January 2010

Landing strategies of athletes with an asymptomatic patellar tendon abnormality

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Recommended Citation

Edwards, Suzi; Steele, Julie R.; McGhee, Deirdre; Beattie, Sue; Purdam, Craig; and Cook, Jill L.: Landing strategies of athletes with an asymptomatic patellar tendon abnormality 2010, 2072-2080.
https://ro.uow.edu.au/hbspapers/548

Landing strategies of athletes with an asymptomatic patellar tendon abnormality

Abstract

Purpose: Risk factors associated with a clinical presentation of patellar tendinopathy are patellar tendon ultrasonographic abnormality (PTA) and excessive loading. It remains unknown whether characteristics of an athlete's landing technique contribute to this excessive patellar tendon loading. This study investigated whether asymptomatic athletes with and without PTA had different landing strategies and hypothesized that asymptomatic athletes with a PTA would create higher patellar tendon loading and a different lower-limb landing strategy compared with athletes with normal patellar tendons. Methods: Seven athletes with no previous history or clinical signs of patellar tendon injury with a PTA were matched to athletes with normal patellar tendons (controls). Participants performed five successful trials of a stop-jump task, which involved a simultaneous two-foot horizontal and then vertical landing. During each trial, the participants' ground reaction forces and lower-limb electromyographic data were recorded, the three-dimensional kinematics measured, and the peak patellar tendon force calculated by dividing the net knee joint moment by the patellar tendon moment arm. Results: Significant between-group differences in landing technique were mostly observed during the horizontal landing phase. Participants with a PTA created similar patellar tendon loading to the controls, but with altered sequencing, by landing with significantly greater knee flexion and extending their hips while the controls flexed their hips as they landed, reflecting a different muscle recruitment order compared with the PTA group. Conclusions: The crucial part in the development of PTA and, in turn, patellar tendinopathy may not be the magnitude of the patellar tendon load but rather the loading patterns. This research provides clinicians with important landing assessment criteria against which to identify athletes at risk of developing patellar tendinopathy.

Keywords

strategies, athletes, asymptomatic, patellar, tendon, landing, abnormality

Disciplines

Arts and Humanities | Life Sciences | Medicine and Health Sciences | Social and Behavioral Sciences

Publication Details

Edwards, S., Steele, J. R., McGhee, D., Beattie, S., Purdam, C. & Cook, J. L. (2010). Landing strategies of athletes with an asymptomatic patellar tendon abnormality. Medicine and Science in Sports and Exercise, 42 (11), 2072-2080.

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Landing Strategies of Athletes with an Asymptomatic Patellar Tendon Abnormality

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ABSTRACT

EDWARDS, S., J. R. STEELE, D. E. McGHEE, S. BEATTIE, C. PURDAM, and J. L. COOK. Landing Strategies of Athletes with an Asymptomatic Patellar Tendon Abnormality. *Med. Sci. Sports Exerc.*, Vol. 42, No. 11, pp. 2072–2080, 2010. **Purpose**: Risk factors associated with a clinical presentation of patellar tendinopathy are patellar tendon ultrasonographic abnormality (PTA) and excessive loading. It remains unknown whether characteristics of an athlete's landing technique contribute to this excessive patellar tendon loading. This study investigated whether asymptomatic athletes with and without PTA had different landing strategies and hypothesized that asymptomatic athletes with a PTA would create higher patellar tendon loading and a different lower-limb landing strategy compared with athletes with normal patellar tendons. **Methods**: Seven athletes with no previous history or clinical signs of patellar tendon injury with a PTA were matched to athletes with normal patellar tendons (controls). Participants performed five successful trials of a stop-jump task, which involved a simultaneous two-foot horizontal and then vertical landing. During each trial, the participants' ground reaction forces and lower-limb electromyographic data were recorded, the three-dimensional kinematics measured, and the peak patellar tendon force calculated by dividing the net knee joint moment by the patellar tendon moment arm. **Results**: Significant between-group differences in landing technique were mostly observed during the horizontal landing phase. Participants with a PTA created similar patellar tendon loading to the controls, but with altered sequencing, by landing with significantly greater knee flexion and extending their hips while the controls flexed their hips as they landed, reflecting a different muscle recruitment order compared with the PTA group. **Conclusions**: The crucial part in the development of PTA and, in turn, patellar tendinopathy may not be the magnitude of the patellar tendon load but rather the loading patterns. This research provides clinicians with important landing assessment criteria against which to identify athletes at risk of developing patellar tendinopathy. **Key Words**: PATELLAR TENDINOPATHY, KNEE, BIOMECHANICS, HYPOECHOIC AREA

Patellar tendinopathy is an overuse knee injury common in individuals who subject their extensor mechanism to intense and repetitive loading. Diagnosis of patellar tendinopathy is confirmed by a history of activity-related pain, focal tenderness, a Victorian Institute of Sport assessment (VISA) score of less than 80 (39), and the presence of a patellar tendon ultrasonographic abnormality (PTA) (25) on diagnostic imaging. Interestingly, although PTA and tendon pain are the diagnostic criteria for patellar tendinopathy, PTA can also be evident in athletes without tendon pain, with a prevalence of 22%–32% (8,10,18,20,28,30). The presence of PTA in asymptomatic athletes has been identified as a risk factor in the development of patellar tendinopathy (9,10,18), whereby the likelihood of an asymptomatic athlete with a PTA developing patellar tendinopathy increases four times in basketball players (10) and 17% in elite soccer players compared with asymptomatic athletes with no evidence of PTA (18). Despite being confirmed as a risk factor, the clinical importance of PTA changes has not yet been clarified (20) because an asymptomatic PTA can resolve, remain unchanged, or worsen in athletes (18,30) without predicting symptoms of patellar tendinopathy (8,20,28).

