

D. S. BLAISE WILLIAMS III, PT, PhD¹ • JAMES A. ZAMBARDINO, MPT² • VALERIE A. BANNING, DPT³

Transverse-Plane Mechanics at the Knee and Tibia in Runners With and Without a History of Achilles Tendonopathy

Achilles tendonopathy (AT) is one of the most prevalent overuse injuries occurring in the lower extremities,²⁴ accounting for 5% to 18% of the total number of running injuries.^{3,7,8,19} A high incidence of AT is seen in middle-aged weekend athletes, dancers, tennis players, racquetball players, soccer players, and basketball players. A commonality among these activities is the repetitive-impact loading and the control of secondary-plane motion

(frontal and transverse) associated with landing.⁶ Therefore, focus on secondary-plane mechanics may provide further information regarding development and

treatment of AT.

A number of anatomical factors have received attention as possible etiological mechanisms in the literature. Most ten-

ons are surrounded by a synovial sheath, while the Achilles tendon is covered by a peritendon sheath,¹¹ which has been implicated in the inflammatory process. Another anatomical factor related to the pathology of AT is the tendon's relatively sparse blood supply, especially 2 to 6 cm proximal to its attachment to the calcaneus.^{1,10,13,20} This area of decreased blood flow has been associated with higher rates of AT injuries^{6,20} and rupture.⁵ Finally, the tendon's path may be an additional anatomical factor contributing to the development of AT. At 12 to 15 cm proximal to its insertion the tendon twists approximately 90°, with the medial fibers of the tendon rotating posteriorly and the posterior fibers rotating laterally.²⁵ Though this rotation enhances the tendon strength, it also places the tendon on constant tension. Excessive rotation of the lower leg as a result of excessive pronation may place the tendon under additional stress and increase risk of injury. Measurement of transverse-plane motion of the tibia, as well as the resisting moments, may provide dynamic evidence for this proposed rotation in the tendon and the subsequent development of AT.

In addition to anatomical factors, improper training and biomechanical factors have been implicated as the most prevalent etiological factors for AT in running populations.⁷ While training errors are relatively easy to address, biomechanical

• **DESIGN:** Retrospective cohort study.

• **OBJECTIVES:** To determine if runners with a history of Achilles tendonopathy (AT) demonstrate a difference in transverse-plane motion and moments at the distal tibia and knee compared to runners without a history of AT.

• **BACKGROUND:** One of the more prevalent overuse running injuries is AT. It has been hypothesized that prolonged pronation causes contradictory rotational forces acting on the AT. Conflicting joint motions may also accentuate the rotation of the tendon. This may further affect the opposing transverse-plane moments at the knee and distal tibia.

• **METHODS AND MEASURES:** Eight runners with a history of AT and a noninjured control group consisting of 8 runners ran along a 20-m runway at a fixed speed. Biomechanical measurements were taken using a 6-camera motion analysis system and a force plate. Student *t* tests were employed to determine statistically significant differences ($P \leq .05$) in transverse-plane motion and moment variables

at the distal tibia and knee between groups.

• **RESULTS:** The AT group showed less tibial external rotation moment ($P = .01$) and peak knee internal rotation ($P = .05$) compared to the control group. There was no difference in external rotation moment at the knee ($P = .34$) or peak tibial internal rotation ($P = .44$).

• **CONCLUSION:** Runners with a previous history of AT exhibited less tibial external rotation moments during running. The lack of control in the transverse-plane at the distal tibia may be due to decreased function of the muscles primarily responsible for transverse-plane motion, resulting in greater strain on the AT in the transverse-plane. Designing an exercise program to strengthen lower leg muscles and improve distal tibial control in the transverse-plane may reduce the risk for developing AT or augment the rehabilitation of AT. *J Orthop Sports Phys Ther* 2008;38(12):761-767. doi:10.2519/jospt.2008.2911

