VIDEO Abstract

A 2-Year Prospective Cohort Study of Overuse Running Injuries

The Runners and Injury Longitudinal Study (TRAILS)

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Background: The National Center for Injury Prevention and Control, noting flaws in previous running injury research, called for more rigorous prospective designs and comprehensive analyses to define the origin of running injuries.

Purpose: To determine the risk factors that differentiate recreational runners who remain uninjured from those diagnosed with an overuse running injury during a 2-year observational period.

Study Design: Cohort study; Level of evidence, 2.

Methods: Inclusion criteria were running a minimum of 5 miles per week and being injury free for at least the past 6 months. Data were collected at baseline on training, medical and injury histories, demographics, anthropometrics, strength, gait biomechanics, and psychosocial variables. Injuries occurring over the 2-year observation period were diagnosed by an orthopaedic surgeon on the basis of predetermined definitions.

Results: Of the 300 runners who entered the study, 199 (66%) sustained at least 1 injury, including 73% of women and 62% of men. Of the injured runners, 111 (56%) sustained injuries more than once. In bivariate analyses, significant ($P \leq .05$) factors at baseline that predicted injury were as follows: Short Form Health Survey–12 mental component score (lower mental health–related quality of life), Positive and Negative Affect Scale negative affect score (more negative emotions), sex (higher percentage of women were injured), and knee stiffness (greater stiffness was associated with injury); subsequently, knee stiffness was the lone significant predictor of injury (odds ratio = 1.18) in a multivariable analysis. Flexibility, quadriceps angle, arch height, rearfoot motion, strength, footwear, and previous injury were not significant risk factors for injury.

Conclusion: The results of this study indicate the following: (1) among recreational runners, women sustain injuries at a higher rate than men; (2) greater knee stiffness, more common in runners with higher body weights (≥80 kg), significantly increases the odds of sustaining an overuse running injury; and (3) contrary to several long-held beliefs, flexibility, arch height, quadriceps angle, rearfoot motion, lower extremity strength, weekly mileage, footwear, and previous injury are not significant etiologic factors across all overuse running injuries.

Keywords: overuse; injury; running; etiology

Running is a popular physical activity with >20 million "regular" runners in the United States[7] and an estimated 60 million people having run at least once in a calendar year.[36] Its popularity is directly related to its numerous health benefits, including improved musculoskeletal health, body composition, cardiovascular health, and psychological state.[17] Unfortunately, running is also implicated in high rates of musculoskeletal injuries, with as many as 65% of all runners reporting overuse running injuries each year.[22,23,39] These injuries can offset the health benefits with decreases or elimination of running activity and can be financially, medically, and emotionally problematic. Also, common treatments, such as rest, physical therapy, bracing, medications, and surgery, may relieve symptoms but do not always address the cause, potentially resulting in attenuated long-term activity levels.

The causes of overuse running injuries are diverse. High forces applied to the lower extremity tissues during running,[7,20,29] as well as behavioral risk factors (eg, training history, injury history)[6,22,25,27,37] and physiologic risk factors (eg, quadriceps and hamstring flexibility, quadriceps angle [Q-angle], arch height, and strengths of muscle, bone, and other tissues),[11,26] have all been implicated as etiologic factors. Such studies have generally been limited by a retrospective design where differences between injured

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and healthy runners may be due to compensation for pain from the injury. Furthermore, past studies focused on a narrow set of potential risk factors that—when evaluated in a larger, more complex framework—may lack significance, leading to incorrect rehabilitation strategies and increased medical expenses and recovery time.

A few research groups used a more favorable design (ie, prospective longitudinal), observing initially uninjured runners to avoid the limitations of previous studies. Specifically, at 2-year follow-up, Davis et al[7] found no main effect of joint loading between female runners who sustained an overuse running injury versus those who remained injury free. Buist et al[4] noted that different etiologic factors were related to injury in male runners (higher body mass index [BMI], previous injury, previous sports participation without axial loading) as compared with female runners (navicular drop) after 13 weeks of training. Nielsen et al[31] used a 1-year observation period and found no difference in rearfoot motion between injured and injury-free runners. Our objective was to use a multifactorial approach to provide evidence of the etiologic factors associated with overuse running injuries, to be used by clinicians and researchers to subsequently reduce injury incidence. Hence, our purpose was to determine the training behavior and physiologic, biomechanical, and psychosocial risk factors that differentiate recreational runners who remain uninjured from those with a diagnosed overuse running injury during a 2-year observational period.

METHODS

Study Design

The Runners and Injury Longitudinal Study (TRAILS) was a prospective longitudinal observational trial of 300 initially uninjured runners that examined the risk factors common to all overuse running injuries sustained during a 2-year observation period. This study was approved by the human subjects committee of Wake Forest Health Sciences. Informed consent was obtained in writing from all participants.

Participants

People who responded to a 12-month recruitment effort completed an eligibility questionnaire during a prescreening visit. Inclusion criteria were age 18 to 60 years, running a minimum of 5 miles per week, and injury free for at least the past 6 months, with current training unaffected by any previous injury. Exclusion criteria were current pregnancy, or previous anterior cruciate ligament tear, reconstructive joint surgery, or joint replacement. Study personnel gave eligible participants an overview of the study, obtained signed informed consent, and collected baseline demographic, training, physiologic, biomechanical, and psychosocial data during 2 screening visits. Questionnaires were administered at 6- and 12-month follow-up and each time that an injury was reported; no follow-up questionnaires were administered during months 13 to 24. Participants were queried biweekly via email for the study duration (24 months) regarding injuries that they may have sustained during the past 2 weeks. A positive response prompted an appointment with our study physician (D.F.M.) and physical therapist (D.W.C.). At study completion, participants received a US $100 gift certificate toward running shoes at a local sporting goods store.

