Correlation Between Achilles Tendon Load Parameters and Risk of Knee Joint Injury in Male Amateur Marathon Runners During the Running Support Stage

Zou Rongxia, Jia Zhiqiang, Ma Rui

2026-08-10

ChinaRxiv

Abstract

Objective To investigate the correlation between Achilles tendon load parameters during the running stance phase and the risk of knee joint injury in male amateur marathon runners. Methods A total of 180 male amateur marathon runners were randomly recruited from May 2022 to January 2023 as study participants. A three-dimensional force platform, an infrared high-speed motion capture system, and an ultrasound imaging system were used to collect Achilles tendon load parameters during the running stance phase (maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain) and knee joint load parameters [peak knee adduction moment (KAM) and peak knee flexion moment (KFM)]. The correlations between Achilles tendon load parameters and knee joint injury, as well as the predictive value of Achilles tendon load parameters for knee joint injury, were analyzed. Results First, age, body mass index, running shoe type, foot strike pattern, and weekly running mileage of the 180 runners were used as covariates for overall propensity score matching, and 150 runners were ultimately selected as the study participants. Based on Achilles tendon load parameters during the running stance phase, the runners were divided into a low-load group (47 runners), a moderate-load group (61 runners), and a high-load group (42 runners). During the running stance phase, the maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, Achilles tendon strain, and KAM values were highest in the high-load group, followed by the moderate-load group and the low-load group, whereas KFM values were lowest in the high-load group, followed by the moderate-load group and the low-load group ($P<0.05$). During the running stance phase, maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain were positively correlated with KAM and negatively correlated with KFM ($P<0.05$). The incidence of knee joint injury was highest in the high-load group, followed by the moderate-load group and the low-load group ($P<0.05$). Runners with knee joint injury had higher maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain during the running stance phase than runners without knee joint injury ($P<0.05$). Maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain during the running stance phase were positively correlated with knee joint injury ($P<0.05$). The AUC values of maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain during the running stance phase for predicting the risk of knee joint injury in male amateur marathon runners were 0.754, 0.742, 0.770, and 0.764, respectively, indicating that all had certain predictive value for knee joint injury in male amateur marathon runners. Conclusion Achilles tendon load parameters during the running stance phase in male amateur marathon runners are associated with knee joint loading and can effectively predict the risk of knee joint injury, providing guidance for the daily training of male amateur marathon runners.

Full Text

Correlation Between Achilles Tendon Load Parameters and Risk of Knee Joint Injury in Male Amateur Marathon Runners During the Running Support Stage

Zou Rongxia[1], Jia Zhiqiang[2], Ma Rui[3]

(1. School of Physical Education, Nanjing Tech University, 211816 Nanjing; 2. School of Education, Beijing Sport University, 100084 Beijing;
3. School of Physical Education and Sport, Zhengzhou University, 450001 Zhengzhou)

Abstract: Objective To investigate the correlation between Achilles tendon load parameters and the risk of knee joint injury in male amateur marathon runners during the running support stage. **Methods** From May 2022 to January 2023, 180 male amateur marathon runners were randomly recruited as research participants. A three-dimensional force platform, an infrared high-speed motion-capture system, and an ultrasonic imaging instrument were used to collect Achilles tendon load parameters during the running support stage (maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain) and knee joint load parameters [peak knee adduction moment (knee adduction moment, KAM) and peak knee flexion moment (knee flexion moment, KFM)]. The correlations between Achilles tendon load parameters and knee joint injury, as well as the predictive value of Achilles tendon load parameters for knee joint injury, were analyzed. **Results** First, the 180 runners were subjected to overall propensity-score matching using age, body mass index, shoe type, landing pattern, and weekly running volume as covariates; 150 runners were ultimately selected as the research participants. According to Achilles tendon load parameters during the running support stage, the runners were divided into a low-load group (47 cases), a medium-load group (61 cases), and a high-load group (42 cases). During the running support stage, the maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, Achilles tendon strain, and KAM values were highest in the high-load group, followed by the medium-load group and then the low-load group, while the KFM value was lowest in the high-load group, followed by the medium-load group and then the low-load group ($P < 0.05$). During the running support stage, maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain were positively correlated with KAM and negatively correlated with KFM ($P < 0.05$). The incidence of knee joint injury was highest in the high-load group, followed by the medium-load group and then the low-load group ($P < 0.05$). In runners with knee joint injury, maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain during the running support stage were higher than those in runners without knee joint injury ($P < 0.05$). During the running support stage, maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain were positively correlated with knee joint injury ($P < 0.05$). The AUC values of maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain during the running support stage for predicting the risk of knee joint injury in male amateur marathon runners were 0.754, 0.742, 0.770, and 0.764, respectively, indicating that all had certain predictive value for knee joint injury in male amateur marathon runners. **Conclusion** In male amateur marathon runners, Achilles tendon load parameters during the running support stage are associated with knee joint loading conditions and can effectively predict the risk of knee joint injury, providing guidance for routine training of male amateur marathon runners.

Keywords: knee joint injury; male; amateur marathon runner; running support stage; Achilles tendon load parameters; predictive value

Chinese Library Classification No.: O39; G804.22 **Document Code:** A **DOI:** 10.11776/j.issn.1000-4939.2026.04.020

Article No.: 1000-4939(2026)04-0949-10 **CSTR:** 32414.14.cjam.issn.1000-4939.2026.04.020

Date received: 2025-11-10
Funding project: National Social Science Fund Project (No. 2023BTY002)
Corresponding author: Ma Rui, Associate Professor. E-mail: zzflccjj@163.com
Citation format: Zou Rongxia, Jia Zhiqiang, Ma Rui. Correlation between Achilles tendon load parameters and risk of knee joint injury in male amateur marathon runners during the running support stage[J]. *Chinese Journal of Applied Mechanics*, 2026, 43(4): 949-958.

Zou Rongxia, Jia Zhiqiang, Ma Rui. Correlation between Achilles tendon load parameters and risk of knee joint injury in male amateur marathon runners during running support stage[J]. *Chinese Journal of Applied Mechanics*, 2026, 43(4): 949-958.