• **KEY WORDS:** injury, running, tendon

¹Director of Graduate Studies, Department of Physical Therapy, East Carolina University, Greenville, NC. ²Rehabilitation Services Coordinator, University Home Health and Hospice, Greenville, NC. ³Department of Physical Therapy, East Carolina University, Greenville, NC. This study was approved by the East Carolina University Institutional Review Board. Address correspondence to Dr D. S. Blaise Williams III, Allied Health and Nursing Building 1425A, Department of Physical Therapy, East Carolina University, Greenville, NC 27858. E-mail: williamsdor@ecu.edu

factors are harder to identify and change. Compensatory pronation and the resulting mechanical stress on the soft tissue structures of the lower leg and rearfoot are major biomechanical factors implicated in the etiology of AT.^{4,6,7,15,22,23,26,29} Compensatory overpronation is defined as either excessive pronation, pronation that occurs too quickly, or a prolonged duration of pronation during the stance phase.¹⁷ Although overpronation is hypothesized to be a principal etiological cause of AT, no experimental studies have provided supporting evidence.^{4,6,7,22,26,29} The amount of pronation in the rearfoot has been shown to be greater in athletes with Achilles peritendonitis than in individuals without it.²⁷ As pronation is a triplanar motion, quantifying motion in all 3 planes is necessary to give clinicians a complete understanding for effective treatment. Because transverse-plane motion of the rearfoot is difficult to evaluate when the foot is on the ground, the tibia is commonly measured because of its tight coupling with talar motion in the transverse-plane.⁹ Therefore, evaluation of the synchrony of joint motion and the associated moments between the foot, lower leg, and knee may provide insight into the mechanism of running-related injuries.

Normally, the rearfoot begins to re-supinate after midstance, while the knee extends and the tibia externally rotates. Because the tibia has a tight articulation with the talus, transverse-plane rearfoot motion (calcaneus relative to talus) and transverse-plane tibial motion (tibia relative to calcaneus) are considered equal and opposite. The tibial internal rotation associated with prolonged pronation contradicts the typical pattern of tibial external rotation coupled with knee extension. These conflicting motions are hypothesized to accentuate the rotation of the tendon and cause a “wringing out” of the avascular zone of the tendon.^{7,16,25} This passive tension is likely to manifest itself as greater transverse-plane joint moments in the lower leg. The coupling of pronation with tibial internal rotation

and supination with tibial external rotation should be relatively synchronous,^{2,12} occurring within 10% of one another during the stance phase of gait. However, compensation as result of muscle weakness or structural differences may occur and significantly disrupt this timing.²¹ Because of the kinetic chain in the lower extremity, changes at the foot can affect the knee and hip, and vice versa, during the stance phase of running. Therefore, changes in rotation at the knee joint (tibia relative to femur) will also affect the demand on the muscles controlling pronation of the rearfoot, which may result in injury.

The mechanisms for development of AT are still uncertain. Most of the research concerning lower extremity mechanics and AT has focused on the motion occurring within the Achilles tendon itself. Research related to the mechanism of AT injury should focus on lower extremity kinetics at the tibia and knee and how these motions contribute to the motion of the Achilles tendon. Finally, the coupling of motion and moment between the tibia and knee has not received significant attention in the literature. Information regarding asynchrony in the lower extremity may provide mechanical evidence for AT as has been suggested.²¹ The purpose of this study was to determine if individuals with a history of AT demonstrate a difference in transverse-plane motion and moments at the knee and lower leg/tibia when compared to previously noninjured controls. Further, the synchrony of these events at the knee and lower leg was compared between groups. It was hypothesized that runners with a history of AT would demonstrate a greater external rotation moment at the knee and lower leg when compared to runners without a history of AT; second, that runners with a history of AT would show a greater peak internal rotation at the knee and lower leg when compared to runners without AT; and, finally, that subjects with AT would demonstrate asynchrony between these events when compared to runners without AT.

METHODS

Subjects

SUBJECTS FOR THIS STUDY WERE recruited from the University, surrounding communities, and local running clubs. All subjects in this study were between 22 and 50 years old at the time of data collection. All runners ran with a rearfoot strike pattern. The study included 8 runners with a history of at least 1 episode (mean, 2.1; range, 1-5) of AT, as diagnosed by a medical professional (physician, physician assistant, athletic trainer, physical therapist). Five participants reported a history of bilateral AT, 2 reported right AT only, and 1 reported left AT only. All runners included in the group with AT were asymptomatic at the time of data collection. A control group consisted of 8 runners with no history of AT. Subjects were closely matched by age, mass, height, and mileage run per week. Participants ran a minimum of 6 miles (9.7 km) per week for at least 3 months prior to this study. No criteria for maximum weekly mileage were set. Subjects were excluded if they had orthopedic or neurological problems. Examples of the exclusion criteria were extreme pes planus, extreme pes cavus, extreme leg length discrepancies, and diabetes with neuropathy. Each participant had a lower extremity musculoskeletal examination by a physical therapist with 12 years experience specific to the running population in order to establish exclusion criteria. Prior to testing, all subjects gave informed consent, filled out an injury history questionnaire, and provided general demographic, including running history (TABLE 1). The protocol for this study was approved by the East Carolina University and Medical Center Institutional Review Board.

