategy may have been present prior to the onset of symptoms. This suggests that other factors in addition to tendon structure may impact the risk of and recovery from tendinopathy.

Stanish et al[25] were one of the early pioneers in research regarding tendinopathy rehabilitation and highlighted the importance of not only eccentric strengthening, but also sport specificity and increasing the velocity of loading. Despite this, current recommendations for exercise in the treatment of tendinopathy focus on heavy, slow resistance (HSR) exercise, and in particular eccentric dominant loading.[6] The support for eccentric exercise was founded on the premise that individuals with Achilles tendinopathy displayed diminished eccentric strength and that maximal loading of the tendon occurred during the eccentric portion of an athletic movement.[18,25] The assumption of these loading programs is that the muscle-tendon unit (MTU) mechanics are similar during slow and fast eccentric activities. However, an emerging body of literature regarding MTU activity points toward a different phenomenon occurring during stretch shortening cycle (SSC) activities.[26–36]

Most of the research investigating the effect of loading on tendinopathy has neglected to consider that the muscle and tendon can lengthen in different amounts and different rates from one another. Recent studies that explore the activity of the individual muscle and tendon components in the MTU when the velocity of loading is increased may help to guide researchers in designing more effective loading programs, as well as the role that loading velocity plays in the rehabilitation of tendinopathy. The SSC is classically thought of as a quick eccentric contraction, followed by an isometric, and then a concentric contraction. During the eccentric phase of an SSC movement, the muscle is isometrically or even concentrically contracting and this allows for the tendon to lengthen and store elastic energy, so that it may be used as a propulsive force in the latter half of a movement.

Unfortunately, the majority of the research in this area has been done on healthy athletes using sports performance metrics as the primary outcome variable.[28–36] Within this article, any activity that elicits the SSC response of an MTU will be referred to as plyometric loading.

The main parameter that elicits a change in the way an MTU functions is movement velocity.[32] At increased velocities, the MTU functions as described above, with greater amounts of muscle shortening concurrent with greater amounts of tendon lengthening.[32] Additionally, the tendon also experiences greater amounts of tensile loading compared to lower velocity modes of loading, ie, eccentrics or HSR training.[32] Increasing the speed of loading would be more applicable to sport specific movements, and potentially more appropriate to apply to sporting populations who are at an increased risk for suffering from tendinopathy and require SSC loads as part of their activity, including runners and field and court athletes that rely heavily on the SSC during participation in their sport.

The purpose of this study was to review the literature related to the neuromuscular adaptations that occur at the triceps surae muscle tendon unit with plyometric loading and the implications these changes have in performance and tendon loading. Additional investigation was to determine whether further research on plyometric loading is warranted within injured populations.

METHODS

Search Methodology

Relevant articles were obtained by using different combinations of the following search terms and Boolean operators: OR/plyometric, stretch shortening, stretch shortening cycle, SSC; OR/loading, training, program, rehabilitation; OR/Achilles, tendon, Achilles tendon, triceps surae, tendo-achilles, gastroc-soleus; OR/ tendinopathy, tendinitis, tendinosis; OR/EMG, electromyography; OR/dynamic ultrasound, dynamic US, ultrasound, US. The search was performed across the Medline, CINAHL, PubMed, PEDro, and Cochrane Review databases. A hand search of references within articles returned by this search strategy and of the APTA's 2010 and 2018 Clinical Practice Guidelines for Achilles Tendinopathy was also performed for relevant literature which fit the inclusion/exclusion criteria as detailed in **Figure 1**.

Inclusion and Exclusion Criteria

Articles that were to be included in this review must have had the following criteria: the study observed the triceps surae, the study needed pre-test, intervention, and post-test components, the intervention needed to include plyometric loading, the data needed to be recorded during the plyometric activity, the measurements needed to be made using EMG and/or dynamic ultrasound (**Table 1**). Articles excluded from this review had the following criteria: The study did not observe the triceps surae, the study was missing either a pre-test, intervention, or post-test component, the intervention did not include plyometric loading, the only recorded data was during non-plyometric activities, the measurements were not made using dynamic ultrasound or EMG.

