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Running-Related Achilles Tendon Injury: A Prospective Biomechanical Study in Recreational Runners

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There are relatively few running studies that have attempted to prospectively identify biomechanical risk factors associated with Achilles tendon (AT) injuries. Therefore, the aim was to prospectively determine potential running biomechanical risk factors associated with the development of AT injuries in recreational, healthy runners. At study entry, 108 participants completed a set of questionnaires. They underwent an analysis of their running biomechanics at self-selected running speed. The incidence of AT running-related injuries (RRI) was assessed after 1-year using a weekly questionnaire standardized for RRI. Potential biomechanical risk factors for the development of AT RRI injury were identified using multivariable logistic regression. Of the 103 participants, 25% of the sample (15 males and 11 females) reported an AT RRI on the right lower limb during the 1-year evaluation period. A more flexed knee at initial contact (odds ratio = 1.146, $P = .034$) and at the midstance phase (odds ratio = 1.143, $P = .037$) were significant predictors for developing AT RRI. The results suggested that a 1-degree increase in knee flexion at initial contact and midstance was associated with a 15% increase in the risk of an AT RRI, thus causing a limitation of training or a stoppage of running in runners.

***Keywords**:* risk factors, knee flexion, ankle dorsiflexion, foot strike pattern

Running has become increasingly popular mainly for its health benefits.[1–3] The number of runners has increased to more than 60 million people worldwide in recent years.[4] However, running-related injuries (RRI) are reported by up to 79% of recreational runners and often result in individuals stopping or limiting their running.[5–8] Achilles tendon (AT) pain is among the most common RRI, with an incidence of up to 22% among recreational runners.[5,7,9–11] Recently, it has been shown that 66% of runners with Achilles tendinopathy had decreased running performance during the first year after injury (frequency, speed, and duration of running).[12] In the running population, males aged 30–50 years are the most susceptible to AT RRI.[13,14] AT RRI is considered an overuse injury, and biomechanical overloading is believed to be the initiation of the injury.[15,16] Different running biomechanics such as footfall patterns, running speed, or running in different conditions affect the AT loading during running.[17–21]

A large volume of published cross-sectional or retrospective studies have described the biomechanical factors associated with AT injuries in runners.[22–30] Runners with AT injury have greater ankle dorsiflexion and eversion during the loading phase of running.[22,24,27,28] Another parameter associated with AT injury is knee flexion, the results of which have been inconsistent between different studies. Donoghue et al[26] reported that runners with AT injury had greater knee flexion during the stance phase.[27] Conversely, results from studies by Azevedo et al[25] and Bramah et al[24] suggested the opposite, that runners with AT injury had a more extended knee during the stance phase.[24,25] A retrospective study by Hollander et al[31] indicated that a midfoot foot strike pattern was associated with AT RRI.[31] However, as these are all cross-sectional, retrospective studies, it is not clear whether the difference in the biomechanics of the ankle and knee are the cause or the consequence of the injury. Only one prospective study has shown that a more extended knee during the midstance phase was associated with an AT injury.[5] In this prospective analysis, injured runners had a lower maximal dorsiflexion ankle angle than healthy runners.[5] However, this study has important limitations, including an exploratory evaluation of AT risk factors (rather than an a priori hypotheses and statistical testing) and the protocol of barefoot running at a controlled speed, which has limited external validity. Thus, it is clear that the current literature lacks a well-designed prospective study to determine the biomechanical factors associated with AT injury.[32,33]

Bertelsen et al[34] described a framework of a multifactorial nature for the etiology of RRI calling for multifactorial studies to identify how running biomechanics interact with physical activity, anthropometric, demographic, and psychosocial variables that are believed to be linked to an AT injury in recreational runners.[5,6,11,14] There is evidence that specific physical activity characteristics (long training distances/time per week, running experience, high training frequency) in runners are risk factors for running injuries.[35–37] Therefore, this study aimed to determine whether biomechanical variables were related to the incidence of AT RRI for 1 year in low-volume runners.

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Methods

Study Design and Participants

The design of this study was a prospective study with 108 recreational, healthy runners who were followed for 1 year. The prospective study examined risk factors related to the incidence of RRI. Participants were recruited through digital advertising on social media from December 2017 to April 2018. All potential participants completed a screening questionnaire upon registration for this study. Participants who met the criteria entered this study and underwent a baseline measurement from August to December 2018. Participants who had a clinically diagnosed previous history of running injuries were excluded from the study. Also, participants who reported at screening that they ran more than 51 km·wk^{-1} were not included in the study. Low-volume recreational runners aged 18–65 years were included in the study. At the start of the study, each participant completed a set of questionnaires and underwent baseline measurements. Prior to the baseline measurement, participants had no musculoskeletal injuries of the lower extremity that limited their running for 6 months. Across the year, data were collected weekly on the incidence of injuries. A flowchart of recruitment procedure and detailed exclusion criteria in this study is presented in Figure 1. All participants signed an approved informed consent form before entering the prospective study. The study's design, data collection methods, and informed consent were approved by the Ethics Committee of the University of Ostrava (OU-54483/45-2019).

