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Achilles Tendon Loading During Heel-Raising and -Lowering Exercises

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Context: Achilles tendinopathies are common injuries during sport participation, although men are more prone to Achilles tendon injuries than women. Heel-raising and -lowering exercises are typically suggested for Achilles tendon rehabilitation.

Objective: To compare the estimated Achilles tendon loading variables and the ankle range of motion (ROM) using a musculoskeletal model during commonly performed heel-raising and -lowering exercises.

Design: Controlled laboratory study.

Setting: University biomechanics laboratory.

Patients or Other Participants: Twenty-one healthy men (age = 21.59 ± 1.92 years, height = 178.22 ± 8.02 cm, mass = 75.81 ± 11.24 kg).

Intervention(s): Each participant completed 4 exercises: seated heel raising and lowering, bilateral standing heel raising and lowering, bilateral heel raising and unilateral lowering, and unilateral heel raising and lowering.

Main Outcome Measure(s): A repeated-measures multivariate analysis of variance ($\alpha = .05$) was used to compare Achilles tendon stress, force, and strain and ankle ROM for each exercise. Kinematic data were recorded at 180 Hz with 15 motion-analysis cameras synchronized with kinetic data collected from a force platform sampled at 1800 Hz. These data were then entered in a musculoskeletal model to estimate force in the triceps surae. For each participant, we determined Achilles tendon stress by measuring cross-sectional images using ultrasound.

Results: Peak Achilles tendon loading was lowest when performing the seated heel-raising and -lowering exercise and highest when performing the unilateral heel-raising and -lowering exercise. Loading was greater for the unilateral exercise or portions of the exercise that were performed unilaterally.

Conclusions: Bilateral and seated exercises with less weight-bearing force resulted in less Achilles tendon loading. These exercises may serve as progressions during the rehabilitation process before full-body weight-bearing, unilateral exercises are allowed. Ankle ROM did not follow the same order as loading and may need additional monitoring or instruction during rehabilitation.

Key Words: kinematics, kinetics, strain, therapeutic exercise, rehabilitation

Key Points

- Bilateral and seated heel-raising and -lowering exercises resulted in less Achilles tendon loading.
- Unilateral exercises and the unilateral phase of the bilateral heel-raising and unilateral heel-lowering exercise resulted in more Achilles tendon loading.

Achilles tendinopathies are common injuries during competitive and recreational sport participation. The highest incidence of reported Achilles tendon injuries occurs in long-distance running.[1] Achilles tendon injuries are more frequent among men than women.[2]

Postoperative rehabilitation for AT injuries postrupture is designed to reduce pain and swelling by using a specific exercise progression that promotes the gradual recovery of ankle range of motion (ROM), strength, and power.[3] Early weight bearing and ankle ROM exercises can result in a more rapid return to normal activity than keeping the area largely immobilized.[4] Full weight bearing and heel-raising and -lowering strengthening exercises are typically implemented about 6 to 8 weeks postoperatively to strengthen the Achilles tendon.[3,5] These exercises are thought to improve the mechanical and structural properties of the tendon.[6] Some protocols have suggested initiating these exercises either earlier or later based on the nature of the injury and tendon healing.[6,7] Despite the lack of a clear consensus regarding when such strengthening exercises should be introduced, regaining muscular strength is thought to be important in producing better patient outcomes. Olsson et al[8] reported that the ability to perform a single-legged heel-raising exercise at 12 weeks post rupture positively influenced patients' self-reported outcomes and physical activity levels. Achilles tendon rehabilitation efforts are likely influenced by the ankle ROM permitted and the magnitude of tendon loading during specific strength-training exercises.

Heel-raising and -lowering exercises are commonly introduced early in a typical Achilles tendon rehabilitation protocol. Clinical practice guidelines[9] and a meta-analysis[10] support the use of these gastrocnemius- and soleus-strengthening exercises. Bilateral heel-raising and -lowering exercises are routinely recommended to evenly distribute weight-bearing force through both lower extrem-

Table. Achilles Tendon Mechanical Properties and Ankle Range of Motion During Strengthening Heel-Raising Exercises