Altered lower-limb landing strategies have also been associated with patellar tendinopathy (5,6,21,35,36). In symptomatic athletes with patellar tendinopathy, Richards et al. (35) observed that during a vertical landing, these athletes landed with a higher rate of knee moment development, a relatively extended knee joint (35,36), but attained a higher maximum knee flexion angle and a greater knee flexion range of motion. The authors claimed that greater maximum knee flexion during landing was a strong predictor of patellar tendinopathy (35) because increased knee flexion can increase the patellar tendon load and, in

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Submitted for publication November 2009.
Accepted for publication March 2010.

0195-9131/10/4211-2072/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0b013e3181e0550b

turn, contribute to development of patellar tendinopathy (35,36). Nevertheless, Bisseling et al. (5) observed that symptomatic athletes with patellar tendinopathy used a "load-avoiding" landing strategy during a vertical landing task. That is, relative to control athletes, symptomatic athletes displayed a significantly lower knee joint moment, work, and power despite no significant differences in peak vertical ground reaction force or loading rate (5). The researchers, however, did not explain how the symptomatic athletes achieved this reduction in load. It was also found that during a vertical landing task, asymptomatic athletes with a previous history of patellar tendinopathy task landed with a higher knee angular velocity and rate of knee moment development relative to athletes with no history of patellar tendon pain (5,6). It remains unknown, however, whether the presence of PTA in asymptomatic athletes affects their landing technique or whether their landing technique might predispose them to developing a PTA and/or patellar tendinopathy. In addition, most of this previous research examining the landing of athletes with patellar tendinopathy has investigated a vertical landing task (5,6,34,35). However, a horizontal landing when compared with a vertical landing places the highest load on the patellar tendon and should be preferably used when investigating lower-limb landing mechanics in athletes with patellar tendinopathy (15).

The purpose of this study was to identify whether asymptomatic athletes with a PTA displayed a different landing technique compared with athletes with a normal patellar tendon. It was hypothesized that asymptomatic athletes with a PTA would create higher patellar tendon loading and a different lower-limb landing strategy compared with athletes with normal patellar tendons.

METHODS

Participants

Twenty-three skilled male athletes (mean age = 23.7 ± 4.0 yr, height = 183.0 ± 6.2 cm, mass = 82.4 ± 10.4 kg) were recruited from team sports involving repetitive landing. All participants were right leg dominant on the basis of their preferred kicking leg (17). Participants reported no history of traumatic lower-limb injuries. The patellar tendon morphology of all participants was documented by an experienced musculoskeletal sonographer (S.B.) using a 13-MHz linear array ultrasound transducer (Antares, Siemens AG, Germany), and the presence of an ultrasound abnormality, as defined by Cook et al. (9), was recorded.

Seven male participants with a PTA (Table 1) but no previous history or clinical signs of patellar tendinopathy (mean age = 25.2 ± 4.7 yr, height = 183.4 ± 7.2 cm, mass = 83.2 ± 9.0 kg, VISA score (38) = 96 ± 8, static dorsiflexion lunge test (3), range of motion = 13.9 ± 3.1 cm) were identified and individually matched for height, mass, and test limb to seven male participants with normal patellar tendons (controls; age = 22.3 ± 2.4 yr, height = 185.9 ± 8.1 cm, mass = 82.0 ± 12.6 kg, VISA score = 99 ± 2, static dorsiflexion lunge test range of motion = 15.5 ± 4.1 cm). If a participant had bilateral PTA, the lower limb with the larger PTA area was selected for analysis. All between-group comparisons were made with independent-samples t-tests, and there were no significant between-group differences in age, height, mass, static dorsiflexion range, or VISA score. Written informed consent was obtained from each participant before data collection, and all the study's methods were approved by the institution's Human Research Ethics Committee (HE06/205).

TABLE 1. PTA measurements in PTA participants.

Measurement (mm)	PTA Dimensions
Sagittal plane height	3.3 ± 2.7 (1.4–8.8)
Axial plane height	3.3 ± 2.6 (1.2–9.6)
Axial plane width	6.6 ± 3.2 (3.2–11.9)

Values are presented as mean ± SD (range).

Experimental Task

A stop jump was chosen as the experimental task because it places large loads on the patellar tendon during landing and involves two landing phases, a horizontal landing phase and a vertical landing phase (15). The horizontal landing phase required the participants to accelerate forward for four steps toward two force platforms to stop and perform the simultaneous two-foot landing with each foot contacting a separate force platform. The vertical landing phase immediately followed and required the participants to jump vertically upward to strike a ball suspended from the ceiling and to then perform the simultaneous two-foot landing a second time with each foot again contacting a separate force platform. During the stop-jump task familiarization, the effort among the participants at which they performed the task was standardized by using a set starting position before the force platform. The participants' average approach speed was measured immediately before the horizontal landing phase using infrared timing lights (OnSpot, University of Wollongong, Australia) and was similar in both participant groups (controls = 4.5 ± 0.5 $\mathrm{m \cdot s^{-1}}$, PTA = 4.7 ± 1.0 $\mathrm{m \cdot s^{-1}}$, P = 0.762). Both participant groups also achieved a consistent jump height before the vertical landing phase (controls = 50.5 ± 5.9 cm, PTA = 52.0 ± 6.0 cm, P = 0.646). Jump height effort was standardized among the participants by positioning the ball at the maximum height that each participant could touch the ball with both hands after performing the stop-jump movement. Each participant's height, body mass, lower-limb dimensions, and static ankle dorsiflexion lunge test range of motion (3) were measured before performing the stop-jump task.

