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ABSTRACT

Background and Purpose: The capacity of the Achilles tendon during a 1-repetition eccentric maximum contraction is largely unknown. This study examined the maximum ankle torque during a concentric/eccentric heel raise/lowering task and while running in healthy individuals and participants with chronic Achilles tendinopathy. These findings were applied to a 10-week training program for a patient with chronic Achilles tendinopathy. **Methods:** A total of 13 subjects (9 healthy and 4 with Achilles tendinopathy) participated in this study. Subjects were asked to perform a maximum eccentric contraction wearing a weighted vest while collecting 3-dimensional biomechanical variables. Subjects also ran along an instrumented runway to assess torque at the ankle joint. All participants completed VISA-A **Outcomes:** On the VISA-A, subjects with Achilles tendinopathy (AT) scored on average 28 points less than the healthy controls and were 27% weaker. The peak ankle torque during a single leg lowering task and running was 3.1 Nm/kg and appeared similar between controls and participants with chronic AT. Findings of the study when applied in a 10-week high load eccentric rehabilitation program demonstrated improved tendon characteristics and VISA-A score. **Conclusion:** Unhealthy tendons likely can tolerate high loads during rehabilitation and AT programs should consist of progressive resistive exercises instead of movements that emphasize repetitions.

Key Words: exercise, progressive resistance exercise, strength training

INTRODUCTION

Chronic mid-portion Achilles tendinopathy (AT) is characterized by pain, localized tendon thickening, and results in degeneration of the tendon, changes in collagen, and activity limitation.[1,2] With the use of diagnostic musculoskeletal ultrasound, additional pathoanatomical features include hypoechoic areas and a decrease in stiffness.[3,4] Although the incidence of AT primarily occurs in athletic populations that include novice and elite running, soccer, and rock climbing, other sedentary individuals are susceptible as well.[5-11]

Eccentric exercise is the most common type of rehabilitative treatment for AT but with various levels of success.[10,12-14] The scientific literature is replete with the Alfredson protocol that consists of up to 180 repetitions daily, and as appropriate additional weight could be added via a backpack.[15] A few studies cite using a backpack. In the clinic, performing an eccentric exercise with a backpack in excess of 20 Kg requires significant therapist oversight. This may be one reason most studies only use bodyweight with high repetitions. In a 5-year follow-up study comparing eccentric exercise to active rest for patients with AT, Silbernagel et al[12] demonstrated that 65% of the participants rated themselves as painfree. This included participants in the active rest only group. All-in-all, only about 50% of patients with AT respond to eccentric exercise. Similarly, in an 8-year follow-up study, 29% of patients went on to have surgery and 41% began having problems with the noninjured tendon after returning to previous activity.[10]

The precise cause of AT is still unclear, is likely multifactorial, and is the failure of the body's ability to adapt to the stress applied. For appropriate adaptation of the tendon to occur, significant mechanical loading is required.[16-19] Performing 180 eccentric ankle dorsiflexion repetitions may not effectively load the tendon high enough to produce the appropriate collagen synthesis necessary for tendon healing and remodeling. Interestingly, collagen synthesis may be irrespective of the type of load applied.[19,20] Arampatzis et al[19] conducted a 14-week study comparing high and low strain isometric plantar flexion strengthening exercises and discovered that high load provides a coordinated muscle-tendon unit adaptation to the plantar flexor group, whereas low load only showed positive adaptations to the muscle. This suggests that tendons require high strain activities to achieve collagen remodeling and a positive change in tendon thickness and stiffness. In a randomized controlled trial, Beyer et al[21] demonstrated a significant reduction in tendon thickness and symptoms in both the concentric and eccentric exercise groups. This particular protocol progressively loaded the tendon over a 12-week period with the highest loads and lowest repetitions occurring in weeks 9 to 12. Specifically, weeks 9 to 12 consisted of 4 sets of 6 repetition maximums. The higher loads consisted of using either a leg-press or barbell weight system. This essentially achieves the same outcome as the Alfredsen protocol which requires 180 repetitions, with higher load and dramatically fewer repetitions. Although the load was higher in the Beyer et al[21] study, subjects performed 3 different types of 2-legged exercises that may not have loaded the tendon high enough for full remodeling to occur.