Definition of Injury

Overuse running injuries were graded with the method defined by Marti et al[23]: grade 1, maintained full activity in spite of symptoms; grade 2, reduced weekly mileage; and grade 3, interrupted all training for at least 2 weeks.

Testing Visits

Two baseline screening visits were scheduled 2 to 4 weeks apart. Screening visit 1 included consent, medical history, medication, training history, injury history, demographics, anthropometrics, and knee and ankle strength; screening visit 2 included psychosocial questionnaires, hip strength, and gait analysis. The medication, training history, and psychosocial questionnaires administered at baseline were repeated at 6- and 12-month follow-up and at follow-up visits subsequent to reporting running-related injuries. Data from baseline testing and subsequent injury diagnoses were used in the injury prediction equations.

Training and Injury History

Training and injury history questionnaires were used to gather information regarding weekly mileage, years

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running, average training pace, shoe classification, mileage in shoes before discarding, and past injuries.

Physiologic Testing

Flexibility (quadriceps, hamstring, and ankle), Q-angle, and arch height were measured with digital photographs (Nikon Coolpix L22) and ImageJ software (National Institutes of Health) to calculate angles and areas.

Anthropometric Evaluation. Hamstring flexibility was measured as maximum knee extension: the participant was supine; the hip and knee were flexed to 90°; and a strap was placed over the contralateral thigh to secure the participant to the table. Quadriceps flexibility was measured as maximum knee flexion: the participant lay prone; both thighs were strapped to the examining table; and the knee was actively flexed until it met resistance or the hip began to flex.

Ankle flexibility was measured with the participant's legs extended and the foot placed in a neutral angle equivalent to 90° of dorsiflexion. Plantar flexion and dorsiflexion active range of motion were calculated as change from the neutral angle. For all flexibility measures, 3 trials were averaged to yield a representative value for each side.

Q-angle was measured with the participant standing, with feet standardized by a template and markers placed on the anterior superior iliac spine, midpoint of the patella, and tibial tuberosity. Q-angle was the angle formed by the intersection of 2 lines that connected the midpoint of the patella to the anterior superior iliac spine superiorly and to the tibial tuberosity inferiorly.

Arch index, a surrogate measure of arch height, was assessed with the technique of Cavanagh and Rodgers.[5] A footprint, created by having the participant step onto a Harris mat with one-half of total bodyweight, was divided into thirds, not including the toes. The area of the middle third was divided by the total area to yield an arch index.

Strength Measurements. Knee and ankle concentric strength was measured with an isokinetic dynamometer set at an angular velocity of 60 deg/sec. Both legs were tested, with the order of testing (right vs left) alternated to limit any practice or fatigue effects. The first joint evaluated (knee or ankle) was alternated for each successive participant. Before testing, a warm-up habituated participants to the equipment. The activation force for each muscle group test was set at 50% of maximal voluntary isometric contraction. Two maximal reproducible trials were averaged from, at most, 6 trials for each test.

Knee Strength. Each participant was secured with torso and tested leg strapped to the testing chair, with hands across the chest, the dynamometer axis aligned with the knee, and the resistance pad attached to the lower leg proximal to the ankle joint. Gravity effect torque was calculated according to leg weight at a 45° angle. Knee extensors and flexors were tested through a joint arc from 90° to 30° (0° = full extension). The first and last 10° were deleted to account for the dynamometer's acceleration and deceleration at the ends of the range of motion and for possible inconsistent effort. Hence, average force was calculated between joint angles of 40° to 80°.

Ankle Strength. Ankle plantar flexors and dorsiflexors were tested through a joint arc from 15° of dorsiflexion to 15° of plantar flexion. The first and last 5° were deleted to account for the dynamometer's acceleration and deceleration at the ends of the range of motion.

Hip Strength. Hip abduction strength was measured through a joint arc from 0° to 30° (0° = anatomic position) with the dynamometer set at an angular velocity of 30 deg/sec. The first and last 5° were deleted to account for the dynamometer's acceleration and deceleration at the ends of the range of motion.

Biomechanical Gait Analysis

Three-dimensional kinematic and kinetic data were used to analyze lower extremity mechanics. A 6-camera motion capture system (Motion Analysis Corporation) set to sample data at 200 Hz was synchronized with a strain gauge force platform (Advanced Mechanical Technology, Inc) set to sample data at 480 Hz. Participants ran in their normal training shoes at their average training speed (±3.5%) on a 22.5-m runway while motion and force data were captured. Running speed was recorded and monitored with a photoelectric control system (model 63501; Lafayette) interfaced with a digital timer. A set of 37 passive reflective markers arranged in the Cleveland Clinic full-body configuration was attached to the runners. Markers were also placed on the rearfoot and shank to calculate frontal plane subtalar motion. Three acceptable trials for each side were averaged to yield representative values. An acceptable trial was defined as running within a normal training pace and contacting the force platform with the appropriate foot in normal stride.