Quality Assessment

The PEDro scale was used as a measure of quality for each article. The score of each article is depicted in **Table 2**. Two of the authors performed quality assessments of each of the selected articles, a third author then reviewed each of the two assessments in order to resolve any discrepancies between the two assessments. Limitations of the quality of the articles are discussed further in the discussion section.

RESULTS

See results in **Table 3**.

DISCUSSION

It is well documented in the literature that the storage of elastic energy that occurs in tendons during the SSC has direct implications to performance.[35–40] During plyometric exercise, the MTU is lengthened and then quickly shortened to produce force. It stands to reason that if MTU lengthening

Figure 1. This Figure Depicts the Process of Article Selection for This Review

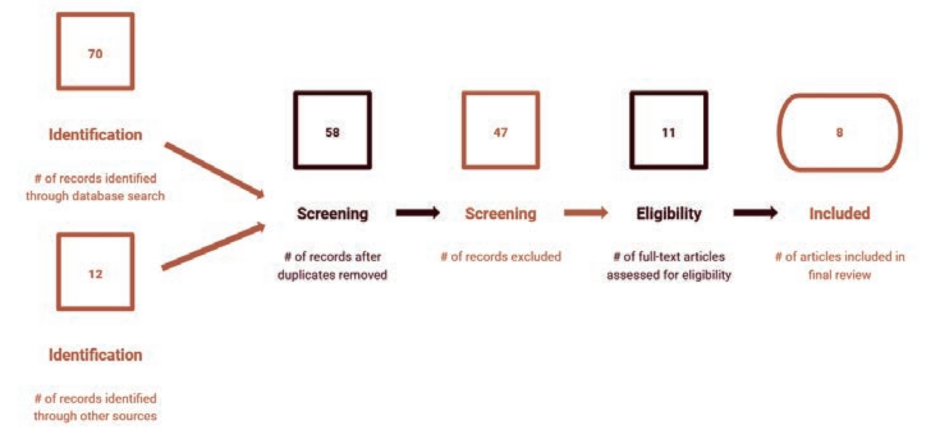

Table 1. Inclusion and Exclusion Criteria for Selecting the Articles Within This Review

Inclusion Criteria	Exclusion Criteria
- Looks at triceps surae - Has pre-test, intervention and post-test components - Used plyometric loading intervention - Data recorded during plyometric activity (in-task) - Measurement made using either EMG or dynamic ultrasound	- Does not look at triceps surae - Missing a pre-test, intervention, post-test or any combination of those components - Does not use plyometric loading intervention - Data only recorded during non-plyometric activity (out-of-task) - Measurement not made using either EMG nor dynamic ultrasound

*Viitasalo et al[43] did not perform an intervention but the athletic background of the experimental group was accepted as a sufficient independent variable

occurs without a change in length from the muscle component, the increase in length of the overall MTU is primarily achieved by the tendon. This review supports the idea that neural adaptations to plyometric exercises optimize this elastic behavior of the MTU. For clarity in this discussion, the phases of a plyometric movement will be described in binary terms, using the terms braking and propelling to distinguish between the lowering and rising phases of a jump.

