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Immediate effect of photobiomodulation therapy on Achilles tendon morphology and mechanical properties: an exploratory study

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Abstract

Objectives: Evaluate the immediate (within 4 hours) effects of laser-induced photobiomodulation (PBM) therapy on Achilles tendon morphology and mechanical properties in healthy and pathologic tendons.

Materials and Methods: Twenty people with healthy Achilles tendons and twelve people with Achilles tendinopathy participated. One Achilles tendon received PBM treatment following an established protocol and the contralateral side received a placebo treatment. Achilles tendon morphology and mechanical properties were evaluated bilaterally with ultrasound imaging and continuous shear wave elastography immediately before treatment, immediately after treatment, then 2- and 4-hours after treatment.

Results: There were no immediate effects of PBM on tendon morphology or mechanical properties when comparing the PBM-treated side and placebo-treated side within each cohort. Additionally, the effects of PBM did not differ between healthy and pathologic Achilles tendons.

Conclusion: When treated with a laser-induced PBM treatment, healthy and pathologic Achilles tendons do not have immediate (within 4 hours) changes in tendon morphology or mechanical properties. These findings suggest that PBM therapy can be administered before other clinical treatments or high-load activities.

Keywords

Tendinopathy; Tendinitis; Laser Therapy; Material Properties; Elastography; Ultrasound

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Conflict of Interest Statement

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Introduction

The Achilles tendon is a collagenous tissue that is designed to efficiently store and release elastic energy during locomotor activities. The efficiency of this energy transfer relies on many factors, including the integrity of the Achilles tendon.^{1–6} Achilles tendinopathy is an overuse injury that reduces the integrity of the tendon.^{7,8} This manifests as fusiform thickening of the tendon and reduced mechanical properties.^{9–13} Pain during loading activities and functional impairments accompany these structural changes and lead patients to seek treatment.

Exercise therapy is currently the standard of care for treating Achilles tendinopathy.¹⁴ Throughout a long-term exercise program, the mechanical properties (e.g. strength and stiffness) of the Achilles tendon increase.^{15,16} Interestingly though, there appears to be immediate (within 30 minutes) and short-term (within 7 days) reductions in mechanical properties after a single bout of exercise.^{17,18} Taken together, these findings illustrate that the Achilles tendon is a metabolically active tissue and undergoes complex remodeling in response to exercise. There are, however, other treatments (e.g. injection therapies, shock-wave therapy, laser therapy) that are commonly used as adjuncts to exercise that may influence the remodeling process. In order to improve outcomes and tailor treatments for patients with Achilles tendinopathy, the mechanisms that explain the effectiveness of each adjunct treatment need elucidated.

Laser therapy has been investigated for the treatment of tendinopathies, with mixed outcomes in human-subjects research.¹⁹ For Achilles tendinopathy specifically, Tumilty et al²⁰ found that after 12 weeks of treatment patients who receive exercise plus laser therapy have better outcomes than patients who receive only exercise therapy. Furthermore, Stergioulas et al²¹ noted that patients who are treated with only exercise therapy for 12 weeks have similar outcomes to patients who are treated with exercise plus laser therapy for 4 weeks. These positive outcomes may be attributed to the physiologic effects of laser therapy, which include reducing inflammation,^{22,23} and cell apoptosis,²⁴ inhibiting activity of matrix metalloproteinases (MMPs),²⁵ and increasing collagen synthesis^{26,27} and angiogenesis.²⁸ However, changes in patient-reported symptoms (e.g. pain) have been the primary focus for evaluating the efficacy of laser therapy rather than also considering tissue-level changes.^{19,21,29–32} This is problematic since full symptomatic recovery does not ensure full structural or functional recovery of the musculotendinous unit.^{33,34} In order to optimize clinical outcomes for patients with Achilles tendinopathy, there is a need to further evaluate the physiological effects of laser therapy on human tendon.