Raw coordinate data were collected and smoothed with EVA and Cortex software (Motion Analysis Corp) with a Butterworth low-pass digital filter set with a cutoff frequency of 6 Hz. The smoothed video-coordinate data and ground-reaction, gravitational, and inertial forces provided input to calculate temporal and lower extremity kinematic and kinetic variables with Visual3D software (C-Motion). Outcome variables included rearfoot motion parameters, medial/lateral tibial rotation, knee kinematics, and ground-reaction forces. Rearfoot and midfoot/forefoot strikers were included in the analysis, with the vertical force impact peak being absent for the latter group.

We also calculated knee joint stiffness (N·m/deg), defined as the ratio of the maximum change in the internal knee extension moment with the maximum change in the knee flexion angle during the first half of the support phase and in which these maxima occurred within 10% of one another[12]; 98% of the trials and data from all 300 runners met these criteria:

$$k_{\text{joint}}(\text{N}\cdot\text{m/deg}) = \Delta M(\text{N}\cdot\text{m})/\Delta\theta(\text{deg}),$$

where k_{joint} = maximum knee stiffness during the first 50% of the stance phase, ΔM = maximum change in internal knee extension moment during the first 50% of the stance phase, and $\Delta\theta$ = maximum change in knee flexion angle during the first 50% of the stance phase.

The lower extremity was modeled as a rigid linked segment system. Magnitude and location of the segmental masses, mass centers, and segmental moments of inertia were estimated from position data with a previously published mathematical model,[19] relative segmental masses reported by Dempster,[8] and the participant's anthropometric data. Inverse dynamics with linear and angular Newtonian equations of motion were used to calculate the joint reaction forces and moments at each joint. These data were used to determine hamstring, quadriceps, and gastrocnemius muscle forces and lateral collateral ligament force, which were used to determine bone-on-bone tibio- and patellofemoral compressive forces and tibiofemoral anteroposterior shear force with a torque-driven model developed by DeVita and Hortobagyi.[9] Our predictions for knee muscle and joint forces compare favorably with other predictive models[34,46] and are similar to measured forces from instrumented knee joint prostheses.[16,18] Details of this model and its limitations are published elsewhere.[28]

Psychosocial Measures

Psychosocial questionnaires administered included the following:

- Exercise Self-efficacy Scale (0, lowest self-efficacy; 100, highest self-efficacy)—which assesses beliefs in the ability to continue to run at one's training pace for periods of 1 to 8 weeks[24]
- 12-Item Short Form Health Survey (SF-12) health-related quality-of-life survey (0, low; 100, high)—which measures perceived health (mental subscale) and functioning (physical subscale)[43]
- Satisfaction With Life Scale (5, extremely dissatisfied; 35, highly satisfied)—which assesses global judgment of life satisfaction[10]
- Positive and Negative Affect Scale (PANAS) (10, very slightly; 50, extremely for each scale)[45]
- State-Trait Anxiety Inventory–S Scale (20, not at all; 80, very much)—which asks participants to report how they feel right now[35]
- Visual analog scale for pain (0, no pain; 10, extreme pain)

Statistical Analysis

Descriptive statistics and visualization were first used to summarize the data, including demographics, anthropometrics, medical history, runner's history, training behavior, strength, biomechanical gait data, and psychosocial measures.

For bivariate analysis, we tested whether a specific anthropometric, biomechanical, training, or psychosocial variable predicted injury. Training pace and body weight were included as covariates in bivariate analyses of biomechanical variables. Group averages by injury status were included for explanatory purposes.

Variables that were identified as significant ($P < .05$) in the bivariate analyses were included as independent variables in a multivariable logistic regression model in which injury remained the dependent variable. Additionally, training pace and body weight were included as covariates. All statistical tests of significance of the independent variables were 2-sided with significance level set at .05. All analyses were conducted in SAS (v 9.4; IBM).

Strength variables for the final 116 participants were collected on an isokinetic dynamometer (Humac Norm; CSMi), which replaced the dynamometer (KinCom; Chattanooga Corp) used to collect data on the first 184 participants. We conducted a pilot study on 8 participants with 3 repeated measurements to obtain strength data on both dynamometers, and we used regression analysis to calibrate a model for the conversion between the strength measures from each machine. The machine effect was analyzed as a fixed effect in the model and was not statistically significant. Consequently, we did not include isokinetic dynamometer (Humac or KinCom) as a variable in subsequent analyses.

TABLE 1
Location of First Injury During the 2-Year Observation Period

	n (%)
Knee	56 (28)
Foot	42 (21)
Hip	25 (13)
Ankle	24 (12)
Leg	24 (12)
Thigh	15 (8)
Back	7 (3)
Pelvis	6 (3)

RESULTS

Of the 809 people prescreened, 300 entered the study; 290 (97%) completed 12-month testing; and 252 (84%) replied to biweekly injury status emails throughout the 24-month observation period. Women represented 43% of the cohort (women, n = 128; men, n = 172). At least 1 overuse running injury was sustained by 199 (66%) runners; 111 (56%) of the injured runners were injured more than once within the 24-month observation period. Most of the first injuries occurred during year 1 (83%, n = 166); 33 first injuries were diagnosed during year 2. Severity of the first injuries was equally divided between grade 1 (maintain weekly mileage; n = 96) and grades 2 + 3 (altered or discontinued training attributed to injury; n = 103). The knee was the most often injured site of the first injury, followed closely by the foot (Table 1). Thirty-five acute injuries were not considered overuse and thus not included in this analysis; trip/fall (n = 9) and sprained ankle (n = 8) were the most common.

