Journal of Athletic Training 2022;57(11/12):1062–1071
doi: 10.4085/1062-6050-0548.20

www.natajournals.org

Differences in Biomechanical Loading Magnitude During a Landing Task in Male Athletes With and Those Without Patellar Tendinopathy

Laura S. Pietrosimone, PhD, DPT, PT*; J. Troy Blackburn, PhD, ATC†‡; Erik A. Wikstrom, PhD, ATC†; David J. Berkoff, MD‡; Sean I. Docking, PhD§; Jill Cook, PhD, PT§; Darin A. Padua, PhD, ATC†‡

*Department of Orthopaedic Surgery, School of Medicine, Duke University, Durham, NC; Departments of †Exercise and Sport Science and ‡Orthopaedics, University of North Carolina at Chapel Hill; §La Trobe Sports and Exercise Research Centre, La Trobe University, Bundoora, Australia

Context: Researchers have not established if overloading or underloading movement profiles are present in symptomatic and asymptomatic athletes with patellar tendon structural abnormality (PTA) compared with healthy athletes.

Objective: To compare involved-limb landing biomechanics between male athletes with and those without patellar tendinopathy.

Design: Cross-sectional study.

Setting: Laboratory.

Patients or Other Participants: A total of 43 male athletes were grouped based on patellar tendon pain and ultrasound imaging of the proximal patellar tendon: symptomatic with PTA (SYM; n = 13; age = 19.62 ± 1.61 years, height = 1.82 ± 0.05 m, mass = 83.46 ± 5.12 kg), asymptomatic with PTA (ASYM; n = 15; age = 21.13 ± 1.88 years, height = 1.84 ± 0.07 m, mass = 81.45 ± 13.26 kg), and healthy control (CON; n = 15; age = 19.60 ± 1.55 years, height = 1.84 ± 0.09 m, mass = 79.09 ± 12.37 kg).

Main Outcome Measure(s): Three-dimensional biomechanics were collected during a double-limb jump-landing task. Kinematic (knee-flexion angle [KF]) and kinetic (vertical ground reaction force, internal knee-extension moment [KEM], patellar tendon force [F_{PT}]) variables were analyzed as continuous waveforms during the stance phase for the involved limb. Mean values were calculated for each 1% of stance, normalized over 202 data points (0%–100%), and plotted with 95% CIs. Statistical significance was defined as a lack of 95% CI overlap for a minimum of a consecutive 3% of the stance phase.

Results: The SYM group had less KF than the CON group throughout the stance phase (8%–76%: Cohen d = 1.14 ± 0.12, mean difference [MD] = 15.83° ± 2.71°). The ASYM group had less KF than the CON group in the early (8%–13%: Cohen d = 0.99 ± 0.04, MD = 7.99° ± 0.39°; 21%–24%: Cohen d = 1.01 ± 0.01, MD = 11.11° ± 0.32°) and late (74%–94%: Cohen d = 0.96 ± 0.07, MD = 9.55° ± 1.13°) stance phases. The SYM group had a smaller KEM (6.5%–9%: Cohen d = 1.21 ± 0.08, MD = 0.04 ± 0.004 N·m/[N_{bw}·m_{ht}]) and less F_{PT} (6%–9%: Cohen d = 1.15 ± 0.15, MD = 0.85 ± 0.15 body weight) than the CON group in the early stance phase. The SYM group also displayed a smaller KEM (38%–56%: Cohen d = 1.17 ± 0.06, MD = 0.03 ± 0.001 N·m/[N_{bw}·m_{ht}]) and less F_{PT} (36%–60%: Cohen d = 1.22 ± 0.08, MD = 0.66 ± 0.05 body weight) than the ASYM group in the midstance phase.

Conclusions: The SYM group demonstrated a patellar tendon load-avoidance profile compared with the ASYM and CON groups. The ASYM group showed no evidence of overloading compared with the CON group. Our findings support the need for individualized treatments for athletes with tendinopathy to maximize load capacity.

Key Words: biomechanics, waveform analysis, tendon

Key Points

- During landing, male athletes with symptomatic patellar tendinopathy moved through less knee-flexion motion than healthy male athletes.
- Patellar tendon load-avoidance movement profiles should be targeted through individualized treatment programs to improve the load capacity of the tendon tissue in athletes with patellar tendinopathy.

Patellar tendinopathy (pain and dysfunction in the patellar tendon) is a load-based condition that is prevalent in individuals who are physically active, particularly athletes who participate in sports with repetitive jumping manueveurs.[1–4] Some athletes are able to maintain sport participation, but the long-term consequences of chronic tendinopathy include reduced physical activity and quality of life.[5,6] Researchers have identified differences in lower extremity kinematics, kinetics, and energetics between individuals with and those without tendinopathy,[7–10] as well as between asymptomatic individuals with and those without patellar tendon structural abnormality (PTA).[11,12] However, to date, no investigators have compared movement profiles while controlling for both symptoms and structural tendon abnormalities and simultaneously including a healthy control group. Determining if biomechanical profiles are different between individuals at different stages along the PTA continuum[13] may inform the development of enhanced impairment-based, individualized treatment programs.

Symptomatic and asymptomatic athletes with PTA perform landing tasks with different movement profiles: underloading and overloading, respectively. Individuals with symptomatic patellar tendinopathy typically use a *tendon load-avoidance movement profile*, described as reduced sagittal-plane excursion, internal extension moment, and mechanical energy absorption at the knee.[7–10] The presence of PTA in asymptomatic athletes has been cited as a risk factor for symptom development.[14–17] Several authors have evaluated biomechanics in asymptomatic individuals with PTA and suggested a tendon-overloading movement profile. In a systematic review, Van der Worp et al[18] found that the greatest differences in kinematic and kinetic variables during landing tasks were reported in studies that compared healthy control participants and asymptomatic individuals with PTA.[18] In comparative cohorts of junior pre-elite male basketball athletes with and those without PTA, several kinematic variables predicted the presence of PTA, including less hip-joint excursion and greater knee-flexion angle at initial ground contact.[12] Furthermore, Edwards et al[11] observed that asymptomatic individuals with PTA landed with more knee flexion at initial contact, displayed less sagittal-plane knee-flexion excursion, and exhibited aberrant hip-knee sequencing patterns versus asymptomatic individuals without PTA.[11] This stiff movement profile is thought to reduce interjoint force distribution and increase combined tensile and compressive strain across the proximal patellar tendon; this tendon overload has been described as a key mechanical factor leading to tendinopathy.[19]

To better understand loading-pattern differences in symptomatic and asymptomatic athletes with PTA, researchers should compare these distinct groups with a group of healthy individuals. Additionally, no investigators to date have evaluated the movement profiles of individuals with patellar tendinopathy across the entire stance phase of a landing task; instead, they have looked at discrete kinematic and kinetic values (eg, at initial ground contact or at peak). Traditional analyses of biomechanical data have focused on reducing the continuous data over a specified period (eg, stance phase) into a series of discrete variables (eg, peak moment). However, discrete variables cannot completely capture all the variability in continuous data. As such, we used a waveform-analysis method that considers the time-dependent structure of the continuous biomechanical data (eg, kinematic and kinetic curves) and may, therefore, better reveal differences that can be overlooked using traditional analyses or provide further insight.[20]

Therefore, the purpose of our study was to compare involved-limb biomechanical profiles across the stance phase of a double-limb landing task in 3 distinct groups: individuals who were symptomatic with PTA (SYM), those who were asymptomatic with PTA (ASYM), and healthy control participants (CON). We hypothesized that individuals in the SYM group would demonstrate less sagittal-plane knee motion and loading on the involved limb, while individuals in the ASYM group would demonstrate greater sagittal-plane knee motion and loading on the involved limb than the matched limb of those in the CON group.

