Exercise Progression to Incrementally Load the Achilles Tendon

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ABSTRACT

BAXTER, J. R., P. CORRIGAN, T. J. HULLFISH, P. O'ROURKE, and K. G. SILBERNAGEL. Exercise Progression to Incrementally Load the Achilles Tendon. *Med. Sci. Sports Exerc.*, Vol. 53, No. 1, pp. 124–130, 2021. **Purpose:** The purposes of our study were to evaluate Achilles tendon loading profiles of various exercises and to develop guidelines to incrementally increase the rate and magnitude of Achilles tendon loading during rehabilitation. **Methods:** Eight healthy young adults completed a battery of rehabilitation exercises. During each exercise, we collected three-dimensional motion capture and ground reaction force data to estimate Achilles tendon loading biomechanics. Using these loading estimates, we developed an exercise progression that incrementally increases Achilles tendon loading based on the magnitude, duration, and rate of tendon loading. **Results:** We found that Achilles tendon loading could be incrementally increased using a set of either isolated ankle movements or multijoint movements. Peak Achilles tendon loads varied more than 12-fold, from 0.5 bodyweights during a seated heel raise to 7.3 bodyweights during a forward single-leg hop. Asymmetric stepping movements like lunges, step ups, and step downs provide additional flexibility for prescribing tendon loading on a side-specific manner. **Conclusion:** By establishing progressions for Achilles tendon loading, rehabilitative care can be tailored to address the specific needs of each patient. Our comprehensive data set also provides clinicians and researchers guidelines on how to alter magnitude, duration, and rate of loading to design new exercises and exercise progressions based on the clinical need. **Key Words:** MOTION ANALYSIS, TENDINOPATHY, RUPTURE, LOADING, REHABILITATION, BIOMECHANICS

Achilles tendon injuries are treated with tendon loading exercises and progressive exposure to physical activities. Although tendon loading has been shown to improve patient symptoms, normalize tendon structure, and optimize functional performance, there are negative consequences when over- and underloading both acute and chronic Achilles tendon injuries. For example, aggressively loading the tendon after Achilles tendon rupture may cause tendon elongation and rerupture (1), whereas prolonged immobilization underloads the healing tendon and leads to inferior long-term outcomes (2–4). Similarly, for patients with Achilles tendinopathy, adequate loading is needed to stimulate tendon remodeling and increase tissue tolerance. By leveraging Achilles tendon loading biomechanics with patient reported pain, we expect that rehabilitation protocols can be more effectively developed to address symptoms and accelerate return to play (5). To improve patient outcomes and safely return to desired physical activities, there is a need to understand loading mechanics during rehabilitation exercises and common physical activities so that progressive loading programs can be designed.

Walking and dynamic activities, such as running and jumping, are popular physical activities that tend to bookend the rehabilitative care of patients with Achilles tendon injuries. During walking, the Achilles tendon undergoes loading equivalent to approximately three bodyweights (6). However, these loads can exceed 12 bodyweights during running (7), highlighting the large increase in tendon loading mechanics that patients must tolerate before fully returning to high demand activities. Based on our experience (8), patients are typically progressed from low-intensity exercises, like bilateral heel raises, to high-intensity exercises, like single-leg hopping and drop jumps. However, the Achilles tendon biomechanics during these rehabilitation exercises have not yet been quantified using consistent methodology that is necessary to determine the progressive order of exercises to most safely transition patients from walking, to running and jumping, and ultimately to full return to activity.

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Submitted for publication April 2020.
Accepted for publication July 2020.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.acsm-msse.org).

0195-9131/20/5301-0124/0
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DOI: 10.1249/MSS.0000000000002459

The purpose of this study was to establish an exercise progression to incrementally increase the rate and magnitude of Achilles tendon loading. We selected a battery of clinically relevant rehabilitation exercises and physical activities and calculated a "loading index" based on the peak loading, loading impulse, and rate of loading for each exercise. By identifying an exercise progression that incrementally increases Achilles tendon loading, our study aimed to address an unmet clinical need. We expected that by splitting exercises into four tiers for both isolated ankle movements as well as multijoint movements, we could operationally define subgroups of exercises that progressively load the Achilles tendon.