Bivariate Analyses

Sex was a significant predictor of injury. Female runners were more likely than male runners to sustain an overuse running injury; 73% of women and 62% of men sustained

TABLE 2
Participant and Training Behavior Characteristics Used to Predict Injury[a]

	Injured	Uninjured	Range	*P* Value
Age, y	42.3 ± 9.7	40.0 ± 10.3	18-60	.06
Height, m	1.73 ± 0.09	1.74 ± 0.09	1.51-1.98	.35
Weight, kg	71.6 ± 13.1	74.4 ± 14.6	45.8-131.2	.10
Body mass index, kg/m^2	23.9 ± 3.3	24.5 ± 3.4	17.4-37.7	.16
Miles per week	20.4 ± 11.6	19.9 ± 14.5	5-100	.75
Running experience, y	10.5 ± 9.9	11.9 ± 9.3	0.8-40.3	.24
Training pace, min/mile	9.1 ± 1.2	8.9 ± 1.2	6.5-15.0	.2
Previous injury, n (%)	148 (74)	66 (65)		.10
Sex, %				
Female	73	27		.05
Male	62	38		
Changed shoe classification, n (%)	59 (30)	21 (21)		.10

[a]Values presented as mean ± SD unless noted otherwise.

TABLE 3
Anthropometric and Strength Characteristics Used to Predict Injury[a]

	Injured (n = 199)	Uninjured (n = 101)	*P* Value	
			Unadjusted	Adjusted[b]
Anthropometric, deg[c]				
Q-angle	14.2 ± 7.0	12.9 ± 7.3	.14	
Arch index	0.22 ± 0.06	0.22 ± 0.05	.85	
Quadricep flexibility	54.7 ± 7.6	54.9 ± 7.6	.86	
Hamstring flexibility	157.0 ± 12.1	155.2 ± 13.0	.35	
Plantar flexor flexibility	15.3 ± 6.3	15.7 ± 5.7	.60	
Dorsiflexor flexibility	40.4 ± 6.8	40.4 ± 7.1	.95	
Strength, N·m[d]				
Hip abductors	76.4 ± 18.9	78.4 ± 19.6	.41	.74
Knee extensors	88.7 ± 35.8	95.5 ± 39.1	.14	.63
Knee flexors	54.2 ± 18.1	57.8 ± 19.1	.12	.61
Knee flexion/extension ratio	0.65 ± 0.21	0.65 ± 0.20	.96	.92
Ankle plantar flexors	40.6 ± 14.9	40.8 ± 15.1	.90	.60

[a]Values presented as mean ± SD. Q-angle, quadriceps angle.
[b]Adjusted for sex. Knee flexion/extension ratio adjusted for sex and body weight.
[c]Values in degrees, except arch index.
[d]Values in N·m, except knee flexion/extension ratio.

at least 1 injury. Of the 128 female runners, 35 (27%) remained injury-free during the 2-year observation period, as opposed to 66 (38%) of the 172 male runners.

Training Behaviors. The injured and uninjured groups reported similar training regimens at baseline. On average, both groups ran 20 miles per week, had 11 years of running experience, and trained at a pace of 9 min/mile. Female runners trained at a significantly slower pace than male runners (men, 8.72 ± 1.18 min/mile; women, 9.35 ± 1.12 min/mile; $P < .001$). Previous injury was not a significant predictor of current injury (Table 2).

We combined lightweight, minimalist, motion control, and stability footwear into 2 groups—lightweight/minimalist (only 14 of 170 were classified as minimalist) and stability/motion control—to determine if shoe type was a significant risk factor for injury. The injured and uninjured groups tended to prefer lightweight/minimalist footwear by a small margin: 56% of injured runners and 59% of uninjured runners (P = .87). During the first 12 months, 30% (59 of 199) of the injured group and 21% (21 of 101) of the uninjured group changed shoe classification (P = .10). The direction of change between groups was also not significant (changed to stability/motion control, P = .11; changed to lightweight/minimalist, P = .63).

Anthropometrics and Strength. Q-angle, arch height, and flexibility (quadriceps, hamstring, and ankle) were not significant predictors of injury. After adjusting for sex, hip abductor, knee extensor and flexor, and ankle plantar flexor strengths were statistically similar between groups and not predictive of injury (Table 3).

Psychosocial Outcomes. The SF-12 mental component subscale and the PANAS negative affect subscale baseline scores were predictive of injury status; injured runners reported significantly worse mental health–related quality

TABLE 4
Psychosocial Characteristics Used to Predict Injury[a]

Measure[b]	Injured (n = 199)	Uninjured (n = 101)	P Value
SF-12 (0-100)			
Physical	56.0 ± 2.4	55.8 ± 1.7	.37
Mental	47.8 ± 5.9	49.5 ± 3.2	.01
PANAS (10-50)			
Positive affect	38.3 ± 5.7	38.9 ± 4.9	.43
Negative affect	14.7 ± 3.9	13.6 ± 3.0	.02
STAI-S scale (20-80)	29.4 ± 6.3	27.8 ± 5.8	.18
Exercise self-efficacy (0-100)	97.0 ± 5.8	97.9 ± 6.0	.25
Visual analog scale for pain (0-10)	0.85 ± 1.1	1.1 ± 1.2	.37
Satisfaction with life (5-35)	28.5 ± 4.7	29.1 ± 5.1	.30

[a]Values presented as mean ± SD. PANAS, Positive and Negative Affect Scale; SF-12, 12-Item Short Form Health Survey; STAI-S, State-Trait Anxiety Inventory–S Scale.
[b]Range of possible values in parentheses.