METHODS

Design

This study was registered with clinicaltrials.gov (NCT0326218). An a priori sample-size estimate was calculated using G*Power software (version 3.1.9.2; Kiel University). Using an α level of .05, a β of 0.20, and between-groups (SYM and ASYM) knee-flexion angle and peak vertical ground reaction force (vGRF) data (Cohen $d =$ 0.75–1.25),[11,21] we determined that 13 to 15 participants per group would be necessary to adequately power this study.

Participants

A total of 43 male participants with or without patellar tendinopathy were recruited from the local high school and university communities via email correspondence and public flyers (Figure 1). All participants were aged 15 to 28 years old and postpubertal, quantified using Pubertal Development Scale stage 5 (score $>$ 12).[22] Participants were required to be actively engaged in an organized sport setting, quantified using a Tegner Activity Scale score of $\geq$5 (Table 1). All participants provided written informed consent, and the study was approved by the Biomedical Institutional Review Board at the University of North Carolina at Chapel Hill.

Screening Protocol for Patellar Tendinopathy

All individuals underwent a 2-part screening protocol to determine group assignment. They were assigned to the SYM group if they exhibited (1) focal, isolated pain $\geq$2 of 10 on the numeric rating scale (identified in the patellar tendon region on the pain map [Appendix]) during performance of the single-legged decline squat (SLDS) test[23] and (2) ultrasonographic (US) evidence of proximal PTA (a hypoechoic region $\geq$2 mm evident on both the longitudinal and transverse scans).[24] All US images were obtained by a single trained investigator (L.S.P.). If a participant noted bilateral SLDS pain, criteria of $\geq$5 of 10 for the "worse" limb and $\leq$2 of 10 for the contralateral limb were required. Recruits were assigned to the ASYM group if they had no SLDS pain but demonstrated US evidence of PTA. Finally, participants were assigned to the CON group if they had no SLDS pain and no PTA.

Volunteers were excluded if they exhibited any of the following: (1) known neurologic disorder or cardiopulmonary disease, (2) a history of any lower extremity surgery, (3) a history of lower extremity injury in the 6 months before the study, (4) an injection to the patellar tendon in the 3 months before the study, (5) involvement in formal rehabilitation for anterior knee pain in the 3 months before the study, (6) nontendinopathic knee pain during the SLDS test (ie, patellofemoral pain syndrome presentation), or (7) any other medical condition that would prevent them from engaging in the normal activities of daily living.

Patient-Reported Outcomes

The Victorian Institute of Sport Assessment-Patellar Tendon (VISA-P) questionnaire was used to quantify self-

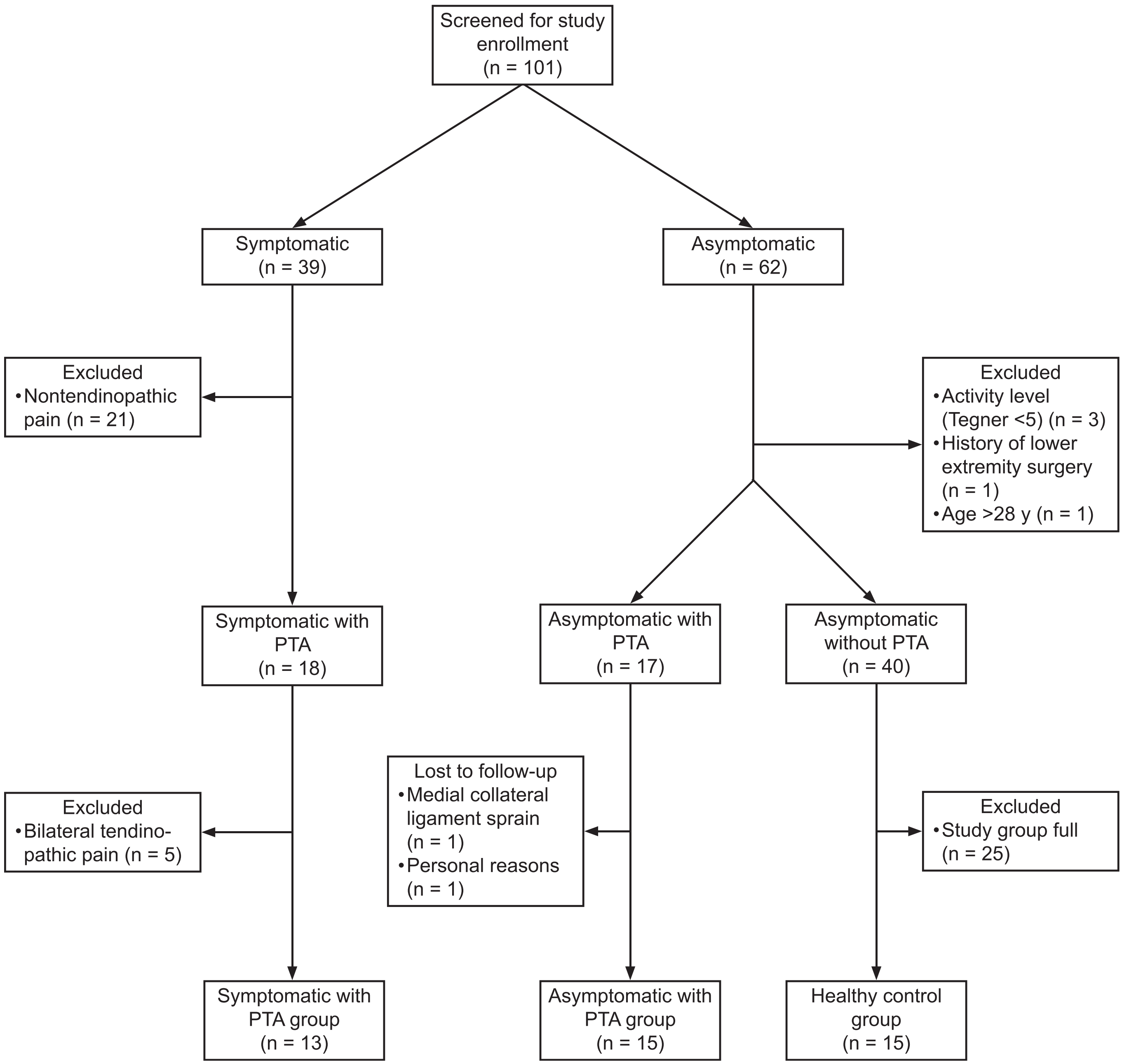


Figure 1. Consolidated Standards of Reporting Trials diagram for study recruitment and enrollment. Abbreviation: PTA, patellar tendon structural abnormality.

reported symptoms and knee function during the screening session (score range = 0–100, with 100 indicating *no symptoms and full knee function*).[25]

Three-Dimensional Landing Assessment

Testing Protocol. On a single testing day, participants visited the laboratory for a 3-dimensional biomechanical landing assessment. They performed a 5-minute warmup on a stationary bicycle at a self-selected pace.