METHODS

Study design. We recruited eight healthy adults (six males, two females; mean ± SD = 30 ± 4 yr; body mass index = 24.1 ± 3.2 kg·m^{-2}) and collected written informed consent for this study approved by the institutional review board (University of Pennsylvania IRB protocol no. 824466). All procedures were performed in accordance with the relevant guidelines and regulations. We excluded participants if they had a history of diagnosed Achilles tendon injuries or current self-reported tendon pain.

After providing written informed consent, participants changed into laboratory standard clothing (running shorts and tank top) and running shoes (Air Pegasus; Nike, Beaverton, OR). Next, we secured retroreflective markers (9.5 mm, B&L Engineering, Santa Ana, CA) to the pelvis and lower extremities using the skin-safe tape (Fig. 1A) that we have described in a previous report (9). Briefly, we placed markers over anatomic landmarks of the pelvis: anterior and posterior superior iliac spines; legs: medial and lateral knee condyles and ankle malleoli; and feet: calcaneus, first and fifth metatarsal heads, and the great toe that were placed on the shoes. We also placed additional tracking markers on the pelvis and lower extremities: two markers on the sacrum, one marker on the thigh, and two markers on the shank. Before instructing the participants to perform any exercises, we acquired a static trial with the participants standing in the anatomic position.

Data collection. Participants completed a battery of exercises in addition to walking and running at self-selected speeds. We selected these exercises based on literature reports (8) and our current rehabilitation programs used for patients with Achilles tendon rupture and tendinopathy. Based on pilot testing, we tested a battery of rehabilitation exercises in this order to minimize participant fatigue during testing: seated single-legged heel raise with 15 kg placed on the thigh, single-leg and double-leg heel raises done at both comfortable and fast speed, single-leg and double-leg hopping, single-leg and double-leg drop jumps and counter movement jumps, lunges, squats, and step ups and step downs from a low box (12 cm) and a high box (20 cm). After completing these exercises, participants walked and ran over force plates at self-selected speeds for 10 trials where we visually confirmed clean foot strikes on one of three force plates. Participants performed 5 repetitions for the jumps, lunges, squats, and step ups and downs and 10 repetitions of the heel raises. Between exercises, we provided participants 2- to 5-min breaks to prevent fatigue. During these rest periods, we provided visual and verbal guidance on how to perform each exercise. To eliminate potential investigator bias, we decided to include all trials that had complete motion capture data.

During each activity, we acquired reflective marker trajectories using a 12-camera motion capture system (Eagle Series; Motion Analysis Corporation, Rohnert Park, CA) sampling at 100 Hz and ground reaction forces using three-embedded force plates (BP600900; AMTI, Watertown, MA) sampling