The full capacity of the AT is also unknown and current strengthening programs may potentially under dose the necessary strain/stress needed for collagen remodeling. Achilles tendon rehabilitation programs seldom calculate either a 1-repetition maximum concentrically or eccentrically and likely stress the tendon around one-third of its maximum output.[20] As an example, the peak ankle plantar flexion moment during running is between 2-3 Nm/kg, depending upon the speed. In contrast, a single-leg (body weight only) heel rise is between 1.2 and 1.6 Nm/kg.[20,22] In addition, during a squat jump, the ankle moment can reach as high as 5-6 Nm/kg.[23] Although Alfredsen protocol does not reach these loads despite the heavy slow resistance program using one maximal concentric contraction, higher load is likely achievable using one maximal eccentric contraction. The first purpose of this current study was to determine single-leg 1-repetition concentric and eccentric maximums for healthy controls and subjects with a past history of AT. Secondly this study aimed to compare the ankle joint planar flexion moment during running with a single-leg heel rise during a maximal eccentric contraction. Finally, the study attempted to determine whether a 10-week maximum tendon-loading eccentric exercise program produced changes in tendon characteristics.

METHODS

Nine healthy subjects (5 male and 4 female) and 4 subjects with AT (2 male and 2 female) participated in this study. Subjects in the AT group had a history of chronic Achilles tendinopathy for greater than 1-year. Participants were recruited from the university and consisted of students and staff and ranged in age from 23-44 years. Exclusion criteria was current AT symptoms or previous surgery. All subjects read and signed a university approved consent prior to the testing. Subjects were then instructed to complete the Victorian Institute of Sport Assessment – Achilles (VISA-A) form as well as a questionnaire regarding their activity and training habits. All participants consented to participate and the procedures described here were approved by a university committee overseeing human subjects' research.

Kinematic and Kinetic Measurements

To obtain ankle joint kinematic and kinetic data, prior to testing, reflective markers were placed on key anatomical landmarks to define a 2-segment biomechanical model of the ankle and shank (Figure 1). Three-dimensional ground reaction force was captured using an AMTI (Advanced Mechanical Technology Inc., Watertown MA) 400mm X 600mm force plate sampled at 1000 Hz. Ten infrared cameras were used to calculate ankle kinematics. During the heel-rise trial, data was collected at 60 Hz while during the running trial, data was collected at 120 Hz. Ankle kinematics were defined by foot motion relative to tibial motion. Kinematic and kinetic data were synchronized through Visual 3-D software (C-Motion Research Biomechanics) and ankle joint moments were then calculated using inverse dynamics.

Figure 1. Reflective markers defining the 2-segment biomechanical model of the lower leg and foot.

Musculoskeletal Ultrasound Measurements

Tendon thickness (longitudinal and cross-section) was measured before and after a 10-week pilot eccentric exercise program. Images were determined using a Hitachi-Aloka (Alpha6-PD2,) musculoskeletal ultrasound with a linear array probe at a frequency of 10-12 MHz. All image measurements were analyzed using the accompanying onboard Hitachi-Aloka software.