Protocol

Subjects who met the inclusion criteria completed a 3-dimensional running analysis. A standing calibration trial was collected, during which retroreflective markers were placed unilaterally on the side of previous injury on the segments

TABLE 1

SUBJECT DEMOGRAPHIC DATA*

Characteristics	Achilles Tendonopathy	Control	P Value
Gender (n male, female)	6, 2	5, 3	
Age (y)	36.0 ± 8.2	31.8 ± 9.3	.19
Distance (km/wk)	41.3 ± 20.8	35.3 ± 23.1	.31
Years running	19.1 ± 7.7	11.0 ± 9.1	.05
Mass (kg)	67.3 ± 11.4	65.6 ± 13.5	.41
Height (m)	1.76 ± 0.07	1.70 ± 0.10	.10

* Data, except for gender, are mean ± SD.

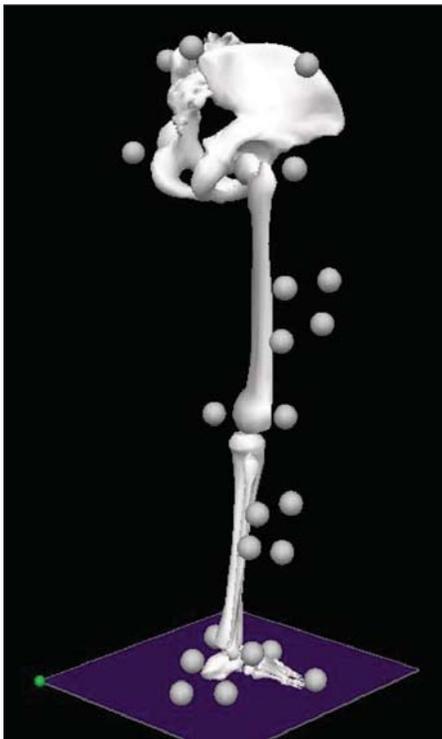


FIGURE 1. Unilateral marker placement. Joint centers were established during the standing calibration at the hip with trochanteric markers, at the knee with medial and lateral knee markers, and at the ankle, with medial and lateral maleolar markers.

of the calcaneus, shank, thigh, and pelvis (FIGURE 1). Markers were placed by the same investigator to reduce intersubject variability. Investigators were not blinded to subject group inclusion. Tibial motion was defined as the tibia moving relative to a fixed foot. Knee motion was defined as the tibia moving relative to the femur. Before dynamic data collection, static markers (bilateral greater trochanters, medial and lateral knees, medial and

lateral malleoli, and medial and lateral forefoot) were removed and subjects were allowed to run along the runway as many times as necessary to feel comfortable with the markers and the lab environment. Kinematic data were collected at 120 Hz with a 6-camera Qualisys motion analysis system (Qualisys Inc, Glastonbury, CT). Qualisys software was used to reconstruct 3-dimensional coordinates for each marker. The subjects were asked to run along a 20-m runway at a speed of 3.35 m/s ($\pm 5\%$). Speed was monitored with photocells placed 4 m apart. This was a comfortable pace for all runners. A fixed pace was chosen to reduce differences in lower extremity biomechanics related to differences in speed. A force plate (AMTI, Watertown, MA) mounted in the floor of the runway recorded ground reaction forces at 960 Hz. Ground reaction force data were filtered at 50 Hz and a vertical ground reaction force threshold of 12 N was used to define heel strike and toe-off. Ten successful foot strikes on the force plate were collected for each subject. Participants were instructed not to target the force plate. If the subject did not hit the force plate as part of a normal stride, the trial was disregarded.

Data Reduction

Pelvis, thigh, shank, and foot segments were created. The 3-dimensional data were filtered using a second-order recursive Butterworth filter with a 12-Hz cutoff frequency. All data were time synchronized at the time of collection through system hardware. Data were further ana-

lyzed between heel strike and toe-off and normalized to 100 data points, each representing 1% of the stance phase of running. Utilizing Visual 3-D software (C-Motion Inc, Bethesda, MD), joint rotations were calculated via Cardan sequencing, where motion about the local z (vertical) axis at the knee was defined as internal/external rotation. The y and z axes are rotated 90° for the foot segment. Therefore, motion about the local y (vertical) axis at the rearfoot/tibia was defined as internal/external rotation. Internal joint moments were calculated using standard inverse dynamic calculations. Joint moments were normalized to subject mass. Mean curves were created for each group for tibia and knee motions and moments in the transverse-plane. Peak values of tibial internal rotation, knee internal rotation, tibial external rotation moment, and knee external rotation moment were compared between the 2 groups. Differences in time to these peak values of motion and moment between the knee and the tibia were also calculated.

