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The effect of speed on Achilles tendon forces and patellofemoral joint stresses in high-performing endurance runners

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Achilles tendinopathy and patellofemoral pain are common running injuries associated with increased Achilles tendon (AT) forces and patellofemoral joint (PFJ) stresses. This study examined AT forces and PFJ stresses at different running speeds in high-performing endurance runners. Twenty runners ran overground at four running speeds (3.3, 3.9, 4.8, and 5.6 m/s). AT forces and PFJ stresses were estimated from kinematic and kinetic data. Repeated measures ANOVA with partial eta squared effect sizes was conducted to assess differences between running speeds. Increased peak AT forces (19.5%; $p < 0.001$) and loading rates (57.3%; $p < 0.001$) from 3.3 m/s to 5.6 m/s were observed. Cumulative AT loading was greater in the faster speeds compared to the slower speeds. Faster running speeds resulted in increased peak plantar flexor moments, increased peak plantar flexion angles, and a more flexed knee and an anterior center of pressure position at touchdown. Peak PFJ stress was lower in the slowest speed (3.3 m/s) compared to the faster running speeds (3.9–5.6 m/s; $p = 0.005$). PFJ stress loading rate significantly increased (43.6%; $p < 0.001$). Greater AT loading observed could be associated with strategies such as increased plantar flexor moments and altered lower body position at touchdown which are commonly employed to generate greater ground contact forces. Greater AT and PFJ loading rates were likely due to shorter ground contact times and therefore less time available to reach the peak. Running at faster speeds could increase the risk of developing Achilles tendinopathy and patellofemoral pain or limit recovery from these injuries without sufficient recovery.

KEYWORDS
Achilles tendon, high-performance running, patellofemoral joint, running speed

1 | INTRODUCTION

Injuries to the lower extremities are common in runners.[1] In particular, Achilles tendinopathy and patellofemoral pain are among the most common running-related injuries accounting for 6.2–10% and 5.5–17% of all running-related injuries, respectively.[1,2]

The Achilles tendon largely comprises of collagen and elastin fibers and contributes significantly to the mechanical work done by the plantar flexors.[3-5] During running, the Achilles tendon experiences considerable repetitive loads.[5] Repetitive loading without sufficient time for repair can lead to cumulative microtrauma of the Achilles tendon and result in either inflammation and/or degeneration of the tendon.[3,6]

High Achilles tendon forces and loading rates may inhibit recovery from Achilles tendinopathy owing to the associated diminished mechanical and material properties.[3] In addition to high prevalence, Achilles tendinopathy also has considerably higher reinjury rates with 35% of marathon runners who developed Achilles tendinopathy reporting a previous Achilles tendinopathy 12 months prior to their injury.[7] When running at faster speeds, the contribution from Achilles tendon increases to support efficient mechanical work done by the plantar flexors.[4] Greater cumulative loading of the Achilles tendon has been associated with faster running speeds in recreational runners.[8] With increasing levels of tendon fatigue, morphological changes have been observed.[9] Without sufficient recovery, running at faster speeds could lead to increased degeneration of the tendon. However, habitual loading has demonstrated positive adaptations of the Achilles tendon[6,10] and high-performing runners exhibit different running patterns to recreational runners.[11] Therefore, understanding factors such as running speed and the consequential potential changes in loading in high-performing runners can support the development of appropriate training and competition programs to minimize the risk of developing Achilles tendinopathy.

Patellofemoral pain is defined as pain in the knee behind the patella that is aggravated by activity that loads the patellofemoral joint (PFJ).[12] Factors associated with patellofemoral pain include high compressive loads generated by the quadriceps, excessive shear stress, greater hydrostatic pressure, quadriceps weakness, and abnormal tacking or joint alignment.[12,13] Greater PFJ force and stress have also been associated with patellofemoral pain.[13,14] Previous studies adopting a reduced step length, cadence or adopting a forefoot strike pattern have reduced PFJ stress.[15,16] Running at faster speeds has been associated with spatiotemporal changes[17] which could affect the loading of the PFJ, but there is limited evidence exploring this.