Procedure

Subjects were asked to perform one double limb calf raise on a 7-cm block to assess their maximum dorsiflexion and plantar flexion range of motion. In order to estimate their 1-repetition eccentric maximum, a 1-repetition concentric maximum plantar flexion was accomplished with the use of weighted vests. Each subject started with approximately 150% of their body weight. For example, if a subject weighed 75 Kg, the weighted vest consisted of 37.5 Kg. Subjects were instructed to perform a single-leg heel rise and achieve full plantar flexion, even if they felt minimal pain. They were instructed to stop if they thought the pain was either moderate or severe. If any of the subjects needed additional support for balance, a platform was available for them to lightly stabilize themselves. Subjects were able to achieve their 1-repetition concentric maximum within 2 to 3 trials. Once this was achieved a starting point of an additional 40% was added to the vest. Using the example above, an additional 15 Kg was added to the weight vest. The subjects were then instructed to rise up with both feet, then to remove one foot, and attempt to eccentrically lower themselves in a controlled manner using only the remaining foot. Subjects were visually assessed as achieving a slow controlled motion by the examiner watching their movement. If the subject reported the trial felt too easy, more weight was added and the subject tried again. Most subjects were able to find their maximum eccentric weight within 2 to 3 repetitions. Following the single-leg heel lowering task, subjects removed the weighted vest and performed 3 running trials on the force plate.

Pilot Eccentric Exercise Program

A single male subject who had chronic Achilles tendinopathy for 15 years participated in the pilot study. To maximally load the tendon, an eccentric exercise program was developed whereby in a single session, the total repetitions did not exceed 24 (3 sets of 6-8 repetitions). Since performing an eccentric exercise with a backpack or weight vest in excess of 90 Kg requires significant therapist oversight, a leg-press weight machine was used for the exercise protocol. The subject was supervised during their exercise session and was asked to increase their weights when they could reach 8 repetitions. Each session's weight program and repetitions were documented. This pilot eccentric exercise program was investigated on a single subject. Analysis

Concentric and eccentric 1-repetition maximum for each subject was recorded and group means were calculated. VISA-A was recorded for both groups prior to testing. Statistical analysis was not performed because of the small sample size. Descriptive data is provided to support each hypothesis. For the subject with the 15-year history of tendinopathy, tendon thickness was taken before and after the 10-week pilot eccentric exercise progressive resistive exercise program.

OUTCOMES

Results displayed in Table 1 demonstrate the 1-repetition maximum eccentric and concentric contractions between the 2 groups. The AT group demonstrated less capacity and was unable to eccentrically or concentrically load the tendon as much as the healthy group. The differences were more profound during the eccentric contraction condition, resulting in 27% lower output.

Results presented in Table 2 demonstrate the VISA-A scores across both the healthy group and the AT group. All of the healthy participants scored 100 while the AT group scored much less. The average score for the AT group was 72.

Table 3 shows the average peak ankle joint moment (torque) during a maximally weighted single-leg eccentric movement and during running. Both conditions and groups yielded similar results with average peak (ankle torque) values ranging between 2.9 and 3.1 Nm/kg.

This data was used to motivate a maximum load (or 80% 1 rep max) pilot eccentric training program for a patient with chronic AT. This particular subject was a 40-year-old

Table 1. Average 1-repetition Maximum Concentric and Eccentric Contraction Between the Healthy Group and Subjects with Achilles Tendinopathy Expressed as a Percentage of Body Weight

Subjects		Concentric Maximum	Eccentric Maximum
Healthy	S1	155%	201%
	S2	147%	223%
	S3	167%	217%
	S4	179%	209%
	S5	150%	229%
	S6	181%	230%
	S7	144%	233%
	S8	134%	215%
	S9	162%	220%
	Average (SD)	**157% (SD=15.9)**	**218% (SD=10.9)**
Achilles Tendinopathy	S1	144%	189%
	S2	157%	196%
	S3	143%	198%
	S4	155%	183%
	Average (SD)	**149% (SD=7.3)**	**191% (SD=6.9)**

Table 2. VISA-A Scores in Healthy Subjects and in the Achilles Tendinopathy Group

Subjects		VISA-A
Healthy	Subjects 1-9	100
Achilles Tendinopathy	S1	68
	S2	72
	S3	74
	S4	74
	Average (SD)	**72 (2.8)**

Table 3. Average Peak Ankle Joint Moments (Nm/kg) During a Maximally Weighted Single-leg Lowering Task and While Running