Laser therapy, similar to exercise therapy, may induce temporary changes to the tendon's morphology and mechanical properties. This would affect the efficiency of the muscle-tendon unit and potentially increase the tendon's susceptibility to further tissue damage. Additionally, laser therapy may affect the tendon's response to exercise therapy if administered beforehand. Therefore, the purpose of this exploratory study is to evaluate the immediate (within 4 hours) effects of a laser-induced photobiomodulation (PBM) treatment on Achilles tendon morphology and mechanical properties in healthy and degenerative tendons. We hypothesize that changes in tendon morphology and mechanical properties will

be greater in a laser-treated side compared to a placebo-treated side in people with healthy Achilles tendons and people with Achilles tendinopathy. Additionally, we hypothesize that changes in tendon morphology and mechanical properties would be greater in tendinopathic Achilles tendons compared to healthy Achilles tendons when treated with PBM.

Materials and Methods

Study Design

Two cohorts of participants were enrolled in this study. The first cohort included participants with healthy Achilles tendons and the second cohort included participants with Achilles tendinopathy. After determining each participant's eligibility, demographics, anthropometrics, and a subjective history of current and previous lower body injuries were gathered. Achilles tendon morphology and mechanical properties were acquired bilaterally at baseline. PBM treatment was then administered to one Achilles tendon following an established protocol²⁰ and a placebo treatment was administered to the other Achilles tendon. Tendon morphology and mechanical properties were measured bilaterally immediately after the PBM treatment, 2 hours after the PBM treatment, and 4 hours after the PBM treatment. To reduce the effects of loading between measurements, participants were asked to refrain from performing activities thought to influence mechanical properties (e.g. running, jumping, and stretching). A single, experienced evaluator performed all experimental procedures. Prior to data collection, each participant provided written consent after being thoroughly introduced to the study procedures and potential risks. This study was approved by the Institutional Review Board at the University of Delaware.

Participants

Twenty participants with healthy Achilles tendons were enrolled and their descriptive information are reported in Table 1. Healthy participants were at least 18 years old with no history of Achilles tendon injury or pain. To ensure the healthy participants had no underlying Achilles tendon pathology or tissue degeneration (i.e. asymptomatic Achilles tendon degeneration), they were screened with ultrasound imaging, a clinical evaluation performed by a licensed physical therapist, and the Victorian Institute of Sports Assessment - Achilles (VISA-A) questionnaire.³⁵ If there were clinical signs of Achilles tendon pathology (e.g. pain to palpation, palpable tendon thickening) or tissue degeneration (e.g. fusiform thickening or hypoechoic regions visualized with ultrasound) during the screening procedures, the potential participant was excluded.

Twelve participants with midportion Achilles tendinopathy were enrolled and their descriptive information are reported in Table 1. Participants were included in this cohort if they were at least 18 years old, had a clinical diagnosis of midportion Achilles tendinopathy, and had ultrasound-confirmed tendinosis.³⁶ Achilles tendinosis was defined as a minimum of 2 mm of midportion tendon thickening as previously reported in the literature.^{10,37,38} Briefly, tendon thickening is measured by taking the difference in tendon thickness at the thickest part of the tendon and the tendon's thickness 2 cm proximal to the osteotendinous junction.³⁸ Participants were excluded from the tendinopathic cohort if they presented with pathology in addition to midportion Achilles tendinopathy (e.g. insertional Achilles

tendinopathy, retrocalcaneal bursitis, history of Achilles tendon rupture). These diagnoses were ruled out by screening with ultrasound imaging and a clinical evaluation. Exclusion criteria for both cohorts included currently taking heat or light sensitive medications, an open wound in the treatment area, a diagnosis of peripheral neuropathy, or previously received laser therapy to either Achilles tendon.

Laser Treatment

Laser-induced PBM treatment was administered to one Achilles tendon and a placebo treatment to the other Achilles tendon. The order of treatment was randomized. The placebo treatment was identical to the actual treatment, except the finger-trigger that activates the laser was not depressed. Participants were blinded to treatment. Blinding was maintained during the treatment by positioning participants in prone and having them wear noise-cancelling headphones with white noise playing. These procedures ensured that the participant could not see when the finger-trigger was depressed or hear the beeping that occurs when the laser is active.