High-performing runners frequently train and compete at faster running speeds than recreational runners.[18] Faster running speeds are often achieved through either greater ground contact forces to achieve increased step length or by increasing the rate at which force is applied to the ground thus increasing step rate.[17,19] At speeds below 7 m/s, increased step length is the dominant strategy employed to run at faster running speeds to this level,[17] with proportional contribution of the plantar flexors significantly increasing alongside this.[17,19] As increases in step length become less effective in increasing running speed, increasing step rate becomes the dominant strategy to achieving faster running speeds. It is thought that muscles around the hip support the higher step rates associated with faster running speeds[19] Changes in loading at the knee do not appear to increase with faster running speeds, with some studies suggesting the contribution of the knee extensors even decreases with increased running speed.[17,19]

There is limited understanding of the effect that running speed has on loading of lower limb structures such as the Achilles tendon and PFJ. It has previously been proposed that running injuries may differ depending on types of training exposure. In particular, reports have suggested Achilles tendinopathy has been associated with training at faster running speeds, while patellofemoral pain is associated with higher training volumes.[12,20] However, current evidence exploring the influence of running speed upon the biomechanical loading patterns of the Achilles tendon and PFJ is limited. Understanding the loading of the Achilles tendon and PFJ is exposed to when running at different speeds can provide an understanding of the potential mechanisms which may influence injury development. Therefore, this study aimed to compared Achilles tendon forces and patellofemoral stresses when running at different speeds. Based on current evidence, we hypothesize that H_1) increased running speed will result in increased AT forces and H_2) increased running speed will not elicit changes in PFJ stress.

2 | METHODS

Twenty high-performing endurance runners (Table 1) volunteered for this study. Participants were recruited if they had achieved a 10 km personal best of less than 32 min for males and 36 min for females.[11] All participants were free from injury (minimum of 6 months). The study was approved by the Institutional Ethics Committee (HSR1617-163). Informed consent and physical activity readiness questionnaire results were obtained before any testing occurred.

Participants were asked to run along a 40 m running track at four target speeds (3.3, 3.9, 4.8, and 5.6 m/s). Eight successful trials for each speed were collected. Trials were deemed successful if they were within 2.5% of the target speed, assessed using optical timing gates.

Synchronized kinematic (200 Hz; Qualisys Oqus) and kinetic (1000 Hz; Advanced Mechanical Technology, Inc,) data were collected during the running trials. Kinematic data were collected from retroreflective markers placed on the thorax

TABLE 1 Participant demographics (mean and SD)

	Value
Sex, male/female (*n*)	10/10
Age (years)	25.1 ± 7.6
Height (m)	172.3 ± 9.1
Mass (kg)	61.3 ± 7.6
Weekly mileage	60.0 ± 18.7
Running experience (years)	9.0 ± 7.9
5 k race time (min)	14.3 ± 3.5
10 k race time (min)	32.2 ± 2.5

and lower limbs following the CAST marker technique.[21] The markers included anterior superior iliac spine, posterior superior iliac spine, lateral and medial femoral epicondyles, lateral and medial malleoli, 1st and 5th metatarsal heads, and the base of the 2nd metatarsal and posterior aspect of the calcaneus. Rigid clusters were placed laterally on the thighs and shanks to tracking these segment movements. In addition, a rigid cluster with three markers was placed on the thorax to track thoracic movement.

Kinematic and kinetic data were processed for the right side only using Visual3D software (v6; C-Motion, Inc.,). A low pass Butterworth filter (12 Hz, 4th order) was applied to kinetic and kinematic data. A six degree of freedom model was used whereby hip joint centers were estimated from anterior and posterior superior iliac spine locations.[22] Knee joint centers were determined as the mid-point between the lateral and medial femoral epicondyles. Ankle joint centers were determined as the mid-point between the lateral and medial malleoli. An inverse dynamics approach was used to calculate internal joint moments. Segment inertial and geometric properties were estimated for each participant.[23] Joint moment data were normalized to body mass and height (Nm/(body mass × height)%).

Achilles tendon forces and patellofemoral joint stresses were estimated using previously reported calculations using a custom-written MATLAB code (MATLAB R2020a, MathWorks). Achilles tendon force during stance was calculated by dividing the sagittal ankle moment by the Achilles tendon moment arm. The Achilles tendon (AT) moment arm was determined as a function of the non-normalized ankle flexion angle (af) based on the regression equation from magnetic resonance imaging (MRI) data on 10 healthy ankles.[24]

$$\text{AT moment arm} = -0.5910 + 0.08297\text{af} - 0.0002606\text{af}^2$$

Patellofemoral joint force and stress were estimated from sagittal joint angles and moments during stance similar to previous studies.[16,25] Quadriceps muscle effective lever arm (L_{eff}) was estimated as a function of knee flexion angle (kf) using a non-linear equation.[26]

$$L_{\text{eff}} = 8.0\text{E-}05\text{kf}^3 - 0.013\text{kf}^2 + 0.28\text{kf} + 46$$