Double-Limb Jump-Landing Task. Participants were provided with spandex shorts and tops and wore their own athletic shoes to perform 5 trials of a jump-landing task from a 30-cm-high box that was positioned at 50% of their height from the front edge of 2 force plates.[26] They were instructed to jump forward off the box to a double-legged landing with 1 foot on each force plate and perform a maximal vertical jump immediately on landing.[26] A minimum of 1 practice trial was performed; practice trials were performed until the participant and investigator (L.S.P.) ensured correct performance of the task. Five jump-landing trials were collected, and the results of the middle 3 were averaged for data analysis. If 1 of the middle 3 trials was not successful, a subsequent trial was used for analysis. A *successful trial* required the participant to leave the box with both feet at the same time, land on the force plates, and jump straight up in the air as high as possible.

Participants were outfitted with 20 retroreflective markers bilaterally on the following bony landmarks: acromion processes, anterior-superior iliac spines (ASISs), greater trochanters, medial and lateral femoral condyles, medial

Table 1. Descriptive Characteristics of the Study Population

Characteristic	Group		
	Healthy Control (n = 15)	Asymptomatic Tendinopathy (n = 15)	Symptomatic Tendinopathy (n = 13)
Age, y	19.60 ± 1.55	21.13 ± 1.88[a]	19.62 ± 1.61
Height, m	1.84 ± 0.09	1.84 ± 0.07	1.82 ± 0.05
Mass, kg	79.09 ± 12.37	81.45 ± 13.26	83.46 ± 5.12
Tegner Activity Scale (0–10)	8.07 ± 0.88	7.93 ± 1.03	8.00 ± 1.00
Pubertal Development Scale (0–12)	11.60 ± 0.63	11.87 ± 0.52	11.39 ± 0.87
Victorian Institute of Sport Assessment-Patellar Tendon (0–100)	97.80 ± 3.34	94.40 ± 7.72	76.15 ± 13.37[b,c]
Screening single-legged decline-squat pain, numeric rating scale (0–10)	0	0	3.69 ± 1.25
Pretesting single-legged decline-squat pain, numeric rating scale (0–10)	0	0	2.38 ± 1.61

[a] Different from the healthy control group ($P = .045$).
[b] Different from the healthy control group ($P < .001$; mean difference = –21.65 [95% CI = –29.81, –13.48]).
[c] Different from the asymptomatic tendinopathy group ($P < .001$; mean difference = –18.25 [95% CI = –26.41, –10.08]).

and lateral malleoli, calcanei, and the first and fifth metatarsal heads. A single marker was placed on the manubrium of the sternum and at the L4-L5 vertebral space. Rigid clusters of 3 or 4 markers were placed at the sacrum and on the thigh, shank, and foot segments bilaterally. A static trial was captured with the individual standing with the upper limbs positioned at 90° of shoulder abduction to estimate the locations of the joint centers. After the static trial, the single markers on the foot, malleoli, femoral condyles, and greater trochanters were removed.

Data Acquisition, Processing, and Reduction. Three-dimensional kinematic data were collected using a 10-camera motion-capture system (model Ultranet MX Controller with Bonita 10 cameras and Nexus version 1.7.1 software; Vicon) sampling at 120 Hz and filtered using a fourth-order, low-pass Butterworth filter with a 20-Hz cutoff frequency. Kinetic data were sampled at 1200 Hz using 2 floor-embedded force plates (model 4060-10; Bertec Corp). *Knee-* and *ankle-joint center coordinates* were defined as the centroid between the medial and lateral condyles and malleoli, respectively, identified during the static trail. *Hip-joint center coordinates* were estimated from the coordinates of the L4–5, right ASIS, and left ASIS markers using the method of Bell et al.[27] *Reference frames* for the foot, tibia, and femur were defined based on 3-dimensional coordinates and segments as follows: first and fifth metatarsal heads, ankle-joint center, and calcaneus (foot); medial and lateral malleoli, knee- and ankle-joint centers, and shank (tibia); and medial and lateral femoral condyles, knee- and hip-joint centers, and thigh (femur). *Joint angles* were defined based on the position of the distal segment relative to the proximal segment using a Cardan angle sequence in the following order of rotation: sagittal (y axis), frontal (x axis), and transverse (z axis).

Marker coordinate and GRF data were transferred into the MotionMonitor software (version 8.0; Innovative Sports Training) to build 3-dimensional link-segment models for biomechanical data analysis and reduction. Lower extremity biomechanics for each limb were evaluated during the *stance phase*, which was defined as the interval from initial contact (IC) to toe-off of the first landing.[28] *Initial contact* was defined as the time when the vGRF exceeded 10 N, and *toe-off* was defined as the time when vGRF decreased to <10 N.[28]

Kinematic variables of interest for this study were knee-flexion (+)/-extension (–) angles. Kinetic variables of interest were the vGRF, internal knee-extension moment (KEM), patellar tendon force (F_{PT}), and knee power. Ground reaction force data and processed segment data were used to calculate net internal sagittal- and frontal-plane knee-joint moments using inverse-dynamics procedures.[29] The F_{PT} was estimated using the previously defined methods of Nisell and Ekholm.[30] The patellar tendon moment arms were calculated as a function of the knee-joint angles using the methods of Herzog and Read.[31] Internal moments were normalized to the product of body weight (BW) and height ($N{\cdot}m/[N_{bw}{\cdot}m_{ht}]$), and vGRF and F_{PT} were normalized to BW. Knee power (J/s) was calculated as the product of the internal sagittal-plane knee moment ($N{\cdot}m/[N_{bw}{\cdot}m_{ht}]$) and knee-flexion velocity (°/ms).

Kinematic and kinetic variables were analyzed as continuous normalized waveforms during the stance phase of the landing tasks using custom MATLAB code (version R2017b; MathWorks). For each dependent variable, the within-group mean values were interpolated and normalized over 202 data points during the stance phase using a cubic spline filter.[32] These data points represented 0% to 100% of the stance phase of the landing task (IC through toe-off).

Statistical Analysis

Descriptive data were compared across groups using a 1-way analysis of variance and Tukey post hoc test for pairwise comparisons (SPSS version 22; IBM Corp; Table 1). Kinematic and kinetic group mean values were calculated for each 1% of the stance phase of the landing task and plotted with 95% CIs for each group comparison. *Statistical significance* was defined as any area of the stance phase in which the 95% CIs did not overlap for a minimum of a consecutive 3% of the stance phase.[32,33] Average mean differences (MDs) and Cohen *d* effect sizes were calculated for any areas that were different. Cohen *d* effect sizes were interpreted as *weak* ($d \leq 0.2$), *small* ($d = 0.2$–0.5), *moderate* ($d = 0.6$–0.8), or *large* ($d \geq 0.8$).