TABLE 5
Biomechanical Force Characteristics Used to Predict Injury[a]

	Injured (n = 199)	Uninjured (n = 101)	P Value	
			Unadjusted	Adjusted[b]
Vertical impact peak, N	1038 ± 237	1088 ± 239	.13	.74
Vertical propulsive force, N	1585 ± 291	1677 ± 300	.02	.06
Braking force, N	204 ± 51	215 ± 50	.10	.79
Propulsive force, N	180 ± 43	192 ± 42	.04	.38
Tibial compressive force, N	6722 ± 1578	7081 ± 1551	.08	.68
Patellofemoral compressive force, N	2911 ± 951	3074 ± 901	.18	.75
Knee abduction moment, N·m	–67.0 ± 29.0	–72.8 ± 26.9	.13	.51
Knee extension moment, N·m	142.4 ± 44.1	149.2 ± 43.8	.23	.88
Max knee flexion, deg	40.0 ± 5.3	40.1 ± 4.7	.89	.82
Knee stiffness, N·m/deg	6.89 ± 2.65	6.72 ± 2.03	.56	.03
Knee power absorption, W	–546 ± 198	–584 ± 196	.15	.63
Knee negative work stance, J	–30.4 ± 11.9	–32.7 ± 11.5	.14	.61

[a]Values presented as mean ± SD. Mean body weight: 701 N (injured) and 728 N (uninjured).
[b]Adjusted for training pace and body weight.

of life and more negative emotions. Both groups reported low levels of pain, above-average physical health–related quality-of-life scores, high satisfaction with life and exercise self-efficacy, and moderately low stress levels (Table 4).

Biomechanical Analysis. Unadjusted peak vertical and anteroposterior propulsive forces were significantly greater in the uninjured group versus the injured group; however, after adjusting for training pace and body weight, no ground-reaction force variables were significant predictors of injury (Table 5). For the uninjured group, vertical ground-reaction forces peaked at 2.3 times body weight; peak braking forces were 0.29 times body weight; and bone-on-bone tibial compressive forces were 9.7 times body weight. Peak knee power absorption and negative work during stance were not significant risk factors ($P >$ .05); however, knee joint stiffness was a significant predictor of injury (P = .03).

Mean rearfoot motion data revealed that both groups touched down 6° inverted, had 13° of total eversion range of motion, abducted the forefoot 4° at heel strike (toe-out), and contacted the ground approximately 13% of the distance from the heel (Table 6). Figures 1 to 3 are angle-angle diagrams that illustrate the timing of subtalar motion with ankle, tibial, and knee motion. No rearfoot motion variables were significant predictors of overuse running injuries.

Multivariable Analysis

Variables that were significant in the bivariate analyses were included in a multivariable logistic regression model. These included maximum vertical ground-reaction force, maximum propelling force, maximum knee stiffness, SF-12 mental component, PANAS negative score, and sex. In this multivariable analysis, maximum knee stiffness (N·m/deg) remained a statistically significant predictor of injury (P = .03): every 1-N·m/deg increase in knee stiffness (maximum knee stiffness = 6.89 N·m/deg) increased the odds of sustaining an overuse running injury by 18% (odds ratio = 1.18). The model explained 12.3% of the variance (Table 7).

TABLE 6
Rearfoot Motion Characteristics Used to Predict Injury[a]

	Injured (n = 199)	Uninjured (n = 101)	*P* Value[b]
Touchdown angle, deg	6.0 ± 3.7	6.4 ± 3.6	.40
Maximum eversion, deg	–7.4 ± 3.5	–7.4 ± 3.5	.94
Eversion range of motion, deg	13.4 ± 3.6	13.8 ± 3.7	.35
Maximum eversion velocity, deg/s	–182 ± 61	–186 ± 61	.59
Forefoot angle, deg (+, adduction)	–3.6 ± 7.1	–4.5 ± 6.7	.38
Strike index, % (distance from heel)	12 ± 18	14 ± 20	.44

[a]Values presented as mean ± SD.
[b]Unadjusted.

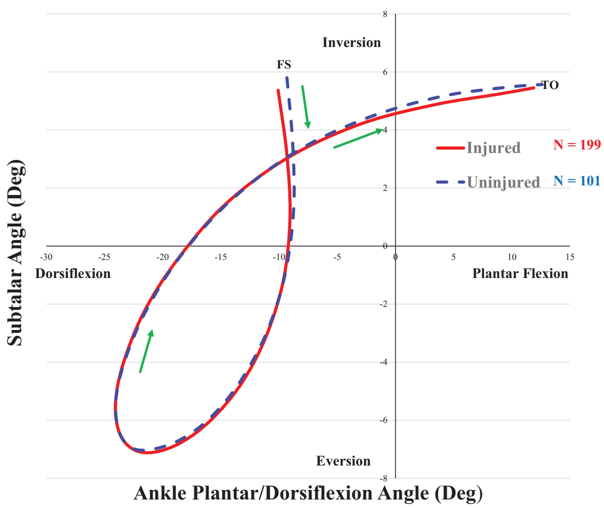

Figure 1. Timing of ankle and frontal plane subtalar movement. FS, foot strike; TO, toe-off.