Experimental Procedure

After completing a standardized 5- to 10-min warm-up of cycling on an ergometer (Monark Model 818E, Sweden), each participant was familiarized with the stop-jump task before performing at least five successful stop-jump trials, whereby a successful trial was defined as a participant placing each foot wholly on a separate force platform during both landing phases and contacting the suspended ball with both hands. During each trial, the ground reaction forces generated at landing were recorded (1000 Hz) using two multichannel force platforms (Type 9281B; Type 9253B; Kistler, Winterthur, Switzerland) embedded in the floor, with each platform connected to a multichannel charge amplifier (Type 9865A; Type, 9865B; Kistler). The participant's three-dimensional lower-limb motion was recorded (100 Hz) using an OPTOTRAK® 3020 motion analysis system (Northern Digital, Waterloo, Canada). Infrared light-emitting diodes were placed on each participant's dominant lower-limb and pelvis, on the shoe at the first and fifth metatarsal head and mid-anterior foot, lateral malleolus, medial malleolus, lateral leg, anterior distal leg, anterior proximal leg, lateral femoral epicondyle, medial femoral epicondyle, lateral femur, anterior distal femur, anterior proximal femur, greater trochanter, anterior superior iliac spine, and iliac crest. To avoid losing view of the infrared light-emitting diodes, the participants wore minimal clothing, a T-shirt and shorts. Socks and sports shoes were worn during the stop jump to minimize potential injury.

Electromyographic activity was recorded bilaterally for vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), tibialis anterior (TA), and medial gastrocnemius (MG) using two TeleMyo systems (Noraxon, Scottsdale, AZ). After standard preparation (2), bipolar silver–silver–chloride surface electrodes (Ambu® Blue Sensor M, electrode size = 40.8 × 32 mm, detection area = 13.2 mm) were placed longitudinally on each muscle belly (interelectrode distance of 20 mm). A common reference electrode was located on the tibial tuberosity of each lower limb. The EMG signals for each lower limb were sampled (1000 Hz, bandwidth = 16–500 Hz) and relayed from two TeleMyo 900 battery powered transmitters (Noraxon, Scottsdale, AZ), firmly fixed around the participant's waist, to two TeleMyo 900 receivers. The kinetic, kinematic, and electromyographic data were time synchronized and collected using First Principles software (Version 1.00.2; Northern Digital).

Data reduction. Analysis of the kinematic and kinetic data was performed using Visual 3D software (Version 3; C-Motion, Germantown, MD). The raw ground reaction force data were initially filtered using a fourth-order zero-phase-shift Butterworth digital low-pass filter (f_c = 50 Hz) before calculating the ground reaction force variables (4). The raw kinematic coordinates, the ground reaction forces, the free moments, and the center of pressure data were then filtered using a fourth-order zero-phase-shift Butterworth digital low-pass filter (f_c = 18 Hz) before calculating individual joint kinematics, knee joint moments and patellar tendon forces (4). The patellar tendon forces were calculated by dividing the knee joint moment by the patellar tendon moment arm (33). Patellar tendon moment arms were calculated as a function of knee joint angle using the method of Herzog and Read (23).

The raw EMG signals were filtered using a fourth-order zero-phase shift Butterworth (high-pass f_c = 15 Hz) to eliminate any movement artifact. To quantify temporal characteristics of the muscle bursts, the filtered EMG data were full-wave rectified with a 20-Hz low-pass filter to create linear envelopes that were then screened using a threshold detector (8% of the maximum amplitude) (11) using customized LabVIEW software (LabVIEW 8, National Instruments, Austin, TX). Each individual muscle's filtered EMG signal was visually inspected to confirm the validity of the calculated results to minimize the probability of an error.

Data analysis. The two landing phases within the stop-jump movement were then identified from the vertical ground reaction force-time curve as (i) the "horizontal" landing phase and (ii) the "vertical" landing phase. The primary outcome variable analyzed during these two landing phases was the peak patellar tendon force (F_{PT}). Secondary variables analyzed during the same two landing phases included the peak vertical ground reaction force (F_V); the ankle, knee, and hip joint kinematics; and the time of the onset and peak muscle activity of each of the seven lower-limb muscles relative to the time of the F_{PT} in each landing phase. Loading rate of the F_V (LR F_V, body weight per second) was calculated by dividing the F_V by the time interval between the initial foot–ground contact (IC) to the time of the F_V. Loading rate of the F_{PT} (LR F_{PT}, body weight per second) was calculated by dividing the F_{PT} by the time interval between IC to the time of the F_{PT}. The temporal events (IC, F_V, and F_{AP}) were defined using the 18-Hz filtered kinetic data, with initial contact defined when the vertical ground reaction force exceeded 30 N. The jump height attained by each participant during the stop-jump movement was defined as the difference in the maximum vertical displacement of the greater trochanter marker minus the vertical displacement of the same marker measured while each participant stood motionless.