Definition of AT Running-Related Injury

A running-related AT injury was defined as musculoskeletal pain in the AT region requiring medical evaluation or causing a stoppage of running or a limitation of distance, speed, duration, or training of running for at least 7 days or 3 consecutive, scheduled running sessions.[38] Based on this definition, if a participant self-reported in the weekly questionnaire that they felt AT pain and running was part of the cause for stopping or limiting running, this participant was included in the AT RRI group. In addition, the AT RRI must have been to the right lower limb.

Baseline Measurements

The questionnaires were administered online using the online Qualtrics XM platform (Qualtrics International) and included the following: questions about running history (running experience and the usual running distance per week); the Victorian Institute of Sports Assessment—Achilles Questionnaire (VISA-A) as an assessment index of the severity of Achilles tendinopathy[39]; and the Leisure-Time Exercise Questionnaire as a self-report assessment of overall physical activity.[40,41]

All questionnaires were translated into the Czech language using the back-translation method with 2 independent, qualified translators. The original version of the questionnaires was translated into Czech by one translator. The second translator translated the Czech version of the questionnaire back into English. Subsequently, both translators and experts in kinanthropology compared the original version of the questionnaire set with the back translation and resolved inconsistencies through discussion. This method of translating the questionnaire has been used in prior literature.[42]

The kinematics and kinetics of the overground running of the lower extremities were recorded using the 10-camera motion capture system (1× Oqus 510+ and 9x Oqus 700+, Qualisys, Inc) and force plate (Kistler 9287CCAQ02, Kistler Instruments AG) with sampling frequencies of 240 and 2160 Hz, respectively. The marker set, which contained 24 individual retroreflective markers (9.5 mm diameter markers), was positioned at anatomical locations in the pelvis and both lower extremities. Retroreflective markers were positioned bilaterally on the posterior and anterior superior iliac spines. On both lower extremities, markers were positioned on the greater trochanter of the femur, medial and lateral femoral epicondyles, medial and lateral malleoli, and the head of the first and fifth metatarsal. Triad markers were placed on the heels of both feet. Marker cluster plates with 4 fixed markers were positioned on the thigh and shank of both lower extremities.[43,44] Afterward, the participants ran on a 17-m-long runway at their self-selected speed in neutral running shoes (Brooks Launch 5, Brooks Sport Inc) provided by the laboratory. The self-selected speed was determined by asking the participant their usual pace for a 45-minute run. Participants who had no such experience or could not imagine a pace for 45 minutes were tasked with choosing a pace that would keep them running as long as possible.[44] Subsequently, each participant ran at this pace continuously for 2 minutes along the runway; in the last 30 seconds, the speed of 6 runs was recorded by the photocells (OPZZ, EGMedical s.r.o.). The average of 6 runs indicated their self-selected speed. Eight successful trials were used to analyze the biomechanics of running. A successful trial was defined as the right foot being on the force plate and the self-selected speed within ±3%. Two photocells controlled the overground self-selected running. One evaluator performed all baseline measurement tests.

One-Year Prospective Evaluation

Study participants reported RRI throughout the year using an online weekly RRI questionnaire[45] that they received every Sunday. The questionnaire included as the first question whether the participant had a problem in the last week that affected their running activity. If the answer was Yes "I had a problem," other questions were asked that sought to examine the region of the body in which the problem occurred, whether the problem was of an acute or chronic nature, how much the problem affected running activity and training, and whether the participant had to seek (para)medical help.[45] Five participants were excluded during the 1-year prospective evaluation. Two females became pregnant at the start of the prospective study and did not complete the 1-year prospective evaluation. Three participants were excluded because they did not complete and return any weekly RRI questionnaire during the 1-year follow-up. The overall response rate to the weekly RRI questionnaire throughout the year was 81.48% for the 103 participants included in the analysis of this study.

Data Analysis

The survey data were exported from Qualtrics XM to SPSS Statistics (version 24) where the questionnaires were analyzed. Result scores for the VISA-A[39] and Leisure-Time Exercise Questionnaire[40,41] questionnaires were evaluated.