Variable	Exercise, Mean ± SD: Seated Heel Raising and Lowering	Bilateral Heel Raising and Lowering	Bilateral Heel Raising and Unilateral Lowering	Unilateral Heel Raising and Lowering	*P* Value	Mean Differences (1–4)	Effect Size (Cohen d) (1–4)
Achilles stress, MPa	6.88 ± 3.87[a]	40.07 ± 16.43[a]	65.85 ± 24.92[a]	89.54 ± 35.31[a]	.001	−82.66	−0.85
Achilles forces, N	209.47 ± 96.96[a]	1250.51 ± 470.41[a]	2052.88 ± 633.21[a]	2760.14 ± 876.56[a]	.001	−2550.67	−0.84
Achilles strain, %	0.71 ± 0.35[a]	3.94 ± 1.62[a]	6.47 ± 2.45[a]	8.80 ± 3.47[a]	.001	−8.09	−0.85
Ankle range of motion, °	36.34 ± 6.89[bc]	31.09 ± 5.72[b]	33.52 ± 6.56	29.95 ± 7.37[c]	.005	6.394	0.41

[a] Differences among 4 groups at the .001 level.
[b] Differences among groups 1 and 2 at the .05 level.
[c] Differences between groups 1 and 4 at the .05 level.

ities. These exercises are part of a progression sequence toward more challenging exercises in which both legs perform the raising portion of the movement but the lowering portion is performed only by the affected lower extremity. Exercises are generally progressed toward to raising and lowering only on the affected extremity.[5,6] To our knowledge, Achilles tendon stress, force, and strain during each of these exercises have not been compared.

Our purpose was to compare the estimated Achilles tendon stress, force, and strain and ankle ROM during heel-raising and -lowering exercises. We hypothesized that progressively increasing levels of tendon peak stress, force, and strain would occur as these exercises progressed from seated to standing position or bilaterally to unilaterally. Additionally, we hypothesized that greater ankle ROM would be achieved during seated than during standing exercises.

METHODS

Participants

Twenty-one healthy and physically active men participated in our study (age = 21.59 ± 1.92 years [range, 18–25 years], height = 178.22 ± 8.02 cm, mass = 75.81 ± 11.24 kg, and Tegner Activity Level = 6.3 ± 1.2). Power analysis ($\alpha = .05$, $\beta = .95$, effect size = 0.85) by G*Power (version 3.0.10; Heinrich-Heine-Universität Düsseldorf, Germany) revealed that a sample size of 16 would be sufficient to achieve high power (0.95). Exclusion criteria were surgery to either lower extremity within the past year, injury to either lower extremity within the past 6 months that prevented participation in typical activities greater than 1 day, a rating of less than 5 on the Tegner Activity Level,[11] or current pain in the lower extremity or trunk. Before the study, each participant was informed of the procedures, benefits, and potential risks and signed an informed consent form approved by the institutional review board at the university.

Protocol

The cross-sectional area of each participant's Achilles tendon was measured using ultrasound (model LOGIQ P6; General Electric Corporation, Waukesha, WI) with an ML6-15 probe placed between the medial and lateral malleoli across the skin surface while ultrasound gel (Aquasonic Clear; Parker Laboratories, Inc, Fairfield, NJ) was applied to the probe and target area on the participant's skin. The individual was positioned prone on a treatment table with the right ankle at a 90° angle as measured by a handheld goniometer[12] (Figure 1). Scaled images of Achilles tendon cross-sectional area were measured using ImageJ (National Institutes of Health, Bethesda, MD) software. Each participants was then fitted with standard footwear (model 625SB, New Balance Athletics, Inc, Boston, MA) and tight spandex shorts (Nike, Beaverton, OR) for testing. A brief warmup was performed while walking at a self-paced speed on a treadmill (model CX-445T; Cybex International, Medway, MA).