For the healthy cohort, the side that received treatment (i.e. right or left) was determined with a computer-generated randomization scheme. This resulted in 11 dominant and 9 non-dominant limbs being treated. Limb dominance was defined as the participants reported preferred kicking leg. For the tendinopathic cohort, the side that received treatment was the side with greater local tendon thickening, which is also typically the side of worse symptoms. This resulted in 4 dominant and 8 non-dominant limbs being treated in the tendinopathic cohort.

PBM treatment was delivered following a previously reported protocol.²⁰ This protocol was selected since it has been shown to improve clinical outcomes for patients with Achilles tendinopathy.²⁰ Briefly, a LightForce EX unit (LiteCure LLC, Newark, DE, USA) was used for treatment. The tendon was irradiated with an in-contact, constant scanning motion (2.5–5 cm/second per manufacturer) from the osteotendinous junction of the Achilles tendon to 10 cm proximal. Ultrasound imaging was used to locate the osteotendinous junction and a tape measure was used to measure 10 cm proximal. Marks were made on the skin to visualize the treatment area. The medial, lateral, and posterior aspects of the Achilles tendon were each treated for 30 seconds (i.e. total treatment time of 1 minute and 30 seconds).

The PBM treatment was administered with a 3 cm² ball applicator. A blend of 810:980 nm laser light in a 20:80 power ratio was used. The total treatment area was 67.5 cm², which was calculated from the length of the treatment area (10 cm), beam diameter (1.95 cm), and the area of the laser end caps (3.0 cm² for each aspect). The power output was 10 W pulsed at a frequency of 100 Hz, resulting in an average power output of 5 W. This led to an average power density of 74.07 mW/cm². Applying the treatment for 1 minute and 30 seconds resulted in a total dose of 450 Joules (150 Joules per aspect) at 6.66 J/cm².

Tendon Morphology

Achilles tendon morphology was evaluated with B-mode ultrasound imaging using a LOGIQ e ultrasound system (GE Healthcare, Chicago, IL, USA) with a wide-band linear array probe (5.0–13.0 MHz). Participants were positioned prone with their feet hanging

naturally over the edge of a treatment table. Images were taken at the same location along the length of the Achilles tendon at each time point by marking and recording the distance from the osteotendinous junction of the Achilles tendon to the center of the treatment area. For the healthy cohort, images were acquired immediately distal to the myotendinous junction of the soleus. For the tendinopathic cohort, the location of greatest tendon thickness was used on the PBM-treated side and an anatomically matched location was used on the placebo-treated side.

Three long- and short-axis images of each Achilles tendon were taken at each time point to measure Achilles tendon thickness and cross-sectional area. Ultrasound images were exported from the ultrasound scanner to an external computer where measurements were made with OsiriX imaging software (Pixmeo SARL, Bernex, Switzerland). Measurements were taken in a random order by a single assessor who was blinded to treatment. Intra-rater reliability for measuring Achilles tendon thickness and cross-sectional area using ultrasound imaging has been found to be excellent.³⁹

Tendon Mechanical Properties

Achilles tendon mechanical properties were quantified with continuous shear wave elastography (cSWE) bilaterally at the same location of morphologic measurements. cSWE has been shown to be a valid and reliable method for quantifying Achilles tendon mechanical properties and is described in detail elsewhere.⁴⁰ Briefly, an external actuator (Mini-Shaker Type 4810, Bruel & Kjaer, Norcross, GA, USA) generates a series of continuous shear waves that propagate along the length of the Achilles tendon at six known frequencies (322, 358, 402, 460, 536, 643Hz). While these waves propagate, a SonixMDP Q + ultrasound system (Ultrasonix, Vancouver, Canada) with a L14-5/38 probe and a 128-channel data acquisition device collect raw radiofrequency data (frame rate=6438 frames/s). These data are used to track tendon displacement and estimate wave speed. Static shear modulus and viscosity of the tendon are then calculated on a pixel-wise basis using viscoelastic modeling. Static shear modulus and viscosity is then averaged for the selected region of interest (i.e. the Achilles tendon), which is identified on a B-mode ultrasound image. Lastly, a dynamic shear modulus at a frequency of 400 Hz was calculated using static shear modulus, viscosity and the Voigt model. Dynamic shear modulus is calculated since it is more comparable to elastography techniques that estimate tendon mechanical properties by measuring the group velocity of a broadband shear wave (e.g. Supersonic Shear Imaging).