For the running biomechanics, a skeletal model of the pelvis and thigh, shank, and foot on each lower limb was created using Qualisys Track Manager (Qualisys, Inc) and Visual 3D version 6 software (C-Motion, Inc). We presented a detailed description of the creation and definition of this skeletal model elsewhere.[46] For the kinematic and ground reaction force data, a fourth-order

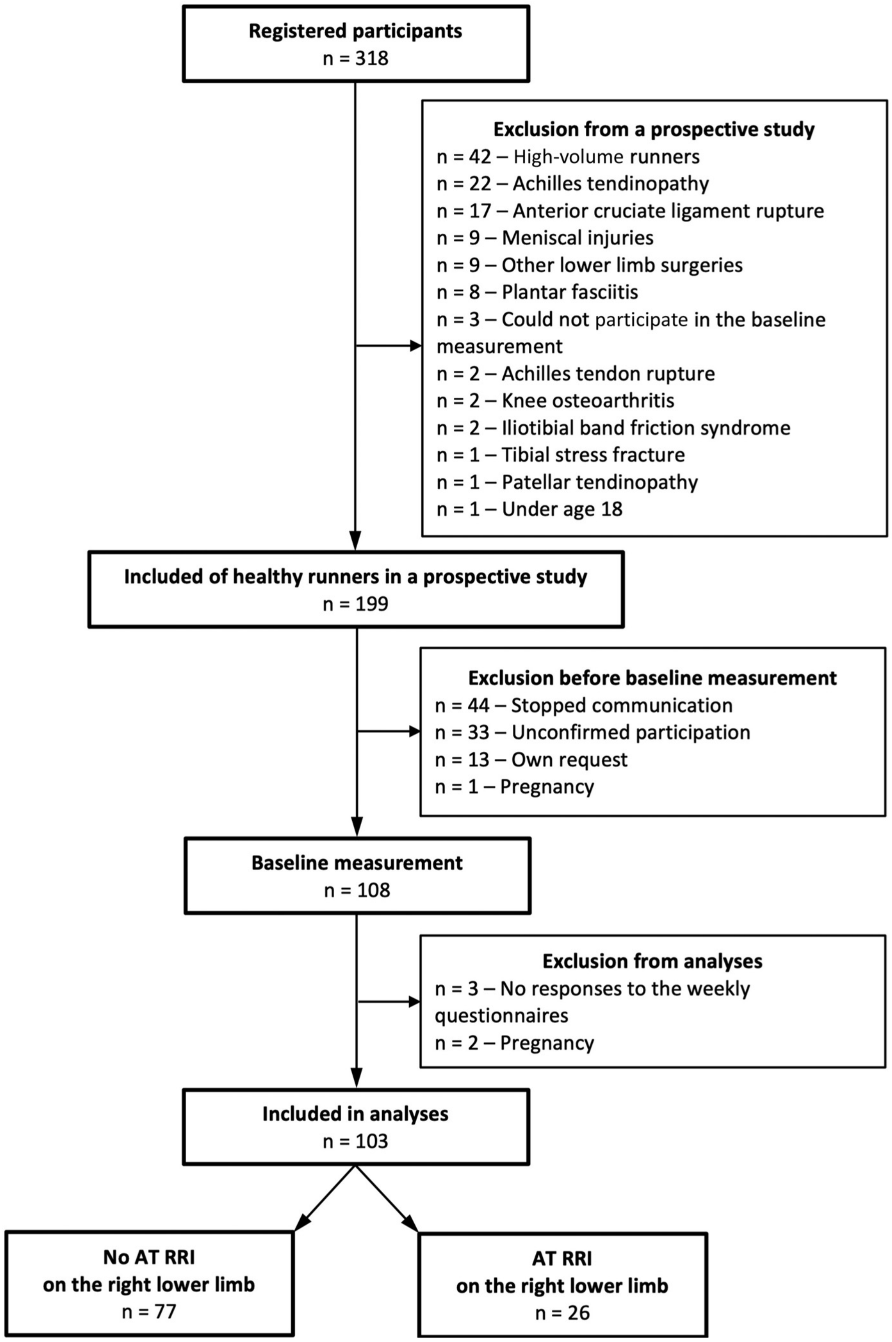

Figure 1 — Flowchart of participants' recruitment in this study. AT RRI indicates Achilles tendon running-related injury.

Butterworth low-pass filter with a cutoff frequency of 12 and 50 Hz was applied, respectively. A standing calibration trial defined the local coordinate systems and the proximal and distal ends of the lower-extremity segments and pelvis. The ankle joint center was defined as the midpoint of the medial and lateral malleoli. The knee joint center was defined as the midpoint between the medial and lateral femoral epicondyles. The knee and ankle 3-dimensional joint angles were analyzed during the stance phase and were calculated using the *x*–*y*–*z* Cardan coordinate sequence.[47] The lower-extremity joint angles were analyzed at initial contact (IC) and at midstance (34%–66% stance phase).[19] The maximum values of joint angles in the sagittal plane during the stance phase were analyzed. A foot strike index determined the foot strike pattern.[48] Biomechanical variables of running from the right lower limb were also analyzed.