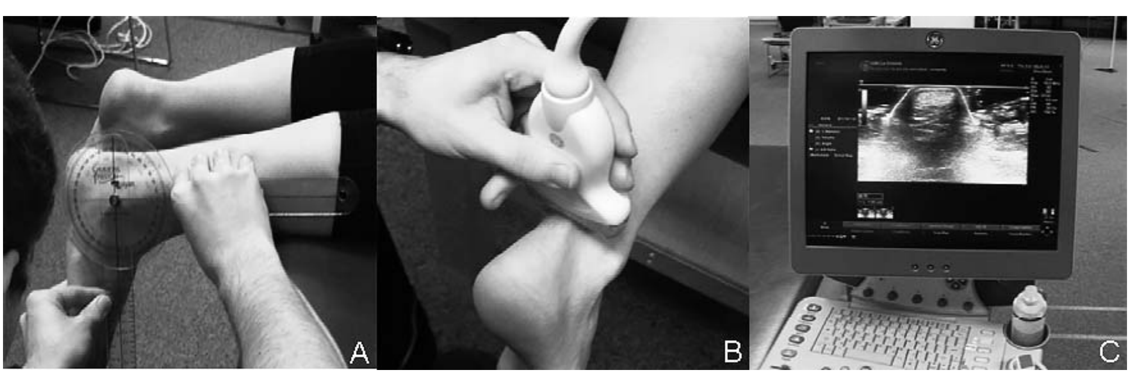

Figure 1. Ultrasound data collection. A, Participant's ankle placed in neutral position. B, Ultrasound head position used for data acquisition. C, Computerized image used to obtain cross-sectional area measurements.

Figure 2. Participant positioning for A, seated bilateral heel raising and lowering, B, standing bilateral heel raising and lowering, C, unilateral heel raising and lowering, and D, bilateral heel raising and unilateral lowering. The last exercise was a combination of B for the raising portion of the exercise and C for the lowering portion.

After each exercise was instructed, demonstrated, and practiced, the participants completed the exercises in random order. For the bilateral seated heel-raising and -lowering (Seated) exercise, the participants were seated off both force platforms with their hips and knees flexed to approximately 90° and both feet on the force platforms. Specific instructions were given to maintain equal weight bearing on both lower extremities throughout the raising and lowering portions of this exercise while moving the ankle through its available ROM. For the bilateral standing heel-raising and -lowering (Bilateral) exercise, participants stood and were provided similar instructions regarding weight bearing and ROM criteria. For the bilateral raising and unilateral lowering (B/U) exercise, the raising portion was performed bilaterally and the lowering portion was performed by only the right lower extremity. The unilateral heel-raising and -lowering exercise (Unilateral) was conducted on only the right lower extremity. Each exercise was paced with the use of a metronome set at 0.5 Hz: the raising and lowering portions each took approximately 1 second (Figure 2). A random-number generator was used to determine the order of exercises. If any aspect of the left foot made contact with the ground or the right lower extremity during the 2 unilateral exercises (B/U, Unilateral) based on visual observation, the exercise was repeated. Five successful trials of each exercise were completed, and only data from the right lower extremity were analyzed.

Instrumentation

Before completing these exercises, we prepared participants for 3-dimensional motion analysis by applying 47 reflective markers (model 850-1569-004; Motion Analysis Corporation, Santa Rosa, CA).[13] A static, neutral standing calibration trial was collected before all dynamic trials. Kinematic data were recorded at 180 Hz with 15 motion-analysis cameras (models Osprey, Kestrel, and Eagle) surrounding the measurement space. Synchronized kinetic data were collected from a force platform (model 4080; Bertec Corporation, Columbus, OH) sampled at 1800 Hz. The kinematic and kinetic data and muscle forces were calculated from a 44 degrees-of-freedom (DOF) musculoskeletal model with 16 rigid segments using the Human Body Model (HBM; Motek Medical, Amsterdam, Netherlands). This model has the head as a single segment with 3 DOF relative to the thorax, the trunk as 3 segments (pelvis, midtrunk, and thorax) with 3 DOF, the upper arms with 6 DOF relative to the thorax, the elbow with 2 DOF, the wrist with 2 DOF, and the pelvis with 6 DOF and the ability to rotate and translate in all 3 dimensions with respect to the ground.[14] The hip is a ball-and-socket joint with 3 rotational DOF, and the knee was a single DOF hinge joint in which tibiofemoral translations and nonsagittal rotations were both constrained as a function of knee flexion. Each foot segment has 2 DOF. The inertial characteristics of the musculoskeletal model segments were based on participants' total body mass and segment lengths. A total of 300 muscle-tendon units were represented (86 in the legs, 204 in the arms, and 10 in the trunk); the muscle insertion points, wrapping points, and moment arms were based on the work of Delp et al.[15] The HBM uses a full-body marker set that provides estimates of force output from 300 muscles, although for this project we examined only the lower leg muscles.