	Single-leg Lowering	Running
Healthy	3.0 Nm/kg	3.1 Nm/kg
Achilles Tendinopathy	2.9 Nm/kg	3.0 Nm/kg

male with a 15-year history of chronic AT who did not respond to traditional eccentric exercise protocols (using body weight and high repetitions). His initial VISA-A was 76, starting eccentric load was 240 pounds, and pre-exercise Achilles thickness was 0.63 cm. The progressive resistive exercise program consisted of 3 sets of 6 to 8 repetitions lasting 10 weeks in length and the subject was instructed to increase weight as soon as they could perform 8 repetitions. Following the 10-week program, VISA-A was 100, ending eccentric load was 320 pounds, and tendon thickness was 0.48 cm. Figure 2 demonstrates a reduction in tendon thickness and a decrease in hypoechoic areas following the exercise program. There was a 0.15 cm reduction in tendon thickness resulting in a 24% decrease in overall thickness and the VISA-A score improved by 24 points.

DISCUSSION

The current study shows that the capacity of the AT is much higher than most of the AT rehabilitation programs used in the clinic or in research articles.[21] Effective treatment for AT depends upon how much remodeling occurs in the tendon and traditional AT programs may not load the tendon high enough for reorganization of collagen.[19] There is a clear difference in the eccentric strength (Table 2) of subjects with AT compared to controls. Although the AT groups did not complain of pain during the testing, the differences could be accounted for because of discomfort during the task. However, this still supports the notion that most AT rehabilitation programs do not load the tendon to capacity. In addition, strength deficits of nearly 30% indicate that the muscle/tendon complex may not be strong or stiff enough to overcome the force required during athletic tasks without injuring the tendon. Although this was just a pilot study, the data may prompt clinicians to review AT protocols and encourage therapists to include maximal tendon loading as part of the training. Consistent comments from runners with AT is that if they want to increase their mileage or pace, this results in increased symptoms. This phenomenon may also be the result of a weak or less stiff muscle/tendon. It is hypothesized that because of the limited number of fibroblasts in a tendon, collagen synthesis is best accomplished with higher loads, which might be the basis of a "set point" before remodeling happens.[19] Since higher loads on muscle and tendons result in higher blood flow and oxygenation, it may be in order for adequate protein synthesis to occur at the tendon, the exercises required need to be maximized.[24] While strength gains occur within just a few weeks as a result of neuromuscular effects, it is well known that muscle tissue adaptation to progressive resistive exercise occurs only after 6 weeks; keeping in mind that progressive loading is necessary for muscle adaptation. It may be that current AT programs are not adequate in length as well as load for tendon adaptation to materialize. Interestingly, recent studies suggest that it is not the type of load (eccentric, concentric, or isometric) that produces an effect, but the amount of load.[19,21]

Musculoskeletal ultrasound provides a visual and quantifiable description of tendon morphology and can differentiate between healthy and unhealthy tissue.[25] Unhealthy tendons exhibit hypoechoic areas surrounded by areas of consistent or homogenous tissue. In a recent study, intra- and inter-reliability measures of tendon thickness was determined to be excellent with Interclass Correlation Coefficients (ICC) of 0.98.[26] The unhealthy tendon in this study demonstrated greater thickness (longitudinal) and hypoechoic areas compared to their uninjured healthy tendon. In addition, following the 10-week maximal loading exercise program, the tendon demonstrated a 24% reduction in localized thickness as well as a more homogenous appearance (Figure 2). Although many studies demonstrate improvement with more traditional rehabilitation programs,[10,12,27] as introduced by Alfredson et al,[15] many studies have inconsistent effects across subjects. It may simply be that the tendon requires higher loads for remodeling to occur. Structural changes,