RESULTS

No differences in height or mass were observed among groups ($P > .05$; Table 1), but the ASYM group was

Table 2. Sport Type for Each Participant Group

Sport	Group, n		
	Healthy Control (n = 15)	Asymptomatic Tendinopathy (n = 15)	Symptomatic Tendinopathy (n = 13)
Basketball	7	9	6
Volleyball	2	1	3
Ultimate Frisbee	3	2	2
Soccer	1	2	0
Lacrosse	1	0	1
Handball	1	0	1
Football	0	1	0

slightly older than the CON group ($P = .045$). The VISA-P score was lower in the SYM group than in both the ASYM and CON groups ($P < .001$ for both), and the MDs exceeded the minimal clinically important difference (13 points).[34] Most participants in the study played either basketball or Ultimate Frisbee (Table 2).

Kinematics

The SYM group demonstrated smaller knee-flexion angles than did the CON group throughout most of the stance phase (8%–76%: Cohen $d = 1.14 \pm 0.12$, MD = 15.83° ± 2.71°). The ASYM group demonstrated smaller knee-flexion angles than did the CON group during the early (8%–13%: Cohen $d = 0.99 \pm 0.04$, MD = 7.99° ± 0.39°; 21%–24%: Cohen $d = 1.01 \pm 0.01$, MD = 11.11° ± 0.32°) and late (74%–94%: Cohen $d = 0.96 \pm 0.07$, MD = 9.55° ± 1.13°) portions of the stance phase (Figure 2). No differences were present between the SYM and ASYM groups in sagittal-plane knee angle.

Kinetics

The SYM group displayed a smaller KEM than did the CON group during early stance (6.5%–9%: Cohen $d = 1.21 \pm 0.08$, MD = 0.04 ± 0.004 N·m/[N_{bw}·m_{ht}]) and the ASYM group during midstance (38%–56%: Cohen $d = 1.17 \pm 0.06$, MD = 0.03 ± 0.001 N·m/[N_{bw}·m_{ht}]; Figure 3). The ASYM and CON groups did not differ in internal sagittal-plane knee moment.

We found no differences in vGRF among groups (Figure 4). However, the SYM group exhibited less F_{PT} during early stance than did the CON group (6%–9%: Cohen $d = 1.15 \pm 0.15$, MD = 0.85 ± 0.15 BW) and during midstance than did the ASYM group (36%–60%: Cohen $d = 1.22 \pm 0.08$, MD = 0.66 ± 0.05 BW; Figure 5). We noted no differences between the ASYM and CON groups in F_{PT}. Finally, the SYM group had less knee power than both the CON group (6%–9%: Cohen $d = 1.24 \pm 0.17$, MD = 0.48 ± 0.06 J/s; 18.5%–23%: Cohen $d = 1.34 \pm 0.13$, MD = 0.17 ± 0.01 J/s) and the ASYM group (20.5%–25%: Cohen $d = 1.14 \pm 0.08$, MD = 0.20 ± 0.01 J/s) during early stance (Figure 6). Knee power between the ASYM and CON groups did not differ.

DISCUSSION

The SYM group demonstrated a tendon load-avoidance movement profile for the involved limb, suggestive of a quadriceps-avoidance loading pattern compared with both the ASYM and CON groups. This pattern reduces demand on the extensor mechanism (quadriceps muscle and tendon and patellar tendon) to control the external knee-flexion moment. Based on our data, the ASYM group did not display tendon-overloading profiles, indicating that greater mechanical loading may not be a major factor driving the development of PTA. However, the ASYM group showed less knee-flexion motion than the CON group.

The biomechanical profile of the SYM group revealed a general pattern of underloading. Early in the energy-absorption phase of the landing task, the SYM group exhibited a smaller KEM than the CON group (Cohen $d = 1.21$, MD = 0.04 ± 0.004 N·m/[N_{bw}·m_{ht}]). In this same early phase of the landing task, we also observed less F_{PT} in the SYM than the CON group (Cohen $d = 1.15$, MD = 0.85 ± 0.15 BW). Finally, less knee-joint power during this landing phase was evident in the SYM than in the CON group (Cohen $d = 1.24$, MD = 0.48 ± 0.06 J/s), reflecting a reduction in the KEM absorption rate during the eccentric phase.

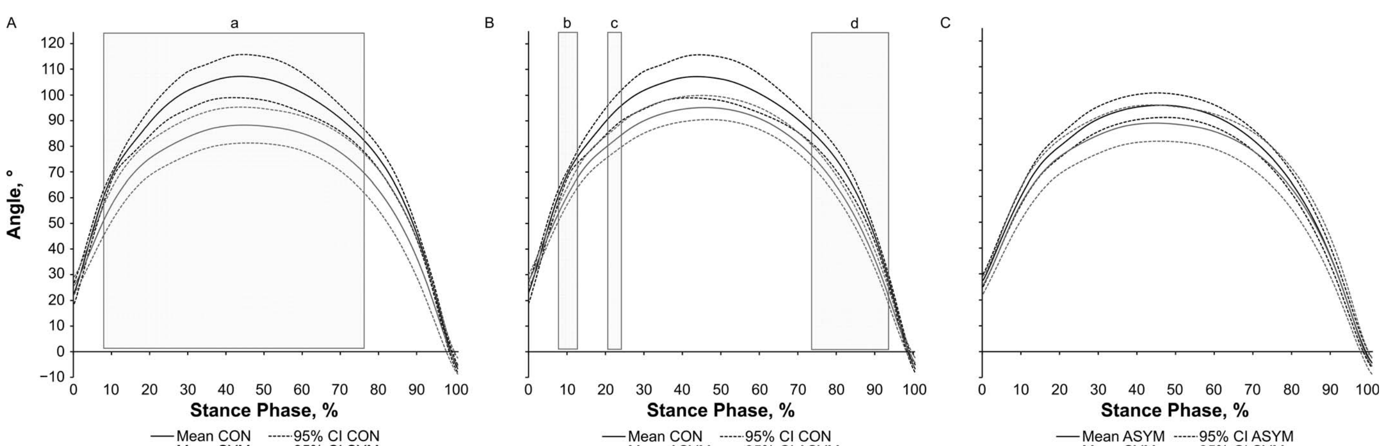


Figure 2. Mean and 95% CI waveforms for involved-limb sagittal-plane knee motion during the double-limb jump-landing task. A, Healthy control group (CON) versus symptomatic group (SYM). B, CON versus asymptomatic group (ASYM). C, ASYM versus SYM. Gray boxes indicate the areas of nonoverlap between the 95% CIs with the Cohen *d* and mean difference (MD) values. [a] Cohen *d* = 1.14 ± 0.12; MD = 15.83° ± 2.71°. [b] Cohen *d* = 0.99 ± 0.04; MD = 7.99° ± 0.32°. [c] Cohen *d* = 1.01 ± 0.01; MD = 11.11° ± 0.32°. [d] Cohen *d* = 0.96 ± 0.07; MD = 9.55° ± 1.13°.