The HBM used global optimization to determine skeletal model kinematics, and we then obtained joint moments from equations of motion. Within the inverse-dynamics processing algorithm of the HBM, the residual loads, 3 forces, and 3 moments on the pelvis were minimized. For each time step, the muscle forces were estimated from the joint moments by minimizing a static cost function whereby the sum of squared muscle activations was related to maximum muscle strengths.[14]

The muscle forces from the HBM were then used to quantify total Achilles tendon force by summing the muscle forces of the medial and lateral gastrocnemius and soleus for each exercise. Achilles tendon stress was calculated by dividing the Achilles tendon force by the participant's cross-sectional area. Strain was calculated using the average Young modulus of 819 cm reported by Wren et al.[16] Strain rate was determined from the instantaneous slope of the strain versus time curve.

Statistical Analysis

We calculated a multivariate analysis of variance with repeated measures and α set to .05 to compare the stress, force, strain, and ankle ROM for each exercise. Follow-up univariate tests were then used for each dependent variable. Finally, the Bonferroni procedure was conducted for pairwise comparisons. All statistical procedures were performed using SPSS software (version 22; IBM Corp, Armonk, NY).

RESULTS

Our multivariate analysis of variance identified differences among the 4 heel-raising and -lowering exercises for

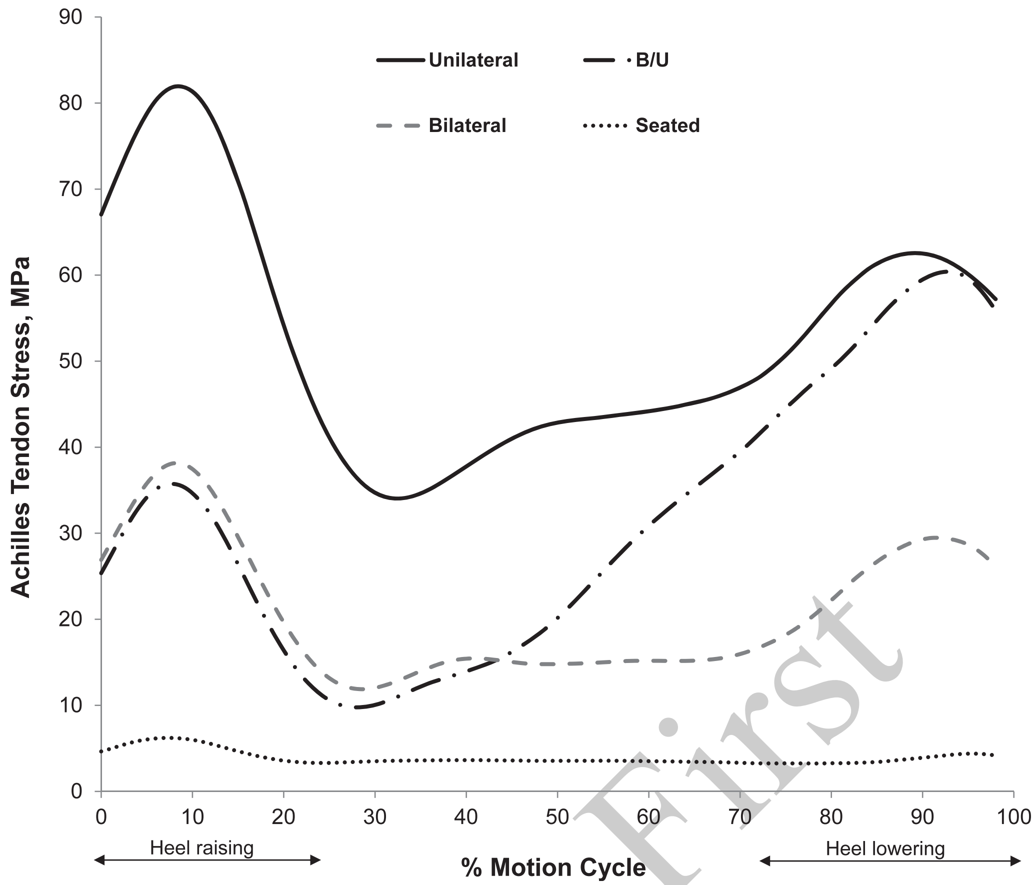

Figure 3. Ensemble average Achilles tendon stress during heel-raising and -lowering exercises: seated bilateral heel raising and lowering, bilateral heel raising and lowering, bilateral heel raising and unilateral lowering (B/U), and unilateral heel raising and lowering.

estimated Achilles tendon loading (stress, force, strain; Wilks' $\lambda = 0.84$, 0.12, and 0.13, respectively, all P values $<$ .001) and ankle angle (Wilks' $\lambda = 0.48$, $P = .005$). Follow-up univariate analyses demonstrated differences in peak AT force, stress, and strain for all 4 exercises. However, ankle ROM was different only between the Seated and Bilateral exercises ($P = .011$) and the Seated and Unilateral exercises ($P = .017$).