EMG Changes

One of the primary adaptations that was observed by this review was a shift in EMG activity towards the braking phase of a plyometric movement. If the primary neural adaptation to plyometric training is centered around taking advantage of the elastic nature of the muscle tendon unit, then timing is critical. Internally generated forces need to be sufficient enough to resist external forces. In order to suit this need, it appears that the nervous system pre-tenses the musculature before initial contact during a predictable plyometric task.[40–42] Increases in EMG activity of the triceps surae were also seen during the braking phase of plyometric activities.[36,40–44] Often times, the results of the selected studies demonstrated that the overall amount of EMG would remain unchanged following plyometric exercise intervention, but the timing of peak contraction would occur sooner.[36,40,41]

There are other variables that can be changed during the training process in order to alter the timing of the contraction. For example, the height of the box, which would dictate the force of the impact, as well as the type of training prior to testing or the dosage of training prior to testing. It was shown that increasing the height of the box moves the peak of the EMG activity to occur later on during a plyometric task, meaning that there is increased time to complete the braking phase of the plyometric.[40,43,44] While performing plyometric activities from lower heights, enables better usage of MTU elasticity.[44] Clinically, if one of the goals of rehabilitation is to improve the use of tendon elasticity, which would demonstrate improved recovery of the tendon and improve performance in jumping activities leading to greater readiness to return to athletic activities, then increasing the height of a box could serve as a potential exercise progression as long as the patient demonstrates peak muscle activity sooner in the braking phase. As shown by Viitasalo et al,[43] without any pre-test training outside of their respective sport elite level triple jumpers were able to increase the amount of pre-activation and early braking phase muscle activity as they progressed from a 40 cm drop jump to an 80 cm drop jump. Whereas, the control group demonstrated significantly decreased amounts of pre-activation and breaking phase activity, and increased their amount of latter phase propulsion activity as the height of the box increased. Thus, delaying the timing of peak muscular contraction and limiting the amount of elastic utilization. It is worth noting that that the jumper's potential natural proclivity for this strategy should be considered, but their extensive training history should not be disregarded. Taube et al[44] also demonstrated that training at lower heights of 30 cm drop jumps shifted peak EMG to occur sooner, thus having a shorter braking phase, even when tested at higher heights of 50 cm drop jump. Whereas individuals who trained at much higher box heights of 50 cm to 75 cm demonstrated a peak EMG that occurred much later and thus the braking phase took longer to complete. These results suggest that plyometric training done with a box at lower heights will enable peak EMG to occur sooner, and that this has the potential to transfer to plyometric activities done with higher box heights and thus greater external forces. However, if initial training is done with a box height that forces the peak EMG to occur later and prolong the braking phase then use of tendon elasticity will not be optimized.

Table 2. Quality Assessment Scores of Each

Description
Eligibility criteria were specified
Subjects were randomly allocated to groups (in a crossover study, subjects were randomly allocated an order in which treatments were received)
Allocation was concealed
The groups were similar at baseline regarding the most important prognostic indicators
There was blinding of all subjects
There was blinding of all therapists who administered the therapy
There was blinding of all assessors who measured at least one key outcome
Measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups
All subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analyzed by "intention to treat"
The results of between-group statistical comparisons are reported for at least one key outcome
The study provides both point measures and measures of variability for at least one key outcome
Total **0-3 "poor", 4-5 "fair", 6-8 "good", 9-10 "excellent"**

The specific methods of training were also shown to be relevant to the timing of muscular contraction. Arabatzi et al[42] demonstrated that 8 weeks of Olympic weight lifting increased the EMG activity of the triceps surae during the propulsion phase of a vertical jump, but decreased its braking activity, whereas 8 weeks of plyometric training shifted peak EMG to occur sooner during the braking phase. Interestingly, the group that combined weight training and plyo-

Article via the PEDro Scale

Kryölänen et al[46]	Kannas et al[40]	Arabatzi et al[42]	Viitasalo et al[43]	Taube et al[44]	Hirayama et al[35]	Kubo et al[31]	Kryölänen et al[41]
N	N	Y	Y	Y	Y	Y	N
N	Y	Y	N	Y	N	Y	N
N	N	N	N	N	N	N	N
Y	Y	Y	N	Y	Y	Y	Y
N	N	N	N	N	N	N	N
N	N	N	N	N	N	N	N
N	N	N	N	N	N	N	N
Y	Y	Y	Y	Y	Y	Y	Y
Y	Y	Y	Y	Y	Y	Y	Y
Y	Y	Y	Y	Y	Y	Y	Y
Y	Y	Y	Y	Y	Y	Y	Y
5	**6**	**7**	**5**	**7**	**6**	**7**	**5**

metric training still showed a more eccentric dominant strategy in testing, however, this was shown in quadricep musculature as opposed to the gastroc/soleus. This can be attributed to the practice of more hip and knee dominant strategies in Olympic and resistance training with compound movements, but also the practice of using elastic energy during plyometric training.