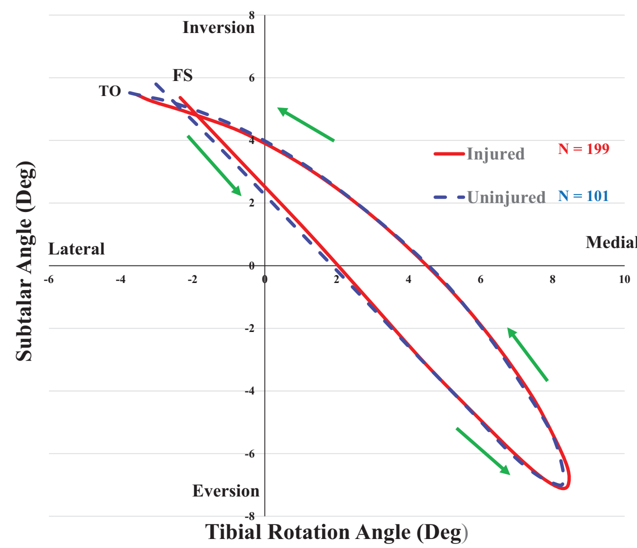

Figure 2. Timing of tibial rotation and frontal plane subtalar movement. FS, foot strike; TO, toe-off.

DISCUSSION

Bivariate Analyses

The distribution of observed injuries was similar to that of prior studies,[7,37,38] with the knee and foot being the most common injury sites. In contrast to earlier studies, previous injury was not a significant risk factor and not predictive of injury.[22,23]

Macera et al[22] found that men and women had similar rates of overuse running injuries, approximately 50% per year, whereas Taunton et al[37] noted that the frequency of some injuries was sex dependent. Our data indicate that sex was a significant predictor of injury incidence: female runners were injured more often than male runners (73% vs 62%, *P* = .046), and approximately half of each sex was injured more than once during the 2-year period. In contrast, a cohort study of 532 novice runners training for 13 weeks in preparation for a 4-mile race revealed that men were injured at 1.5 times the rate of women (hazard ratio = 1.5, *P* = .04) and had different etiologic factors.[4] It is possible that the lack of running experience in this study accounted for the difference with our data (novice vs a mean of 11 years). For example, there is considerable variability in stride length among novice runners for at least the initial 7 weeks of training.[1] The higher injury rate in female runners over male runners is important, but it is also meaningful to recognize that both sexes were injured at high rates.

Training Behavior. For >40 years, sports medicine clinicians and researchers have cited excessive weekly mileage as a significant risk factor for overuse running injuries.[2,3,40] Macera et al[22] found that running >40 miles per week during a 12-month observational period was the most important predictor of injury among 583 habitual runners. In contrast, our previous retrospective studies revealed little difference in mileage between injured and uninjured groups.[11,25-27] Similarly, there was no difference in weekly mileage or running experience between the groups in the current study, with both groups averaging 20 miles per week (range, 5-100) and having 11 years of running experience, thereby suggesting similar long-term cumulative loads on the lower extremity. We previously speculated that each runner has a threshold for weekly mileage, above which other abnormal stressors have

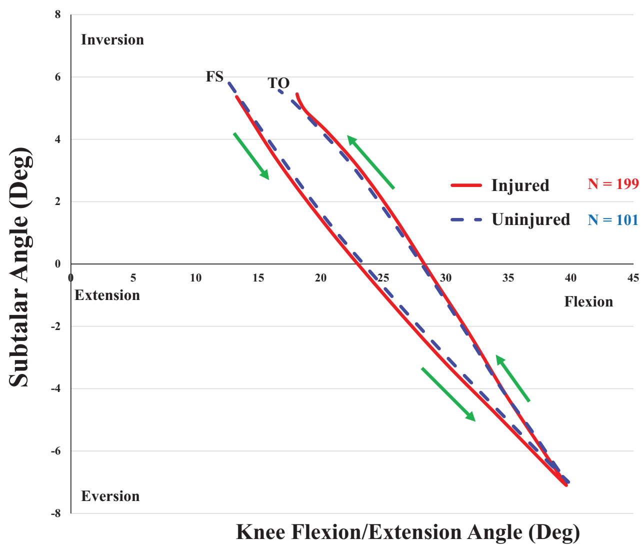

Figure 3. Timing of knee flexion/extension and frontal plane subtalar movement. FS, foot strike; TO, toe-off.

sufficient time to cause musculoskeletal injury.[26] Our results suggest that the uninjured group was below this weekly mileage threshold for injury or had fewer additional stressors or that, among a cohort of experienced recreational runners, weekly mileage is not an independent risk factor for overuse running injuries.