Achilles tendon stress, force, and strain all increased with large effect sizes ($>$0.80) for all exercises: Seated, Bilateral, B/U, and Unilateral ($P < .001$; Table). The greatest differences in AT force, stress, and strain occurred between the Seated and Unilateral (2550.7 N, 82.7 MPa, and 8.9%, respectively). In addition, ankle ROM decreased moderately (effect size = 0.41) between the Seated and Unilateral exercises.

The ensemble average of the time-normalized Achilles tendon stress from the exercises is depicted in Figure 3. Maximum stress occurred during the Unilateral exercise, followed by the B/U, Bilateral, and Seated exercises (Figure 3). The Seated exercise exhibited the smallest amount of Achilles tendon stress during the movement. Achilles tendon stress peaked early during each exercise at approximately 10% of the heel-raising portion of the exercise, when the ankle was being actively plantar flexed. A second peak was prominent during all exercises except during Seated. This second peak occurred near the end of the lowering phase of each exercise at approximately 90% to 95% of the movement, when the ankle was nearing the end of the dorsiflexion portion of the movement and close to its starting neutral position. The B/U Achilles tendon stress curve had a different pattern than the other 3 exercises. It closely resembled the Bilateral stress pattern during the first 40% of the movement when the exercise was being performed bilaterally; however, the stress increased rapidly to levels more similar to those of the Unilateral pattern when participants transitioned weight bearing from both legs to a single leg.

The ensemble average of the time normalized ankle angle during the 4 exercises is illustrated in Figure 4. Plantar flexion occurred during approximately 0% to 25% of the movement trial, and dorsiflexion occurred from approximately 65% to 100% of the movement during all exercises. Maximum ankle ROM occurred with the Seated exercise, which had a more rapid change in ankle plantar flexion and dorsiflexion (Table). The patterns of ankle motion during the Bilateral, Unilateral, and B/U exercises were similar: a small peak near the end of the heel-raising phase and then a slow decline during the lowering phase as the participant resisted gravity in a plantar-flexed ankle position. Based on the Achilles tendon stress (Figure 3) by ankle angle (Figure 4) patterns during each phase of the exercise, we found that the stress was higher during the heel-raising phase than during the lowering phase.