As for dosage of plyometric training, Hirayama et al[35] demonstrated that peak EMG would occur sooner, muscle fascicles would increase the amount of shortening, and tendon would increase the amount of lengthening during the braking phase of a plyometric activity within a single practice session. Subjects performed 2 intervals of 3 sets of 3 counter movement jumps on a sledge apparatus with 3 minutes of rest between each set. It is unclear how long this change in performance would be retained over longer periods of time. All other studies reviewed performed their interventions over a time period of 4 weeks,[40,44] 8 weeks,[42] 12 weeks,[31,41] and 15 weeks[46] with a frequency of activity between 2 and 4 times per week. Dosage of sets and repetitions as well as types of plyometric activities varied between studies, however most of the studies reviewed demonstrated similar results in changes in timing of triceps surae EMG despite wide variations in exercise prescription.[35,40–44,46]

Joint Kinematics

There were notable differences in the timing of peak dorsiflexion and knee flexion after plyometric training. Kyrolainen et al[41] observed that although the angular velocities did not change, the timing of knee and ankle flexion occurs sooner in response to plyometric training. This suggests that the experimental group made neuromuscular adaptations to plyometric training that enabled the peak EMG and braking phase to occur sooner thus causing the peak knee and ankle flexion to occur sooner, supporting the idea that one of the primary adaptations to plyometric training is an increase use of elastic energy of the MTU.

Viitasalo et al[43] observed the hip, knee, and ankle kinematics at different stages within the drop jump and found significantly different kinematics between athletes and non-athletes. The athletes demonstrated significantly less angular displacement at the hip, knee, and ankle than the non-athletic control group during the braking phase and during the propulsive phase. Greater angular velocities were observed at the ankle in the athletic group during the braking phase. The athletic group was able to increase their jump height by moving through a smaller range of motion faster than the non-athletic group. This difference is likely due to improved neuromuscular coordination and utilization of the MTU.

Table 3. This Table Presents the Structure of Each Study as well as the Pertinent Results

Authors	Participants	Test Battery & Intervention Duration	Dynamic Ultrasound	EMG	Joint Kinematics	Jump Performance
Kryölänen et al[46]	N=23 (23 males) Mean Age=24 Control group=10 Experimental group =10	Countermovement jump on sledge apparatus 2x/wk for 15 wks	N/A	Control group: no change Experimental group: no change	N/A	Control Group: no change Experimental Group: increased take off velocity
Kannas et al[40]	N=20 (20 males) Mean Age=21.3 Incline plyometric group=10 Plane plyometric group=10	Countermovement jump Drop jump 20 cm Fast drop jump 20 cm Drop jump 40 cm Fast drop jump 40 cm 4x/wk for 4wks	Fascicle length of medial gastrocnemius: Decreased during initial jump phases in majority of testing trials for both groups	Gastrocnemius EMG: increased significantly more during the initial phases of jumping in majority of testing trials for both groups	N/A	Jump height: increased in the majority of trials for both groups
Arabatzi et al[42]	N=36 (36 males) Mean Age=20.3 Plyometric group=9 Olympic weight lifting group=9 Weights and plyometrics group=10 Control group=8	Countermovement jump Plyometric group trained with only plyometric exercises Olympic weight lifting group only trained with Olympic weightlifting Weights and plyometrics group trained with a combination of weight training and plyometrics. 3x/wk for 8 wks	N/A	EMG of gastrocnemius: - Plyometric group: increased in eccentric phase, decreased in concentric phase - Olympic weight lifting group: increased in concentric phase - Weights and plyometrics group: decreased in eccentric and concentric phases EMG of Rectus Femoris: - Plyometric group: decreased in eccentric phase - Olympic lifting group: increased in concentric phase - Weights and plyometrics group: increased in eccentric phase	Plyometric group: decreased max knee angle Olympic weight lifting group: increased max hip and knee angle Weights and plyometric group: decrease in max hip angle	Plyometric group: increased jump height by 14.6% and eccentric power by 78% Olympic weight lifting group: increased jump height by 14.4% and eccentric power by 57% Weights and plyometric group: improved jump height by 15.1% and eccentric power by 41%
Viitasalo et al[43]	N=18 (18 males) Elite Jumpers=7 (mean age=27.6) Control=11 (mean age=20.6)	Drop jump 40 cm Drop jump 80 cm Prior sporting participation	N/A	EMG of gastrocnemius: -Jumpers showed greater amounts of activity during braking phases of 40 cm and 80 cm drop jumps	Drop jump 40 cm: Jumpers and controls displayed similar knee and ankle kinematics Drop jump 80 cm: Jumpers displayed smaller ankle kinematics and similar knee kinematics	Jumpers: significantly shorter contact times than controls in both drop jump 40 cm and drop jump 80 cm