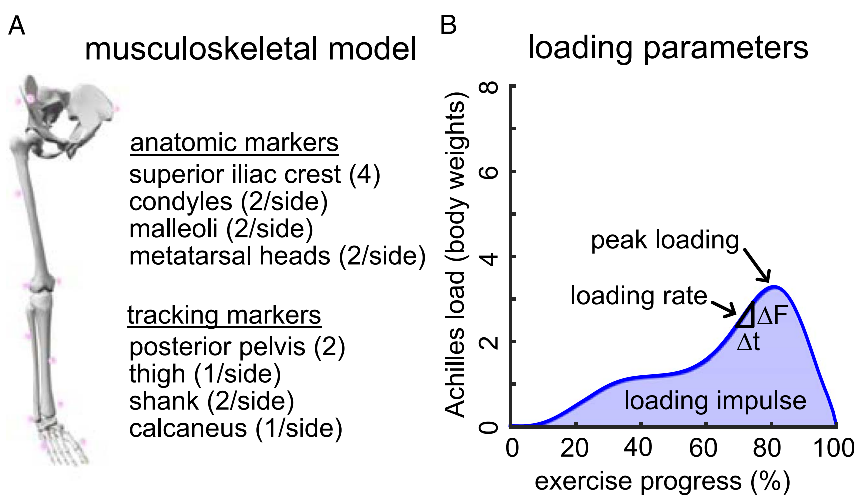

FIGURE 1—A, We defined participant-specific models (left leg hidden for clarity) by scaling a generic musculoskeletal model to fit anatomic markers placed over the pelvis, condyles, malleoli, and metatarsal heads. To improve labeling and inverse kinematic fidelity, we included additional markers on each segment. B, We calculated three Achilles tendon loading parameters from each exercise condition: 1) peak loading, which we identified as the maximal Achilles tendon load; 2) loading impulse, which we calculated as the area under the force-time curve; and 3) loading rate, which we defined as the peak loading rate over a 5% moving window. We normalized these Achilles tendon loads by first dividing the plantarflexion moment by a constant moment arm of 5 cm and then normalizing tendon load by participant bodyweight.

at 1000 Hz. Next, we postprocessed the motion capture data by confirming that marker labeling was correct, filling any small gaps (<0.5 s) using a cubic spline (10), and filtering marker trajectories using a low-pass Butterworth filter with a 6-Hz cutoff (11). During preprocessing, we found that most of these small gaps were pelvis markers occluded by the arms or trunk during slow movements like the squat and lunge. We did not fill larger gaps and instead leveraged a kinematically constrained model, which our previous work demonstrated to have excellent kinematic fidelity with reduced markers. We corrected the errors in ground reaction forces using an established force plate calibration produced (12,13). Next, we transformed the ground reaction forces applied to the rigid platforms placed on the force plates that were used during the step up and step down exercises. Then we converted these marker and force data into files that were compatible with open-source musculoskeletal modeling software (14).

Data analysis. We used a constrained kinematic model to calculate lower extremity kinematics and kinetics (14), which were necessary to calculate Achilles tendon loading during each exercise. First, we scaled a generic musculoskeletal model (gait2392; Fig. 1A) using each participant's bodyweight and markers placed over anatomic landmarks. Next, we moved the scaled model into the anatomic position by fitting the experimental data collected during the static trial using best practices (15). The markers placed on the anterior superior iliac spines, condyles and malleoli, calcaneus, first and fifth metatarsal heads, and toe markers were all given equal weighting. Similarly, hip, knee, ankle, and toe joints were all weighted toward neutral sagittal alignments, which we visually confirmed during the static trial. We then confirmed the scaled models by superimposing the experimental marker positions over the model. After each participant-specific model was generated, we performed inverse kinematic and inverse dynamic analyses on all the motion capture trials. We estimated Achilles tendon load as the plantarflexion moment calculated with inverse dynamic analysis divided by a plantarflexor moment arm of 5 cm (16) and normalized tendon load by participant bodyweight.

Using these Achilles tendon loading profiles, we developed guidelines to incrementally increase Achilles tendon loading using rehabilitation exercises currently used by clinicians to treat patients with Achilles tendon injuries. Based on the highly elastic properties of the Achilles tendon (17), we assigned greater importance to loading magnitude and impulse than to loading rate. To calculate these exercise rankings, we calculated and averaged the three loading parameters (Fig. 1B) for each exercise: 1) *peak loading* was the peak tendon load, 2) *loading impulse* was the cumulative loading applied to the tendon, and 3) *loading rate* was the peak change in tendon load divided by the change in time over a 5% moving window. We normalized each of these loading parameters by their respective maxima calculated from the exercises we captured. For example, single-leg forward hopping produced the greatest tendon peak loads, so we normalized peak loading from each exercise by the forward hopping peak loading magnitude. Similarly, tendon loading impulse was greatest during a single-leg drop jump, and peak loading rate occurred during single-leg lateral hopping, so we normalized loading impulse by the single-leg drop jump loading impulse and peak loading rate by the single-leg lateral jump loading rate. We then applied scaling factors of 50% for peak loading, 30% for loading impulse, and 20% for loading rate. By summing these three scaled and normalized loading parameters, we ranked Achilles tendon loading by exercise between a loading index of 0 and 1, with 0 representing no tendon loading and 1 representing the most tendon loading. Because we measured peak values for each of the three loading parameters in different exercises, our final ranking for Achilles tendon loading was slightly less than 1. We selected these scaling factors based on our own clinical experience but also provided a supplemental file so users can select different scaling factors. To operationally define these loading indices, we split the exercises into four tiers based on their loading index: tier 1 < 0.25, 0.25 < tier 2 < 0.50, 0.50 < tier 3 < 0.75, and tier 4 > 0.75. We calculated 95% confidence intervals using a boot strapping approach (18,19) to visualize the loading variability in the results figures (Figs. 2–4).