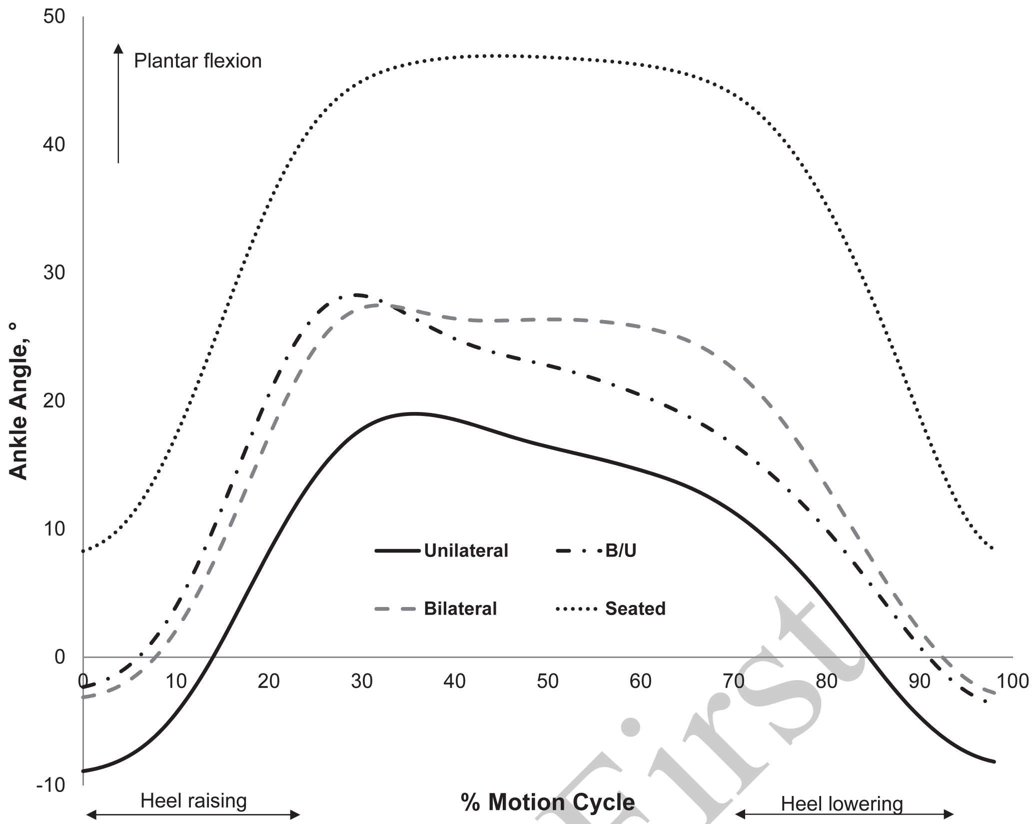

Figure 4. Ensemble average ankle range of motion during heel-raising and -lowering exercises: seated bilateral heel raising and lowering, bilateral heel raising and lowering, bilateral heel raising and unilateral lowering (B/U), and unilateral heel raising and lowering.

DISCUSSION

Our purpose was to compare the estimated AT stress, force, and strain and the ankle ROM during 4 common heel-raising and -lowering exercises. As hypothesized, peak stress, force, and strain increased from seated to standing position as well as from bilateral to unilateral heel-raising and -lowering exercises. We will examine if the AT loading magnitudes follow a typical exercise progression sequence commonly used in clinical settings.[5,6] A large effect size between the Seated and Unilateral exercises indicated meaningful differences in AT loading variables. Our additional hypothesis that ankle ROM would be greater while seated versus standing was also supported. The greatest ankle motion occurred during the Seated exercise, and the least occurred during the Unilateral exercise with a moderate effect size between these.

Our findings demonstrated an increase in peak AT stress during each of the heel-raising and -lowering exercises. The peak stress magnitudes follow a typical exercise progression sequence commonly used in clinical settings.[5,6] The estimated peak AT stress was 6.9 MPa during the Seated exercise and 89.5 MPa during the Unilateral exercise, with peak stress during the Bilateral and B/U exercises falling between these values at 40.1 MPa and 65.9 MPa, respectively.

Similar Achilles tendon forces to those in our investigation (approximately 2600 to 3100 N) have been reported by Rees at al[17] for males during a unilateral heel-raising and -lowering exercise. Arya and Kulig[18] also reported similar force, stress, and strain levels (approximately 2250 N, 40 MPa, and 4.3%, respectively) estimated from the plantar-flexor moment generated during a maximal-effort isometric contraction against a dynamometer. Other investigators, using a 90% maximal isometric contraction of the plantar flexors, reported maximal force, stress, and strain on the Achilles tendon of 875 N, 32.4 MPa, and 4.9% to 5.1%, respectively; their tendon forces were estimated from the moment generated based on tendon-travel methods.[19] Additionally, Geremia et al[20] also estimated Achilles tendon loading during a maximal plantar-flexion contraction after a short-term bout of physical therapy and reported average stress and strain of 53.9 MPa and 6.9%, respectively, for a healthy control group using tendon-travel methods. Their results are likely higher than the stress and strain magnitudes during the Bilateral exercise in our study because our participants used only the resistance of their body weight and our muscle forces were calculated from inverse-dynamics and static-optimization techniques.

Our force and strain values are well below the reported failure load range of 4635 to 5579 N and the failure strain range of 12.8% to 49.2%.[16,21] The stresses during the Seated, Bilateral, and B/U exercises were lower than the reported failure stress range of 56 to 86 MPa,[16,22] whereas the Unilateral exercise stress (89 MPa) in our study was close to this reported failure stress. It seems that, during the Unilateral exercise, loading is higher than during other heel-raising and -lowering exercises and closest to the reported failure stress. No other studies investigating Achilles tendon loading variables during heel-raising and -lowering exercises were identified.