Statistics analysis. Means and SD were calculated for each kinetic, kinematic, and muscle activity variable for the participants with PTA and their counterparts with normal patellar tendons (controls) during the horizontal and vertical landing phases of the stop-jump task. After confirming normality and equal variance, the data were analyzed using a series of independent-samples *t*-tests to determine whether there were any significant differences ($P < 0.05$) in the primary and secondary outcome variables during the two landing phases of the stop-jump task between the two participant groups. Although multiple statistical tests were conducted, increasing the chance of incurring an error, no adjustment to the alpha level was deemed necessary given the exploratory nature of the study and the low cost associated with incurring a type I error. All statistical procedures were conducted using the Statistical Package for the Social Sciences (Version 15; SPSS Inc., Chicago, IL).

RESULTS

Patellar tendon loading. The PTA and the control groups generated a similar mean F_{PT}, F_{PT} loading rate, and duration from IC to the time of the F_{PT} during the horizontal and vertical landing phases of the stop-jump task (Fig. 1).

Ground reaction forces. During the horizontal landing phase of the stop-jump task, there was no significant between-group difference in the F_V, F_V loading rate, or the duration from IC to the time of the F_V over which each group sustained these loads. However, during the vertical landing phase of the stop-jump task, the PTA group displayed a significantly lower F_V loading rate than the controls ($P = 0.03$), although no significant difference was found between groups in the F_V or the duration from IC to the time of the F_V (Fig. 1).

Joint kinematic data. During the horizontal landing phase, compared with the controls, the PTA group landed with significantly greater knee flexion ($P = 0.05$) and slower knee flexion velocity at IC ($P = 0.05$), then displayed greater internal knee rotation at the time of the F_V ($P = 0.04$), and continued to display a slower knee flexion velocity at the time of the F_{PT} ($P = 0.01$). The PTA group also displayed significantly less knee flexion ROM from the time of IC to the time of F_{PT} compared with the controls (PTA = 36° ± 11°, controls = 50° ± 9°, $P = 0.030$). Relative to the controls, the PTA group used a very different hip movement strategy when landing, whereby they initially displayed a strong trend for greater hip flexion at IC ($P = 0.06$) but then extended, not flexed, their hips, displaying significantly faster hip extension velocity at IC ($P = 0.05$), greater hip adduction angle at the time of the F_V ($P = 0.01$), and faster hip external rotation velocity at the time of the F_{PT} ($P = 0.03$; Figs. 2 and 3).

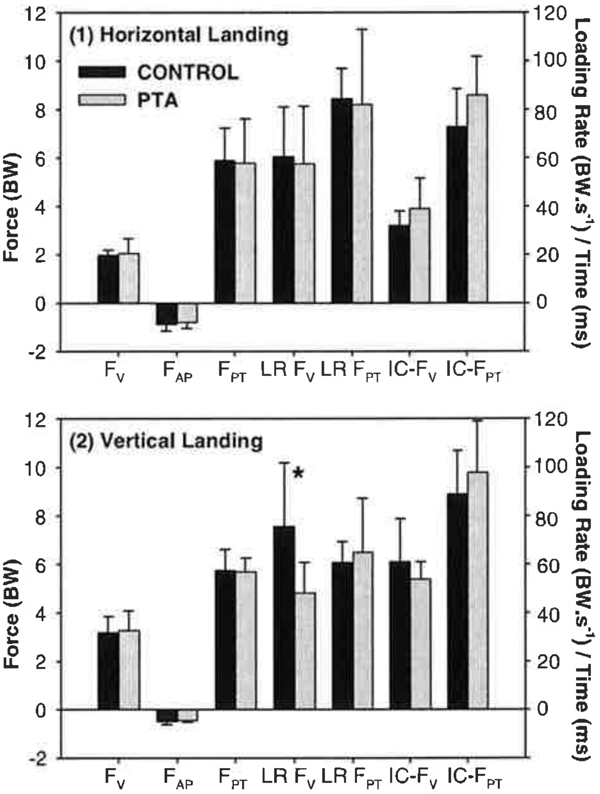

FIGURE 1—Mean (SD) values of the peak patellar tendon forces and the peak vertical ground reaction forces (normalized to body weight) generated by the PTA group and the controls during 1) the horizontal and 2) the vertical landing phases of a stop-jump task. F_V, peak vertical ground reaction force; F_{AP}, peak anterior-posterior ground reaction force; F_{PT}, peak patellar tendon force; LR F_V, loading rate of the F_V; LR F_{PT}, loading rate of the F_{PT}; IC–F_V, time from initial foot–ground contact (IC) to the time of the F_V; IC–F_{PT}, time from IC to the time of the F_{PT}. *Indicates a significant difference ($P < 0.05$) between the two participant groups.

During the vertical landing phase, the PTA group landed with significantly greater ankle inversion at the time of the F_{PT} ($P = 0.04$) and faster hip flexion velocity at the time of the F_V ($P = 0.05$) compared with the controls (Figs. 2 and 3). No other lower-limb landing technique differences were noted between the two participant groups during the vertical landing phase of the stop-jump task.