Table 3. *(Continued from page 82)*

Authors	Participants	Test Battery & Intervention Duration	Dynamic Ultrasound	EMG	Joint Kinematics	Jump Performance
Taube et al[44]	N=33 (19 males, 14 females) Mean Age=24 stretch-shortening cycle group 1=11 stretch-shortening cycle group 2=11 Control=11	Drop jump low height (30 cm) Drop jump moderate height (50 cm) Drop jump high height (75 cm) Stretch-shortening cycle group 1 trained with DJs from the varying heights Stretch-shortening cycle group 2 trained with drop jumps from only from low height Both groups trained 3x/wk for 4 wks	N/A	EMG of soleus: -Stretch-shortening cycle group 1: displayed greater EMG during the latter phases of drop jump height -Stretch-shortening cycle group 2: displayed greater amounts of EMG activity during the early phases of drop jumps	Stretch-shortening cycle group 1: displayed greater amounts of flexion during braking phase of all drop jumps Stretch-shortening cycle group 2: not measured due to device malfunction	Stretch-shortening cycle group 1: significantly increased jump height in all 3 jumps Stretch-shortening cycle group 2: upward trend of jump height in all drop jumps Stretch-shortening cycle group 1: increased their ground contact time for all 3 drop jumps, stretch-shortening cycle group 2 decreased their ground contact time for all 3 phases
Hirayama et al[35]	N=8 (8 Males) Mean Age=22	Countermovement jumps on a sledge apparatus situated to 30° Each subject performed 2 initial test trials, then 3x3 of practice Countermovement jumps, then 2 final test trials	-In the first trial, subjects displayed both fascicle and tendon lengthening during braking, and then rapid tendon shortening during propulsion -In the fourth trial, subjects displayed slight fascicle lengthening and then isometric and slight fascicle shortening with greater amounts of tendon lengthening in braking, and even more rapid tendon shortening during propulsion	EMG of gastrocnemius heads and soleus: -Amount of EMG activation did not change between trials -Fourth trial had a faster onset of EMG activity when compared to the first trial	-There was no difference in the amount of dorsiflexion between the first and fourth trial	-There was a significant increase in the maximal ground reaction force during trial 4 compared to trial one
Kubo et al[31]	N=10 (10 Males) Mean Age=22 Plyometric training on one leg Weight training on the other leg	Countermovement jump - Squat jump -Drop jump Plyometric training included hopping	N/A (used during isometric testing) N/A	EMG of gastrocnemius: No significant difference between weight training group and plyometric training group	-There were no differences in ankle kinematics pre- and post-testing or in between groups	Plyometric training leg showed significantly greater ability to perform countermovement jump and drop jump when compared to weight training leg