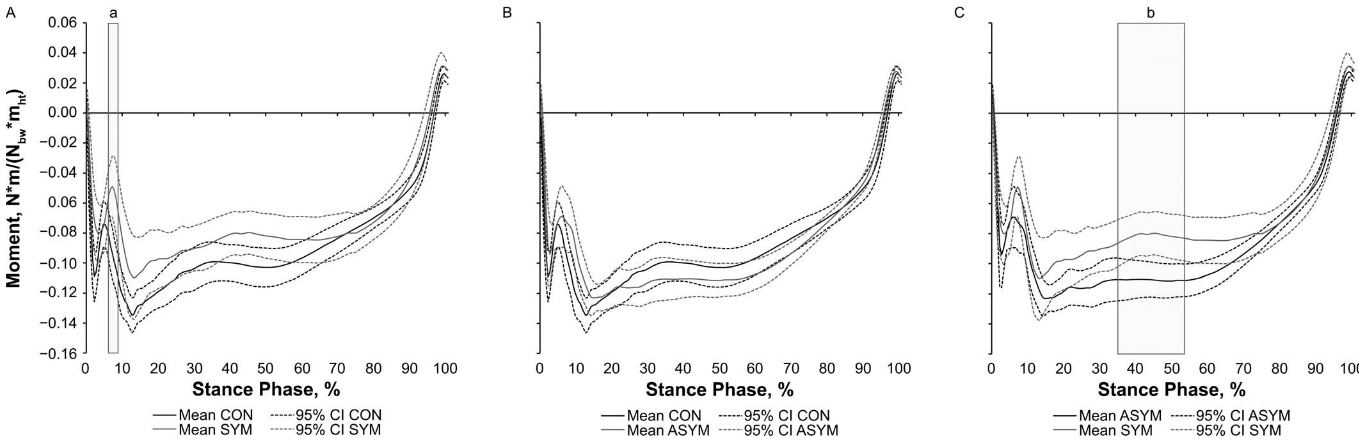


Figure 3. Mean and 95% CI waveforms for involved-limb sagittal-plane internal knee moment during the double-limb jump landing. A, Healthy control group (CON) versus symptomatic group (SYM). B, CON versus asymptomatic group (ASYM). C, ASYM versus SYM. Gray boxes indicate the areas of nonoverlap between the 95% CIs with the Cohen *d* and mean difference (MD) values. [a] Cohen $d = 1.21 \pm 0.08$; MD $= 0.04 \pm 0.004$ $N \cdot m/(N_{bw} \cdot m_{ht})$. [b] Cohen $d = 1.17 \pm 0.06$; MD $= 0.03 \pm 0.001$ $N \cdot m/(N_{bw} \cdot m_{ht})$. Abbreviations: bw, body weight; ht, height.

Our findings of an underloading biomechanical profile in the SYM group were consistent with previous research.[7,35] Reduced peak knee-flexion motion and knee-flexion excursion during landing tasks have been seen in individuals with current[7] and a history of previous ($\geq$5 months)[35] symptoms compared with healthy control participants. At increasing knee-flexion angles, patellar tendon tissue strain increases,[36] so reducing sagittal-plane motion during landing allows individuals to avoid loading painful tissues during high-energy movements. Conversely, Richards et al[37] observed greater knee-flexion motion in male elite volleyball athletes with patellar tendinopathy. This was the only study to identify elevated sagittal-plane kinematics in symptomatic individuals; therefore, those results should be interpreted cautiously because of the small number of athletes with tendinopathy ($n = 3$) and the exclusive use of palpation as the diagnostic inclusion criteria for tendinopathy.

Interestingly, no participants in the SYM group reported pain during testing that prevented completion of the jump-landing task, despite the presence of SLDS pain immediately before testing. However, they did describe more pain during activity and sport than athletes in the other groups, as quantified by the lower mean VISA-P score. Although we did not account for the duration of activity-related tendon pain, we hypothesized that these simultaneous kinetic and energetic alterations were likely learned behaviors over time to reduce the tendon load due to activity-related pain. Thus, closely monitoring activity-related pain and cumulative training load may be an important feature of both prevention and treatment programs for patellar tendinopathy, as the high frequency of loading during sport-related activities may be more provocative and more noticeable to a patient than during a single bout of landings, as used in this study. Additionally, though reducing knee-flexion motion during landing may be a pain-avoiding strategy, reducing the tissue load across the tendon may, in time, reduce the overall loading tolerance capacity of the tissue.[38]

Our results in the ASYM group did not offer any evidence for overloading across the entire stance phase of the landing task, which may have important clinical implications for the best treatment approach in this patient population. The lack of overloading in the ASYM group in our study was in contrast with previous outcomes. In earlier work,[11,12] asymptomatic male athletes with PTA demonstrated greater sagittal-plane knee-flexion angles at initial ground contact but less knee-flexion displacement than healthy control participants during landing. These movement strategies have been hypothesized to facilitate a stiff

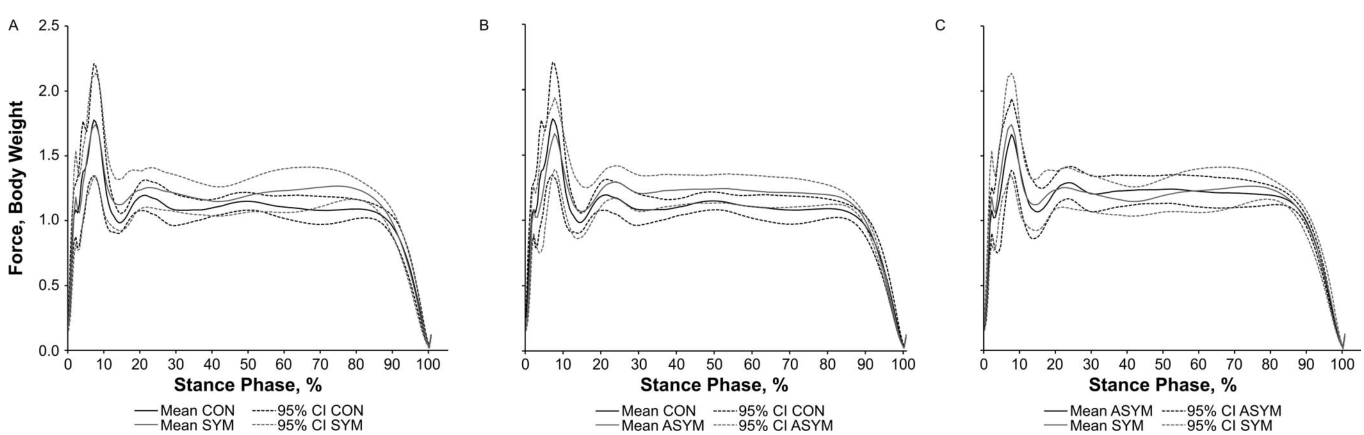


Figure 4. Mean and 95% CI waveforms for involved-limb vertical ground reaction force during the double-limb jump landing. A, Healthy control group (CON) versus symptomatic group (SYM). B, CON versus asymptomatic group (ASYM). C, ASYM versus SYM.