Muscle activation patterns. Although no significant between-group differences were found in the timing of the onset or peak muscle burst activity relative to the time of the F_{PT} during the horizontal or the vertical landing phases (Fig. 4), differences were found in the muscle recruitment order. That is, during the horizontal landing phase, the controls recruited their lower leg muscles first (TA and MG), followed by the hamstring muscles (BF and ST), and finally the quadriceps muscles (VM, VL, and RF). In contrast, during the horizontal landing phase, the PTA group initially recruited their hamstring muscles (ST and BF), followed by the lower leg muscles (TA and MG), and lastly the quadriceps muscles (VM, RF, and VL). During the vertical landing phase, both groups initially recruited their MG, followed by the hamstring muscles (BF and ST). However, the controls then recruited TA and lastly the quadriceps muscles (RF, VM, and VL), whereas the PTA group recruited the quadriceps muscles (VM, VL, and RF) and finally TA (Table 2).

DISCUSSION

Although asymptomatic athletes with a PTA have an increased risk of developing patellar tendinopathy (9,10,18), the clinical relationship of the PTA to lower-limb landing mechanics has not been previously investigated. The results of this study partially support the hypothesis that asymptomatic athletes with a PTA use a different lower-limb landing strategy compared with athletes with normal patellar tendons. Interestingly, this hypothesis was only supported during the horizontal landing phase of the stop-jump task, whereas the two participant groups displayed similar patellar tendon

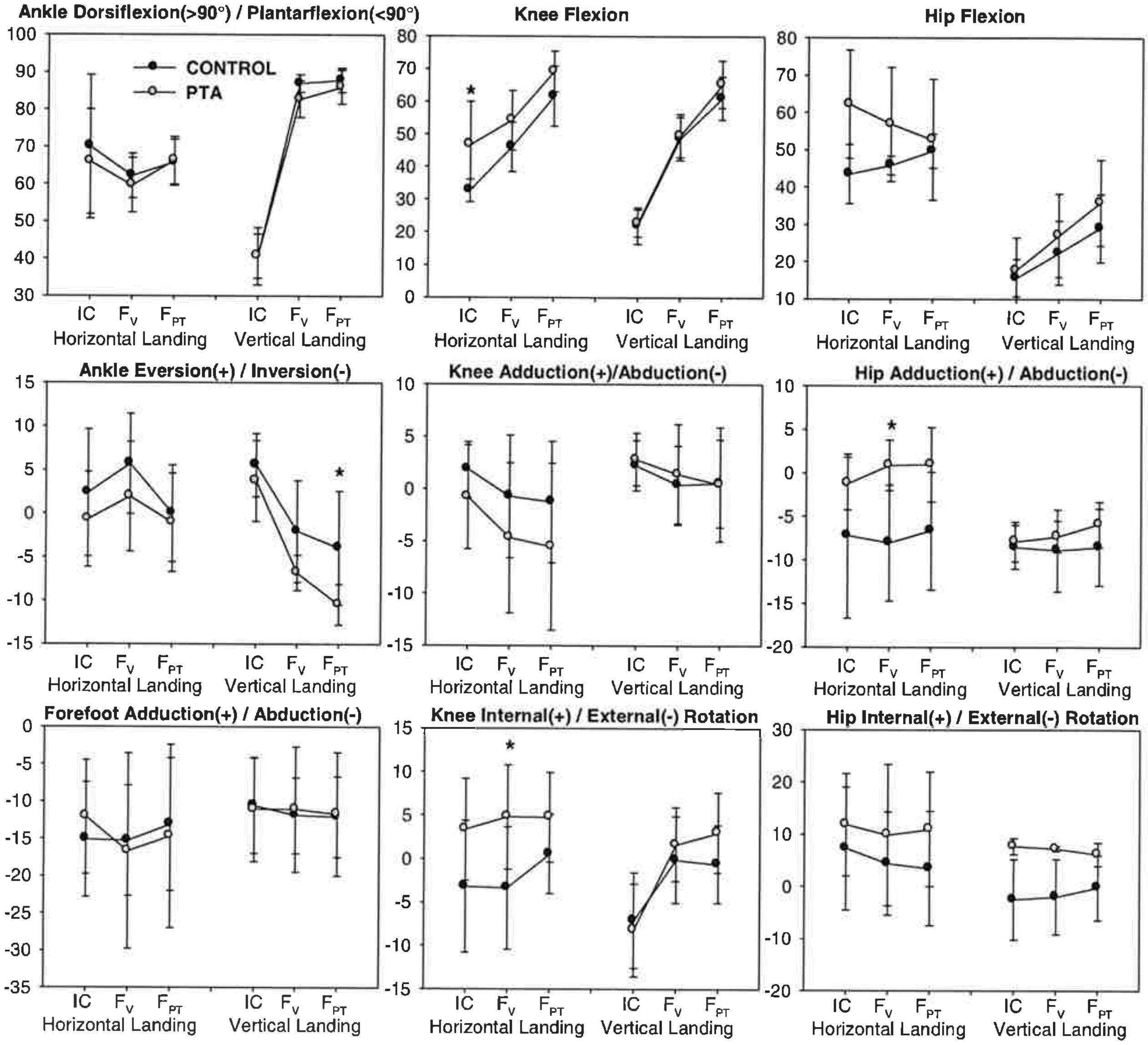

FIGURE 2—Means (SD) values of joint angles (degrees) displayed at initial foot–ground contact (IC), at the time of the peak vertical ground reaction force (F_V), and at the time of the peak patellar tendon force (F_{PT}) during the two landing phases of the stop-jump task for the PTA and control groups. *Indicates a significant difference ($P < 0.05$) between the two participant groups.

loading and a similar landing strategy during the vertical landing phase of the stop-jump task.