During cSWE procedures, participants were secured to a platform in 10° of ankle dorsiflexion. The dorsiflexed angle ensured that the tendon was within the linear elastic region (i.e. constant elastic modulus). The feet were secured to minimize muscle activity and movement. Three trials on each tendon were performed at each time point and the average was used for analysis.

Statistical Analysis

Descriptive data are reported as means and standard deviations (SD). The variables of interest were tendon thickness, cross-sectional area, static shear modulus, viscosity, and

dynamic shear modulus. The immediate (within 4 hours) effects between laser- and placebo-treated sides were compared with 2 (laser-treated side vs. placebo-treated side) x 4 (time) repeated measures ANOVA for each variable of interest. This analysis was performed separately for each cohort (i.e. tendinopathic and healthy). The immediate effects between healthy and tendinopathic tendons treated with laser were compared with a 2 (laser-treated side tendinopathic cohort vs. laser-treated side healthy cohort) x 4 (time) mixed model ANOVA for each variable of interest. For all analyses, Greenhouse-Geisser corrections were applied when assumptions of ANOVA were violated. In addition to raw values, changes in tendon morphology and mechanical properties were calculated as the difference between baseline and each follow-up time point. Changes were compared against the minimal detectable change ($MDC_{95\%}$) for each variable of interest. $MDC_{95\%}$ for each variable are as follows: Static shear modulus= 5.1 kPa; Viscosity= 3.0 Pa*s; Dynamic shear modulus= 11.0 kPa; Tendon Thickness= 0.089 mm; Cross-sectional area= 0.009 cm².

Results

For the healthy cohort, descriptive data obtained at baseline and each post-treatment time point are presented in Table 2. There were no significant treatment by time interactions for measures of tendon morphology or mechanical properties ($p=0.273-0.922$; $\eta^2_{\text{partial}}=0.008-0.066$) for the healthy cohort. On the placebo-treated side, there were no changes in tendon morphology or mechanical properties greater than the $MDC_{95\%}$ (Figure 1–5). On the laser-treated side, there was an increase in tendon thickness and a decrease in cross-sectional area detected 2-hours after treatment and a decrease in tendon thickness 4-hours after treatment that exceeded the $MDC_{95\%}$. There were however no changes in mechanical properties greater than the $MDC_{95\%}$ on the laser-treated side.

For the tendinopathic cohort, descriptive data obtained at baseline and each post-treatment time point are presented in Table 3. There were no significant treatment by time interactions for measures of tendon morphology or mechanical properties ($p=0.316-0.752$; $\eta^2_{\text{partial}}=0.035-0.100$) for the tendinopathic cohort. On the placebo-treated side, there was a decrease in tendon thickness 2-hours and 4-hours after treatment (Figure 1) and a decrease in cross-sectional area immediately after treatment and 4-hours after treatment (Figure 2). There were no changes in mechanical properties greater than the $MDC_{95\%}$ on the placebo side (Figure 3–5). On the laser-treated side, there was a decrease in cross-sectional area at all time points after treatment that exceeded the $MDC_{95\%}$ (Figure 2) and a decrease in static shear modulus 4-hours after treatment that exceeded the $MDC_{95\%}$ (Figure 3). There were no changes in tendon thickness, viscosity, or dynamic shear modulus greater than the $MDC_{95\%}$ on the laser-treated side (Figure 1, 4, and 5).

When comparing the immediate effects between healthy and tendinopathic tendons treated with laser, there were no significant group by time interaction effects for mechanical properties (Dynamic shear modulus: $p=0.586$; $\eta^2_{\text{partial}}=0.021$, Static shear modulus: $p=0.461$; $\eta^2_{\text{partial}}=0.028$, Viscosity: $p=0.514$; $\eta^2_{\text{partial}}=0.025$). Additionally, there were no significant group by time interaction effects for measures of tendon morphology (tendon thickness: $p=0.673$; $\eta^2_{\text{partial}}=0.016$, cross-sectional area: $p=0.062$; $\eta^2_{\text{partial}}=0.084$).