In a randomized controlled trial of female novice runners assigned to wear a neutral, stability, or motion control shoe during a 13-week run training program, Ryan et al[33] concluded that conventional assignment of footwear stability categories had no effect on pain. Runners with pronated feet who wore stability shoes had no less pain than a similar group assigned to wear neutral shoes. Nigg et al[32] recently noted that there is little difference in impact and motion control characteristics among running footwear and that comfort is paramount. Taken together, these studies support our data that injury incidence is not influenced by shoe type.

Anthropometrics. The role of BMI as a risk factor for overuse running injuries is uncertain. Buist et al[4] and Vitez et al[42] found that a higher BMI was a risk factor for male runners, suggesting that the added joint stress from the additional weight is a mechanism of injury. In contrast, other studies indicated that a low BMI was a risk for stress fracture in women and that a high BMI was protective of overuse running injuries for men.[37,38] No statistical differences existed in height, weight, BMI, or age between our groups. A mean BMI of 24 kg/m^2, a weekly mileage of 20 miles, a mean age of 41 years, and a training pace of 9 min/mile provide an accurate profile of the injured and uninjured recreational runners in this trial.

Q-angle, arch height, and knee and ankle flexibility were all similar between our injured and uninjured groups. These results are supported by our previous retrospective studies,[11,25,30] with 1 exception.[26] The mean arch index was within the normal range in both groups.[5] Our retrospective

TABLE 7
Parameter Estimates for Multivariable Analysis[a]

Parameter	Odds Ratio	95% CI	Pr > |t|
Dominant vs nondominant	1.064	0.623-1.820	.82
Maximum vertical GRF, N	0.998	0.996-1.001	.17
Maximum propelling force, N	0.998	0.987-1.009	.72
Maximum knee stiffness, N·m/deg	1.184	1.021-1.374	.03
SF-12, mental component	0.962	0.891-1.039	.32
PANAS, negative affect scale	1.048	0.952-1.115	.34
Training pace, min/mile	1.058	0.727-1.540	.77
Weight, kg	1.058	0.951-1.047	.92
Male vs female	1.147	0.482-2.726	.76

[a]This model explained 12.3% of the variance, suggesting that predictors of injury in addition to knee stiffness have yet to be identified. GRF, ground-reaction force; PANAS, Positive and Negative Affect Scale; SF-12, 12-Item Short Form Health Survey.

studies revealed mixed results: compared with uninjured groups, runners with knee pain or Achilles tendinitis had lower arch indices (ie, higher medial longitudinal arch), whereas runners with iliotibial band friction syndrome or plantar fasciitis had similar, normal arch heights.[11,25-27]

It appears intuitive that greater lower extremity flexibility would lower joint stress and diminish the risk of overuse running injuries[4]; however, little supportive scientific evidence exists. The frequency of stretching provides no information on quality and does not directly measure flexibility. Also contributing to the lack of relevant data is the lack of gold standard measures of flexibility. Greater plantar flexion range of motion is a risk factor for plantar fasciitis, although exactly why is unclear.[30,44] Some evidence exists that greater hamstring flexibility lowers the risk of injury.[21] Our previous retrospective studies showed that flexibility was not a risk factor for knee pain,[11,26] iliotibial band friction syndrome,[27] medial tibial stress syndrome,[30] or Achilles tendinitis.[25] Similarly, there were no differences in quadriceps, hamstring, or ankle dorsiflexor and plantar flexor flexibility between our injured and uninjured groups.

Strength. Lack of muscular strength is an oft-cited risk factor for running-related injuries,[11,26,27] attributed in part to the reduced ability of the surrounding muscles to absorb shock.[29] Surprisingly, we found no significant differences in strength between the injured and uninjured groups; the trend was for greater strength in the uninjured group. Proportionally more women were in the injured group, and they had significantly less lower extremity strength ($P <$ .001; data not shown) than the men. Controlling for sex, however, did not alter the statistical results; strength was not predictive of injury. Perhaps enhanced neuromuscular control that improves the runner's ability to utilize muscular strength effectively is more important than strength alone in preventing injury.

Psychosocial Variables. Although many factors have been related to running injuries, there is a dearth of information on potential psychosocial factors that may affect why some runners train for years without injury and others repeatedly incur injuries. In their review of prevention strategies for running injuries, Fields and colleagues[14] reported some evidence for the role that stress plays in injury; however, most of their data were limited to running injuries in the context of sport and competition. In our study of recreational runners, those who reported worse mental health–related quality of life and more negative affective states, such as being jittery, irritable, and nervous, were more likely to sustain overuse running injuries. It may be that runners with poorer mental health exceed their limits or take fewer precautions when experiencing more negative mood states. Negative emotions have been linked to a narrow range of thoughts and actions; runners feeling negative emotions may narrow their attentional focus and awareness of internal cues (eg, less kinesthetic awareness).[15] While these findings suggest that psychosocial factors are predictive of injury among runners, further research is needed to understand how this might relate to the physiologic mechanisms of injury.

Biomechanical Analysis. Running can be characterized as a series of collisions with the ground. Hreljac[20] and Hreljac et al[21] posit that the repeated application of high-impact forces without sufficient time between them can cause injury. While some evidence exists to support this general model of overuse injury,[21] our previous retrospective studies demonstrated that uninjured runners had higher ground-reaction forces than injured runners.[11,26,27] Similarly, maximum vertical ground reaction force and maximum propulsive force were significantly greater in our uninjured group. However, after adjusting for training pace and body weight, these force variables were statistically similar.