Most of the previous biomechanics research examining the landing of athletes with patellar tendinopathy has focused on tasks that involve a vertical landing phase (5,6,34,35). That is, during vertical landing tasks, previous research has reported that landing with less knee flexion at IC (35), greater knee flexion at the time of the F_V (5,6), greater maximum knee flexion angle (35), higher knee flexion velocity (5,6,21), and/or knee flexion moment (5,6,35) is associated with patellar tendinopathy. However, athletes use a different landing movement strategy during the horizontal landing phase of a stop-jump movement compared with the vertical landing phase (15). We speculate that the greater between-group differences in landing technique observed during the horizontal landing phase relative to the vertical landing phase may be due to the horizontal landing task requiring greater musculoskeletal control to decelerate the lower limbs while dissipating higher patellar tendon loads. The results of this study also support the notion that research investigating lower-limb landing mechanics and the risk factors for developing patellar tendinopathy should incorporate a dynamic horizontal landing task (15). This should ensure that athletes who are at an increased risk of developing a PTA and, in turn, patellar tendinopathy are identified. Given that most between-group significant differences in the present study

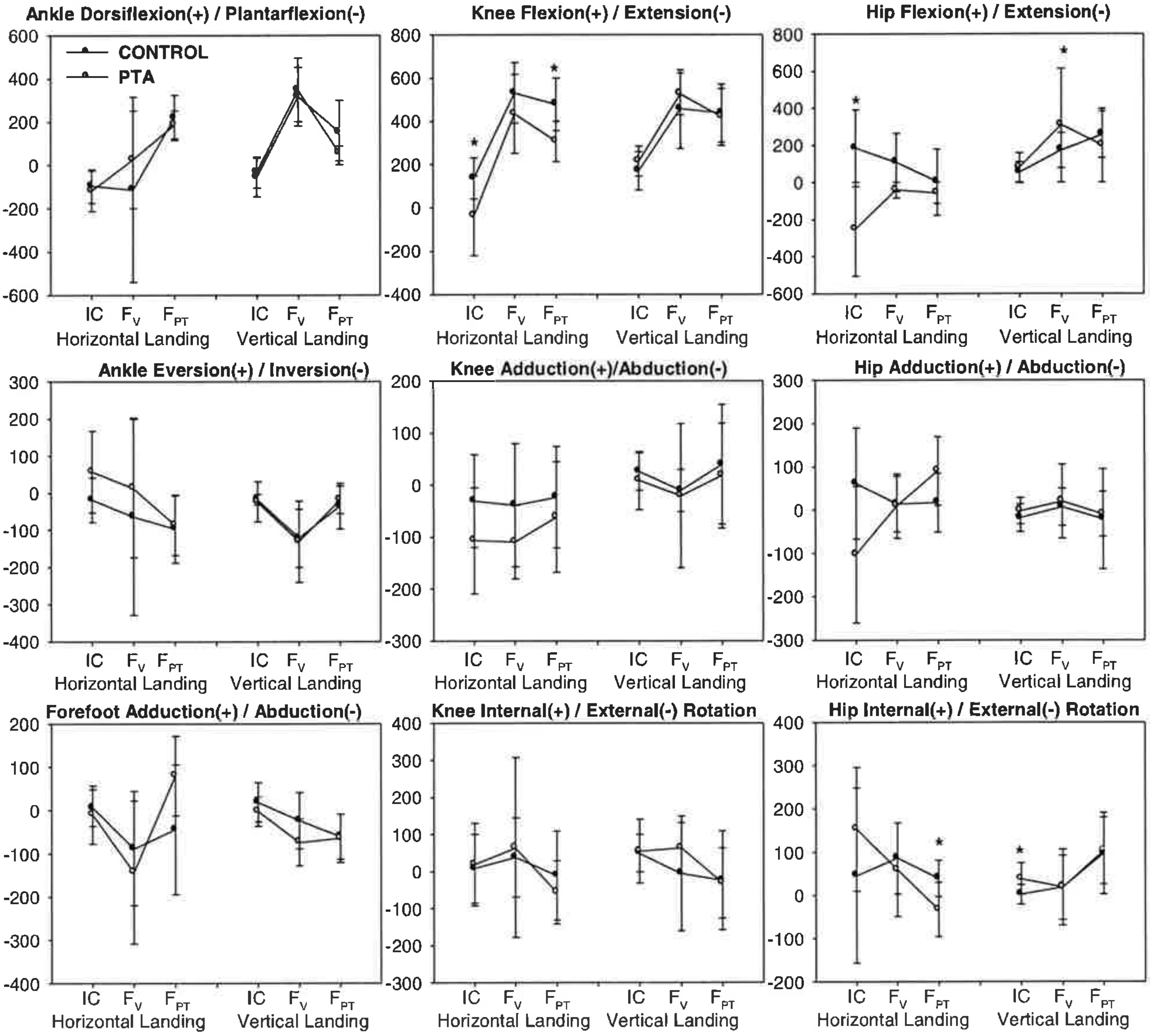

FIGURE 3—Mean (SD) values of joint velocities (degrees per seconds) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force (F_V), and at the time of the peak patellar tendon force (F_{PT}) during the two landing phases of the stop-jump task for the PTA and control groups. *Indicates a significant difference ($P < 0.05$) between the two participant groups.

were evident during the horizontal landing phase, the following discussion will focus only on this component of the experimental task.