To account for co-contraction about the knee, quadriceps force (QF) was calculated as described by DeVita and Hortobagyi.[27] Gastrocnemius force was estimated as the proportion of the Achilles tendon force attributed to the gastrocnemius.[27] This proportion was determined using previously reported cross-sectional areas of the gastrocnemius relative to the soleus.[28] Hip extensor moments, hamstrings and gluteus maximus cross-sectional areas (CSA),[28] and hamstring and gluteus maximus moment arms at the hip as a function of hip angle[29] were used to estimate hamstring force. To estimate QF, the sum of the hamstring and gastrocnemius forces multiplied by their estimated moment arms (MA) at the knee joint as a function of knee angle[30] and the knee extensor moment which was then divided by the quadriceps muscle effective lever arm.

$$\text{QF} = \frac{[\text{Knee extensor moment} + \text{Hamstring force (MA)} + \text{Gastrocnemius force (MA)}]}{\text{L}_{\text{eff}}}$$

Patellofemoral joint (PFJ) force was then calculated as the product of the QF and a constant k. This constant defines the relationship between the QF and PFJ force and was calculated using a non-linear equation as a function of knee flexion angle.[26]

$$k = \frac{-3.84\text{E-}05\text{kf}^2 + 1.47\text{E-}03\text{kf} + 0.462}{-6.98\text{E-}07\text{kf}^3 + 1.55\text{E-}04\text{kf}^2 - 0.0162\text{kf} + 1}$$

$$\text{PFJ force} = \text{QF} \times k$$

PFJ stress was estimated by dividing the PFJ force by the PFJ contact area. PFJ contact area was determined specific to sex based on MRI data from 16 healthy participants (8 males and 8 females) taken at three knee flexion positions (0°, 30°, and 60°) while loading at 45% body weight.[31] To provide a function for PFJ contact area for males and females, these data were interpolated using a second-order polynomial fit.

$$\text{PFJ contact area (males)} = -0.258\text{kf}^2 + 7.4276\text{kf} + 304.0342$$

$$\text{PFJ contact area (females)} = -0.0129\text{kf}^2 + 6.4114\text{kf} + 184.9724$$

Peak values were obtained for PFJ stress and Achilles tendon force during stance. Peak instantaneous loading rates for Achilles tendon force and PFJ stress were calculated during the middle 60% between initial contact and peak values and normalized to body weight.[25] Knee and ankle angles at initial contact and peak values during stance were determined as well as peak sagittal knee and ankle moments. Weighted cumulative Achilles tendon loading and PFJ loading were estimated using the approach described by Firminger et al.[8] which adjusted for cumulative damaged accumulated per stride. Spatiotemporal measures were also calculated. Strike index was determined based on the anterior-posterior center of pressure position at initial contact and as a percentage of foot length.[32] A percentage less than 33% determined a rearfoot strike pattern.[32] The mean of eight stance phases for each participant was calculated. A repeated measures ANOVA with

Bonferroni-corrected *t*-tests was used to determine any differences between running speeds. Effect sizes (ES) were calculated using partial eta squared calculations where 0.01, 0.06, and 0.14 denote small, medium, and high effects; however, caution is needed when applying these thresholds.[33] To test H_2, we conducted an equivalence test for peak PFJ stress between running conditions using the TOSTER software.[34] We used a smallest effect size of interest of $d = 0.376$ which reflects *conservative* PFJ stress effects sizes of 20% lower than that observed between PFP and healthy individuals during running.[14]

3 | RESULTS

Table 2 presents the spatiotemporal outcomes for each running speed. Increased running speed resulted in increased step length for each speed condition. Flight time and step rate were greater for the faster speeds (4.8 and 5.6 m/s) compared to the slower speeds. Stance time significantly reduced with increased running speed, while swing time was reduced at 5.6 m/s compared to all other speed conditions. Strike index shifted toward the forefoot significantly for the faster speeds (4.8 and 5.6 m/s) compared to the slower running speeds (3.3 and 3.8 m/s). During the slowest speed (3.3 m/s), 7 out of 20 exhibited a rearfoot pattern (strike index less than 33%), while at the fastest speed (5.6 m/s), only two out of 20 continued to demonstrate a rearfoot pattern.