Statistical Analysis

Descriptive statistics were used to summarize demographic, running history, questionnaire, anthropometric, and biomechanical data. The Shapiro–Wilk normality test, independent *t* test, or Mann–Whitey *U* test compared baseline characteristics between groups. In addition, an effect size (ES) was calculated and values above 0.5 can be considered a large effect.[49]

Potential risk factors for the development of AT RRI were identified using logistic regression analysis. The first analysis identified independent relationships between individual potential biomechanical risk factors and AT RRI. Subsequently, selected potential risk factors were introduced into the multivariable logistic regression. In addition, the model was controlled for the running speed and the amount of physical activity. Associations between running biomechanics and incidence of AT RRI were analyzed on the right lower limb only due to a complete analysis of running biomechanics during the stance phase (kinematic and kinetic data) on the right lower limb. The results of logistic regression are presented by odds ratio (OR) and confidence interval (95%). Potential risk factors with a *P* value < .05 were considered statistically significant. All analyses were conducted using SPSS Statistics (version 24).

Results

Of the 199 people who completed the screening, 108 entered the prospective study. The 1-year evaluation period was completed by 103 (95%) of the 108 participants and was included in the analysis. Eighteen participants (17%) reported AT RRI on both lower limbs; 8 participants (8%) reported AT RRI on the right lower limb only; and 5 participants (5%) reported AT RRI on the left lower limb only during the 1-year evaluation period. A total of 37% males and 25% females with an average age of 35 years reported an AT injury. The group of runners with and without AT RRI on the right lower limb did not have significantly different ages (*P* = .461, ES = 0.166) with no difference in their anthropometry (height [*P* = .861, ES = 0.104], body mass [*P* = .652, ES = 0.097], and BMI [*P* = .295, ES = 0.233]).

Table 1 presents baseline characteristics of participants at study entry with AT RRI on the right lower limb and without AT RRI on the right lower limb at the 1-year follow-up. At the beginning of the study, runners did not have any previous AT injuries or other health problems related to the AT. Runners who sustained an AT RRI had significantly less fat (*P* = .041, ES = 0.491) and reported more moderate to vigorous physical activity (*P* = .048, ES = 0.410) at baseline. The biomechanical data indicated that runners with AT RRI had significantly greater maximal ankle dorsiflexion (*P* = .036, ES = 0.399) during the stance phase, a more flexed knee at IC (*P* = .010, ES = 0.630) and greater maximal knee flexion at midstance phase (*P* = .034, ES = 0.497) (Figure 2). Foot strike index and self-selected running speed were not significantly different between runners with and without AT RRI (Tables 1 and 2).

The results of the logistic regression of individual potential risk factors show that a more flexed knee at IC (OR = 1.162, *P* = .013) and the midstance phase (OR = 1.128, *P* = .037) are significant predictors for developing AT injury. Self-selected endurance running speed (OR = 2.391, *P* = .141) and foot strike pattern as defined by the foot strike index (OR = 0.997, *P* = .807) were not identified as a potential risk factor associated with the development of AT RRI (Table 2). Table 3 presents the multivariable logistic regression for the selected potential biomechanical risk factors controlled for the covariates self-selected speed and amount of vigorous physical activity. A more flexed knee at IC and the midstance phase during the stance phase was a significant risk

Table 1 Baseline Characteristic of Participants

	Without AT RRI on the right lower limb (n = 77)	With AT RRI on the right lower limb (n = 26)		
	Mean (SD)	Mean (SD)	*P*	ES
Sex (male/female)	31/46	15/11		
Footfall pattern, % (RF/NRF)	82/18	85/15		
Running experience, % (y) (0/<0.5/0.5–1/1–2/2–5/5–8/>8)	3/12/14/25/41/0/5	8/0/11/15/54/4/8		
Running distance per week, % (km) (0–10/11–20/21–30/31–40/41–50/>51)	22/41/26/7/0/4	34/31/27/4/4/0		
Age, y	36.89 (8.45)	35.45 (8.86)	.461	0.166
Mass, kg	71.76 (12.21)	70.42 (15.37)	.652	0.097
Height, m	1.72 (0.08)	1.73 (0.11)	.861	0.104
BMI, kg/m^2	24.14 (3.28)	23.38 (3.23)	.295	0.233
Fat, %	23.27 (7.65)	19.82 (6.33)	.041[#]	0.491
VISA-A score, %	92.38 (7.23)	92.08 (8.85)	.710	0.037
LTEQ_vigorous, $min{\cdot}wk^{-1}$	158.30 (152.45)	234.23 (169.04)	.022[#]	0.472
LTEQ_moderate, $min{\cdot}wk^{-1}$	123.53 (115.91)	115.85 (85.16)	.772	0.076
LTEQ_lite_PA, $min{\cdot}wk^{-1}$	132.39 (177.90)	180.77 (238.61)	.364	0.230
LTEQ_sedentary, $min{\cdot}wk^{-1}$	657.65 (576.57)	822.31 (876.38)	.702	0.222
LTEQ_MVPA, $min{\cdot}wk^{-1}$	440.13 (337.81)	584.31 (364.74)	.048[#]	0.410
LTEQ_score	50.09 (33.48)	60.65 (22.04)	.003[#]	0.373
LTEQ_METs	2439.52 (1565.08)	3229.62 (1691.41)	.018[#]	0.485
Self-selected running speed, $m{\cdot}s^{-1}$	2.76 (0.38)	2.90 (0.36)	.071	0.378