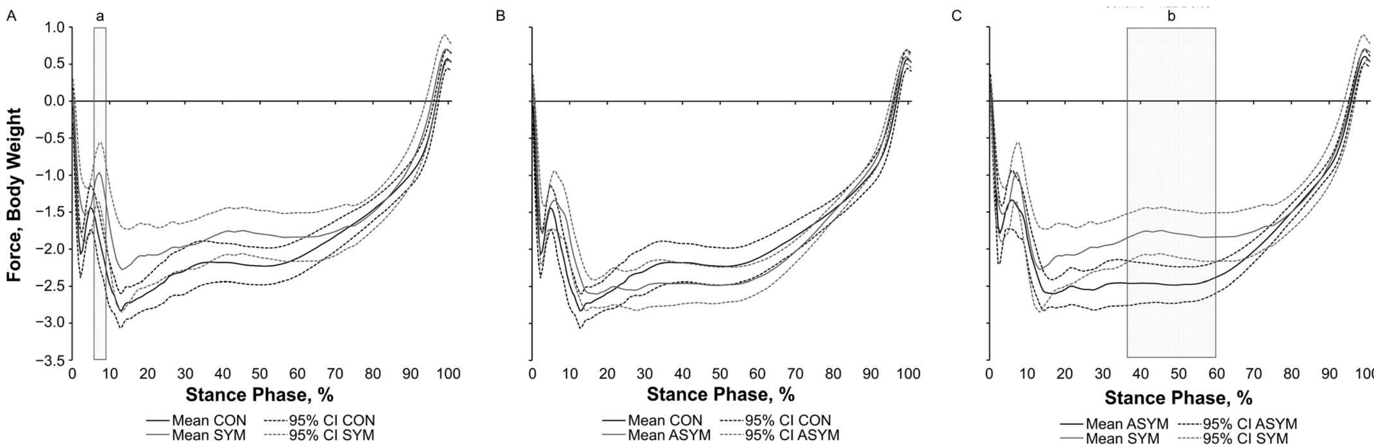


Figure 5. Mean and 95% CI waveforms for involved-limb patellar tendon force during the double-limb jump landing. A, Healthy control group (CON) versus symptomatic group (SYM). B, CON versus asymptomatic group (ASYM). C, ASYM versus SYM. Gray boxes indicate the areas of nonoverlap between the 95% CIs with the Cohen d and mean difference (MD) values. [a] Cohen $d = 1.15 \pm 0.15$; MD $= 0.85 \pm 0.15$ body weight. [b] Cohen $d = 1.22 \pm 0.08$; MD $= 0.66 \pm 0.05$ body weight.

landing movement profile that increases the demand on the knee-extensor mechanism, which may increase the combined tensile and compressive strain across the proximal patellar tendon.[19] However, our ASYM group showed similar vGRF, KEM, F_{PT}, and knee power-loading profiles but less knee flexion during the stance phase than those in the CON and SYM groups.

Importantly, in previous studies, symptomatic patellar tendinopathy was typically defined based on self-reported pain or pain with palpation, without confirmation of PTA. The sensitivity (68%) and specificity (9%) of palpation is poor, and therefore, palpation is not considered a robust diagnostic tool.[39] Additionally, patients with numerous overuse injury conditions, such as patellofemoral pain syndrome, commonly present clinically with activity-related anterior knee pain. Using a systematic and comprehensive approach to define patellar tendinopathy based on both tendon pain and PTA is an important and novel feature of our research.

We believe that our findings are clinically important, as they suggest that using interventions to shield the patellar tendon from load may not be beneficial, as asymptomatic individuals were already demonstrating patterns of underloading. It is possible that underloading may lead to reduced tissue capacity and subsequent symptom development over time. Docking and Cook[24] found that pathological tendons had increased cross-sectional areas of aligned fibrillar structure surrounding the abnormalities, suggesting that the tendon may adapt. This thickening of healthy tendon results in sufficient amounts of load-bearing tissue that should be targeted using progressive load-based interventions to build overall tissue capacity. Despite evidence suggesting that a degenerative tendon matrix is unlikely to be reversible, this evolving concept focused on "treating the doughnut (aligned structure), not the hole (area of disorganization)"[38] is potentially an area that can improve the function and prognosis of asymptomatic individuals with structural abnormalities.

We acknowledge several limitations to this study. The cross-sectional design prevented us from determining whether the observed movement profiles were present before the development of PTA. Using a systematic and comprehensive approach to define *tendinopathy* based on both tendon pain and PTA was an important and novel

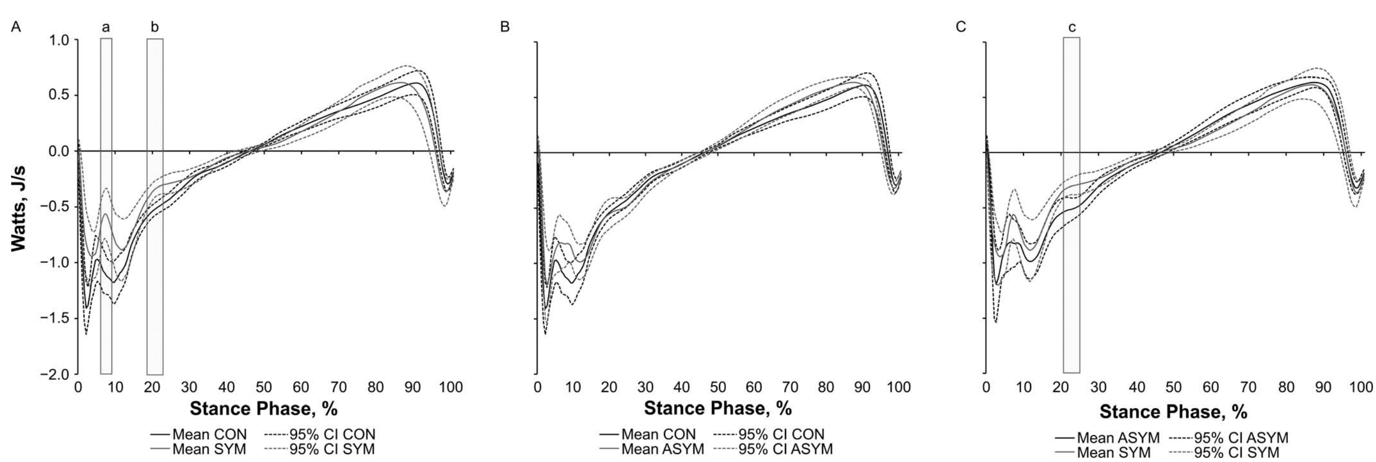


Figure 6. Mean and 95% CI waveforms for involved-limb knee power during the double-limb jump landing. A, Healthy control group (CON) versus symptomatic group (SYM). B, CON versus asymptomatic group (ASYM). C, ASYM versus SYM. Gray boxes indicate the areas of nonoverlap between the 95% CIs with the Cohen d and mean difference (MD) values. [a] Cohen $d = 1.24 \pm 0.17$; MD $= 0.48 \pm 0.06$ J/s. [b] Cohen $d = 1.34 \pm 0.13$; MD $= 0.17 \pm 0.01$ J/s. [c] Cohen $d = 1.14 \pm 0.08$; MD $= 0.20 \pm 0.01$ J/s.

feature of our study. Although we used these robust criteria, we did not account for the duration of symptoms in the SYM group, which may have influenced how long an individual may have developed and used aberrant movement profiles in response to persistent pain. In addition, our SYM cohort demonstrated low to moderate pain levels before the biomechanical assessment. Of the 13 symptomatic athletes, 2 indicated bilateral pain during the SLDS assessment (meeting our inclusion criteria of $\geq$5 of 10 on the worse limb and $\leq$2 of 10 on the contralateral limb), so it is possible this may have influenced our results.