(Continued onpage 84)

Table 3. *(Continued from page 83)*

Authors	Participants	Test Battery & Intervention Duration	Dynamic Ultrasound	EMG	Joint Kinematics	Jump Performance
Kubo et al[31] *(Continued from page 83)*		and drop jumping at 40% 1 RM Weight training included resistance exercises at 80% 1 RM 4x/wk for 12 wks				Both legs showed improvements in squat jump, plyometric training leg showed greater improvements Plyometric training leg showed greater pre-stretch augmentation in both countermovement jump and Drop jump, and a significantly greater relative pre-stretch augmentation when compared to weight training. The weight training leg showed a decrease in pre-stretch augmentation Squat jump: significant ↑ vs control countermovement jump: significant ↑ vs control Drop jump: significant ↑ vs control
Kryölänen et al[41]	N=17 (17 females) Mean Age=25.5 Experimental=10 Control=7	-Two different Drop jumps, one from a height of 20 cm jumping to 90% max height, one from 80 cm jumping to 60% max height Training included sledge jumps, Drop jumps, hurdle jumps, countermovement jumps, and standing 5 jump (5 reps per set) 3x/wk for 12 wks	N/A	EMG of gastrocnemius & soleus: -Peak EMG did not change from before and after, but did occur sooner after training. The concentric EMG also occurred later on post training	-Amount of knee and ankle flexion did not change post training -Participants displayed peak knee and ankle flexion sooner post training	Training group showed an increase in mechanical efficiency during high elastic loading trials. This is due to an increase in eccentric work over a small amount of time and an overall decrease in concentric work

Taube et al[44] had different findings as the experimental group significantly increased maximal ankle joint dorsiflexion during the braking phase of the drop jump. The reason for this increase is likely due to the SSC1 group in which this change was observed had performed drop jump training from 30 cm, 50 cm, and 75 cm over a period of 4 weeks. As discussed in the previous section, it is likely that increasing the height of the drop jump favors a more concentric dominant strategy to create force in response to the cue of "rebound as fast and as high as possible." It is unfortunate that the kinematic data from the SSC2 group, who performed drop jump training from only 30 cm, was not obtained due to a malfunction in the measurement device caused by a "loose contact within the cable connecting the goniometer."[44] It would have been interesting to observe the differences in the kinematics between the SSC2 and SSC1 groups to see if the results from the SSC2 group did suggest a more eccentric dominant strategy.

Arabatzi et al[42] observed a correlation between increased hip and knee joint kinematics and jump height in the group that performed Olympic lifting. One of the reasons for this correlation could be a change in jump strategy as an adaptation to the hip and knee dominant patterns inherent in Olympic lifts. Not only were there no significant increases in hip and knee kinematics in the plyometric training group, there was actually a significant decrease in knee flexion angle. This can likely be attributed to the more ankle and knee dominant patterns inherent in the plyometric training performed in this study, as evidence by the greater amount of knee and ankle movement. It would not be as likely for plyometric training to significantly affect hip flexion angle for this reason.[42] Notably, the insignificant decrease in hip flexion angle and the significant decrease in knee flexion angle in the plyometric training group was accompanied by an increase in max jump height compared to the Olympic lifting group. This suggests that the improvements in counter movement jump height in the plyometric training group were likely a result of better use of elastic energy rather than concentric power obtained by moving quickly through a larger joint range of motion.

This finding is consistent with the work of Viitasalo et al[43] in that the non-athletic control group used larger angular displacements to decelerate their body particularly when the height of the drop jump was increased. The athletic experimental group was able to jump higher than the control group with less angular displacement indicating that the neuromuscular system was better equipped to respond to the high tensile load placed on it during the drop jump.