Abbreviations: AT, Achilles tendon; BMI, body mass index; ES, effect size; LTEQ, Leisure-Time Exercise Questionnaire; METs, metabolic equivalent; MVPA, moderate to vigorous PA; NRF, nonrearfoot; PA, physical activity; RF, rearfoot; RRI, running-related injuries; VISA-A, Victorian Institute of Sports Assessment-Achilles (score 100% is maximum score associated with healthy AT).
[#]Statistically significant difference between runners without AT RRI and with AT RRI (*P* value < .05).

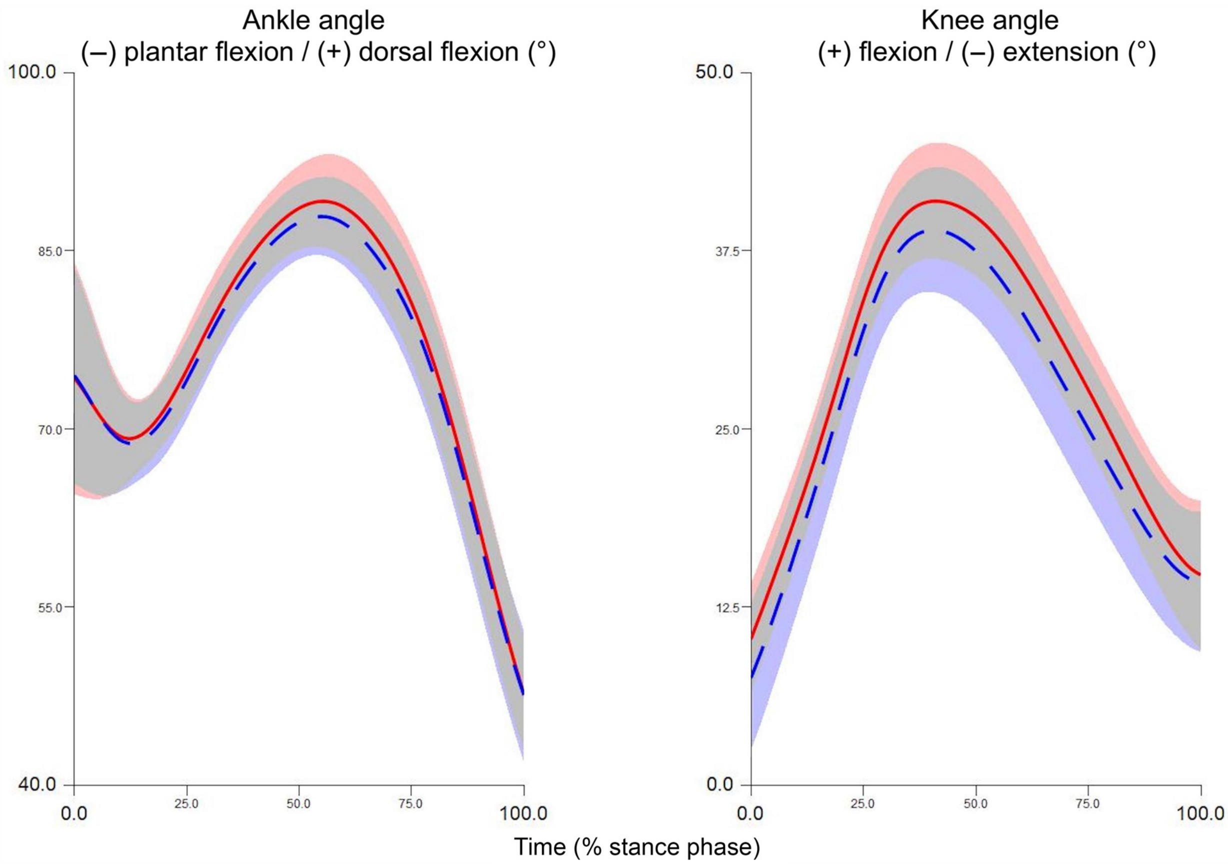

Figure 2 — Ankle angle and knee angle in the sagittal plane during the stance phase of the right lower limb. Solid line indicates runners with AT RRI; dashed line indicates runners without AT RRI. AT RRI indicates Achilles tendon running-related injury.