Data sharing. Our experimental data and musculoskeletal models are available on a publicly hosted repository (https://zenodo.org/record/3967533#.XzHP7TURWUk). We also included the loading index spreadsheet (see Table, Supplemental Digital Content 1, Loading index calculations, http://links.lww.com/MSS/C53) so readers can calculate the loading index based on different weighting factors.

RESULTS

Transitioning from slow multijoint movements to dynamic single-leg movements incrementally increases Achilles tendon loading (Table 1). Seated heel raises loaded the Achilles tendon the least, and performing these exercises with a single-leg (loading index, 0.100) did not double the amount of tendon loading compared with double-leg seated heel raises (loading index, 0.128). Slow multijoint movements like squats, step ups and downs, lunges, walking, and double-leg standing heel raises applied similar loads to the Achilles tendon that were greater than loads from seated heel raises (loading index, 0.167–0.359). Double-leg multijoint dynamic exercises like counter movement jumps, drop jumps, and hopping as well as running and single-leg standing heel raises increased the loading index (loading index, 0.414–0.600) mostly by increasing peak loading and loading impulse. Finally, single-leg movements like counter movement jumps, drop jumps, and hopping in different directions loaded the Achilles tendon the most (loading index, 0.656–0.924) by increasing the peak loads, loading impulses, and loading rates.

These exercises loaded the Achilles tendon under varied amounts of peak loads, loading impulses, and loading rates, which explain the loading index we calculated for each exercise (Table 1 and Fig. 2). For example, seated heel raises loaded the tendon the least in terms of peak loading (0.5–0.7 bodyweights), loading impulse (0.6–0.7 bodyweights seconds), and loading rate (2.7–3.6 bodyweights per second). Single-leg heel raises and double-leg drop jumps had similar loading indices (0.493 vs

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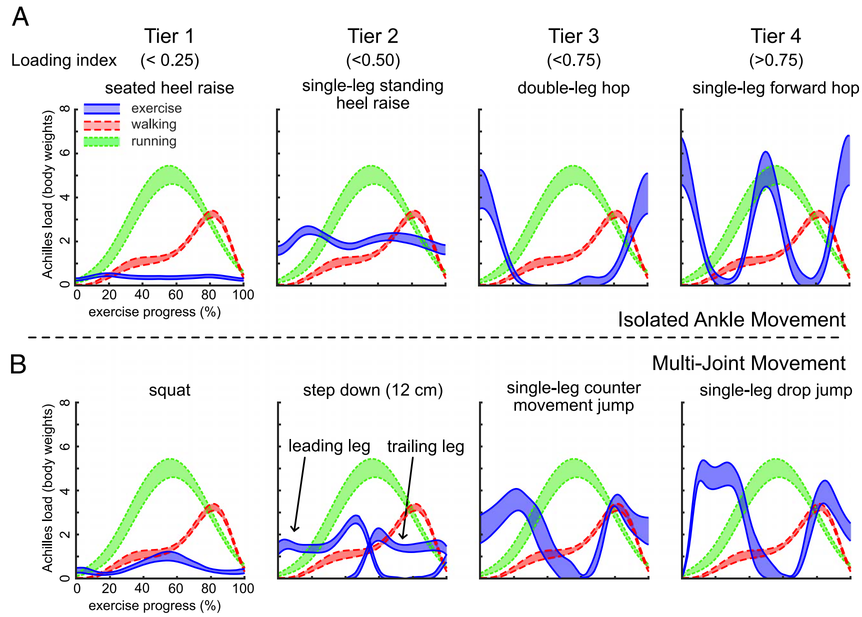

FIGURE 2—We identified exercises that progressively load the Achilles tendon, increasing from least load (tier 1) to most load (tier 4) using our exercise ranking system. To provide greater flexibility in exercise prescription, we identified a sequence of exercises that were isolated ankle movements (A) and a sequence of exercises that were multijoint movements (B). We plotted each exercise (*solid blue*) against Achilles tendon loading profiles for both walking (*dashed red*) and running (*dotted green*).