Interestingly, the PTA group generated similar F_{PT} and F_V when landing in the horizontal phase compared with their control counterparts, suggesting that the PTA group did not use a force reduction strategy when landing. Instead, the PTA group appeared to modify their lower-limb kinematics and muscle recruitment order relative to the control group.

It has been suggested that reduced ankle dorsiflexion range may increase the risk of developing patellar tendinopathy (29) by limiting the range of motion over which the ankle joint plantar flexor muscles can act, thereby causing the knee and the hip joints to have to contribute more to force dissipation during landing (27). In contrast to this previous research, the current study found no significant between-group differences in ankle angles, range of motion, or velocities during the stop-jump task or static ankle dorsiflexion lunge test range of motion.

Participants in the PTA group during the horizontal landing phase displayed greater knee flexion angles at IC and at the time of the F_V combined with a slower rate of knee flexion and less knee flexion range of motion from the time of IC to the time of the F_{PT} than the controls. The compressive force and the mechanical stress acting on the patella and patellar tendon (37) have been found to be greater at higher knee flexion angles and are asymmetrically

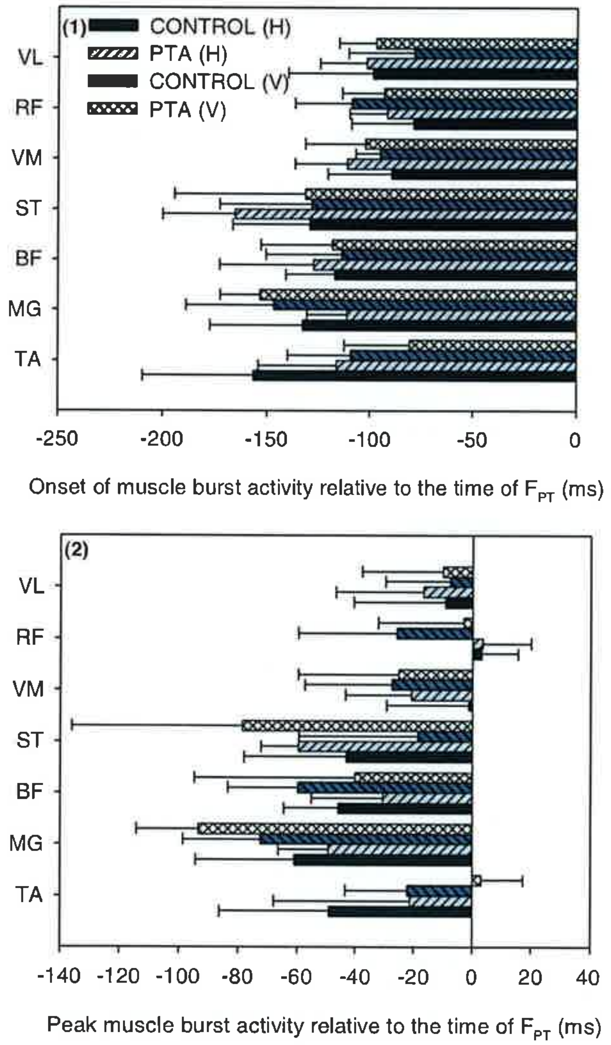

FIGURE 4—Mean (SD) values for the times of 1) the onset of muscle activation and 2) the peak muscle activity relative to the time of the peak patellar tendon force (F_{PT}) generated during the horizontal (H) and vertical (V) landing phases of a stop-jump task for the PTA and control groups. VL, vastus lateralis; RF, rectus femoris; VM, vastus medialis; ST, semitendinosus; BF, biceps femoris; MG, medial gastrocnemius; TA, tibialis anterior.

distributed to be higher on the medial section of the patellar tendon (16,37). Therefore, it may not be the magnitude of the load that the patellar tendon sustains that is crucial to the development of a PTA. Instead, we speculate that the direction of this load and the unique nature of the patellofemoral articulation is more important because proximal patellar tendinopathy is thought to be associated with some compressive load in addition to the tensile loads acting on the patellar tendon, which may result in histological adaptation toward a compression resistant morphology (22). This notion is reinforced by the location of the PTA occurring in the mid or medial part of the proximal patellar tendon, which is in agreement with previous research (8,31). Furthermore, the greater knee abduction and the significantly greater knee internal rotation displayed by the PTA group relative to their control counterparts suggest a mechanism for increased load on the medial and midsection of the proximal part of the patellar tendon and that the PTA group had a poor ability to control their knee joint posture during landing.

Despite lumbopelvic control being considered a vital component of clinical rehabilitation programs for patellar tendinopathy, no previous research has confirmed its importance (26). During the horizontal landing phase, the PTA group used a hip movement strategy that was different from the strategy used by the control group. That is, the PTA participants landed in greater hip flexion at IC and then extended their hips throughout the landing action. The controls, in contrast, landed in less hip flexion and flexed their hips as they landed. The greater hip flexion angle displayed by the PTA group at IC would position their center of mass more posteriorly relative to their base of support, necessitating greater forward translation of the center of mass during the landing phase. This, together with the greater knee flexion, may further increase the tensile and compressive loads on the proximal part of the patellar tendon and contribute to development of a PTA.