Discussion

This exploratory study aimed to evaluate the immediate (within 4 hours) effects of a laser-induced PBM treatment on Achilles tendon morphology and mechanical properties. The main finding was that for both healthy and tendinopathy cohorts there were no differences between the laser-treated and placebo-treated sides over time. Additionally, the effects of PBM treatment did not differ between healthy and tendinopathic Achilles tendons. However, since there was a reduction in tendon cross-sectional area that exceeded the MDC_{95%} following PBM that was not seen with the placebo treatment, the effect of PBM on tendon cross-sectional area warrants further investigation.

Research on laser therapy is currently limited to basic research that use animal models and clinical research that does not necessarily investigate the physiologic mechanisms responsible for positive outcomes. Since increased collagen synthesis^{26,27} and decreased cell apoptosis²⁴ are proposed physiologic effects of laser therapy, measuring changes in tendon mechanical properties following laser treatment may be critical to improve dosage guidelines and elucidate mechanisms responsible for clinical outcomes. The current study used cSWE to evaluate the immediate (within 4 hours) effects of a single laser treatment on human Achilles tendon mechanical properties. This was the first step to evaluate the physiologic effects of laser therapy on tendon mechanical properties. Future research is needed to understand how tendon mechanical properties respond throughout a typical laser therapy program since positive clinical outcomes are commonly reported with longer follow-up periods (e.g. 12 weeks) and programs that involve multiple treatments (e.g. 2 treatments per week for 4 weeks).^{20,31,32}

Tendon morphology is frequently evaluated with ultrasound and magnetic resonance imaging in clinical research and relates to symptom severity and physical activity levels in patients with Achilles tendinopathy.³⁸ Clinical trials have reported positive changes in tendon morphology (i.e. reduction in tendon size) and pain when treated with exercise therapy.^{41,42} Additionally, Tumilty et al.²⁰ found reductions in tendon thickness following a treatment program that incorporated both exercise and laser therapy. Findings from these studies^{20,41,42} suggest that treatment of Achilles tendinopathy should focus on normalizing tendon structure, yet a previous systematic review concluded that improvements in symptoms and function cannot be explained by changes in tendon structure.³⁴ Similar to Tumilty et al., the current study found that laser treatment led to reductions in tendon cross-sectional area that exceeded measurement error in participants with Achilles tendinopathy. This indicates that tendon cross-sectional area may be a variable of interest for monitoring treatment response in patients with Achilles tendinopathy.

In addition to changes in tendon morphology, laser therapy has previously been shown to reduce short- and long-term pain following treatment.^{20,21,29} Reductions in pain may be due to the anti-inflammatory effects of laser therapy or remodeling of the tendon's structure. Evidence also suggests that laser therapy may increase pain-pressure threshold.²² Collectively, it appears advantageous to administer laser treatment early in a treatment session to reduce pain so that more loading exercises can be performed. To investigate this notion further, we performed a secondary analysis evaluating the immediate effects of PBM

on pain. We hypothesized that pain to palpation would decrease on the laser-treated side in patients who presented with palpatory pain (n=10). At each of the four time points a single examiner palpated the midportion of the Achilles tendon using a pinch-grip technique moving up the tendon from distal to proximal. Participants were prone and asked to report the greatest amount of pain experienced during palpation. Pain was reported using the Numeric Pain Rating Scale (NPRS), which is an eleven-point scale ranging from 0 (no pain) to 10 (worst imaginable pain).⁴³ This technique has been previously reported in Achilles tendinopathy literature and has good intra-rater reliability.⁴⁴ The immediate effects of PBM on pain to palpation was analyzed with a one-way repeated measures ANOVA. Changes in pain to palpation were also calculated and compared against a minimal clinically important difference (MCID) of two points on the NPRS.⁴⁵ We found no immediate effects of PBM on pain to palpation (Baseline: 4.4(2.1), Immediate: 3.9(2.2), 2-hours: 3.3(1.9), 4-hours: 3.4(1.8); $p=0.07$; $\eta^2_{\text{partial}}=0.22$). Additionally, reductions in pain were smaller than the MCID. These results suggest that a single PBM treatment does not lead to clinically meaningful reductions in pain to palpation in patients with Achilles tendinopathy. This contradicts Bjordal et al²² who showed an immediate increase in pain-pressure threshold following a low-level laser treatment. However, comparing our findings is difficult since there were major differences in study designs (i.e. subjects who participated in Bjordal et al²² performed pain inducing activity before treatment), laser treatment parameters, and methods for assessing pain. Further research is needed to investigate the analgesic effects of laser therapy.