0.519), but these exercises differed in peak loading (3.0 ± 0.3 vs 3.6 ± 0.6 bodyweights), loading impulse (2.5 ± 0.6 vs 1.7–1.9 bodyweight seconds), and loading rate (13.1 ± 3.4 vs 34.4 ± 6.7 bodyweights per second). Hopping forward and laterally on a single leg loaded the tendon the most (loading index, 0.904–0.924). Although the loading impulse was 23%–30% less than a single-leg drop jump, hopping on a single-leg resulted in the greatest peak loading (>7.3 bodyweights) and loading rate (>67.1 bodyweights per second) of all the exercises we tested.

Asymmetric stepping movements like lunges as well as step ups and downs loaded the Achilles differentially based on whether assessing the leading or trailing leg (Fig. 3). During a lunge, the trailing Achilles tendon was loaded 52% more than the leading limb (loading index, 0.435 vs 0.285) mostly due to increased time under load (loading impulse). During step ups, the trailing limb underwent greater loading than the leading limb regardless of step height (loading index, 0.341–0.432 vs 0.213–0.241). Tendon loading during step downs was similar with no clear effect of step height or limb.

DISCUSSION

In this study, we established an exercise order that incrementally increases Achilles tendon loading. To the best of our knowledge, this is the most complete biomechanical set of Achilles tendon loading data for a battery of exercises commonly prescribed by clinicians as treatment for patients with Achilles tendon pathology. By quantifying three components of Achilles tendon loading, we developed an Achilles tendon "loading index" that ranks total tendon loading based on peak loading, loading impulse, and loading rate (Table 1). Because

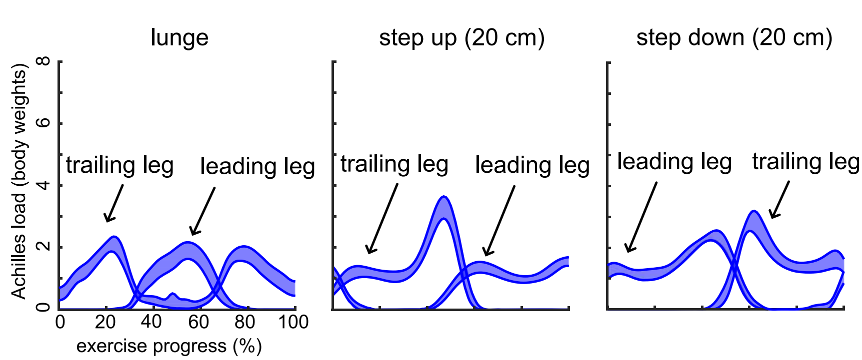

FIGURE 3—Lunges, step ups, and step downs differentially loaded the tendon depending on the leading or trailing leg. These asymmetric stepping movements differed between lunges and step ups and downs. During a lunge, peak loads were similar, but the increased time under load applied to the trailing limb explained a 52% increase in loading index. Conversely, the trailing leg during a step up underwent greater peak loading than the leading leg. These differences in loading parameters were not detected during step downs.