Data Analysis

One-tailed, 2-sample, equal variance Student t tests were employed to determine if there were statistically significant differences in peak tibial internal rotation motion, knee internal rotation motion, tibial external rotation moment, and knee external rotation moment ($P \leq .05$) between the 2 groups. Further, tibia-to-knee synchrony was compared by difference in time to peak between the knee and tibia for internal rotation motion and external rotation moment. Group demographics were also compared.

RESULTS

THERE WERE NO DIFFERENCES IN body mass, height, age, and mileage run weekly between groups. A significant difference was present in number of years running (TABLE 1).

Subjects with a history of AT demonstrated significantly less peak internal rotation motion at the knee ($P =$

.05) (TABLE 2). In fact, the subjects with AT remained in more external rotation throughout stance phase when compared to the subjects in the control group (FIGURE 2). Additionally, subjects with AT had significantly less peak tibial external rotation moment ($P = .01$) when compared to the subjects in the control group (TABLE 2). The subjects in the control group demonstrated an external rotation moment at the distal tibia throughout stance. The group with previous AT exhibited an uncharacteristic internal rotation moment of the tibia present just after heel strike and just before toe-off (FIGURE 3).

No significant differences were observed between groups when comparing peak tibial internal rotation motion ($P = .44$) (FIGURE 4) or peak knee external rotation moment ($P = .34$) (FIGURE 5). No timing differences were observed between the knee and tibia in motion or moment (TABLE 2).

DISCUSSION

THE PURPOSE OF THIS STUDY WAS to determine if runners with a history of AT would demonstrate differences in transverse-plane motion and moment at the knee and distal tibia during running when compared to runners without a history of AT. These variables were of interest, as it has been suggested that the interaction between the knee and the distal tibia/rearfoot may predispose a runner to overuse injury.

Runners with a history of AT exhibited lower peak knee internal rotation when compared to runners without history of AT. However, the tibial internal rotation excursions were similar between the 2 groups. Subjects with AT remained in more relative external rotation position at the knee throughout stance phase. Because there is no difference between groups in tibial peak or excursion angle, this suggests that the femur is in more relative internal rotation in global space. This internal rotation would potentially place a rotational stress on the gastrocnemius, with the lateral head being pulled ante-

BIOMECHANICAL VARIABLES OF INTEREST DURING STANCE PHASE OF RUNNING*			
Variables	Achilles Tendonopathy	Control	P Value
Peak TIR (deg)	13.9 ± 6.5	13.4 ± 5.5	.44
Peak KIR (deg)	3.1 ± 3.8	7.3 ± 4.8	.05
Peak TER moment (Nm/kg)	-0.33 ± 0.35	-0.80 ± 0.34	.01
Peak KER moment (Nm/kg)	-0.54 ± 0.14	-0.52 ± 0.09	.34
KIR-TIR motion timing (% stance) [†]	27.8 ± 23.8	26.5 ± 15.8	.45
KER-TER moment timing (% stance) [‡]	-17.6 ± 12.0	-16.9 ± 5.4	.44

Abbreviations: KER, knee external rotation; KIR, knee internal rotation; TER, tibial external rotation; TIR, tibial internal rotation.
 * Data, except for gender, are mean ± SD. Positive values, internal rotation; negative values, external rotation.
[†] A positive value in timing indicates that peak KIR motion occurred after peak TIR motion.
[‡] A negative value in timing indicates that peak KER moment occurred before peak TER moment.