Comparing our findings with those reported for other movements may provide further insight as to which movements have similar Achilles tendon loading. This can offer guidance in terms of which exercises to perform after Achilles tendon injury. For example, Akizuki et al[23] reported tendon forces of 553 N when participants walked in an ankle boot. This value is above our observed values for the Seated exercise but below those for the Bilateral exercise. These differences could be related to the effect of wearing typical footwear as well as musculoskeletal model estimates of muscle force. These findings are somewhat consistent with those of Fujisawa et al,[24] who used electromyography to examine muscle activation during a bilateral heel-raising and -lowering exercise and treadmill walking. Walking speeds between 20 and 100 m/min resulted in less muscle activation of the gastrocnemius and soleus muscles than that of a maximum-effort bilateral heel-raising movement throughout the plantar-flexion ROM. Taken together, we can surmise that the use of a Bilateral exercise may serve as a progression before the B/U and Unilateral exercises. However, we must be cautious when interpreting electromyography data in terms of muscle force.

Other more load-demanding activities have been examined. Kubo et al[25] reported Achilles tendon strain during running of 6.4% to 6.8%. These results were above our values for the B/U but below those for the Unilateral exercise. Lichtwark and Wilson[26] reported peak in vivo AT forces during single-limb hopping of 3500 to 4000 N,[26] which were greater than our values for the Unilateral exercise. Because it is a more active task, hopping may involve greater Achilles tendon stress and strain than our Unilateral exercise. However, the average peak tendon strain reported during the single-limb hop was 8.3%, with a range of 6.2% to 10.3%. These strain values are very similar to those for the Unilateral exercise. However, Lichtwark and Wilson[26] used a 200-N cutoff to determine zero strain, which may have underestimated their strain by 1%. Also, differences exist between in vivo methods and computer-modeling estimations of muscle force from optimization techniques because computer simulations of movement rely on many mathematical models to represent the musculoskeletal system and on their inherent assumptions. Therefore, direct comparisons between these modeling methods and others should be made with caution.

During each exercise, 2 distinctive peaks in AT stress occurred. One was near the beginning of the heel-raising portion of the movement, as the ankle was being actively plantar flexed, and a second was near the end during the lowering portion when the ankle was being returned to neutral position (Figure 3). The Achilles tendon stress pattern appeared to be based on ankle position (Figure 4) such that stress decreased throughout the later part of the raising portion and then increased more slowly during the lowering portion of each exercise. The exception to this observation was during the B/U exercise, in which the greatest levels of tendon stress occurred in 2 distinct peaks during the heel-raising portion of the exercise rather than during the lowering portion. The raising portion of the motion is commonly described as the *concentric portion* while the lowering phase is commonly described as the *eccentric portion*.[17] The peaks in AT stress we observed largely appeared to correspond to the gastrocnemius-soleus being concentrically activated to accelerate the body upward early in the raising portion of the movement, as the ankle was being actively plantar flexed (Figures 3 and 4). The second peak was likely involved in decelerating the downward momentum during the late stages of the lowering portion of the movement, when the gastrocnemius and soleus were eccentrically activated. Self and Paine[27] reported similar findings of increasing Achilles force throughout the duration of an eccentric plantar-flexion load. Also, Rees et al[17] noted that force during heel raising and lowering reflected 2 peaks, the first at the beginning of the movement and a second during the lowering phase near the end of the movement. They also described slightly higher levels of Achilles tendon force during the raising portion of the movement, when the muscles were working concentrically, compared with the lowering portion, when the muscles were working eccentrically. The only exercise in our study that did not follow this pattern of increasing and decreasing loading was the B/U. As expected, the peak tendon stress during the heel-raising part of the B/U exercise was largely similar to that of the Bilateral exercise. In contrast, the lowering peak more closely resembled the Unilateral exercise: both exercises were performed in a unilateral stance during the lowering phase. Interestingly, Henriksen et al[28] reported no difference in Achilles tendon loads between the raising and lowering portions of the movement associated with concentric and eccentric muscle tension but a higher rate of tendon vibration with eccentric exercises. They stated that the external loads applied determined the magnitude of the tendon load, not necessarily the type of muscle tension. This is largely consistent with our findings, which depict greater differences in tendon loading among exercises from changes in weight bearing rather than from the type of muscle contraction. This also explains the large change in tendon load during the B/U exercise, in which stress was greater during the lowering portion of the exercise than the raising portion due to the greater relative load applied to the tendon as the participant changed from bilateral to unilateral weight bearing.