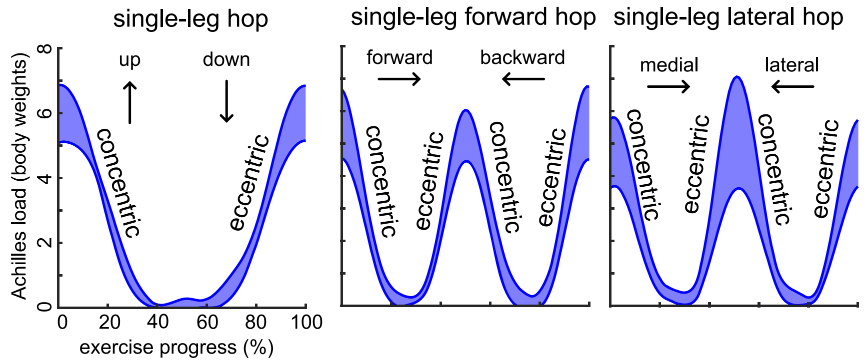

FIGURE 4—The concentric and the eccentric phases of hopping exercises were similar. Loading magnitudes and loading rates were similar between hopping in place and hopping either forward or laterally. However, hopping either forward or laterally doubled the amount of contact, which proportionately increased the loading impulse—explaining the greater loading index.

we used our own intuition and clinical experience to inform this "loading index," the exercise rankings could be subject to debate. We also acknowledge that rehabilitation protocols should differ based on the specific injury. For example, the loading rate might be of a greater concern for avoiding rerupture than loading impulse during the early recovery after an Achilles tendon rupture. Conversely, maximizing tendon loading impulse may be critical for stimulating tendon remodeling and recovery in Achilles tendinopathy. To leverage the intuition and interpretation of other researchers and clinicians, we provided a data spreadsheet (see Table, Supplemental Digital Content 1, Loading index calculations, http://links.lww.com/MSS/C53) so that others can calculate new loading indices and update exercise rankings based on their interpretation regarding the scaling factors for each of the three loading components.

Our measurements of Achilles tendon loading compare favorably to previous reports in the literature. Our participants loaded their Achilles tendons with a peak load of 3.3 bodyweights when walking at an average speed of 1.6 $m{\cdot}s^{-1}$, which compare favorably with recent shear wave tensiometry measurements of 3.7 bodyweights walking at 1.5 $m{\cdot}s^{-1}$ (6). Our measurements of Achilles tendon loading during self-selected running speed compared equally favorably to previous measurements. In one study, running at 3.7 $m{\cdot}s^{-1}$ resulted in peak Achilles loading of 6.3 bodyweights, loading impulse of 0.8 bodyweight seconds, and loading rate of 42 bodyweights per second (20). Although our participants ran slower on average

TABLE 1. Achilles tendon loading indices and metrics for rehabilitation exercises.