Correlation between Achilles tendon load parameters and risk of knee joint injury in male amateur marathon runners during running support stage

Zou Rongxia[1], Jia Zhiqiang[2], Ma Rui[3]

(1. Sport College, Nanjing Tech University, 211816 Nanjing, China; 2. College of Education, Beijing Sport University, 100084 Beijing, China; 3. School of

Kinesiology and Physical Education, Zhengzhou University, 450001 Zhengzhou, China)

Abstract: Objective To explore the correlation between Achilles tendon load parameters and risk of knee joint injury in male amateur marathon runners during running support stage. **Methods** A total of 180 male amateur marathon runners were randomly recruited from May 2022 to January 2023 as the research objects. Three-dimensional force platform, infrared high-speed motion capture system and ultrasonic imager were used to measure the Achilles tendon load parameters (maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, Achilles tendon strain) and knee joint load parameters [knee adduction torque (KAM), knee flexion torque (KFM)] in the running support stage of athletes. The correlation between Achilles tendon load parameters and knee joint injury was analyzed, and the predictive value of Achilles tendon load parameters on knee joint injury was analyzed. **Results** Firstly, the age, body mass index, type of running shoes, landing mode and weekly running volume of 180 athletes were used as covariates to carry out the overall propensity score matching, and a total of 150 athletes were selected as the research objects. According to the Achilles tendon load parameters in the running support stage, the athletes were divided into low load group (47 cases), medium load group (61 cases) and high load group (42 cases). The maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, Achilles tendon strain and KAM in the running support stage of the high load group were higher than those in the medium load group and the low load group, the medium load group was higher than the low load group, the KFM was lower than the medium load group and the low load group, and the medium load group was lower than the low load group ($P < 0.05$). The maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress and Achilles tendon strain in the running support stage were positively correlated with KAM and negatively correlated with KFM ($P < 0.05$). The incidence of knee joint injury in the high load group was higher than that in the middle load group and the low load group, and that in the middle load group was higher than that in the low load group ($P < 0.05$). The maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress and Achilles tendon strain of athletes with knee joint injury during running support stage were higher than those of athletes without knee joint injury ($P < 0.05$). The maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress and Achilles tendon strain in the running support stage were positively correlated with knee joint injury ($P < 0.05$). The AUC of the maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress and Achilles tendon strain in the running support stage to predict the risk of knee joint injury of male amateur marathon runners was 0.754, 0.742, 0.770 and 0.764, respectively, which had certain predictive value for knee joint injury of male amateur marathon runners. **Conclusion** The Achilles tendon load parameters of male amateur marathon runners in the running support stage are related to the knee joint load, which can effectively predict the risk of knee joint injury and provide guidance for the daily training of male amateur

marathon runners.

Key words: knee joint injury; male; amateur marathon runner; running support stage; Achilles tendon load parameter; predictive value

Running, as one of the currently popular forms of mass fitness, has the effects of improving cardiopulmonary endurance, reducing body weight and shaping the body, and lowering the risk of cardiovascular disease

1 − 2

. Among its phases, the running support phase—i.e., the period from the foot's initial contact with the ground to complete toe-off—is the key period during which the lower limb bears and transmits load. In this phase, the Achilles tendon sustains enormous tensile force, and its load characteristics affect the mechanical environment of the entire lower-limb kinematic chain. Because amateur marathon runners lack professional running knowledge and systematic guidance, Achilles tendon disease or knee joint injury inevitably occurs during running, affecting athletes' normal training and daily life

3

. Under normal running conditions, the biomechanical transmission pathway between Achilles tendon load and knee joint injury involves a complex process of coordinated action of the lower-limb kinetic chain. During the running support phase, Achilles tendon load is transmitted through the ankle-leg-knee kinetic chain, while the knee joint is the site most susceptible to injury during running. Studies have shown that Achilles tendon rupture can lead to restricted ankle range of motion and increased joint stress; during the landing phase of an athlete's jump, the increased joint stress may be transferred to the medial patellar cartilage, resulting in knee joint injury

4

. Current research at home and abroad tends to conduct qualitative studies on lower-limb biomechanics and muscles and joints in athletes during the running support process

5 − 6

, whereas the present study performs quantitative analysis of Achilles tendon load parameters. Targeting male amateur marathon runners, it explores the correlation between Achilles tendon load parameters during the running support phase and the risk of knee joint injury, aiming to provide a reference for early assessment of Achilles tendon load parameters during the running support phase and prediction of knee joint injury risk in male amateur marathon runners, and on this basis to guide athletes' running training process, which is conducive to improving athletes' Achilles tendon mechanical characteristics and assisting their daily training.

1 Research Subjects and Methods

1.1 Research Subjects

From May 2022 to January 2023, male amateur marathon runners were randomly recruited as research subjects. According to the sample-size estimation formula:

$$n = \frac{Z_{1-\alpha/2}^2 P(1-P)}{\Delta^2},$$

where $Z_{1-\alpha/2}$ was taken as 1.96, Δ was taken as 0.05, and P, according to the pre-experiment, was taken as 0.10. The minimum sample size obtained was 139, and finally 180 male amateur marathon runners were included for analysis. Their age was 24-39 years, with a mean of (31.27 ± 3.52) years; body mass index was 19-23 kg/m^2, with a mean of (21.07 ± 0.94) kg/m^2. Running-shoe types: 97 cushioning type and 83 control type. Foot-strike pattern: 47 forefoot strikes and 133 rearfoot strikes. Weekly running distance was 25-50 km, with a mean of (37.26 ± 6.09) km. Definition of male amateur marathon runner: male non-professional athlete, regular running duration >6 months, weekly running frequency ( )2 times, weekly running distance ( )25 km, and experience of participating in and completing a full marathon within the past year. Inclusion criteria: confirmed by examination to have no injuries, and no acute lower-limb injury within the past 6 months (such as Achilles tendinitis, knee sprain, etc.); running training time ( )2 years; understood the details of this study and voluntarily signed an informed consent form. This study was reviewed by the ethics committee (No. ZZUIRB2025-07). Exclusion criteria: previous history of lower-limb surgery, history of knee joint injury, history of Achilles tendon injury, etc.