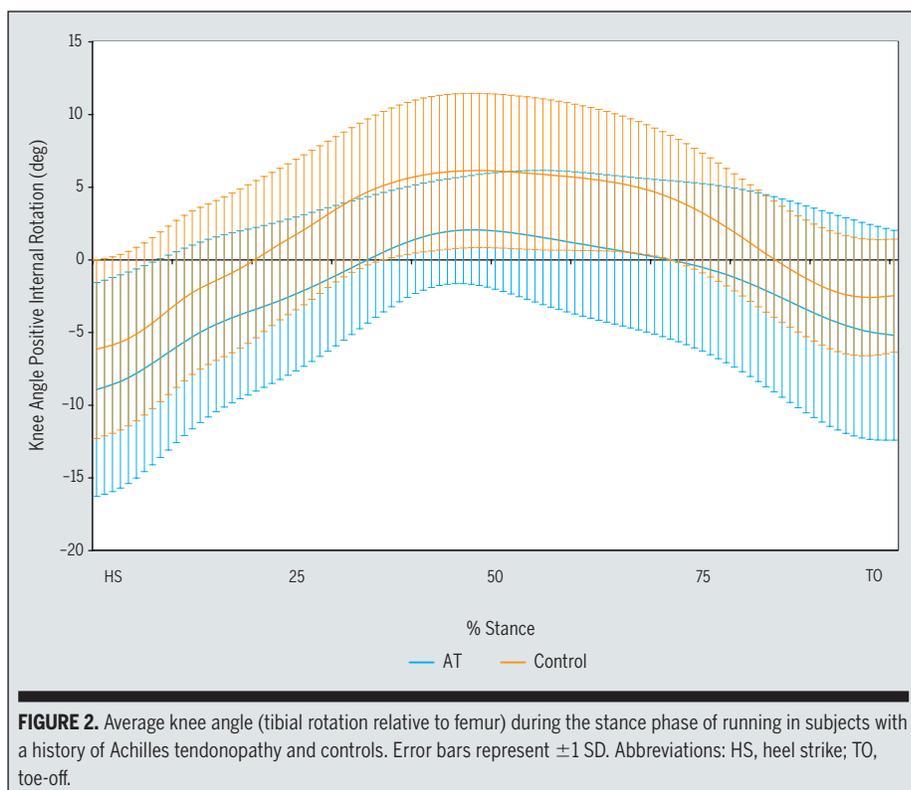


FIGURE 2. Average knee angle (tibial rotation relative to femur) during the stance phase of running in subjects with a history of Achilles tendonopathy and controls. Error bars represent ±1 SD. Abbreviations: HS, heel strike; TO, toe-off.

riorly and the medial head being pulled posteriorly. This would potentially place the gastrocnemius portion of the Achilles tendon in a relatively shortened position on the medial side. This reduction in muscle length may result in changes in mechanical stress at the musculotendinous junction or midsubstance of the tendon, common sites of AT injury.

Runners with a history of AT exhibited lower tibial external rotation mo-

ment compared to control subjects, while demonstrating no difference in tibial internal rotation motion. This suggests a difference in position and or magnitude of the medial/lateral ground reaction force during stance. Small changes in the position or magnitude of the medial ground reaction force can have profound effects on joint moments especially in the transverse-plane.²⁸ It is possible that the runners with AT compensate or change