	Exercise	Loading Index	Loading Peak (BW)	Loading Impulse (BW s)	Loading Rate ($BW{\cdot}s^{-1}$)
Tier 1	Seated heel raise (2-leg)	0.100	0.5 ± 0.2	0.6 ± 0.2	2.7 ± 1.0
	Seated heel raise (1-leg)	0.128	0.7 ± 0.2	0.7 ± 0.3	3.6 ± 1.5
	Squat	0.167	1.1 ± 0.3	0.8 ± 0.2	4.0 ± 1.9
	Low step up (leading leg)	0.213	1.6 ± 0.4	0.7 ± 0.3	10.1 ± 5.0
	High step up (leading leg)	0.241	1.8 ± 0.3	0.8 ± 0.2	11.4 ± 3.4
	Standing heel raise (2-leg)	0.248	1.6 ± 0.2	1.2 ± 0.2	8.7 ± 2.7
Tier 2	Rebounding heel raise (2-leg)	0.282	2.5 ± 0.7	0.5 ± 0.1	19.9 ± 10.6
	Lunge (leading leg)	0.285	2.1 ± 0.6	1.2 ± 0.5	8.4 ± 3.7
	Low step down (leading leg)	0.310	2.2 ± 0.5	0.9 ± 0.2	22.9 ± 6.1
	Low step up (trailing leg)	0.341	2.9 ± 0.4	1.1 ± 0.2	14.2 ± 4.7
	High step down (trailing leg)	0.342	2.6 ± 0.3	1.2 ± 0.2	16.6 ± 6.0
	Walk (stance)	0.359	3.3 ± 0.3	0.8 ± 0.1	18.7 ± 2.7
	Low step down (trailing leg)	0.369	2.9 ± 0.3	1.3 ± 0.3	15.1 ± 5.0
	Forward jump (2-leg)	0.414	3.2 ± 1.0	1.2 ± 0.4	25.4 ± 8.5
	High step down (leading leg)	0.429	3.2 ± 0.6	1.1 ± 0.2	34.2 ± 7.5
	High step up (trailing leg)	0.432	3.7 ± 0.6	1.1 ± 0.2	22.1 ± 7.0
	Lunge (trailing leg)	0.435	2.4 ± 0.5	2.4 ± 0.7	11.5 ± 3.3
	Counter movement jump (2-leg)	0.474	3.4 ± 0.3	1.5 ± 0.3	32.5 ± 5.3
	Rebounding heel raise (1-leg)	0.476	4.2 ± 0.9	1.1 ± 0.1	26.2 ± 10.5
	Standing heel raise (1-leg)	0.493	3.0 ± 0.3	2.5 ± 0.6	13.1 ± 3.4
Tier 3	Drop jump (2-leg)	0.519	3.6 ± 0.6	1.7 ± 0.3	34.4 ± 6.7
	Hopping (2-leg)	0.555	4.8 ± 1.8	0.6 ± 0.2	56.3 ± 26.0
	Run (stance)	0.600	5.2 ± 0.9	0.7 ± 0.1	58.1 ± 12.7
	Forward hopping (2-leg)	0.656	5.2 ± 2.6	1.3 ± 0.5	58.4 ± 33.4
	Counter movement jump (1-leg)	0.705	4.9 ± 0.6	2.4 ± 0.5	46.2 ± 7.1
	Forward jump (1-leg)	0.740	5.4 ± 1.1	2.3 ± 0.4	46.9 ± 11.1
Tier 4	Hopping (1-leg)	0.764	6.7 ± 1.6	1.3 ± 0.2	62.1 ± 16.9
	Drop jump (1-leg)	0.852	5.5 ± 0.8	3.0 ± 0.4	59.2 ± 9.1
	Lateral hopping (1-leg)	0.904	7.3 ± 2.4	2.1 ± 0.7	67.7 ± 25.9
	Forward hopping (1-leg)	0.924	7.3 ± 1.9	2.3 ± 0.3	67.1 ± 18.5

Loading index is the summation of scaled and normalized peak loading, loading impulse, and loading rate ± SD. BW, bodyweights; 1-leg, single-leg; 2-leg, bilateral.

(2.9 m·s^{-1}), they demonstrated similar loading parameters with peak loading of 5.2 bodyweights, loading impulse of 0.7 bodyweight seconds, and 58.1 bodyweights per second. We suspect that our loading rates were greater because we calculated loading rate as the greatest loading rate over a 5% span of each movement rather than an average loading rate. Another study directly measured Achilles tendon loading with instrumented tendon buckles and found similar peak loading during a counter movement jump (3.0 bodyweights vs our measurement of 3.4 bodyweights) and double-leg hopping (5.1 bodyweights vs our measurement of 4.8 bodyweights) (21). Walking and running can also serve as clinical milestones and provide clinicians with confidence that patients can safely perform other exercises with similar loading indices (Table 1). For example, once patients are safely running, they can also perform single-leg heel raises and bilateral drop jumps.

Although we analyzed 25 exercises, our loading index suggests that a much smaller subset of these exercises provide loading diversity necessary to simplify rehabilitative care for patients with Achilles tendon pathology. Based on other clinical constraints, these exercises can be sorted into four loading tiers—increasing tendon load from least (tier 1) to most (tier 4). We were further able to develop two exercise progressions: one consisting of isolated ankle movements and a second consisting of multijoint movements (Fig. 2). Increasing tendon loading can be prescribed with isolated ankle movements: seated heel raise (tier 1), single-leg heel raise (tier 2), double-leg hopping (tier 3), and single-leg forward hop (tier 4). Similar tendon loads can also be prescribed using multijoint movements: squat (tier 1), step up or step down (tier 2), single-leg counter movement jump (tier 3), and single-leg drop jump (tier 4). This tiering system also provides clinicians with more freedom to tailor rehabilitation protocols based on patient preference while meeting tendon loading goals.