Table 2 Logistic Regression Between Individual Potential Risk Factors and AT RRI on the Right Lower Limb

	Without AT RRI	With AT RRI			95% CI	
	Mean (SD)	Mean (SD)	*P*	OR	Lower	Upper
Self-selected running speed, m·s^{-1}	2.76 (0.38)	2.90 (0.36)	.141	2.391	0.749	7.631
Foot strike index, %	20.08 (20.61)	18.93 (21.74	.807	0.997	0.976	1.019
Ankle angle IC_X, °	74.47 (8.95)	74.26 (9.80)	.917	0.997	0.950	1.047
Ankle dorsiflexion max, °	88.15 (3.18)	89.50 (3.57)#	.077	1.145	0.986	1.330
Knee angle IC_X, °	7.91 (4.22)	10.28 (3.24)#	.013*	1.162	1.032	1.309
Knee flexion max, °	39.15 (4.23)	41.17 (3.90)#	.037*	1.128	1.007	1.264

Abbreviations: AT, Achilles tendon; CI, confidence interval; IC, initial contact; OR, odds ratio; RRI, running-related injuries; X, sagittal plane.
#Statistically significant difference between runners without AT RRI and with AT RRI. *Statistically significant logistic regression ($P < .05$).

factor for AT injury development. In some regression models, the amount of vigorous physical activity emerged significantly as a potential risk factor. However, the level of odds ratio was inconsiderable (OR = 0.3%).

Discussion

The study's main purpose was to prospectively determine the incidence of AT RRI and potential biomechanical risk factors associated with the development of AT RRI in recreational runners.

The incidence of AT RRI in the observed participants over a 1-year prospective evaluation was 30%. Of the males and females in this cohort study, 37% and 25%, respectively, reported an AT injury. The incidence of AT RRI in this study is significantly higher than in previous studies (7%–13%).[6,9–11] Compared to the prospective study by Hein et al,[5] where the incidence of AT RRI was 22%, our incidence of AT RRI is 8% higher. The inconsistency may be due to the differences in methodology for evaluating injury (self-report vs clinical diagnosis) and the more intensive method of data collection (weekly using online technology). The higher incidence of AT RRI in this study may also have been due to the

Table 3 Results of Multivariable Logistic Regression Where Individual Potential Biomechanics Risk Factors Are Controlled for Control Covariates of Self-Selected Running Speed and Amount of Physical Activity at Study Entry

			CI (95%)	
	P	OR	Lower	Upper
Ankle angle IC_X, °	.858	1.005	0.954	1.058
LTEQ_vigorous, $min \cdot wk^{-1}$	.068	1.003	1.000	1.005
Self-selected running speed, $m \cdot s^{-1}$	.233	2.077	0.626	6.897
Ankle dorsiflexion max, °	.072	1.151	0.988	1.342
LTEQ_vigorous, $min \cdot wk^{-1}$	.044*	1.003	1.000	1.006
Self-selected running speed, $m \cdot s^{-1}$	.396	1.703	0.498	5.822
Knee angle IC_X, °	.034*	1.146	1.010	1.301
LTEQ_vigorous, $min \cdot wk^{-1}$	.075	1.002	1.000	1.005
Self-selected running speed, $m \cdot s^{-1}$	.631	1.366	0.383	4.877
Knee flexion max, °	.037*	1.143	1.008	1.295
LTEQ_vigorous, $min \cdot wk^{-1}$	.030*	1.003	1.000	1.006
Self-selected running speed, $m \cdot s^{-1}$	.709	1.277	0.354	4.607

Abbreviations: CI, confidence interval; IC, initial contact; LTEQ, Leisure-Time Exercise Questionnaire; OR, odds ratio; X, sagittal plane.
*Statistically significant logistic regression ($P < .05$).

inclusion of runners who ran in hilly conditions and on different running surfaces.