Peak Achilles tendon force increased significantly with increased running speed (Figure 1A). The ankle was more plantarflexed at initial contact for the faster speeds compared to the slowest running speed (3.3 m/s; Table 3). Peak ankle dorsiflexion did not change with speed. Peak plantar flexor moments significantly increased with running speed. In addition to increased peak Achilles tendon forces, Achilles tendon force loading rate (Figure 1B) was also significantly increased with increased running speed. For the fastest running speeds (4.8 and 5.6 m/s), weighted cumulative Achilles tendon force was greater compared to the slower running speeds (3.3 and 3.8 m/s).

TABLE 2 Spatiotemporal outcome for each running speed

	Speed 1	Speed 2	Speed 3	Speed 4	*p*	ES
Speed (m/s)	3.36 ± 0.08	3.92 ± 0.09[a]	4.8 ± 0.10[a,b]	5.63 ± 0.30[a,b,c]	<0.001	.977[d]
Step Length (m)	1.21 ± 0.06	1.38 ± 0.07[a]	1.61 ± 0.10[a,b]	1.73 ± 0.14[a,b,c]	<0.001	.950[d]
Stance time (s)	0.23 ± 0.02	0.21 ± 0.02[a]	0.18 ± 0.01[a,b]	0.16 ± 0.01[a,b,c]	<0.001	.925[d]
Swing time (s)	0.49 ± 0.04	0.50 ± 0.04	0.48 ± 0.04[b]	0.45 ± 0.03[a,b,c]	<0.001	.400[d]
Flight time (s)	0.14 ± 0.02	0.15 ± 0.02[a]	0.15 ± 0.01[a,b]	0.15 ± 0.01[a,c]	<0.001	.495[d]
Step rate (Hz)	2.83 ± 0.25	2.86 ± 0.18	3.03 ± 0.19[a,b]	3.25 ± 0.23[a,b,c]	<0.001	.714[d]
Strike index (%)	46.63 ± 16.16	48.35 ± 16.84	54.73 ± 15.23[a,b]	58.88 ± 14.32[a,b]	<0.001	.410[d]

Abbreviation: ES, effect size (partial eta squared).
[a]Indicates significant difference with speed 1 (3.3 m/s).
[b]indicates significant difference with speed 2 (3.9 m/s).
[c]indicates significant difference with speed 3 (4.9 m/s).
[d]significant ($p < .05$) main effect for speed.

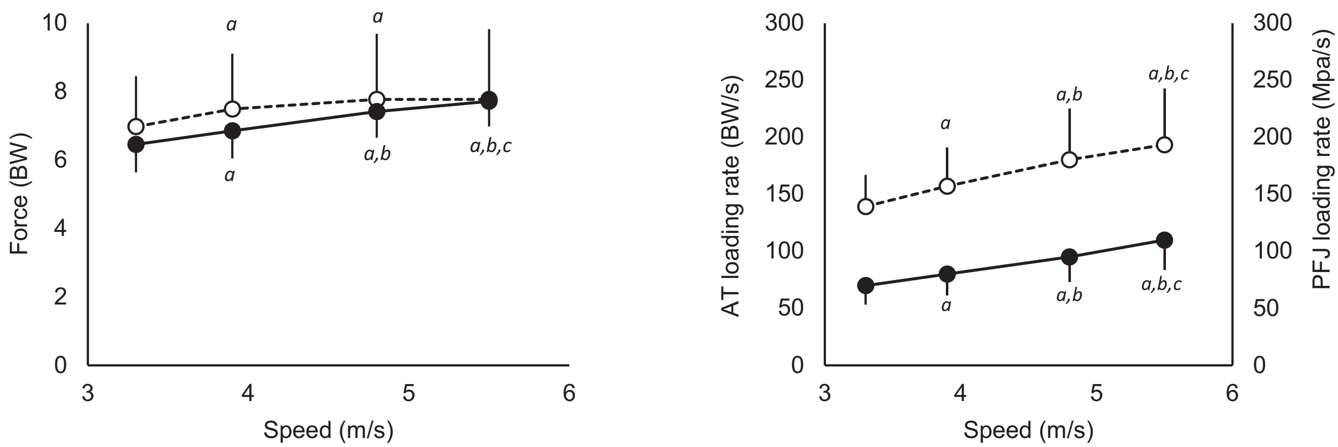

FIGURE 1 (A) Peak Achilles tendon force (solid line) and peak patellofemoral force (dotted line) for each running speed. (B) Peak loading rates for Achilles tendon (AT; solid line) and patellofemoral joint stress (PFJ; dotted line). [a]Indicates significantly different from speed 1 (3.3 m/s), [b]indicates significantly different from speed 2 (3.9 m/s), and [c]indicates significantly different from speed 3 (4.9 m/s)