1.2 Methods

1.2.1 Data Collection

Uniformly trained experimental personnel collected the general information of the 180 recruited male amateur marathon runners, including age, body mass index, running-shoe type (cushioning type, control type), foot-strike pattern (forefoot strike, rearfoot strike), and weekly running distance. They also measured and recorded indicators such as athletes' Achilles tendon load parameters and knee joint load parameters.

1.2.2 Measurement of Achilles Tendon and Knee Joint Load Parameters During the Running Support Phase

After recruitment, a Swiss Kistler 9287CA three-dimensional force platform (1 kHz), a Swiss Qualisys Oqus700+8 camera infrared high-speed motion-capture system (200 Hz), and a Mindray M7 Super ultrasound imaging instrument from

China were used to measure the morphological parameters of the Achilles tendon during the athletes' running support phase, including maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain. During the measurement of maximum Achilles tendon force, Achilles tendon impulse, and knee joint load, athletes were required to wear tight-fitting clothing and pants. After a 15-min full warm-up, the experimental personnel affixed reflective markers to the lower limbs according to the Helen Hayes protocol (24 points in total, including the left and right anterior superior iliac spines, left and right posterior superior iliac spines, sacrum, greater trochanter, lateral femoral epicondyle, medial femoral epicondyle, lateral tibial malleolus, fibular head, lateral malleolus, medial malleolus, base of the fifth metatarsal, head of the first metatarsal, calcaneus, etc.). During the running test, athletes were required to rest sufficiently between each run, with rest time ( )3 min. The parameter settings for the running test in this study were mainly based on the following two considerations: Referring to domestic and international survey studies on training characteristics of amateur marathon runners

, the commonly used pace range for aerobic endurance running is mostly concentrated between 4 min 30 s and 5 min 30 s per kilometer. The pace used in this study was in the middle-to-upper part of this range and is one of the typical speeds for amateur runners during steady-state training; it can effectively reflect the Achilles tendon load conditions in athletes' daily training. A cadence of 180 steps/min is an efficient cadence pattern widely recommended in running biomechanics research and training practice and is considered to help optimize running economy and reduce injury risk. To control variables and accurately compare Achilles tendon biomechanical response parameters among different athletes under controlled conditions, this study used this speed and cadence as standardized test conditions. During the running test, the starting position was 15 m in a straight line from the force platform; athletes ran at a speed of 12 km/h, with speed fluctuation controlled (($\pm$)0.6 km/h), cadence of 180 steps/min, and cadence fluctuation controlled (($\pm$)2 steps/min), requiring …

remaining in normal gait and without any step adjustments; a trial was considered valid when the right foot landed completely within the central area of the force platform. The ground-contact time was fed back in real time from the force-platform data and was required to remain at 200–250 ms. Each group repeated the test three times. The three-dimensional coordinates of the markers were smoothed using a Butterworth low-pass filtering method[^8], with a cut-off frequency of 13.3 Hz, and on this basis pelvic, thigh, shank, and foot coordinate systems were established.

1.2.3 Calculation of Achilles Tendon and Knee-Joint Load Parameters During the Running Stance Phase

The Euler angle and inverse dynamics method[^9] were used to calculate the sagittal-plane knee-joint angle and net joint moment, and on this basis the peak knee adduction moment (KAM) and peak knee flexion moment (KFM) were calculated; the mean value of the three valid trials was used. The maximum Achilles tendon force was calculated using inverse dynamics combined with the muscle force–moment equilibrium equation[^10] (external moment = internal moment). Among these, Achilles tendon impulse was obtained by calculating the time integral of Achilles tendon force using the trapezoidal method.

During Achilles tendon stress and strain testing, the athlete lay prone on the treatment table, ensuring that the included angle between the foot and shank was 90°. Surface electromyography was used to detect the activation level of the gastrocnemius muscle, so as to control the degree of muscle activation between the resting state and maximal isometric contraction in dorsiflexion. Ultrasound imaging was used to determine the Achilles tendon origin and insertion points (the junction between the gastrocnemius–soleus tendon complex and the calcaneus), and the full length was measured. Subsequently, based on each individual' s full Achilles tendon length, the ultrasound probe was placed perpendicular to the long axis of the Achilles tendon at a position 30% of the full Achilles tendon length from the calcaneal insertion point, so as to obtain transverse-sectional images of the Achilles tendon (three consecutive cardiac-cycle images were saved and averaged). This standardized positioning method ensured that measurements among different individuals were made in anatomically similar regions of Achilles tendon function, improving the comparability and reliability of the data. Achilles tendon stress = Achilles tendon force / Achilles tendon cross-sectional area; Achilles tendon strain = change in Achilles tendon length / resting Achilles tendon length. The change in Achilles tendon length was the change in length from the resting state to the time of maximal isometric contraction in dorsiflexion from the muscle to the Achilles tendon attachment point; the resting Achilles tendon length was the distance between the Achilles tendon insertion point and the gastrocnemius–soleus–Achilles tendon junction[^11-12].

1.2.4 Quality Control for Measurement of Achilles Tendon and Knee-Joint Load Parameters During the Running Stance Phase

All indicators requiring measurement were tested twice and evaluated by the intra-class correlation coefficient (ICC). The ICC value was required to be greater than 0.9. For indicators requiring calculation, the mean of the two measured values was used before calculation.

1.2.5 Assessment of Knee-Joint Injury

Follow-up was conducted every 3 months by combining athletes' training-log records with telephone interviews. Failure to respond or data loss greater than

50% in two consecutive follow-ups was regarded as loss to follow-up. After 1 year of follow-up, the occurrence in the athlete of any one of the following—muscle strain around the knee joint, knee sprain or fracture, anterior cruciate ligament injury, meniscal injury, or patellofemoral pain syndrome—was defined as knee-joint injury; otherwise, it was defined as no knee-joint injury.