Our data reported that the participants with AT RRI ran with greater ankle dorsiflexion and knee flexion angles during the stance phase (Figure 2). However, our logistic regression model highlighted that only knee flexion was a significant risk factor associated with the development of AT RRI. This finding contradicts the results of previous studies which suggested that runners who had AT injuries had more extended knees during the stance phase.[5,24] However, one study was cross-sectional and running biomechanics were measured on a treadmill at a controlled speed of 3.2 $m \cdot s^{-1}$.[24] In a 1-year prospective study by Hein et al,[5] of 269 healthy recreational runners at the start of the study, 10 runners reported an AT injury. Only an exploratory risk factor assessment was used for statistical data analysis.[5] The injured runners were paired with 10 healthy runners,[5] and the running biomechanics in the baseline measurement were measured barefoot, which could not be applied to running in shoes.[50–53] Running barefoot is not the same as running in shoes because some runners may change their foot strike pattern.

An explanation for increased knee flexion as a potential risk factor of AT RRI could be attributed to the gastrocnemius length-tension relationship. The force-generation capacities of the medial (MG) and lateral (LG) gastrocnemius are greatest when the knee is fully extended.[54,55] This may mean that, if the runner goes into greater knee flexion and ankle dorsiflexion, the force–length relationship for the ability to generate maximum force at the MG and LG becomes disadvantageous and, therefore, the soleus may take on a greater role for force generation.[55,56] Larger values of ankle dorsiflexion and knee flexion could increase the external moment arm at the knee and ankle, reducing the effective mechanical advantage (EMA: the ratio between internal and external moment arms) increasing the stress along AT line of action.[57] Indeed, smaller EMAs require a greater muscle force to exert a specified force on the ground, thus increasing the tension along the elastic structures.[58] An EMA is smaller when the joints are more flexed and/or less aligned with the resultant ground reaction force. Consequently, higher knee flexion and ankle dorsiflexion values reduce the EMA, increasing the muscular force needed to sustain and propel the body during the stance phase (Figure 3). Due to the biarticular nature of the LG and MG, this additional force is transmitted to the AT level increasing the stress acting along its line of action. This hypothesis was reinforced by the study of Baur.[59] The author showed that tendinopathy runners had increased plantar flexor muscle activity duration during running.[59] For a given contraction, lower values of EMA require upregulation of the electromyographic activity.[58] This may create a prolonged load on the AT and contribute to the development of AT RRI.

Several studies suggest and speculate that foot strike pattern may play a role in AT RRI.[18,19,31] This may be because AT load, stress, and impulse are significantly higher in nonrearfoot runners compared to rearfoot runners.[17–19] A recent retrospective study by Hollander et al[31] indicated that midfoot foot strike pattern is associated with AT RRI.[31] However, based on this retrospective study, when the running biomechanics were measured after the AT RRI was diagnosed and the foot strike pattern was classified using video recording, we cannot deduce whether the foot strike pattern is a consequence or cause of the AT RRI. The results of our study suggest that foot strike patterns interpreted by the foot strike index variable do not appear to be a risk factor for AT RRI in our tested logistic regression analysis model. The finding that foot strike pattern was not a predictor of AT RRI was confirmed by the results of the logistic regression for the variable ankle angle during initial contact (Table 2), which can be considered as variables describing foot strike patterns.[51,60] The current systematic review study by Willwacher et al[33] does not show that foot strike pattern is a potential risk factor for other running injuries.[33] We can speculate whether the AT loading in different foot strike patterns may be a risk factor associated with development of AT RRI. However, our prospective study results may suggest that AT loading with a different foot strike pattern may not play an important role in the development of AT RRI. Rather, how long the AT resists a given load during running could play a role. Several studies indicate how lower-extremity biomechanics change after prolonged running.[60–62] However, the findings of the Farris et al[63] study show that AT force and AT mechanical properties do not change significantly after prolonged