Jump Performance

In a majority of cases the primary variable required for return to sport following Achilles tendinopathy is the resolution of symptoms. Authors have shown that full symptom resolution does not ensure full recovery of muscle-tendon function. Silbernagel et al[45] revealed that only 25% of patients who had full symptomatic recovery had fully recovered muscle-tendon function following Achilles tendinopathy when measured against a battery of jump performance tests. This suggests that the critical neural adaptations required for proper muscle-tendon function are not being met by current rehabilitation protocols.

This review revealed positive impacts on jump performance following plyometric training despite using several different measurement metrics. Jump height was improved in both training groups observed in Kannas et al.[40] While the improvement was determined to be insignificant between groups, this can be attributed to both groups being exposed to plyometric training for 4 weeks.[40] If the two plyometric training groups had been compared to a control group rather than to one another, it is likely that a more significant improvement in jump height would have been observed. Improved jump height was also observed in Arabatzi et al,[42] Kubo et al,[31] and Kryölänen et al.[41] Each study exposed their subjects to training 3 times a week for 8 weeks, 4 times per week for 12 weeks, and 2 times per week for 15 weeks, respectively. The improved jump height in these studies was attributed to an improved pre-stretch augmentation.[31,41,42] An improved ability to rapidly decelerate and absorb the impact forces before efficiently transitioning into the concentric phase demonstrates increased neural drive and an improved ability to use elastic energy via the stretch shortening cycle.

Kyrölänen et al[46] reported improved take off velocities following plyometric training. The improved take off velocity was attributed to an increase in mechanical efficiency, ie, decreased energy expenditure through improved use of elastic energy. This change in MTU behavior was also exhibited in Hirayama et al.[35] However, in this study the change in MTU behavior resulting in improved ground reaction force production was attributed to neural modulation. What must also be taken into consideration is that this intervention lasted one day, which exhibits the speed at which the neuromuscular adaptations to plyometric training can occur.[35]

Limitations

Of the 8 studies under review, 2 of them observed no differences in neuromuscular adaptations between groups. However, these studies still demonstrated differences in jump performance. There are a few potential reasons that jump performance improved without any significant change in EMG signal.

The first article under review by Kyrölänen et al[46] showed that there was an increase in take-off velocity and an improvement in mechanical efficiency after 15 weeks of SSC style power training, but also showed no differences in muscular recruitment strategy as well as ground contact time. In their conclusion, the researchers explained that these improvements were a result of improved joint control and an increase in the rate of force development of the knee extensors. A limitation this group noted was the difference in the parameters for testing when compared to their training style. Athletes trained with a sledge apparatus and additionally performed different quick hopping and jumping activities independent of the sledge. However, when tested on the sledge apparatus, the athletes were to assume a knee flexion angle of ~90°. This type of jump strategy is presumably much different from those used in training. Beginning a jump from 90° of knee flexion would likely bias a hip and knee dominant strategy as evident in previous studies reviewed.[42,44] A hip or knee dominant jump strategy favors concentric rather than eccentric power generation and would likely limit the amount of MTU elasticity usage at the triceps surae/Achilles tendon complex. This could explain why no differences were seen pre- and post-training in this particular study.

Kubo et al[31] also obtained EMG activity data that is somewhat inconsistent with the majority of the other studies reviewed. This study observed better jump performance as measured by jump height and pre-stretch augmentation when comparing an SSC trained leg with a resistance trained leg of the same subject. In their conclusion, the main variable that they deem responsible for this difference is joint stiffness. They define joint stiffness as the joint's resistance to angle change during the eccentric portion of the jump. This change in joint stiffness cannot be explained from the results that they reported. Resistance training showed greater relative structural changes, including muscle volume and tendon stiffness, however, this group demonstrated lower stiffness than the SSC group during the jump testing. Kubo et al[31] also showed no significant difference between a resistance trained group and an SSC trained group in regards to the overall amount of EMG activity during the different phases of the jump testing for the plyometric group.