1.3 Observational Indicators

Propensity-score matching and K-means cluster analysis were used to group the included athletes, and Achilles tendon load parameters (maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, Achilles tendon strain) and knee-joint load parameters (KAM, KFM) during the running stance phase were compared among the groups; the correlations between Achilles tendon load parameters and knee-joint load parameters during the running stance phase were analyzed; the occurrence of knee-joint injury among athletes in each group was compared; Achilles tendon load parameters during the running stance phase were compared between patients with knee-joint injury and those without knee-joint injury; the correlations between Achilles tendon load parameters during the running stance phase and knee-joint injury in patients were analyzed; the predictive value of Achilles tendon load parameters during the running stance phase for knee-joint injury in patients was analyzed.

1.4 Statistical Analysis

SPSS 22.0 software was used for statistical analysis in this study. Count data were described as $n(\%)$, and intergroup comparisons were performed using the χ^2 test. For measurement data, the Kolmogorov-Smirnov test for normality and Levene test for homogeneity of variance were first performed. All measurement data in this study conformed to a normal distribution and homogeneity of variance. Comparisons of measurement data between two groups were performed using the independent-samples t test; overall comparisons among multiple groups were performed using one-way analysis of variance; pairwise comparisons between groups were corrected using Bonferroni multiple correction, and after correction, $P < 0.017$ was considered statistically significant; detailed pairwise comparisons between groups were performed using the LSD-t test. Propensity-score matching was used to include baseline data with balanced covariates for the study subjects. At the same time, the K-means clustering algorithm was used to perform subgroup classification of the study population. Linear associations between variables were analyzed using Pearson correlation analysis. The correlation between continuous observational indicators and the dichotomous outcome of knee-joint injury was analyzed using point-biserial correlation analysis. The receiver operator characteristic curve (ROC) and area under the curve (AUC) were used to evaluate the predictive efficacy of each indicator for knee-joint injury. Except for Bonferroni multiple-comparison correction, all other statistical tests considered $P < 0.05$ to indicate a statistically significant difference.

2 Results

2.1 Achilles Tendon and Knee-Joint Load Parameters During the Running Stance Phase in Different Groups

2.1.1 Grouping Status and General Data Analysis First, propensity-score matching was used in this study to control baseline confounding bias. Age, body mass index, running-shoe type, landing pattern, and weekly running volume were used as covariates to calculate propensity scores. The nearest-neighbor method was then used for 1:1 matching without replacement, and the caliper value was set to 0.02. After matching, the standardized mean differences (SMDs) of all covariates were all <0.1,

This indicates that the baseline characteristics among groups were well balanced. After initial matching of 180 athletes, 150 athletes were successfully paired and retained for subsequent analysis. After standardizing the Achilles tendon load parameters during the running support phase—maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain—K-means cluster analysis ($k = 3$) was used to classify Achilles tendon load into a low-load group (47 participants), a medium-load group (61 participants), and a high-load group (42 participants). There were no statistically significant differences among the three groups in age, body mass index, running-shoe type, foot-strike pattern, or weekly running distance ($P > 0.05$), as shown in Table 1.

Table 1 Comparison of general information among the three groups

Tab. 1 Comparison of general information among the three groups

Group	Cases	Age/years	Body mass index/(kg·m^{-2})	Running-shoe type/n (%) – Cushioned	Running-shoe type/n (%) – Stability	Foot-strike pattern/n (%) – Forefoot strike	Foot-strike pattern/n (%) – Rearfoot strike	Weekly running distance/km
Low-load group	47	30.87±3.44	21.23±0.90	25(53.19)	22(46.81)	10(21.28)	37(78.72)	37.51±5.83
Medium-load group	61	31.16±3.50	21.20±0.92	33(54.10)	28(45.90)	15(24.59)	46(80.33)	37.28±6.11
High-load group	42	31.05±3.39	21.18±0.95	22(53.38)	20(47.62)	10(23.81)	32(76.19)	37.43±5.62
F		0.094	0.033	0.030	0.030	0.170	0.170	0.021

Group	Cases	Age/years	Body mass index/(kg·m^{-2})	Running-shoe type/n (%) – Cushioned	Running-shoe type/n (%) – Stability	Foot-strike pattern/n (%) – Forefoot strike	Foot-strike pattern/n (%) – Rearfoot strike	Weekly running distance/km
P		0.910	0.967	0.985	0.985	0.918	0.918	0.979

2.1.2 Achilles tendon and knee joint load parameters in the three running support-phase groups

One-way analysis of variance showed that, among the three groups, the maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, Achilles tendon strain, KAM, and KFM during the running support phase differed significantly ($P < 0.017$).

Pairwise comparisons: comparison of maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, Achilles tendon strain, and KAM during the running support phase showed that the high-load group was higher than the medium-load group and higher than the low-load group; the KFM value showed that the high-load group was lower than the medium-load group and lower than the low-load group ($P < 0.017$), as shown in Table 2.

Table 2 Comparison of Achilles tendon load parameters and knee joint load parameters in the three groups during the running support phase

Tab. 2 Comparison of Achilles tendon load parameters and knee joint load parameters in the three groups of running support stages

Group	Cases	Maximum Achilles tendon force/BW	Achilles tendon impulse/(BW·s^{-1})	Achilles tendon stress/MPa	Achilles tendon strain/%	KAM/(Nm·kg^{-1})	KFM/(Nm·kg^{-1})
Low-load group	47	5.95 ± 0.61	0.63 ± 0.05	38.15 ± 6.31	20.26 ± 3.72	0.15 ± 0.03	0.26 ± 0.04
Medium-load group	61	6.38 ± 0.64^{a}	0.66 ± 0.07^{a}	42.77 ± 7.05^{a}	22.81 ± 4.06^{a}	0.18 ± 0.04^{a}	0.24 ± 0.03^{a}
High-load group	42	6.87 ± 0.73^{ab}	0.74 ± 0.09^{ab}	48.23 ± 8.39^{ab}	25.79 ± 4.18^{ab}	0.22 ± 0.04^{ab}	0.21 ± 0.02^{ab}

Scatter plots showing correlations between Achilles tendon load parameters and KAM: maximum Achilles tendon force ($r = 0.738$), Achilles tendon impulse ($r = 0.775$), Achilles tendon stress ($r = 0.795$), and Achilles tendon strain ($r = 0.768$).