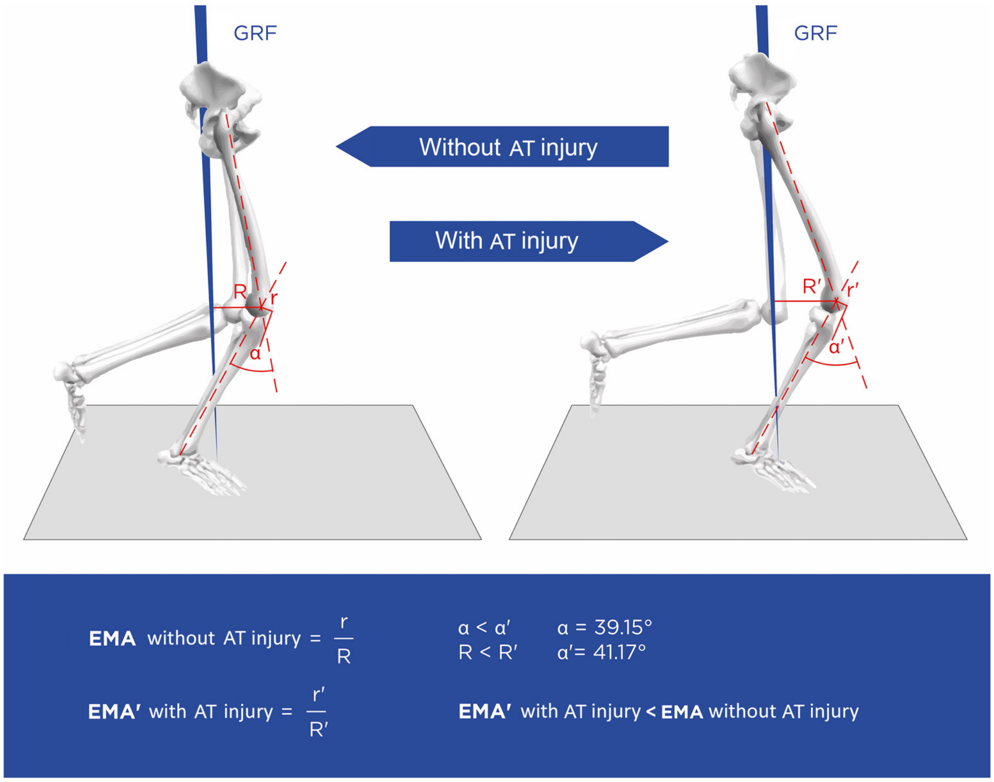

Figure 3 — Healthy runners who sustained an AT RRI within 1-year evaluation had significantly increased knee flexion and external moment arm at the knee at baseline measurement. Increased knee flexion reduced the EMA. AT RRI indicates Achilles tendon running-related injury; EMA, effective mechanical advantage—ratio between internal (*r*) and external (*R*) moment arms; GRF, resultant ground reaction force; *r*, agonist muscle moment arm; *R*, moment arm of the ground reaction force; *α*, maximum knee flexion during the stance phase of running—mean of group.

running.[63] Nevertheless, as we do not have information on the forces and loads on the AT, AT mechanical properties, or running biomechanics after prolonged running in this study, we cannot answer these questions.

The main strength of this study is the prospective design with healthy recreational runners and a detailed biomechanical analysis of running. Another strength of this study is the attempt to analyze the biomechanical causes of AT RRI and control for whether they may be influenced by the physical activity of runners. The study results may point to a possible mechanism of AT overuse injuries in runners.

A limitation of the study is that AT injuries were not clinically diagnosed, except in 2 cases where recreational runners sought medical evaluation and were diagnosed with Achilles tendinopathy. However, a weekly standardized questionnaire was used to assess AT RRI.[38] Another limitation of this study is that running exposure was not assessed and thus the timing of the accumulation of exposure and injury occurrence could not be accounted for.[64] Consequently, future studies should strive for more intensive monitoring of running parameters and other physical activity during the 1-year evaluation period, for example, by using a smartwatch. From our results, we must consider that only the right lower limb biomechanics were analyzed. We did not consider in our analysis whether the AT RRI may have occurred on the left lower limb. In this study, we did not determine the typical measurement error for the running biomechanical analysis. Although the difference between the AT RRI and non-AT RRI groups were on average only 2.37 and 2.02 degrees at IC and at maximum flexion during the midstance phase, respectively. This is, however, a larger difference than the typical measurement error reported for knee flexion during the stance phase while running.[65] Studies have suggested changes in running biomechanics when a runner is fatigued.[61,62] Therefore, another limitation is that we do not have a biomechanical analysis of running due to fatigue. Another limitation is that we analyzed running biomechanics only in standardized, laboratory neutral shoes. The footwear in which participants ran during the 1-year follow-up was not controlled. Ideally, it would have been advantageous to have running biomechanics in the standardized lab shoe and the participants' shoes. A final limitation is that we do not have information on whether participants' running biomechanics may have changed during the 1-year follow-up.

The purpose of the current study was to determine potential biomechanics risk factors for the development of AT RRI. One of the more significant findings to emerge from this study is that a more flexed knee during IC and midstance of the stance phase of running is a risk factor for the development of AT RRI. Each 1° increase in knee flexion is associated with a 15% increase in risk of AT RRI in healthy recreational runners. Another finding shows that runners with AT RRI had greater ankle dorsiflexion during the midstance of the stance phase of running. The combination of larger ankle dorsiflexion and greater knee flexion may cause greater AT loading during running, leading to AT overload and injury over time. Foot strike pattern is not a risk factor associated with the development of AT RRI in recreational runners. Health care providers and experts in sport practice may use information about biomechanical predictors of AT injury for development of preventive strategies against AT RRI.

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