The greatest change in ankle ROM occurred during the Seated exercise, which had nearly 6° of additional motion than the Unilateral exercise, which had the least. All 4 exercises followed a similar ankle-motion pattern with early ankle plantar flexion followed by a plateau during the middle of the exercise and then dorsiflexion at the end. Lunsford and Perry[29] observed that males achieved an average plantar-flexion angle of nearly 25° during a standing bilateral heel-raise assessment. This value is lower than in our study (31.1° ± 5.7°), probably because they examined older participants (mean age = 34.7 years) and measured ankle motion during the 28th repetition of a heel-raise test, so fatigue may have been a factor. Also, they used an electrogoniometer designed to measure angular motion in the sagittal plane, which was different than the motion-capture methods of our study. In contrast, Fujisawa et al[24] reported a maximum plantar-flexion angle during a bilateral heel raise of 50° ± 6°. This higher amount may be attributed to the emphasis these authors placed on achieving maximum plantar flexion, whereas our participants received no specific instructions about heel-raise height or motion other than to perform maximum ROM while matching the exercise cadence from our metronome. These authors also used a goniometer for measuring ankle angle, which was different than our methods.

Few researchers have examined Achilles tendon loading during different heel-raising and lowering exercises and how they contribute to a postinjury rehabilitation plan. In most of those studies, tendon loading was estimated by electromyography,[17] dynamometer,[18] and tendon-travel methods,[19,20] whereas we used musculoskeletal modeling with inverse-dynamics–based static optimization. Geremia et al[20] demonstrated that the mechanical properties of the Achilles tendon were altered compared with both the uninvolved limb and healthy controls for at least 2 years postrupture. In addition, tendinopathy has been reported to weaken and alter the mechanical properties of the structure.[18] The deficits associated with tendinopathy or postrupture may leave the Achilles tendon at greater risk of sustaining further damage from stress during normal daily activities that prolong recovery. Therefore, a treatment strategy that progressively loads the tendon may foster rehabilitation efforts. Our data appear to support a specific progression of these exercises relative to tendon loading and ankle ROM.

Meanwhile, certain limitations should be considered when interpreting our findings. We used surface-based motion capture and force platforms in a musculoskeletal model to estimate muscle force from inverse dynamics and then static optimization. Such models require various anatomical assumptions and approximations to represent the neuromuscular and skeletal system. Therefore, these approaches provide only an estimate of muscle force across each exercise. The musculoskeletal model and moment arms used in our investigation were based on the Delp et al model,[15] although the each participant's Achilles tendon cross-sectional area was measured. In addition, these images obtained using the 2-dimensional ultrasound techniques may have imposed measurement error in determining the tendon cross-sectional area.[30] The restrictions of our 2-dimensional images to a single transverse view may neglect regional differences in the tendon cross-sectional area and overestimate tendon thickness by up to 10%.[12] As such, our data may not portray the precise amount of stress throughout the entire length of the tendon. Strain was based on literature sources of data describing freshly frozen Achilles tendons from human donors (mean age = 56.8 years),[16] so it is possible that these values were not representative of our samples. The literature values of mechanical properties and stiffness may account for the lower estimate of tendon strain during each exercise. Also, each participant's ability to perform the exercises at the selected tempo was determined subjectively by the assessors and may have been susceptible to some error in the rate actually performed. However, because we used a repeated-measures design, we expect that many of these errors associated with our chosen techniques are systematic, making our comparisons among exercises robust. Therefore, one might be more confident in the relative change in Achilles tendon loading and relevant motion data among these specific exercises than in comparing our findings with other data sources based on different methods.

CONCLUSIONS

Our results suggest that the estimated Achilles tendon peak stress, force, and strain were lowest during the Seated exercise and highest during the Unilateral exercise. Values for the Bilateral and B/U were between those for the other 2 exercises. Understanding the relative tendon loading for each of these exercises may aid in determining progressions for rehabilitation programs. Bilateral exercises with less body weight may be more desirable earlier in the rehabilitation process, whereas exercises that employ the performer's full body weight and are unilateral may be more useful in later exercise progressions. Our data show that the ankle ROM may need additional monitoring or the use of upper body support during single-legged exercise to achieve greater ROM.

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