Figure 1: Scatter plots showing correlations between Achilles tendon load parameters and KAM: maximum Achilles tendon force ($r = 0.738$), Achilles tendon impulse ($r = 0.775$), Achilles tendon stress ($r = 0.795$), and Achilles tendon strain ($r = 0.768$).

Group	Cases	Maximum Achilles tendon force/BW	Achilles tendon impulse/(BW·s^{-1})	Achilles tendon stress/MPa	Achilles tendon strain/%	KAM/(Nm·kg^{-1})	KFM/(Nm·kg^{-1})
F		21.716	28.340	21.519	21.291	39.471	28.541
P		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Note: compared with the low-load group, $^aP < 0.05$; compared with the medium-load group, $^bP < 0.05$.

2.2 Correlation between Achilles tendon load parameters and knee joint load parameters during the running support phase

Pearson correlation analysis of Achilles tendon load parameters with KAM and KFM is shown in Figures 1-2. The figures show that maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain during the running support phase were positively correlated with KAM and negatively correlated with KFM ($P < 0.05$).

Figure 1 Correlation between Achilles tendon load parameters and KAM

Fig. 1 Correlation between Achilles tendon load parameters and KAM

Fig. 2 Correlation between Achilles tendon load parameters and KFM

2.3 Occurrence of Knee Joint Injuries in the Three Groups

During the 1-year follow-up, 2 athletes in the low-load group were lost to follow-up, 3 athletes in the moderate-load group were lost to follow-up, and 1 athlete in the high-load group was lost to follow-up, giving an overall loss-to-follow-up rate of 4% (6/150). Comparison of the baseline characteristics between those lost to follow-up and those not lost to follow-up showed no statistically significant differences in all key covariates ($P > 0.05$), indicating that loss to follow-up was a random event. Therefore, loss to follow-up did not significantly affect the representativeness of the final sample or the internal validity of the study results. The incidence of knee joint injury was higher in the high-load group than in the moderate- and low-load groups, and higher in the moderate-load group than in the low-load group ($\chi^2 = 13.337, P = 0.001$), as shown in Table 3.

Table 3 Comparison of Knee Joint Injury in the Three Groups

n (%)

Group	Cases	Knee periarticular muscle strain	Knee sprain or fracture	Anterior cruciate ligament injury	Meniscal injury	Iliotibial band syndrome	Overall incidence
Low-load group	45	1 (2.22)	0 (0.00)	1 (2.22)	1 (2.22)	0 (0.00)	3 (6.67)
Moderate-load group	58	5 (8.62)	2 (3.45)	2 (3.45)	2 (3.45)	1 (1.72)	12 (20.69)^{a}
High-load group	41	5 (12.20)	3 (7.32)	2 (4.88)	4 (9.76)	2 (4.88)	16 (39.02)^{ab}

Note: Compared with the low-load group, $^{a}P < 0.05$; compared with the moderate-load group, $^{b}P < 0.05$.

2.4 Achilles Tendon Load Parameters During the Running Support Phase in Athletes With and Without Knee Joint Injury

The maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain during the running support phase were higher in athletes with knee joint injury than in those without knee joint injury ($P < 0.05$), as shown in Table 4.

2.5 Correlation Between Achilles Tendon Load Parameters During the Running Support Phase and Knee Joint Injury

Point-biserial correlation analysis showed that the maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain during the running support phase were positively correlated with knee joint injury ($P < 0.05$), as shown in Table 5.

Table 4 Comparison of Achilles Tendon Load Parameters Between Athletes With and Without Knee Joint Injuries During the Running Support Phase

Group	Cases	Maximum Achilles tendon force/BW	Achilles tendon impulse/(BW·s^{-1})	Achilles tendon stress/MPa	Achilles tendon strain/%
Knee joint injury	31	6.90 ± 0.72	0.73 ± 0.08	48.32±8.34	25.86±4.05
No knee joint injury	113	6.25 ± 0.64	0.66 ± 0.07	41.03±7.16	22.03±3.59
t		4.874	4.780	4.843	5.117
P		<0.001	<0.001	<0.001	<0.001

Table 5 Correlation Between Achilles Tendon Load Parameters During the Running Support Phase and Knee Joint Injury

Indicator	Knee joint injury r_{pb}	Knee joint injury P	Indicator	Knee joint injury r_{pb}	Knee joint injury P
Maximum Achilles tendon force	0.711	<0.001	Achilles tendon stress	0.718	<0.001
Achilles tendon impulse	0.724	<0.001	Achilles tendon strain	0.722	<0.001

2.6 Predictive Value of Achilles Tendon Load Parameters During the Running Support Phase for Knee Joint Injury

Athletes with knee joint injury were used as the positive data set, and athletes without knee joint injury were used as the negative data set. ROC curve analysis showed that, for predicting the risk of knee joint injury in male amateur marathon runners, the AUC values of maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain during the running support phase were 0.754 (95% CI: 0.675–0.822), 0.742 (95% CI: 0.662–0.811), 0.770 (95% CI: 0.692–0.836), and 0.764 (95% CI: 0.686–0.831), respectively. Maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain during the running support phase were entered into a binary Logistic regression model, and the regression predicted probability

Fig. 3 ROC curves showing the predictive value of Achilles tendon load parameters during the running support phase for knee joint injuries. The axes are sensitivity/% and 100-specificity/%. The legend includes maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, Achilles tendon strain, and combined prediction.

Figure 2: Fig. 3 ROC curves showing the predictive value of Achilles tendon load parameters during the running support phase for knee joint injuries. The axes are sensitivity/% and 100-specificity/%. The legend includes maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, Achilles tendon strain, and combined prediction.

Logit(P) was used as the independent test variable. The AUC of the combined prediction was 0.898 (95% CI: 0.837-0.942), and the predictive value was significantly improved ($Z = 2.379, 2.296, 2.053, 2.076$; $P = 0.017, 0.021, 0.040, 0.038$), as shown in Fig. 3. This suggests that maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain during the running support phase all have the ability to predict knee joint injury, and that the combined predictive ability is stronger.