General limitations were identified throughout the reviewed articles. One of which was the ambiguity and variability in the definition of jump performance. In the articles reviewed, there were many aspects of jumping that could be included in the appraisal of jump performance, making it difficult to interpret due to a heterogenous data set. However, because the timing of the eccentric portion of the jump is relevant to the use of an MTU, the variables that would be related to this were taken into consideration.

The participants and the sample sizes within these articles also limits the generalizability of the results. The sample sizes ranged from 8 to 36 subjects, but the experimental group was never more than 11. Only 2 studies had a total sample size of >20 participants. Articles reviewed did test either male or female, but the number of female participants were limited. Only one study tested both males and females. Lastly, the mean age of the participants tested never surpassed 25.5 years and was never less than 20. Future studies should seek to acquire larger sample sizes as well as more diverse age and sex populations.

The authors of this review are interested in the implications of plyometric training for a population of patients with Achilles tendinopathy; however, all of the subjects in this review were healthy. Information on neuromuscular ability to access MTU elasticity, as well as the ability to respond to plyometric training is limited in the injured population. Some studies have demonstrated a decrease in jump performance in patients with Achilles tendinopathy,[3,45,47,48] as well as efficacy for using plyometric loading with tendinopathy patients.[3,25,48] However, the exact neuromuscular strategies exhibited by an unhealthy population and the subsequent adaptations from training are not yet known.

Suggestions for future research

Suggestions for further research should include studies looking at MTU use in a population of patients with Achilles tendinopathy. It would be useful for subsequent research to look at the effect of a more structured training protocol than was described in the majority of the studies in this review. Periodization, progression and specificity are well documented strength and conditioning principles and would likely have an effect on the outcome of any graded plyometric loading program.[49] The plyometric loading protocols that were presented in the studies reviewed were wide ranging, both in their exercise selection as well as dosage. Though the majority of them showed an increase in the ability to use elasticity of an MTU, guidance as far as selecting the best exercise and dosage for patients with Achilles tendinopathy is limited. In the future, studies demonstrating a more principled way of exercise selection and construction of periodization may be helpful in order to decrease the heterogeneity in exercise program design.

Although all the studies in this review used EMG as a measurement tool, few of them segmented their data to look at timing of EMG, as it appears the timing of muscle activation is the primary adaptation to plyometric training. It is recommended that future research investigates the timing of the EMG signal and applies dynamic ultrasound to better quantify the tendon versus fascicle length change during plyometric activities.

Finally, a limitation of the research in this area is the quality of the evidence as there are a lack of randomized controlled trials investigating this population.

CONCLUSION

Previous research has shown an inconsistent correlation between tendon structural changes, pain, and rehabilitation outcomes.[20,45,50] Studies have also demonstrated that individuals with Achilles tendinopathy have a reduced ability to harness elastic energy from the MTU.[3,45,47,48] Additionally, recent literature supports the idea that protocols of heavy slow resistance or eccentric overload training will improve the perceived pain of tendinopathy, but may not be effective in returning individuals with Achilles tendinopathy to prior levels of function.[20,45] Evidence shows that the MTU in healthy subjects functions via contraction of the muscle and elongation of the tendon during loading situations with greater velocities.[26–28,32,36,37,40,51] This review suggests that the neuromuscular adaptations to plyometric loading increased the speed and timing of the muscular contraction of the triceps surae thereby improving the ability to load the Achilles tendon and use stored elastic energy. Based on these findings, the authors of this review suggest that progressive, plyometric based loading may be an integral component in rehabilitation. More research needs to be done to investigate using plyometric based loading in patients with Achilles tendinopathy.

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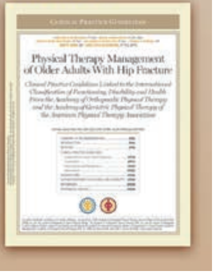

Physical Therapy Management of Older Adults With Hip Fracture