Additionally, we focused on biomechanical differences at the knee; in the future, researchers should consider using waveform analyses to explore differences at the hip and ankle in these specific diagnostic groups. We also recognize that more between-groups differences in movement profiles may have been absent because of the relatively small sample size in each group and the high degree of variability, particularly in the SYM group, which had wide 95% CIs. We used a single bilateral landing task, which may not fully mimic the demands of sport for all participants. Finally, we conducted this study with only college-aged men, so our findings cannot be extrapolated to females or males of a different age range. In the future, investigators should continue to assess both laboratory and real-world movement characteristics of individuals at various stages of the continuum of tendinopathy to best design targeted rehabilitation strategies to improve tissue resilience and performance.

CONCLUSIONS

Participants with symptomatic patellar tendinopathy demonstrated differences in sagittal-plane biomechanics that are associated with high patellar tendon stress and extensor-mechanism demand. Patellar tendon load-avoidance movement profiles should be targeted using individualized treatment programs to improve the load capacity of the tendon tissue in athletes with patellar tendinopathy.

ACKNOWLEDGMENTS

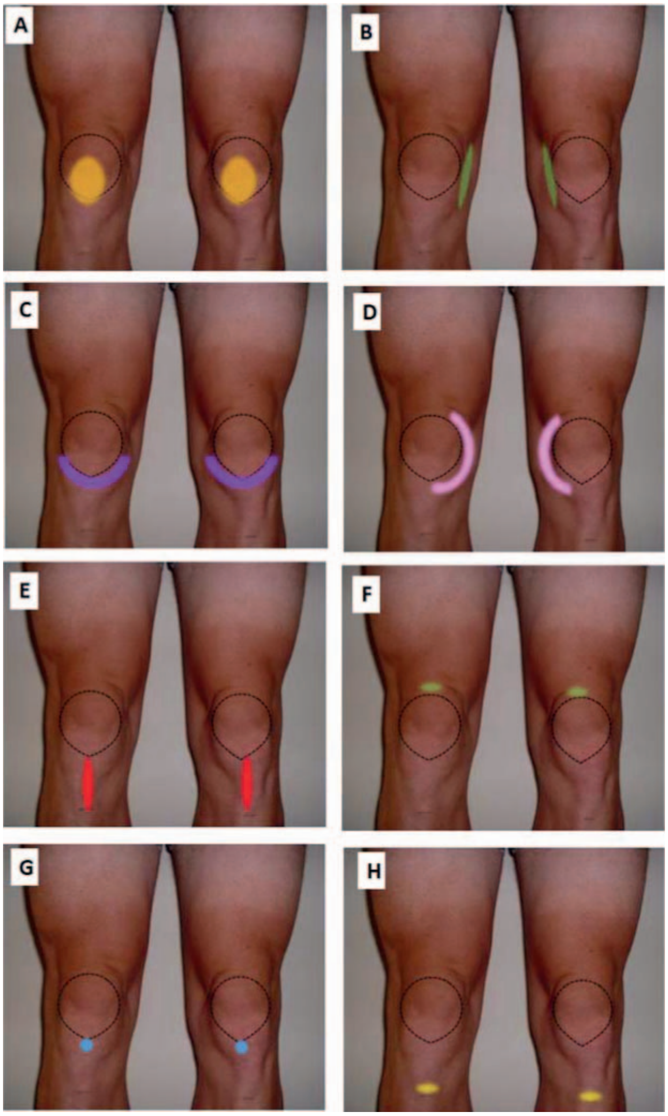
Funding for this study was provided by the Foundation for Physical Therapy Promotion of Doctoral Studies II Scholarship (Dr Pietrosimone).

REFERENCES

1. Cook JL, Khan KM, Kiss ZS, Griffiths L. Patellar tendinopathy in junior basketball players: a controlled clinical and ultrasonographic study of 268 patellar tendons in players aged 14–18 years. *Scand J Med Sci Sports*. 2000;10(4):216–220. doi:10.1034/j.1600-0838.2000.010004216.x
2. Cook JL, Kiss ZS, Khan KM, Purdam CR, Webster KE. Anthropometry, physical performance, and ultrasound patellar tendon abnormality in elite junior basketball players: a cross-sectional study. *Br J Sports Med*. 2004;38(2):206–209. doi:10.1136/bjsm.2003.004747
3. Zwerver J, Bredeweg SW, van den Akker-Scheek I. Prevalence of jumper's knee among nonelite athletes from different sports: a cross-sectional survey. *Am J Sports Med*. 2011;39(9):1984–1988. doi:10.1177/0363546511413370
4. Lian ØB, Engebretsen L, Bahr R. Prevalence of jumper's knee among elite athletes from different sports: a cross-sectional survey. *Am J Sports Med*. 2005;33(4):561–567. doi:10.1177/0363546504270454
5. Silbernagel KG, Crossley KM. A proposed return-to-sport program for patients with midportion Achilles tendinopathy: rationale and implementation. *J Orthop Sport Phys Ther*. 2015;45(11):876–886. doi:10.2519/jospt.2015.5885
6. Cook JL, Khan KM, Harcourt PR, Grant M, Young DA, Bonar SF. A cross sectional study of 100 athletes with jumper's knee managed conservatively and surgically: the Victorian Institute of Sport Tendon Study Group. *Br J Sports Med*. 1997;31(4):332–336. doi:10.1136/bjsm.31.4.332
7. Rosen AB, Ko J, Simpson KJ, Kim SH, Brown CN. Lower extremity kinematics during a drop jump in individuals with patellar tendinopathy. *Orthop J Sports Med*. 2015;3(3):2325967115576100. doi:10.1177/2325967115576100
8. Bisseling RW, Hof AL, Bredeweg SW, Zwerver J, Mulder T. Relationship between landing strategy and patellar tendinopathy in volleyball. *Br J Sports Med*. 2007;41(7):e8. doi:10.1136/bjsm.2006.032565
9. Sorenson SC, Arya S, Souza RB, Pollard CD, Salem GJ, Kulig K. Knee extensor dynamics in the volleyball approach jump: the influence of patellar tendinopathy. *J Orthop Sports Phys Ther*. 2010;40(9):568–576. doi:10.2519/jospt.2010.3313
10. Siegmund JA, Huxel KC, Swanik CB. Compensatory mechanisms in basketball players with jumper's knee. *J Sport Rehabil*. 2008;17(4):358–371. doi:10.1123/jsr.17.4.358
11. Edwards S, Steele JR, McGhee DE, Beattie S, Purdam C, Cook JL. Landing strategies of athletes with an asymptomatic patellar tendon abnormality. *Med Sci Sports Exerc*. 2010;42(11):2072–2080. doi:10.1249/MSS.0b013e3181e0550b
12. Mann KJ, Edwards S, Drinkwater EJ, Bird SP. A lower limb assessment tool for athletes at risk of developing patellar tendinopathy. *Med Sci Sports Exerc*. 2013;45(3):527–533. doi:10.1249/MSS.0b013e318275e0f2
13. Cook JL, Purdam CR. Is tendon pathology a continuum? A pathology model to explain the clinical presentation of load-induced tendinopathy. *Br J Sports Med*. 2009;43(6):409–416. doi:10.1136/bjsm.2008.051193
14. Cook JL, Khan KM, Kiss ZS, Coleman BD, Griffiths L. Asymptomatic hypoechoic regions on patellar tendon ultrasound: a 4-year clinical and ultrasound followup of 46 tendons. *Scand J Med Sci Sports*. 2001;11(6):321–327. doi:10.1034/j.1600-0838.2001.110602.x
15. McAuliffe S, McCreesh K, Culloty F, Purtill H, O'Sullivan K. Can ultrasound imaging predict the development of Achilles and patellar tendinopathy? A systematic review and meta-analysis. *Br J Sports Med*. 2016;50(24):1516–1523. doi:10.1136/bjsports-2016-096288
16. Fredberg U, Bolvig L. Significance of ultrasonographically detected asymptomatic tendinosis in the patellar and Achilles tendons of elite soccer players: a longitudinal study. *Am J Sports Med*. 2002;30(4):488–491. doi:10.1177/03635465020300040701
17. Cook JL, Khan KM, Kiss ZS, Purdam CR, Griffiths L. Prospective imaging study of asymptomatic patellar tendinopathy in elite junior basketball players. *J Ultrasound Med*. 2000;19(7):473–479. doi:10.7863/jum.2000.19.7.473
18. Van der Worp H, de Poel HJ, Dierkes RL, van den Akker-Scheek I, Zwerver J. Jumper's knee or lander's knee? A systematic review of the relation between jump biomechanics and patellar tendinopathy. *Int J Sports Med*. 2014;35(8):714–722. doi:10.1055/s-0033-1358674
19. Cook JL, Purdam C. Is compressive load a factor in the development of tendinopathy? *Br J Sports Med*. 2012;46(3):163–168. doi:10.1136/bjsports-2011-090414
20. Kuenze C, Hertel J, Weltman A, Diduch DR, Saliba S, Hart JM. Jogging biomechanics after exercise in individuals with ACL-