Although there were no significant differences in the onset or timing of the peak muscle burst activity relative to the time of the F_{PT} during the horizontal landing phase, the two participant groups displayed a different muscle recruitment order. Earlier recruitment of the hamstrings by the PTA group, particularly the medial hamstrings (ST), occurred when the participants' centers of mass were located posteriorly relative to their base of support. As such, we speculate that this earlier recruitment of the biarticular hamstring muscles also helped to stabilize the torso during landing via their action at the hip joint. Furthermore, the line of action of the hamstring muscles displayed by the PTA group during landing will create a greater posterior shear and compressive force at the knee joint and increase the demand on the knee extensor muscles, relative to the control group. This together with earlier VM onset, which attaches to the medial aspect of

TABLE 2. Lower-limb muscle recruitment order relative to the time of F_{PT} during the horizontal and vertical landing phases of a stop-jump task.

	Horizontal Landing Phase		Vertical Landing Phase	
Onset Order	PTA (n = 7)	Control (n = 7)	PTA (n = 7)	Control (n = 7)
1st	ST	TA	MG	MG
2nd	BF	MG	[illegible]	[illegible]
3rd	TA	BF	[illegible]	[illegible]
4th	MG	ST	VM	TA
5th	VM	VL	VL	RF
6th	VL	VM	RF	VM
7th	RF	RF	TA	VL

■ = Hamstring muscles (biceps femoris (BF); semitendinosus (ST))
▒ = Quadriceps muscles (vastus medialis (VM); rectus Femoris (RF); vastus lateralis (VL))
□ = Lower leg muscles (medial gasrocnemius (MG); tibialis anterior (TA))

The order of muscle recruitment was based on the mean of the muscle activity onset time for each of the seven lower-limb muscles relative to the time of the F_{PT} in each landing phase.

the patellar tendon (37), suggests greater compression of the medial posterior aspect of the patellar tendon, which is a primary area where a PTA develops (8,25,31,40). The relatively more lengthened position of the quadriceps muscle because of the higher knee flexion angle displayed by the PTA group may also contribute to patellar tendon compression via greater tensile loading of the superficial fibers of the patellar tendon on the anterior surface of the patella (1) and via a higher quadriceps tendon force-to-patellar tendon force ratio (7,24). The distribution of force through the patella and patellar tendon has been found to be asymmetrically concentrated and greater medially (16,37), which corresponds to the area most vulnerable to patellar tendinopathy (8,25,31). This suggests that the site of maximum stress is affected by the relative pull of VM (37) and that muscle dysfunction, which was evident in the PTA group in this study, may be a primary causative agent in the etiology of patellar tendinopathy. Lastly, we speculate that because of the later TA activation evident in the PTA group relative to their control counterparts, the dorsiflexion that occurred during landing was not initiated by leg muscle activation, but rather the greater forward translation of the center of mass as the participants initially contacted the ground with their rear foot.

Interestingly, most of the between-group differences in lower-limb landing strategy primarily occurred in the sagittal plane during the horizontal landing task. That is, the PTA group landed with greater knee and hip flexion and extended their hips as they landed during the horizontal landing phase. These biomechanical characteristics are relatively simple to observe, providing clinicians with possible criteria to identify athletes who might be at risk of developing a PTA and, in turn, patellar tendinopathy. It also provides clinicians with a framework to assess and to manage lower-limb landing strategies in athletes with patellar tendinopathy because changes in joint angle can be achieved through simple verbal instruction (12).

We acknowledge that potential between-group differences in landing technique may have been masked in the present study by the small participant number in each group and high variability, as reflected by the high SD, particularly in the hip kinematic and electromyographic data. However, the large SD may also reflect individual variations in landing strategies, which have been confirmed in numerous landing studies (14,32). The inclusion of both unilateral and bilateral PTA participants within the PTA group may have also influenced the results because the etiology of bilateral patellar tendinopathy is thought to be different from the etiology of unilateral patellar tendinopathy (13,19), such that these subgroups may need to be treated separately (13), although this is yet to be confirmed. We also acknowledge that there are limitations when using a two-dimensional model to estimate patellar tendon force as the patellar tendon is considered to be a three-dimensional structure and that the net knee joint moment was used to estimate patellar tendon force, which may have lead to an underestimation of the patellar tendon force.

CONCLUSIONS

During the horizontal landing phase of a stop-jump task, asymptomatic athletes with a PTA displayed a different landing strategy compared with their counterparts with normal patellar tendons by contacting the ground with greater knee flexion and then extending rather than flexing their hips throughout the horizontal landing action, although both participant groups generated similar patellar tendon loading. We speculate that it may not be the magnitude of the load that the patellar tendon sustains that is crucial to the development of a PTA but rather the direction of this load, caused by differences in landing kinematics, and the unique nature of the patellofemoral articulation that are more important. As the differences in landing displayed by asymptomatic athletes with a PTA primarily occurred in the sagittal plane, these biomechanical characteristics provide clinicians with important landing assessment criteria against which to identify athletes at risk of developing a PTA and, in turn, patellar tendinopathy.

The authors acknowledge the New South Wales Sporting Injuries Committee (Australia) for financial support of this research.

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