Fig. 3 The predictive value of Achilles tendon load parameters during the running support phase for knee joint injuries

3 Discussion

The Achilles tendon is the largest tendon in the human body and has the largest elastic structure at the foot-shoe interface. It can transmit force from the triceps surae to the foot and release energy during walking and running[^13-14]. At the same time, the Achilles tendon is sensitive to the mechanical environment; larger loads can have adverse effects on the Achilles tendon. Especially for marathon runners, long-term repeated traction of the Achilles tendon and excessive movement within the shoe affect the stability of Achilles tendon tension. Over time, the incidence of cumulative muscle-tendon lesions increases. This is particularly true for amateur athletes: when systematic guided training has not been received, the risk of tendon lesions may further increase[^15-16].

This study used propensity-score matching combined with K-means cluster analysis to group athletes. This can improve comparability between groups while reducing confounding bias between groups, and cluster analysis was used to explore intergroup heterogeneity, thereby improving the rigor of the study. The results showed that, in male amateur marathon runners, maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain during the running support phase were significantly correlated with KAM and KFM, suggesting that Achilles tendon load parameters during the running support phase in male amateur marathon runners are related to knee joint load. Among them, as maximum Achilles tendon force increases, excessive Achilles tendon load forces the lower leg to internally rotate or changes the manner of foot contact with the ground, thereby increasing medial knee-joint load[^17]. Achilles tendon impulse reflects the cumulative effect of force during movement. Especially in marathon competitions, athletes need to perform long-distance endurance exercise; the greater the cumulative work borne by the Achilles tendon, the more likely it is to cause collagen-fiber fatigue in people with high Achilles tendon load, and it is highly possible to increase the risk of Achilles tendon rupture[^18-19]. KAM is a key indicator for evaluating load on the coronal plane of the knee joint. An abnormally increased value is closely related to the occurrence and development of knee joint injury. After the Achilles tendon produces a large tensile force, in order to maintain body balance and generate forward acceleration, the human body needs to generate ground reaction force, and the increase in this force directly leads to an increase in the KAM value, possibly raising the risk of knee joint injury. KFM is an indicator of supporting body mass and generating propulsive force in the sagittal plane. A higher KFM indicates that the quadriceps femoris needs to contract to resist knee flexion and thereby stabilize the knee joint. When Achilles tendon load increases significantly and the ankle plantar-flexion moment is enhanced, the ankle joint becomes the main joint generating propulsive force. In this situation, the lower-limb kinematic chain is more inclined to propel the movement process through strong ankle plantar flexion, causing Achilles tendon load to be negatively correlated with the KFM value. Most amateur marathon runners have not received professional training and are often accompanied by repetitive injuries. High Achilles tendon load may lead to degenerative lesions, affect the local Achilles tendon cross-sectional area, increase the force borne per unit cross-sectional area of the Achilles tendon, and increase the Achilles tendon stress value[^20]. Achilles tendon strain is a parameter of the rate of change in an athlete' s Achilles tendon length. In people under long-term high load, Achilles tendon stiffness increases, markedly reducing cushioning capacity and possibly increasing the risk of Achilles tendon rupture[^21]. Although the knee joint and Achilles tendon are not directly connected physiologically, under the combined action of the Achilles tendon–triceps surae–femur–knee joint chain and mechanical transmission, they jointly bear lower-limb load; when Achilles tendon load parameters increase, knee joint load increases accordingly[^22-23].

The results of this study show that, while Achilles tendon load parameters change, the risk of knee joint injury increases, and Achilles tendon load parameters are positively correlated with knee joint injury, similar to the findings of Ertman et al.[^24]. The reason is that knee joint injury is often related to insufficient muscle endurance and strength in athletes. When athletes have decreased muscle strength or fatigue, the incidence of knee joint injury increases significantly[^25-26]. The increase in Achilles tendon load parameters may cause Achilles tendon injury or increase the risk of Achilles tendon fatigue.

risk, and the plantarflexion moment decreases. During running, higher Achilles tendon load parameters may affect the propagation of vibration waves and increase high-frequency oscillatory loading of the knee joint[^27^-^28^]. In addition, an increase in Achilles tendon load means an increase in the ankle plantarflexion moment. To generate sufficient plantarflexion moment to push off from the ground, the triceps surae must complete the movement through strong contraction; at this time, an knee-extension moment is generated at the knee joint to participate in the movement.

On this basis, the present study further used Achilles tendon load parameters to predict knee joint injury. The results showed that the maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain during the running support phase all had certain predictive efficacy for the risk of knee joint injury in male amateur marathon runners. Previous related studies[^29^] have constructed models with relatively high predictive ability; however, their sample sizes were small, their target participants were subjects with athletic ability and good health, and mechanical impact simulators were used for the research. By contrast, the present study is based on real-world conditions and analyzes male amateur marathon runners, which has greater guiding value for subsequent training of athletes. Therefore, by detecting parameters such as the maximum Achilles tendon force, Achilles tendon impulse, Achilles tendon stress, and Achilles tendon strain during the running support phase in male amateur marathon runners, knee joint injury risk can be predicted, and athlete training can be guided accordingly, improving Achilles tendon adaptability, reducing Achilles tendon load as much as possible, and lowering the risk of knee joint injury.