Excessive rearfoot motion has long been discussed as clinically meaningful[3]; however, few studies found it to discriminate statistically between injured and uninjured runners.[30,41] Our results support a similar 1-year observational prospective study that found no statistical difference in rearfoot motion between injured and uninjured groups.[31] Moreover, there were no differences in the timing of rearfoot motion with other lower extremity segments. These data suggest that subtalar motion does not predict overuse running injuries, thus supporting Nigg et al's[32] assertion that the most important qualities required in running footwear are fit and comfort.

Multivariable Analysis

Maximum knee stiffness—the ratio of the change in the internal knee extensor moment with the change in knee flexion during the first half of the support phase—was the lone significant predictor of injury in the multivariable analysis: knee stiffness was significantly higher in the injured group after controlling for training pace and body weight. Peak knee extension moment, created by quadriceps eccentric contraction while the knee flexes after foot strike, and peak change in joint angle occur at approximately the same time. Accordingly, Farley et al[12] suggested that the knee acts like a torsional spring, dissipating energy during foot strike; higher joint stiffness (greater eccentric contraction of the quadriceps, attenuated knee flexion, or both) would therefore suggest less

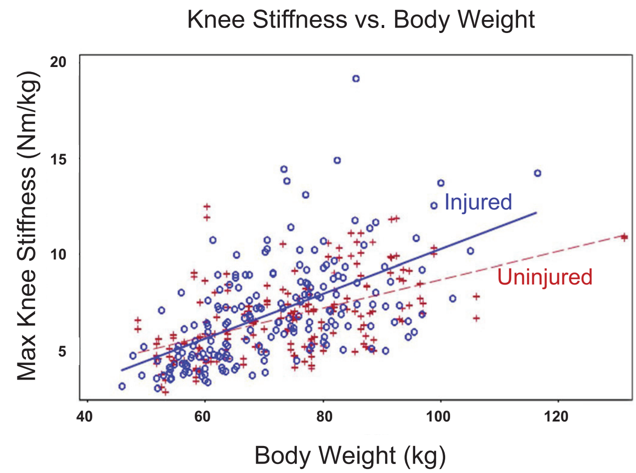

Figure 4. Relationship between knee stiffness and body weight relative to injury status.

energy dissipation, which may be detrimental to knee joint structures. We suggest that reductions in knee stiffness could be accomplished by either shortening step length or running on a stable but softer surface; each would likely lead to attenuated ground-reaction forces and a subsequent reduction in knee extensor moments.[13]

Despite the small (2%) difference in group means, knee stiffness was a significant predictor of injury. The relationship between body weight and knee stiffness provides insight that influenced this statistical outcome. Specifically, body weight and knee stiffness were more strongly correlated within the injured group (Figure 4). The biggest separation between the regression lines for each group occurred as body weights approached 80 kg; however, the distribution of body weights was skewed toward values between 40 kg and 80 kg, where there was little separation between the regression lines. Hence, knee stiffness was a significant predictor of injury owing largely to the greater stiffness values in the injured group at higher body weights, with the skewed distributions resulting in a small difference in group means. We suggest that greater knee stiffness, more common in runners with higher body weights ($\geq$80 kg), significantly increases the odds of sustaining an overuse running injury. Since knee stiffness involves aspects of force (knee extensor moment) and motion (knee flexion angle), it is not surprising that a measure that incorporates both would be a viable predictor of overuse running injuries. In addition to the suggestions noted here, reducing the body weight of runners at the higher end of the distribution may reduce stiffness and the chance of injury. Our evidence, however, is based on correlational data, which do not indicate causality.

With 12.3% of variance accounted for by this model and a significant odds ratio of only 1.18, it seems clear that predictors of injury other than knee stiffness have yet to be identified. For example, we speculate that runners who become injured have tissues that cannot withstand the relatively high, rapidly and frequently applied loads that overwhelm the tissues' resiliencies. Unfortunately, these tissue characteristics are not easily measured.

Note that some variables (eg, self-efficacy) that showed strong bivariate relationships with injury were not statistically significant in the multivariable model. It is possible that the complex interactions among variables—for example, self-efficacy related to general fitness, fitness to age, and age to less power—render certain strong bivariate relationships beyond detection after adjustment within the multivariable statistical model. The results from bivariate analyses, however, should be used to inform future investigations.

Limitations

Extreme values for rearfoot motion, Q-angle, arch height, flexibility, and weekly mileage are thought to be important risk factors for injury. Whether the subgroup of our runners with extreme values for these variables responds differently than that at the mean is an intriguing question. We attempted to determine if there are risk factors that are common across all lower extremity injuries. Future analyses will focus on those runners who sustained the most common running-related injuries. Finally, all prediction variables were measured at baseline; any variability between baseline and the time of injury was not assessed.

CONCLUSION

The results of this study indicate the following: (1) among recreational runners, women sustain injuries at a higher rate than men; (2) greater knee stiffness, more common in runners with higher body weights ($\geq$80 kg), significantly increases the odds of sustaining an overuse running injury; and (3) contrary to several long-held beliefs, flexibility, arch height, Q-angle, rearfoot motion, lower extremity strength, weekly mileage, footwear, and previous injury are not significant etiologic factors across all overuse running injuries.

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