There are several limitations to this study. One limitation is how power density was calculated for the laser treatment. The World Association of Laser Therapy recommends a power density of less than 100mW/cm² for irradiating the Achilles tendon,⁴⁶ but it is unclear if this should be calculated over the spot size of the laser or over the treatment area. A power density of 74.07 mW/cm², which was calculated over the entire treatment area, was used for the PBM treatment in the current study. This calculation however neglects to consider that the laser treatment targeted the same tissue from three different directions (i.e. medial, lateral and posterior) and therefore could be considered to have a power density of 222mW/cm². Regardless of how power density was calculated, the PBM treatment parameters were based on Tumilty et al.²⁰, who demonstrated positive clinical outcomes in patients with Achilles tendinopathy. A second limitation is heterogeneity within the tendinopathic cohort. Participants with and without pain to palpation were included in the tendinopathic cohort and there was large variability in the patient's duration of symptoms. This may partially explain why the short-term effects of PBM treatment did not differ from the effects of a placebo treatment. However, the relatively high VISA-A scores indicate a conservative sample was used (i.e. greater changes might be expected in a sample with more severe pathology). A third limitation is that the tendinopathic cohort had a relatively small sample size and an a priori power analysis was not completed. A post-hoc power analysis was performed using the determined interaction effect for tendon cross-sectional area in the tendinopathic cohort ($\eta^2_{\text{partial}}=0.1$) with $\alpha=0.05$ and 80% power. This showed that a sample size of 36 subjects would be needed to detect differences between PBM and placebo treatments in the tendinopathic cohort. This study was however the first study to explore the immediate effects of laser therapy with innovative techniques and therefore an a priori power

analysis was not feasible. Lastly, the healthy and tendinopathic cohorts were not matched for possible covariates (e.g. age, sex). Therefore, the comparison between healthy and tendinopathic tendon treated with PBM treatment should be interpreted with caution.

Conclusion

Laser therapy does not have immediate (within 4 hours) effects on Achilles tendon morphology or mechanical properties when administered with the presented laser parameters. This was found in both healthy and degenerative Achilles tendons. Findings suggest that tendon cross-sectional area may be a variable of interest for monitoring treatment response in future research and that laser therapy can be administered at any time during a clinical treatment session without influencing other treatments.

Perspectives

This is the first study to investigate the effects of a laser-induced photobiomodulation therapy on human Achilles tendon structural properties. Our findings suggest that a single treatment does not have immediate effects on morphology or mechanical properties in healthy and pathologic tendons. In order to optimize outcomes for patients with Achilles tendinopathy, further research is needed to understand the mechanisms that explain the efficacy of laser therapy.

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Figure 1.
Change in Achilles tendon thickness in the four-hour period following photobiomodulation therapy.

Figure 2. Change in Achilles tendon cross-sectional area in the four-hour period following photobiomodulation therapy.

Figure 3. Change in Achilles tendon static shear modulus in the four-hour period following photobiomodulation therapy.

Figure 4. Change in Achilles tendon viscosity in the four-hour period following photobiomodulation therapy.

Figure 5. Change in Achilles tendon dynamic shear modulus in the four-hour period following photobiomodulation therapy.

Figure 6.
Legend for Figures 1–5.

Table 1.

Demographics for healthy and tendinopathy cohorts.