We found that similar loading profiles can be achieved during the concentric phase of rehabilitation exercises. The most notable example is single-leg hopping in any direction (Fig. 4). During both the concentric and eccentric phases of these movements, peak loads and impulse were very similar. We posit that it is not eccentric loading but rather the loading impulse that is an important mechanism responsible for tendon recovery and healing. This is analogous to "time under tension," which is easily controlled by resisting a heavy load for a prescribed amount of time. However, our study suggests that the total mechanical loading applied to the Achilles tendon can be manipulated by changing several loading parameters simply by performing a different type of movement. Another biomechanical analysis of rehabilitation exercises found similar loading magnitudes during the eccentric and concentric phases (22). However, this previous study found higher frequency oscillations in tendon force during eccentric exercises compared with concentric exercise. This information should be considered when selecting scaling factors for peak loading, loading impulse, and rate of loading (see Table, Supplemental Digital Content 1, Loading index calculations, http://links.lww.com/MSS/C53). Although not surprising given the spring-mass properties of simple bouncing (23), these biomechanical findings support a series of reviews (24–27) that challenge the concept that eccentric loading is superior to concentric loading for treating tendinopathies. Recent advances in wearable technology (28,29) provide new capabilities to quantify Achilles tendon loading biomechanics in patients during activities and rehabilitation outside traditional biomechanics laboratories. These technologies provide clinicians and researchers with additional capabilities to better explore these fundamental questions surrounding rehabilitation programming.

This study was affected by several limitations that should be considered when interpreting our findings. We assessed Achilles tendon loading in a healthy cohort of recreationally active young adults. Although patients with chronic tendon pain may decrease movement speed, we anticipate that decreased tendon loading would be uniform across movements (6,28)—preserving the exercise rankings we report in this study. Outside the scope of this study, it is possible that individuals with different training histories respond differently to similar rehabilitation loads. Although our cohort has eight participants, we performed a sensitivity analysis and found that removing one random participant did not affect the loading parameters or exercise ranks. Because the exercises we tested can be modeled as an oscillating mass, we expect that adding additional participants would only confirm our reported findings. Instead of directly measuring Achilles tendon loading, which requires invasive techniques (21,30), we approximated tendon loading as the plantarflexion ankle moment divided by moment arm. To simplify analyses, we used a constant moment arm of 5 cm (16), which does not capture the variable nature of joint moment arm between participants (31) and throughout human movement (32). In addition, we assumed that all plantarflexion torque resulted from Achilles tendon loading because the product of plantarflexor muscle contributions (33) and their moment arms (34) reveals that Achilles tendon loading accounts for approximately 94% of total plantarflexion moment during gait. However, in future studies that quantify patient-specific tendon loading profiles during rehabilitation in patients with Achilles tendon pathology, we believe that implementing subject-specific muscle contributions moment arms is an important consideration. Because the Achilles tendon is a viscoelastic material (35), we calculated the "loading index" as a scaled summation of peak load, loading impulse, and loading rate. Although we used our intuition to scale these three loading parameters, changing the scaling factors of each of these parameters may affect the exercise ranking. To accommodate this limitation, we have provided a spreadsheet so that readers can recalculate the exercise rankings based on their own interpretation about the importance of each loading parameter.

CONCLUSION

We established an exercise ranking that gradually increased Achilles tendon loading across a diverse set of exercises routinely used in our physical therapy clinic. We found that exercises fell within several loading tiers and that a subset of these exercises may be adequate in loading the tendon to stimulate healing. This report is also, to our knowledge, the most complete data set available that characterizes Achilles tendon loading during clinically relevant exercises. By leveraging these loading indices, exercise prescriptions can be tailored to the individual loading needs of patients.

The study was supported by the Department of Orthopaedic Surgery at Penn Medicine. The authors thank Ms. Kayley Dear for assisting with data collection. The authors have no conflicts of interest to report. This work does not constitute endorsement by the American College of Sports Medicine and is presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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