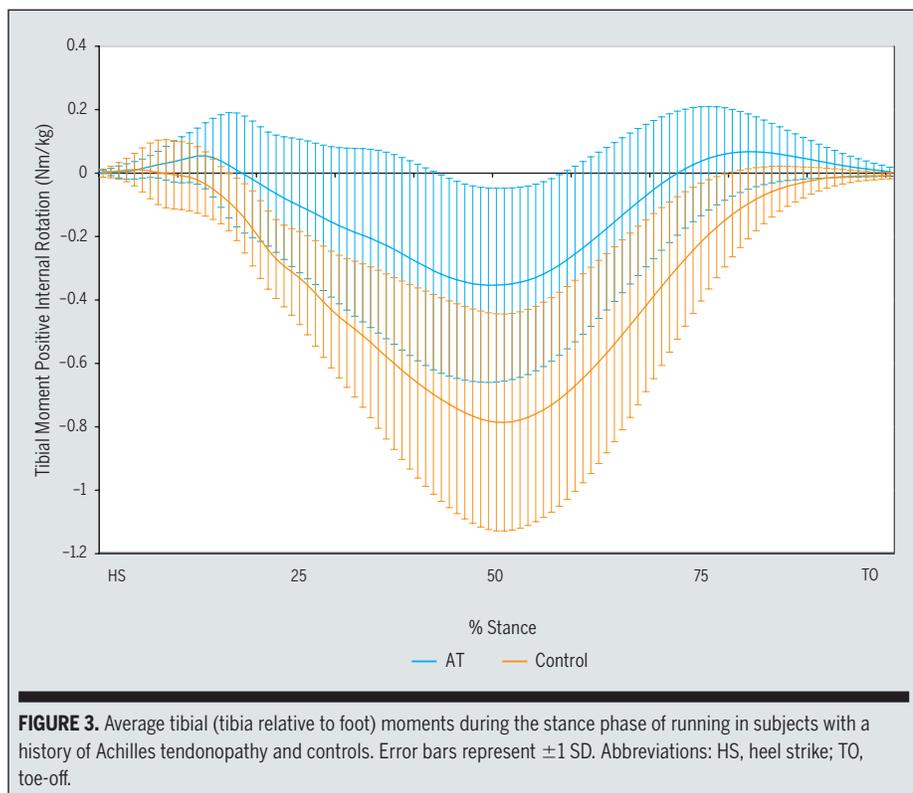


FIGURE 3. Average tibial (tibia relative to foot) moments during the stance phase of running in subjects with a history of Achilles tendonopathy and controls. Error bars represent ± 1 SD. Abbreviations: HS, heel strike; TO, toe-off.

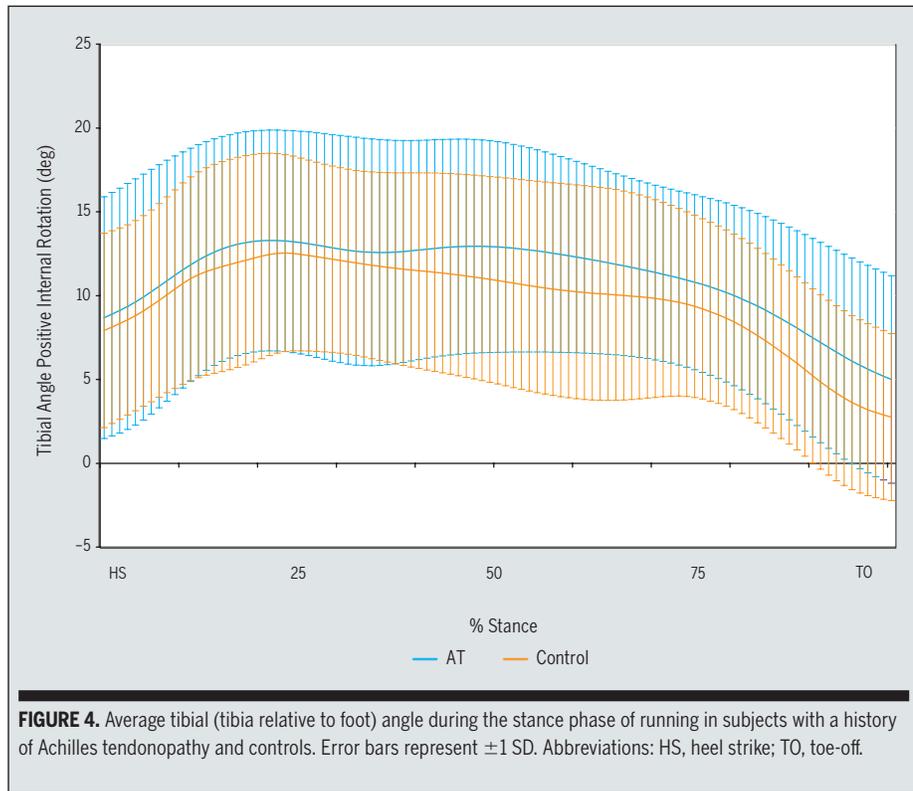


FIGURE 4. Average tibial (tibia relative to foot) angle during the stance phase of running in subjects with a history of Achilles tendonopathy and controls. Error bars represent ± 1 SD. Abbreviations: HS, heel strike; TO, toe-off.

their medial loading in an attempt to reduce the load on the muscles eccentrically controlling internal rotation of the

tibia. Specifically, the tibialis posterior is the primary muscle responsible for controlling pronation in the rearfoot during

loading. Abduction motion of the foot relative to the ground during stance is limited by its contact with the ground and therefore is not evident in kinematic measures. Abduction of the foot would be defined as lateral motion of the foot relative to the tibia. However, abduction of the foot is controlled in part by the medial ground reaction force. A lower force would result in a lower transverse-plane joint moment without a change in the angle. Although not specifically tested in the current study, there was an approximately 50% reduction in the magnitude of the medial ground reaction force during the first half of stance in the group with AT. Recent studies have shown similar results in comparing older runners to younger runners.¹⁸ If the posterior tibialis muscle does not function properly, it is possible that the gastrocnemius complex, particularly the medial side, may be forced to assist in eccentric control of tibial internal rotation or foot abduction. Other factors, such as midfoot mobility, rearfoot mobility, and foot orthotic device use, may also be considered as possible modifiers of the medial/lateral ground reaction force.