reconstructed knees. *Med Sci Sport Exerc*. 2014;46(6):1067–1076. doi:10.1249/mss.0000000000000217
21. Edwards S, Steele JR, Cook JL, Purdam CR, McGhee DE, Munro BJ. Characterizing patellar tendon loading during the landing phases of a stop-jump task. *Scand J Med Sci Sport*. 2012;22(1):2–11. doi:10.1111/j.1600-0838.2010.01119.x
22. Carskadon MA, Acebo C. A self-administered rating scale for pubertal development. *J Adolesc Health*. 1993;14(3):190–195. doi:10.1016/1054-139x(93)90004-9
23. Purdam CR, Cook JL, Hopper DM, Khan KM; VIS Tendon Study Group. Discriminative ability of functional loading tests for adolescent jumper's knee. *Phys Ther Sport*. 2003;4(1):3–9. doi:10.1016/S1466-853X(02)00069-X
24. Docking SI, Cook J. Pathological tendons maintain sufficient aligned fibrillar structure on ultrasound tissue characterization (UTC). *Scand J Med Sci Sports*. 2016;26(6):675–683. doi:10.1111/sms.12491
25. de Michelis Mendonça L, Ocarino JM, Bittencourt NF, Fernandes LM, Verhagen E, Fonseca ST. The accuracy of VISA-P questionnaire, single-leg decline squat and tendon pain history to identify patellar tendon abnormalities in adult athletes. *J Orthop Sports Phys Ther*. 2016;46(8):673–680. doi:10.2519/jospt.2016.6192
26. Padua DA, Marshall SW, Boling MC, Thigpen CA, Garrett WE II, Beutler AI. The Landing Error Scoring System (LESS) is a valid and reliable clinical assessment tool of jump-landing biomechanics: the JUMP-ACL study. *Am J Sport Med*. 2009;37(10):1996–2002. doi:10.1177/0363546509343200
27. Bell AL, Pedersen DR, Brand RA. A comparison of the accuracy of several hip center location prediction methods. *J Biomech*. 1990;23(6):617–621. doi:10.1016/0021-9290(90)90054-7
28. Goerger BM, Marshall SW, Beutler AI, Blackburn JT, Wilckens JH, Padua DA. Anterior cruciate ligament injury alters preinjury lower extremity biomechanics in the injured and uninjured leg: the JUMP-ACL study. *Br J Sports Med*. 2015;49(3):188–195. doi:10.1136/bjsports-2013-092982
29. Winter DA. *Biomechanics and Motor Control of Human Movement*. 4th ed. Wiley; 2009.
30. Nisell R, Ekholm J. Patellar forces during knee extension. *Scand J Rehabil Med*. 1985;17(2):63–74.
31. Herzog W, Read LJ. Lines of action and moment arms of the major force-carrying structures crossing the human knee joint. *J Anat*. 1993;182(part 2):213–230.
32. Frank BS, Hackney AC, Battaglini CL, et al. Movement profile influences systemic stress and biomechanical resilience to high training load exposure. *J Sci Med Sport*. 2019;22(1):35–41. doi:10.1016/j.jsams.2018.05.017
33. McKeon PO, Paolini G, Ingersoll CD, et al. Effects of balance training on gait parameters in patients with chronic ankle instability: a randomized controlled trial. *Clin Rehabil*. 2009;23(7):609–621. doi:10.1177/0269215509102954
34. Hernandez-Sanchez S, Hidalgo MD, Gomez A. Responsiveness of the VISA-P scale for patellar tendinopathy in athletes. *Br J Sports Med*. 2014;48(6):453–457. doi:10.1136/bjsports-2012-091163
35. Bisseling RW, Hot AL, Bredeweg SW, Zwerver J, Mulder T. Are the take-off and landing phase dynamics of the volleyball spike jump related to patellar tendinopathy? *Br J Sports Med*. 2008;42(6):483–489. doi:10.1136/bjsm.2007.044057
36. Defrate LE, Nha KW, Papannagari R, Moses JM, Gill TJ, Li G. The biomechanical function of the patellar tendon during in-vivo weight-bearing flexion. *J Biomech*. 2007;40(8):1716–1722. doi:10.1016/j.jbiomech.2006.08.009
37. Richards DP, Ajemian SV, Wiley JP, Zernicke RF. Knee joint dynamics predict patellar tendinitis in elite volleyball players. *Am J Sports Med*. 1996;24(5):676–683. doi:10.1177/036354659602400520
38. Cook JL, Rio E, Purdam CR, Docking SI. Revisiting the continuum model of tendon pathology: what is its merit in clinical practice and research? *Br J Sports Med*. 2016;50(19):1187–1191. doi:10.1136/bjsports-2015-095422
39. Cook JL, Khan KM, Kiss ZS, Purdam CR, Griffiths L. Reproducibility and clinical utility of tendon palpation to detect patellar tendinopathy in young basketball players: Victorian Institute of Sport tendon study group. *Br J Sports Med*. 2001;35(1):65–69. doi:10.1136/bjsm.35.1.65

Address correspondence to Laura S. Pietrosimone, PhD, DPT, PT, Department of Orthopaedic Surgery, School of Medicine, Duke University, 311 Trent Drive, Durham, NC 27705. Address email to laura.pietrosimone@duke.edu.



Appendix. Pain map that participants used to determine the location of pain immediately after a single-legged decline squat. Selections E and G were considered positive for patellar tendon pain to meet the study inclusion criteria.