TABLE 3 Ankle and Achilles tendon outcomes for each running speed

	Speed 1	Speed 2	Speed 3	Speed 4	*p*	ES
Ankle angle at IC (°)	2.54 ± 7.24	0.74 ± 8.72[a]	−2.25 ± 7.89[a]	−2.72 ± 8.38[a]	0.001	.389[d]
Peak ankle dorsiflexion angle (°)	24.97 ± 4.01	24.91 ± 4.29	24.47 ± 4.63	23.92 ± 4.88	0.100	.130[d]
Peak Ankle PF moment (Nm/[kg·Ht]%)	1.68 ± 0.20	1.79 ± 0.21[a]	1.95 ± 0.21[a,b]	2.04 ± 0.19[a,b,c]	<0.001	.847[d]
Peak AT force (BW)	6.46 ± 0.82	6.85 ± 0.81[a]	7.42 ± 0.77[a,b]	7.71 ± 0.73[a,b,c]	<0.001	.842[d]
AT loading rate (BW/s)	69.86 ± 16.62	80.02 ± 18.45[a]	95.16 ± 21.95[a,b]	109.89 ± 26.09[a,b,c]	<0.001	.859[d]
Weighted cumulative AT force (N.s/km)	5347.20 ± 1053.28	5536.82 ± 1098.44	5938.91 ± 1102.25[a,b]	6043.59 ± 1127.34[a,b]	<0.001	.582[d]

Abbreviations: AT, Achilles tendon; BW, body weight; ES, effect size (partial eta squared); PF, plantar flexion.

[a]Indicates significant difference with speed 1 (3.3 m/s).

[b]indicates significant difference with speed 2 (3.9 m/s).

[c]indicates significant difference with speed 3 (4.9 m/s).

[d]significant ($p < 0.05$) main effect for speed.

TABLE 4 Knee and patellofemoral joint outcomes for each running speed

	Speed 1	Speed 2	Speed 3	Speed 4	*p*	*ES*
Knee flexion angle at IC (°)	15.61 ± 5.56	16.06 ± 5.42	17.66 ± 4.99[a,b]	20.08 ± 4.08[a,b,c]	<0.001	.567[d]
Peak knee flexion angle (°)	41.73 ± 4.75	42.32 ± 4.81	41.89 ± 5.67	41.89 ± 5.86	0.638	.015
Peak knee extensor moment (Nm/[kg·m]%)	1.52 ± 0.22	1.59 ± 0.23	1.62 ± 0.30	1.57 ± 0.33	0.101	.103
Peak PFJ force (BW)	6.98 ± 1.47	7.49 ± 1.62[a]	7.77 ± 1.92[a]	7.77 ± 2.05	0.012	.252[d]
Peak PFJ Stress (MPa)	8.35 ± 1.11	8.90 ± 1.14[a]	9.27 ± 1.49[a]	9.26 ± 1.72[a]	0.005	.313[d]
PFJ stress loading rate (MPa/s)	139.30 ± 27.69	157.11 ± 34.00[a]	180.17 ± 44.96[a,b]	193.46 ± 49.41[a,b,c]	<0.001	.781[d]
Weighted cumulative PFJ force (N.s/km)	5652.24 ± 1427.51	5913.00 ± 1561.05[a]	6031.31 ± 1694.54	5951.55 ± 1828.66	0.152	.100

Abbreviations: BW, body weight; ES, effect size (partial eta squared); PFJ, patellofemoral joint.

[a]Indicates significant difference with speed 1 (3.3 m/s).

[b]indicates significant difference with speed 2 (3.9 m/s).

[c]indicates significant difference with speed 3 (4.9 m/s).

[d]significant ($p < 0.05$) main effect for speed.

At initial contact, greater knee flexion was observed for the faster running speeds (4.8 and 5.6 m/s) compared to the other speed conditions Table 4. No differences between running speeds were observed for peak stance phase knee flexion and peak knee extensor moments. Peak PFJ forces were lower in the slowest running speed (3.3 m/s) compared to 3.9 and 4.8 m/s running speeds (Figure 1A). Peak PFJ stress was also lower in the slowest running speed (3.3 m/s) compared to all other running speeds (3.9, 4.8, and 5.6 m/s). There were no statistical differences in peak PFJ stress when increasing from 3.9 m/s to either 4.8 m/s or 5.6 m/s. Following the equivalence tests, peak PFJ stress was not statistically equivalent to zero between running speeds. The PFJ stress loading rate significantly increased with increased running speeds (Figure 1B). Figure 2 presents the sagittal kinematic and kinetic curves and Achilles tendon force and PFJ stress curves for all participants across the four running speeds. Cumulative PFJ loading was lower in the slowest running speed (3.3 m/s) compared to the second slowest speed (3.9 m/s), but no other statistical differences were observed.