There were 2 distinct subgroups within the group with AT (FIGURE 6). Each subgroup consisted of 4 runners. One group exhibited a very low tibial external rotation moment and demonstrated an internal rotation moment near heel strike and toe-off (IR group). This internal rotation may be present as a compensation for the past AT or as a prediacting factor. The other subgroup (ER group) demonstrated a pattern similar to the uninjured group. Although the pattern was similar to the uninjured group in this ER group, the magnitude of the peak external rotation moment was still approximately 40% lower when compared to the control group. This suggests that less external rotation moment at the tibia may be an important factor in the presence of AT. Therefore, strengthening in the transverse-plane may place runners at lower risk for injury to the Achilles tendon. Upon further evaluation of the IR group, subjects ran significantly greater mileage per week

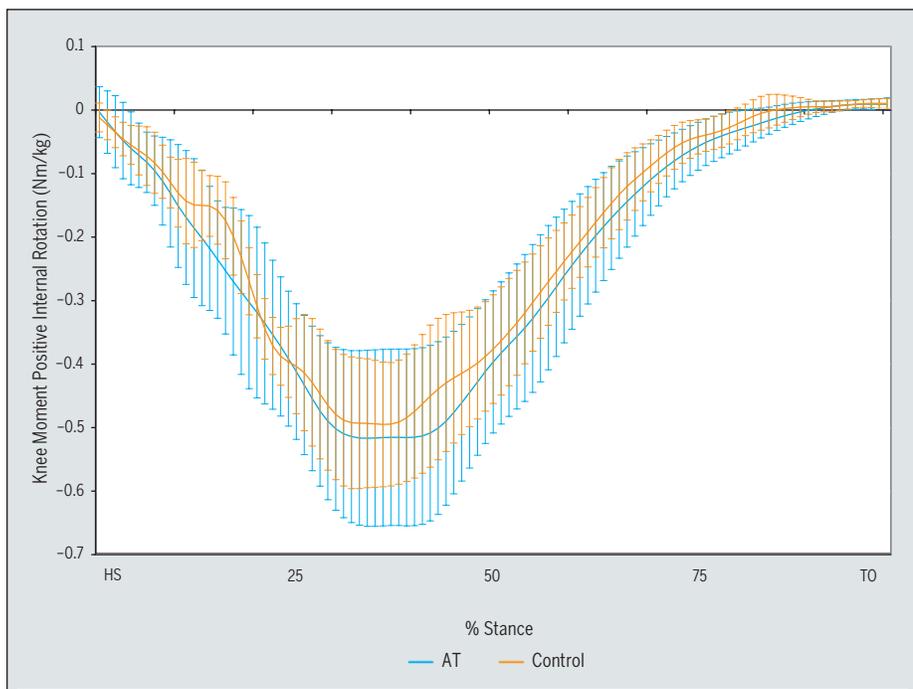


FIGURE 5. Average knee (tibia relative to femur) moments during the stance phase of running in subjects with a history of Achilles tendonopathy and controls. Error bars represent ± 1 standard deviation. Abbreviations: HS, heel strike; TO, toe-off.