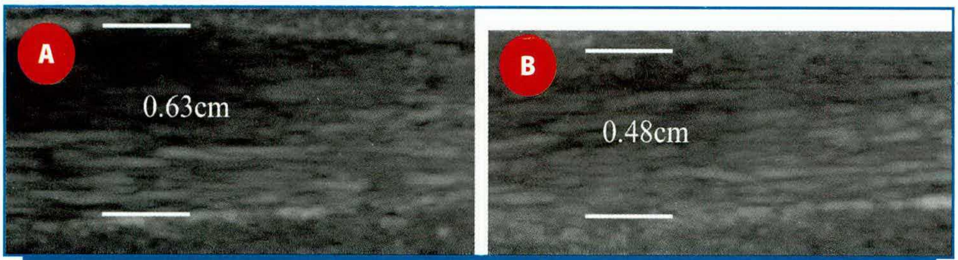

Figure 2. Tendon thickness in an unhealthy Achilles tendon. A, before and B, after a 10-week maximal eccentric loading program.

such as tendon thickness, following exercise was evident in this current study but not all studies agree that changes in collagen occur nor is abnormal tendon structure related to symptom severity. Interestingly, it may be that studies which demonstrated no changes in tendon structure did not load the tendon adequately enough. Although the Beyer et al[21] study achieved a 1-repetition maximum, the contraction type was concentric and the subjects performed all exercises with 2 legs. Both of these protocols had similar outcomes, likely because they did not load the tendon maximally. However, based on the data of this current study, it appears that performing a maximum eccentric contraction may load the tendon 40% to 60% more than a concentric contraction, which is what therapists may need to prescribe for better outcomes.

The Alfredson protocol requires subjects to achieve a total of 180 single-leg body weight only heel lowering exercises.[15] The load applied to the tendon during a single-leg body weight only heel lowering task is 2 to 3 times less than the load during running. A body-weight only exercise program minimally loads the tendon compared to the tendon's total capacity that may not produce enough positive change in the tendon. The concentric maximum during a heel rise was 61% and 42% lower than the eccentric maximum heel rise in the controls and participants with AT, respectively (Table 1). This suggests a heavy slow resistance protocol using a concentric 1-repetition maximum would result in significantly lower loads as compared to an eccentric lowering program. And, the ankle joint moment during a 1-repetition eccentric maximum (weighted vest) is comparable to running and matching the load required during a sport task. However, running requires a high number of repetitions and high load (in excess of 2000 steps per mile) which many patients with AT may not tolerate. An important concept may be to control repetitions of high loads, using short bouts of running in conjunction with the weighted vest or a leg press machine to return patients to running.

Using the protocol described above, a single participant with a 15-year history of AT improved his VISA-A score to 100 and reduced his tendon thickness on ultrasound. The case study participant started at an eccentric 1-repetition maximum of 240 pounds (141% of BW). At completion of the program the eccentric 1-repetition maximum increased to 320 pounds (188% of BW) an increase of 33% from their starting eccentric 1 repetition maximum. This case illustrates the practical application of the eccentric 1-repetition maximum protocol. Although it is certain not all patients will have a similar response, the positive response of this patient with long standing AT suggests the potential for a therapeutic effect with high load and low repetition protocols.

Limitations

This was a pilot study and consisted of a low number of overall subjects. The data is more useful in planning larger studies and describing likely overall capacity of healthy participants and participants with AT. Because the sample size of the AT groups was very small, and likely not representative of a large diverse set of participants with AT, general inferences should be avoided until studies with larger sample sizes are completed.

CLINICAL RELEVANCE

With further testing and additional subjects, this topic of investigation has significant clinical relevance. The literature suggests that between 45% and 50% of subjects with AT benefit from rehabilitation. This data suggests with significantly greater tendon loading, more collagen remodeling may be achieved. It is also worth noting that unhealthy tendons can tolerate higher loads during rehabilitation and AT programs should consist of progressive resistive programs instead of programs that emphasize repetitions.

CONCLUSIONS

This study supports the need for higher tendon loading during AT rehabilitation programs. Although the mode that was used in this study was an eccentrically derived training program, the type of load is likely inconsequential. In addition, both the healthy and the unhealthy tendon can tolerate significantly more load than most current studies employ.

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