4 | DISCUSSION

We examined Achilles tendon forces and patellofemoral joint stresses with increased running speeds in high-performing endurance runners. Our findings partially supported our hypotheses, where (H_1) Achilles tendon forces and loading rates increased with increased running speed, while (H_2) peak PFJ stress increased from the slowest running speed to the faster running speeds but did not statistically differ between the faster running speeds. Following the equivalence test, we

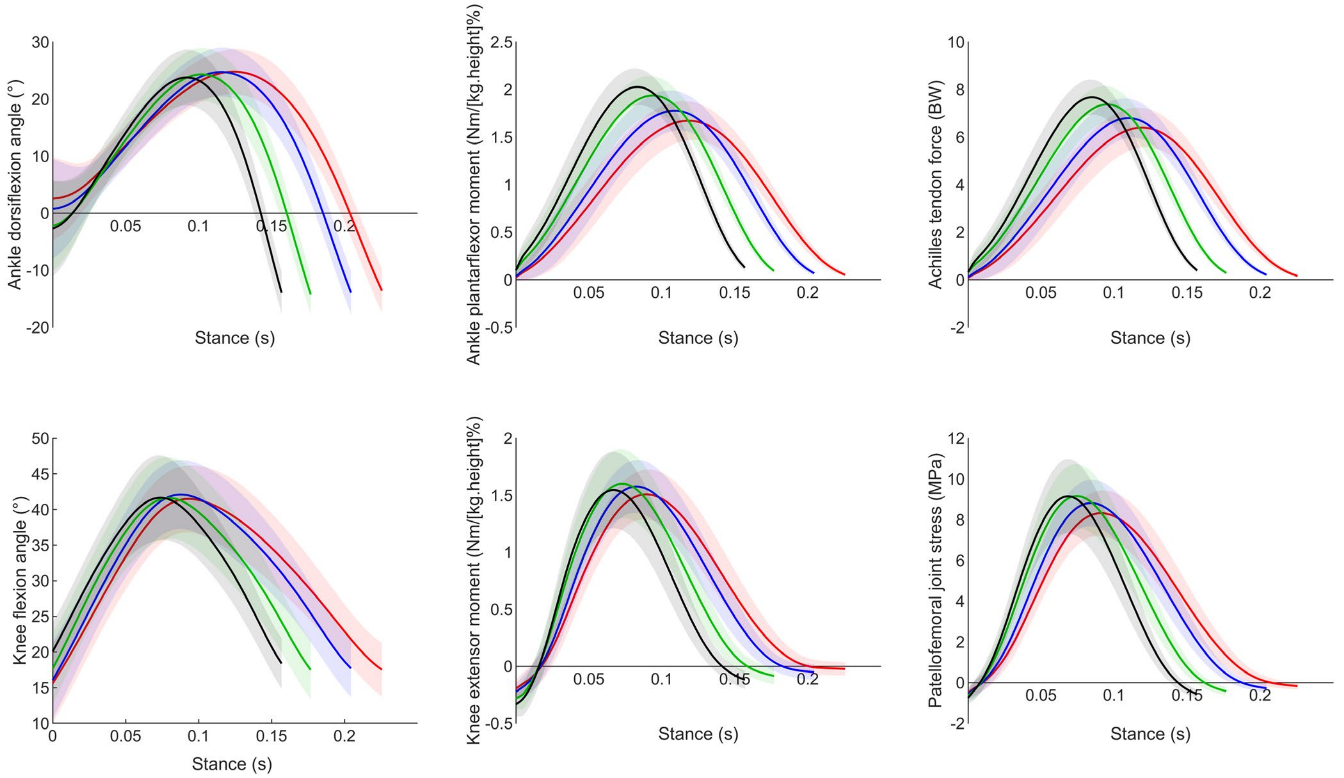

FIGURE 2 Sagittal ankle angles, moments, and Achilles tendon force (top), and knee angles, moments, and patellofemoral stress (bottom) for 3.3 m/s (red), 3.9 m/s (blue), 4.8 m/s (green), and 5.6 m/s (black)

cannot conclude that PFJ stress was similar between running speeds and therefore further evidence is required. PFJ stress and Achilles tendon loadings rate increased with increased speed. The differences observed are likely to be a result of the strategies commonly employed by runners to increase their running speed. Changes in loading rate for Achilles tendon and PFJ stress could be a result of a change in lower limb mechanics at touchdown.