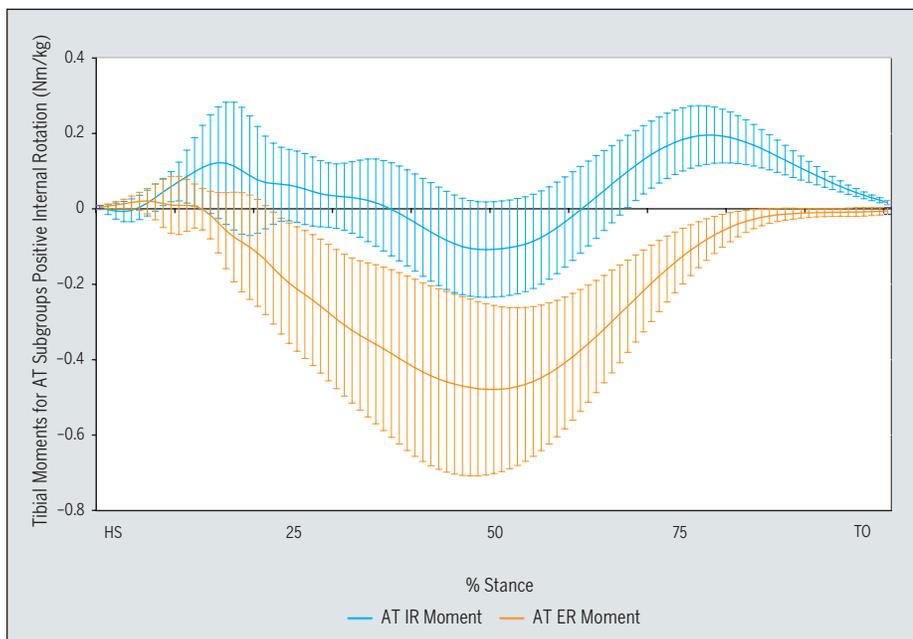


FIGURE 6. Average tibial (tibia relative to foot) moment during the stance phase of running in subjects with a history of Achilles tendonopathy. Subjects represented in blue have a more normal pattern of movement. Subjects in gray demonstrate an atypical internal rotation moment. Error bars represent ± 1 standard deviation. Abbreviations: HS, heel strike; TO, toe-off.

limits the use of the muscles responsible for transverse sagittal-plane motion, larger muscles may be required to compensate for these muscles. This shift in control at the joint could result in overuse or acute injury to that structure (in this case the Achilles tendon). Although it is nearly impossible to control for all variables, it is important to recognize all potential contributing factors. It is important to note that all subjects in the current study were rearfoot strikers. Therefore, none of the differences in mechanics can be attributed to strike pattern.

Interestingly, there were no significant findings in any of the timing variables between groups. In both groups, peak tibial internal rotation motion was reached at approximately 25% of stance prior to peak knee internal rotation motion. This is in contrast to the relative synchrony of timing (10% difference) between knee flexion and rearfoot pronation previously found in runners.¹² Transverse-plane motion is more inconsistent and therefore more likely to be uncoupled when compared to frontal- and transverse-plane motion. However, both groups exhibited peak knee external rotation moment at approximately 15% of stance prior to peak tibial external rotation moment. While timing of joint motion has been previously suggested to be related to structure and potential injury,¹⁴ the results of the current study indicate that there is no difference between runners with and without a history of AT. It is important to note that no subjects in the current study were classified as overpronators or were determined to have extreme foot types (pes cavus or pes planus). Anatomic and mechanical factors such as these have been previously shown to affect lower extremity mechanics.^{22,30} Finally, peak joint motion and moment do not seem to be synchronous in the transverse-plane at the knee or tibia during running. Further evaluation of optimal timing of motion and moment may be necessary if this is to be a future variable of interest for running-related injuries.

There are several limitations that are worth noting. The current study is ret-

(54.4 versus 28.2 km) and showed trends toward a greater number of years running (23.3 versus 15.0) and greater years of age (41 versus 31). Greater mileage per week

or running for more years may stress the tissues in the lower extremities to the extent that compensations are made to continue performing. If stress or fatigue

rospective in nature and it is unknown whether these biomechanical deviations were present prior to the development of AT. Therefore, no cause-and-effect relationship can be determined. Although statistical significance was obtained in several variables, some variables did not reach significance. Based on a power analysis of the current knee external rotation moment data, an additional 15 subjects in each group would have been necessary. It is possible that additional subjects would have strengthened our results for this variable. All subjects had a history of previous injuries that were not specifically evaluated as part of this study. It is possible that other injuries might have indirectly resulted in, or combined with, the AT to contribute to the mechanical results presented here. Further stratification based on a history of only AT would have further limited the subject pool.

CONCLUSION

THE CURRENT STUDY DETERMINED that differences in transverse-plane motion at the knee and moment at the tibia exist between runners with a history of AT and those without. Specifically, runners with a history of AT exhibit less internal rotation of the knee and a lower external rotation moment of the tibia. Evaluation of injured runners should focus on motion and control in all 3 planes, even if the injury is to a muscle or other structure dominant in the sagittal plane. Future studies should include a prospective evaluation of runners and their injuries in an attempt to strengthen the finding of the current study. If AT is related to preexisting transverse-plane biomechanics, specific preventative strategies could be developed to address these faulty mechanics. ●

KEY POINTS

FINDINGS: Runners with a history of AT exhibit greater internal rotation at the knee and less external rotation moment at the tibia.

IMPLICATION: Evaluation and treatment

of transverse-plane motion and control during running may have implications for function in other planes.

CAUTION: Subject groups were determined based on a history of AT. Other factors such as training, foot morphology, and age were not considered.

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