4 Conclusion

This study found that, during the running support phase, Achilles tendon load parameters were significantly correlated with knee joint indicators. An increase in Achilles tendon load may increase knee joint stress by altering the efficiency of force transmission in the lower-limb kinetic chain, thereby leading to an elevated risk of knee joint injury. The findings of this study may, to a certain extent, reveal the potential biomechanical role of Achilles tendon function in the risk of knee joint injury, suggesting that Achilles tendon load parameters can serve as potential biomechanical markers for evaluating the risk of knee joint injury in male amateur marathon runners. Based on the above findings, it is suggested that during training, male amateur marathon runners should focus training on the eccentric strength of the triceps surae and the concentric strength of the toe flexor muscle group. Strengthening eccentric strength helps more effectively buffer impact force during the foot-contact phase and thereby reduce the instantaneous loading rate of the Achilles tendon; strengthening concentric strength helps improve pre-activation before landing and swing efficiency after takeoff, optimizing the force-bearing pattern of the Achilles tendon. During training, heel-raise eccentric training and seated heel raises may be considered: stand at the edge of a step, hold the wall with both hands to maintain balance, push off with both forefeet, raise the body evenly to the highest point, then shift the body' s center of mass to one foot while the other foot is suspended, and lower the supporting foot in a controlled, slow manner until the heel is below the plane of the step, allowing the posterior calf muscles to be fully stretched; on this basis, seated heel-raise exercises may be added to specifically strengthen the soleus muscle, which is related to regulation of Achilles tendon load in the middle phase of running support. During training, the initial load intensity should mainly use body weight; after adaptation, an external load of 5–10 kg may be gradually added with the aid of a backpack. The training volume should be set at 8–12 repetitions per set, completing 3–4 sets, with 90 s of rest between sets. Training frequency should be 2–3 times per week, and it should be scheduled on the day after high-intensity or long-distance running training to avoid movement deformation due to fatigue and to ensure training quality and safety. Athletes should use this program as a basic strength-training component and persist with it over the long term, following the principle of progressive overload: that is, when athletes can easily complete the current load, they should prioritize increasing the load rather than simply increasing the number of repetitions, so as to continuously provide effective training stimuli.

This study preliminarily verified that Achilles tendon load parameters during the running support phase are correlated with knee joint injury in male amateur marathon runners, but it did not analyze different running postures, different external conditions, or other types of athletes. In future research, different ground-contact patterns or different running-shoe types may be considered, or overall athletes may be studied, to enhance the generalizability of the research and further improve and verify the predictive value of the present findings for knee joint injury in male amateur marathon runners.

At the same time, this study used fixed running speed and cadence during testing. Although this setting ensured comparability of data among subjects, it may differ from the individualized speed and cadence patterns exhibited by amateur marathon runners in daily training. Therefore, the Achilles tendon load parameters obtained in this study are only observations under specific standardized conditions, which may affect the generalizability of the results. Future studies may incorporate individualized combinations of speed and cadence to better capture individualized biomechanical characteristics of amateur runners under real exercise conditions. In addition, in order to precisely evaluate the independent role of Achilles tendon load parameters, this study used PSM to control confounding factors such as age, BMI, and weekly running volume. This method can effectively balance baseline characteristics between groups and ensure comparability between groups. However, after application of this method, it is not possible to directly evaluate the independent predictive efficacy of factors such as age in the matched data, resulting in the inability of this study to analyze the absolute incremental value of the study indicators through increases in AUC values. Nevertheless, this design also reflects the core finding of this study: after effective control of confounding factors, Achilles tendon load parameters still show a stable and significant association with knee joint injury risk, and their predictive efficacy is confirmed against a more balanced background. This in itself implies their unique potential as a novel biomechanical marker.

In the future, comprehensive models including both traditional risk factors and novel biomechanical parameters may also be constructed in larger-scale unmatched cohorts to directly calculate and verify the precise incremental contribution of Achilles tendon load, which will provide more direct evidence for translating the findings of this study into clinical practice tools. The conclusions of this study are based on standardized testing scenarios; application to daily training still needs to be adjusted in combination with individual movement parameters. This study only included

male amateur marathon runners. This choice helps to control sex-related biomechanical variation at the initial stage of the study, but it also means that the conclusions cannot be extrapolated to female athlete populations. Considering that sex may also be an important factor affecting Achilles tendon load response and injury mechanisms, future studies should specifically conduct parallel investigations in female amateur athlete populations, or carry out comparative studies including sufficient sample sizes of both men and women, so as to construct, as far as possible, a more complete and more generalizable biomechanical model of the Achilles tendon in amateur runners.

References:

[1] Edwards J J, Deenmamode A H P, Griffiths M, et al. Exercise training and resting blood pressure: a large-scale pairwise and network meta-analysis of randomised controlled trials[J]. British Journal of Sports Medicine, 2023, 57(20): 1317-1326.

[2] Braschler L, Nikolaidis P T, Thuany M, et al. Physiology and pathophysiology of marathon running: a narrative review[J]. Sports Medicine-Open, 2025, 11(1): 10.

[3] O' riordan C, Savage E, Newell M, et al. Cardiovascular disease risk factor profile of experienced male amateur marathon runners: a systematic review[J]. Sports Health: A Multidisciplinary Approach, 2023, 15(5): 661-672.

[4] Mu Yingxiu, Xing Xing, Tang Qiao. Research on the influence of running gait on sports injuries of lower limb in middle-and long-distance teenage runners[J]. Chinese Journal of Sports Medicine, 2024, 43(1): 17-28.
Mu Yingxiu, Xing Xing, Tang Qiao. Research on the influence of running gait on sports injuries of lower limb in middle-and long-distance teenage runners[J]. Chinese Journal of Sports Medicine, 2024, 43(1): 17-28 (in Chinese).

[5] Bai Xiaotian, Zhu Yaojia, Huo Hongfeng. Effects of exercise-induced fatigue on synergy of foot and ankle muscles during running[J]. Chinese Journal of Sports Medicine, 2023, 42(3): 191-200.
Bai Xiaotian, Zhu Yaojia, Huo Hongfeng. Effects of exercise-induced fatigue on synergy of foot and ankle muscles during running[J]. Chinese Journal of Sports Medicine, 2023, 42(3): 191-200 (in Chinese).

[6] Lopes A D, Mascarinas A, Hespanhol L. Are alterations in running

biomechanics associated with running injuries? A systematic review with meta-analysis[J]. Brazilian Journal of Physical Therapy, 2023, 27(4): 100538.

[7] Li D X, Liu Y L, Feng Y Y, et al. Interlimb asymmetries of lower limb isometric strength for predicting plantar fasciitis in male amateur marathon runners: a prospective cohort study[J]. BMC Sports Science, Medicine and Rehabilitation, 2025, 17(1): 255.