		Healthy Cohort (n=20)	Tendinopathy Cohort (n=12)
Age (years)		29 (4)	59 (8)
Height (cm)		177 (8)	173 (11)
Weight (kg)		82 (18)	78 (12)
Sex (Male: Female)		11: 9	8: 4
Duration of Symptoms (months)		N/A	29 (23) Range: 11–98
Pain to palpation (NPRS)	Placebo	N/A	1.4 (1.8) Range: 0–8
	Laser	N/A	3.7 (2.6) Range: 0–5
VISA-A Score	Placebo	100 (0.2) Range: 99–100	85 (11) Range: 63–100
	Laser	100 (0.2) Range: 99–100	79 (11) Range: 63–100

VISA-A– Victorian Institute of Sports Assessment- Achilles Questionnaire

NPRS– Numeric Pain Rating Scale

N/A– Not Applicable

Table 2.

Achilles tendon morphology and mechanical properties at baseline and after photobiomodulation therapy in participants with healthy Achilles tendons.

		Baseline	Immediate	2 hours	4 hours	p-value	Interaction Effect (η^2_{partial})
Thickness (mm)	Placebo	4.645 (0.551)	4.646 (0.607)	4.628 (0.563)	4.627 (0.601)	0.273	0.066
	Laser	4.731 (0.661)	4.704 (0.673)	4.842 (0.610)	4.625 (0.586)		
Tendon CSA (cm ²)	Placebo	0.553 (0.128)	0.556 (0.129)	0.549 (0.115)	0.552 (0.112)	0.922	0.008
	Laser	0.562 (0.132)	0.558 (0.129)	0.552 (0.123)	0.556 (0.123)		
Static Shear Modulus (kPa)	Placebo	95.0 (16.0)	94.6 (15.8)	94.8 (15.4)	94.0 (13.0)	0.819	0.013
	Laser	90.9 (14.7)	90.4 (14.9)	94.1 (10.7)	93.0 (12.5)		
Viscosity (Pa*s)	Placebo	57.4 (13.4)	55.5 (12.4)	58.4 (13.3)	58.5 (11.5)	0.886	0.011
	Laser	57.1 (10.7)	57.8 (13.1)	58.5 (10.1)	57.3 (8.9)		
Dynamic Shear Modulus (kPa)	Placebo	226.8 (49.4)	218.0 (46.2)	230.7 (49.0)	230.6 (42.2)	0.812	0.017
	Laser	224.4 (39.0)	227.6 (49.2)	229.2 (37.4)	225.0 (32.2)		

CSA– Cross-sectional area

Table 3.

Achilles tendon morphology and mechanical properties at baseline and after photobiomodulation therapy in participants with Achilles tendinopathy.

		Baseline	Immediate	2 hours	4 hours	p-value	Interaction Effect (η^2_{partial})
Thickness (mm)	Placebo	6.531 (1.301)	6.487 (1.206)	6.366 (1.210)	6.390 (1.514)	0.455	0.070
	Laser	8.585 (2.364)	8.548 (2.391)	8.657 (2.634)	8.611 (2.504)		
Tendon CSA (cm ²)	Placebo	0.757 (0.234)	0.745 (0.224)	0.752 (0.219)	0.740 (0.206)	0.316	0.100
	Laser	1.102 (0.445)	1.048 (0.418)	1.062 (0.440)	1.049 (0.431)		
Static Shear Modulus (kPa)	Placebo	95.5 (19.7)	99.9 (16.8)	97.6 (12.6)	95.5 (19.4)	0.381	0.088
	Laser	103.2 (21.5)	98.6 (16.5)	102.6 (18.4)	95.4 (19.7)		
Viscosity (Pa*s)	Placebo	54.7 (10.7)	54.9 (12.1)	54.3 (14.3)	54.9 (13.7)	0.729	0.038
	Laser	53.6 (10.6)	52.6 (10.3)	51.3 (12.0)	56.5 (10.9)		
Dynamic Shear Modulus (kPa)	Placebo	216.7 (38.1)	217.5 (42.8)	215.7 (49.8)	217.5 (50.9)	0.752	0.035
	Laser	212.9 (41.1)	209.0 (37.9)	204.8 (44.2)	221.7 (42.1)		

CSA– Cross-sectional area