Two strategies that have been established to allow a runner to increase their running speed include a) increasing step length and b) increasing step rate.[17,19] Increasing step length as a consequence of generating greater ground contact forces is the dominant strategy employed by runners to achieve faster running speeds up to 7 m/s.[17] The runners in this study also demonstrated this increase in step length with a 43.5% increase from 3.3 m/s to 5.6 m/s compared to only 14.7% increase in step rate.

The ankle plantar flexors are the main contributors for increasing ground contact forces and therefore increasing step lengths.[19] Our findings are consistent with previous studies where greater plantar flexor moments have been observed with faster running speeds.[17,19] Lai et al.[4] demonstrated increased contribution from the Achilles tendon compared to the soleus and gastrocnemius when running speeds increased. The increased contribution by Achilles tendon allows muscle fibers to maintain at an optimum shortening velocity when ground contact time is limited.[5,17] However, the increased contribution from the Achilles tendon at these faster running speeds could explain the greater forces and loading rates observed which may increase the risk of injury to the Achilles tendon or limit recovery from tendinopathy. Compared to healthy individuals, those with Achilles tendinopathy often present with lower stiffness and greater CSA which could limit recovery and ability to transmit force.[3]

There is some evidence to suggest that foot strike patterns influence Achilles tendon loading during running.[35,36] Those identified as non-rearfoot or forefoot strikers demonstrated 24–31% greater Achilles tendon forces and 18% greater loading rates compared to habitual rearfoot strikers.[35,36] Forefoot strikers typically land with a more anterior center of pressure, plantarflexed ankle position, and more flexed knee.[37] At the faster running speeds (4.8 and 5.5 m/s), runners in the current study demonstrated similar traits to forefoot runners with a plantarflexed ankle, greater knee flexion, and a more anterior center of pressure location (indicated with a greater strike index) at touchdown compared to the slower running speeds. Preece et al.[11] demonstrated a similar shift from rearfoot to forefoot strike pattern with increased running speed.

Greater plantar flexor moments were observed as speed increased and lower limb mechanics at touchdown shifted toward that often observed with forefoot runners.[36] This position requires greater eccentric control during weight acceptance toward maximum dorsiflexion at midstance.[36,37]

Therefore, the change in posture at touchdown, as speed increases, resulted in greater load transmitted through the plantar flexor muscles and in turn the Achilles tendon to control greater change (from initial contact to peak dorsiflexion) and speed of ankle dorsiflexion due to shorter ground contact times. These changes could explain the greater forces and loading rates at the Achilles tendon which may increase the risk of injury.

The evidence exploring the association between pacing or speed training strategies and Achilles tendinopathy is conflicting.[20,38] McCrory et al.[20] reported those who developed Achilles tendinopathy trained at a higher average pace (before injury) compared to those who did not develop Achilles tendinopathy, while Ramskov et al.[38] did not find differences in injury between recreational runners who completed a 16-week intensity-specific schedule and those who completed a volume-specific schedule. However, these runners achieved 12 km/h in only 8% of intensity-specific sessions. High-performing runners have greater exposure to higher training and competition speeds[18] than these and therefore are likely to experience higher loads in the Achilles tendon. In addition to greater load and rate of loading of Achilles tendon during faster speeds, we also observed greater cumulative loads similar to previous findings.[8] Without appropriate rest to allow for collagen synthesis following mechanical load, the higher repetitive loading exhibited at the faster running speeds could lead to degradation of the tendon collagen fibers and disorganized collagen orientation weakening the tendon and leaving it prone to injury.[6] Our findings provide some evidence to explain the higher incidence and prevalence rates for Achilles tendinopathy reported for elite middle and long-distance runners compared to recreational runners.[2,7,39] Coaches must be aware of the greater loads exhibited when running at faster running speeds and modulate training and competition appropriately. However, further epidemiological studies are required to explore this relationship between running speeds and the development of Achilles tendinopathy.