[8] Augustus S, Amca A M, Hudson P E, et al. Choice of low-pass filter influences practical interpretation of ball kicking motions: the effect of a time-frequency filter method[J]. Sports Biomechanics, 2023, 22(11): 1412-1429.

[9] Gong T X, Zhao A X, Zhou J Q, et al. A facile inverse dynamics method to study the impacts of fatigue on the lower limb biomechanics[J]. Biotechnology and Genetic Engineering Reviews, 2023, 39(2): 676-687.

[10] Voukelatos D, Evangelidis P E, Pain M T G. The hamstrings to quadriceps functional ratio expressed over the full angle-angular velocity range using a limited number of data points[J]. Royal Society Open Science, 2022, 9(4): 210696.

[11] Zhang Xini, Wang Junqing, Yang Yang, et al. Effects of simulated barefoot running on Achilles tendon mechanical properties[J]. China Sport Science, 2019, 39(4): 63-70.
Zhang Xini, Wang Junqing, Yang Yang, et al. Effects of simulated barefoot running on Achilles tendon mechanical properties[J]. China Sport Science, 2019, 39(4): 63-70 (in Chinese).

[12] Joseph M F, Lillie K R, Bergeron D J, et al. Measuring Achilles tendon mechanical properties: a reliable, noninvasive method[J]. Journal of Strength and Conditioning Research, 2012, 26(8): 2017-2020.

[13] Xergia S A, Tsarbou C, Nikolaos I L, et al. Risk factors for Achilles tendon rupture: an updated systematic review[J]. The Physician and Sportsmedicine, 2023, 51(6): 506-516.

[14] King C M, Vartivarian M. Achilles tendon rupture repair: simple to complex[J]. Clinics in Podiatric Medicine and Surgery, 2023, 40(1): 75-96.

[15] Waugh C M, Mousavizadeh R, Lee J, et al. Mild hypercholesterolemia impacts Achilles sub-tendon mechanical properties in young rats[J]. BMC Musculoskeletal Disorders, 2023, 24(1): 282.

[16] Jakubowski K L, Ludvig D, Perreault E J, et al. Non-linear properties of the Achilles tendon determine ankle impedance over a broad range of activations in humans[J]. Journal of Experimental Biology, 2023, 226(14): jeb244863.

[17] Kuşcu B, Bilal Ö, Doğar F, et al. Effects of L-carnitine on healing of Achilles tendon in rats[J]. Joint Diseases and Related Surgery, 2023, 34(1): 84-91.

[18] Faria A, Gabriel R, Brás R, et al. Free-oscillation technique: the effect of the magnitude of the impulse applied on muscle and tendon stiffness around the

ankle[J]. PLoS One, 2023, 18(6): e0286847.

[19] Chen Shiqin, Yang Yang, Zhang Qin, et al. Relationship of running economy with lower-limb kinematics and spatiotemporal gait characteristics in recreational runners[J]. Chinese Journal of Applied Mechanics, 2025, 42(2): 473-482. Chen Shiqin, Yang Yang, Zhang Qin, et al. Relationship of running economy with lower-limb kinematics and spatiotemporal gait characteristics in recreational runners[J]. Chinese Journal of Applied Mechanics, 2025, 42(2): 473-482 (in Chinese).

[20] Yurteri A, Mercan N, Çelik M, et al. The effect of caffeic acid on tendon healing in rats with an Achilles tendon injury model[J]. Joint Diseases and Related Surgery, 2023, 34(3): 669-678.

[21] Adam N C, Smith C R, Herzog W, et al. In vivo strain patterns in the Achilles tendon during dynamic activities: a comprehensive survey of the literature[J]. Sports Medicine-Open, 2023, 9(1): 60.

[22] Cooper K, Alexander L, Brandie D, et al. Exercise therapy for tendinopathy: a mixed-methods evidence synthesis exploring feasibility, acceptability and effectiveness[J]. Health Technology Assessment, 2023, 27(24): 1-389.

[23] Shi Xiaohui, Liang Man, Zhao Min. Effects of step-frequency differences on lower-limb impact force and micro-⋯

运动学特征的影响研究 [J]. 应用力学学报, 2024, 41(6): 1436–1446.

Shi Xiaohui, Liang Xiao, Zhao Min. Influence of step frequency difference on the impact force and kinematic characteristics of lower limbs of college students during running[J]. Chinese Journal of Applied Mechanics, 2024, 41(6): 1436–1446 (in Chinese).

[24] Ertman B, Klaeser M, Voie L, et al. Alterations in Achilles tendon stress and strain across a range of running velocities[J]. Journal of Sports Sciences, 2023, 41(5): 495–501.

[25] Patra R C, Gupta S, Yashudas A, et al. Effects of isoinertial training on muscle power, endurance, isometric strength, and balance: randomized clinical trial in patients with post-ACL reconstruction[J]. Trials, 2025, 26(1): 257.

[26] Murray I R, Makaram N S, Geeslin A G, et al. Multiligament knee injury (MLKI): an expert consensus statement on nomenclature, diagnosis, treatment and rehabilitation[J]. British Journal of Sports Medicine, 2024, 58(23): 1385–1400.

[27] Gould H P, Lostetter S J, Samuelson E R, et al. Lower extremity injury rates on artificial turf versus natural grass playing surfaces: a systematic review[J]. The American Journal of Sports Medicine, 2023, 51(6): 1615–1621.

[28] Hullfish T J, Woods M M, Kwon M P, et al. The difference in achilles tendon loading within immobilizing boots based on ankle angle, boot type,

and walking speed[J]. Orthopaedic Journal of Sports Medicine, 2024, 12(10): 23259671241283806.

[29] Schilaty N D, Bates N A, Kruisselbrink S, et al. Linear discriminant analysis successfully predicts knee injury outcome from biomechanical variables[J]. The American Journal of Sports Medicine, 2020, 48(10): 2447–2455.

(Editor: Li Kunlin)

Submission website: https://cjam.xjtu.edu.cn WeChat public account: *Chinese Journal of Applied Mechanics*

This version posted 2026-08-10.

Note: Figure translations are in progress. See original paper for figures.