In contrast to Achilles tendon forces, increases in PFJ stress, force, and cumulative loading were only seen when increasing running speed between 3.2 and 3.9 m/s and then there was no increase thereafter. The initial increase in PFJ stress, force, and cumulative loading may be partially explained by muscular co-contractions about the knee from the hamstrings and gastrocnemius[17] as runners shift to a more forefoot running gait. Although we cannot confirm that PFJ stresses between 3.9 m/s and 5.6 m/s were statistically equivalent, the differences observed were remarkedly similar, particularly between 4.8 and 5.6 m/s (0.01 MPa difference in PFJ stress). Further evidence is required to confirm these findings.

Spatiotemporal measures and foot posture have often been associated with changes in PFJ force and stress owing to changes in knee position and moments. Increasing step rate, reducing step length, and running with a forefoot strike pattern have been associated with reduced PFJ forces and stresses.[15,16] The anterior shift of the center of pressure, similar to forefoot strike patterns,[37] is likely to counteract larger ground reaction forces associated with increased running speed[17] and explain the lack of change in knee joint moment and therefore PFJ force and stress. Although we observed increased step rate and a shift toward a forefoot running pattern with increased speed, step length, a common component associated with faster running speeds, also increased. The increased step length is likely to offset any changes in step rate and running pattern and therefore limit any effect on potentially decreasing PFJ forces and stresses.

The observed increase in PFJ stress loading rate is likely to be attributed to the shorter ground contact times and time to reach peak PFJ stress resulting in a quicker rate to peak stress (Figure 2). PFJ force, stress, and loading rates have previously been associated with increased patellofemoral pain risk.[13,14] High-performing endurance runners often train and compete at faster speeds, and the higher PFJ stress and cumulative load when running faster than a slow jog (3.3 m/s) and the increased rate of PFJ stress applied could suggest some risk in patellofemoral pain associated with running speed. However, there is limit evidence on the prevalence of patellofemoral pain in high-performing runners and therefore further evidence is needed to confirm this increased risk.

There are several limitations in this study that should be acknowledged. The models in this study did not account for subject-specific moment arms or patellofemoral contact area which could led to error in our calculations. For example, there is likely to be 3–5% error with Achilles tendon moment arm estimation.[24] Our models only accounted for sagittal plane changes in knee moments and angles and did not account for transverse and frontal plane motion which could affect the tracking of the patella and, in turn, the stress applied at the patella during running. Interpretation of our Achilles tendons results is limited as we did not assess Achilles tendon stiffness. We used a convenience sample of 20 high-performing runners who had previously achieved a 10 km personal best of less than 32 min for males and 36 min for females. It possible that the lack of statistical differences observed particularly at the knee is likely to be a result of low sample size. However, our findings reflect similar studies examining joint kinetics and running speed.[19] In this study, we pooled data from male and female high-performing runners. There is evidence to suggest differences in joint kinematics and kinetics between male and female recreational runners. Currently, there is limited evidence to suggest similar differences in elite runners and therefore future research is warranted for elite runners.

5 | CONCLUSIONS

Increased running speed resulted in greater peak Achilles tendon forces. While patellofemoral joint stress initially increased when the high-performing endurance runners increased speed from the slowest speed but did not increase beyond 3.9 m/s, the differences observed with Achilles tendon forces and with the initial increase in patellofemoral joint stress are likely to be a result of the strategies commonly employed by runners when running at faster running speeds. Faster running speeds led to greater plantar flexor moments and change in posture at touchdown contributing to the increased forces and loading rates at the Achilles tendon. Increased Achilles tendon force and patellofemoral joint stress loading rates with increased running are likely to be attributed to shorter time to peak stress and could be associated with increased patellofemoral pain risk. Our results provide some evidence to suggest training and competing at higher running speeds could lead to a greater risk of Achilles tendinopathy and patellofemoral pain or limit recovery from these injuries if not modulated for through appropriate training programs and graded transitions to these higher running speeds.

6 | PERSPECTIVE

The results of this study offer several clinical implications. Firstly, as running speed increases, the greater peak Achilles tendon loads could increase the risk of biomechanical overload and injury to the Achilles tendon. Particularly, if changes to training loads are sudden and do not allow sufficient time for adaptation, the observed differences in loading patterns may explain the higher frequency of Achilles tendinopathy observed among competitive runners. The initial increase in PFJ loads could increase the risk of patellofemoral pain, but further research is needed. It is possible that the training behaviors of certain groups of runners could influence their risk of specific injuries due to the differences in biomechanical loading patterns.

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DATA AVAILABILITY STATEMENT

Research data are not shared.

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