

Original Article

Musculoskeletal Health, Quality, and Injury Profiles in Collegiate Track and Field and Cross-Country Athletes

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Abstract

Objectives: Collegiate Track and Field and Cross-Country (TF-XC) athletes require high training volumes, potentially contributing to their elevated injury rates. But concurrent examination of musculoskeletal injury (MSKI), health, anatomical structure, and performance is rare. This study's purpose was to compare training habits, MSKI history, bone health, body composition, muscle morphology, and neuromuscular characteristics between collegiate TF-XC athletes and controls. **Methods:** Thirty TF-XC athletes (n=21 females; n=9 males) and 30 physically active, sex-, age-, and body mass-matched controls completed training and MSKI history questionnaires, Dual-energy X-ray Absorptiometry scans, ultrasonography of the lower body musculature, and knee extensor isometric force testing with surface electromyography. Independent *t*-tests, analyses of covariance, and Cohen's *d* effect sizes compared group differences, and $\alpha=0.050$. **Results:** Athletes presented a 3-fold higher MSKI incidence than controls ($p<0.001$; $d=0.96$), despite greater total body bone mineral density (BMD) Z-Scores ($p=0.008$; $d=0.81$) and regional BMD (all $p\leq 0.005$; $d\geq 0.78$), and lower muscle echogenicity (better muscle quality) (all $p\leq 0.002$; $d\geq 0.87$). However, athletes' muscle size and force production were similar to controls (both $p\geq 0.200$; $d\leq 0.62$). **Conclusions:** Though TF-XC demonstrated better bone health and muscle quality than non-athletes, their muscle size and force similarities may suggest potential sport-specific mechanical loading inadequacies, coinciding with high MSKI rates.

Keywords: Athletic Injuries, Bone Mineral Density, Diagnostic Ultrasound, Dual-energy X-ray Absorptiometry, Neuromuscular Performance

Introduction

Traditionally, participation in collegiate athletics has been shown to elicit positive influences on bone¹, muscle², and nerve³, leading to improvements in sport performance and increased athlete longevity⁴. However, chronic repetitive loading, as is required of many Track and Field and Cross-Country (TF-XC) athletes, can result in increased risk of overuse injuries to these tissues^{5,6}. For instance, TF-XC athletes demonstrate some of the highest rates of overuse musculoskeletal injury (MSKI) across collegiate sports^{7,8}. These rates can be influenced by high training specificity and insufficient recovery⁶, in addition to underlying

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physiological characteristics, such as low regional bone mineral density (BMD) and total body BMD Z-Scores⁹, reduced muscle size¹⁰, or diminished force production and muscle excitation^{11,12}. Due to these multi-factorial TF-XC risk factors, holistic evaluation of athletes' physical training characteristics, regional bone mineral indices, and muscle morphology, force, and gross electrical traits may illuminate crucial factors impacting injury etiology, health, and performance while also potentially identifying interventional targets for injury risk reduction.

TF-XC athletes present with elevated overuse injury rates, brought on by sport-specific requirements and physiological underpinnings. For example, Yang et al.⁹ indicated that from 2005-2008, male and female TF-XC athletes incurred 17.6 and 8.3 musculoskeletal overuse injury rates per 10,000 athlete exposures, respectively. These injuries may be the result of repetitive micro-trauma, coalescing to form micro-cracks in bone¹³, fiber tearing in muscle¹⁴, and overall, structurally compromised tissue less resistant to repetitive deformation. Aside from epidemiological investigation, the underlying musculoskeletal characteristics of injured TF-XC athletes have demonstrated conflicting findings. Though Popp et al.¹⁰ indicated that female cross-country athletes with a history of bone stress fracture presented similar regional BMD but reduced muscle size compared to their uninjured counterparts, Roelofs and colleagues¹⁵ found that BMD, and muscle size and quality were similar between injured and uninjured TF-XC cohorts. While musculoskeletal injuries undoubtedly impact musculoskeletal health, divergent structural results warrant investigation of tissue function to fully identify pertinent factors impacting TF-XC athletes' health and performance.

Participation in collegiate sport and physical training often promotes musculoskeletal and neuromuscular development^{3,16}; however, the chronic repetitive mechanical nature of TF-XC may blunt these benefits. While Duncan et al.¹⁷ reported runners having greater BMD compared to swimmers, cyclists, and triathletes, Fredricson and colleagues¹⁸ found that distance runners' BMD was similar to sedentary controls and lower than soccer players. These findings suggest that although running loading patterns may be favorable compared to predominantly unloaded sports, the cyclical mechanical nature may attenuate bone accrual compared to multi-directional sports. Additionally, Degens et al.¹¹ identified that endurance athletes produced less knee extensor torque and lower-body power than non-athletes and team sport athletes, and Kubo et al.¹² observed that distance runners had lower quadriceps strength and similar neuromuscular properties to untrained individuals, proposing that the chronic repetitive stimuli of TF-XC may dampen neuromuscular development. While previous investigations identifying TF-XC musculoskeletal traits are undeniably beneficial, their isolated scope may be neglecting pertinent factors within the whole musculoskeletal and neuromuscular systems that concurrently impact health and performance. Thus, simultaneous evaluation of injury history, training behaviors, skeletal health, muscle size

and quality, and neuromuscular characteristics may fully encompass vital aspects influencing TF-XC athletes' health, performance, and injury risk.

Therefore, the primary purpose of this investigation was to evaluate the physical training habits, MSKI history, total and lower-body bone health and mineral indices, and body composition, site-specific muscle morphology, and neuromuscular characteristics in NCAA Division I TF-XC athletes compared to physically active, non-athlete, matched controls. Our two central hypotheses were that: 1) TF-XC athletes would present higher weekly training volumes coinciding with greater lower body MSKI rates, and 2) Athletes would demonstrate better bone health and body composition measures, muscle size and quality, and force and electromyographic characteristics due to the nature of collegiate TF-XC training.

Materials and Methods

Subjects

Athlete inclusion criteria consisted of 18 to 26-year-olds who were active members of the Oklahoma State University NCAA Division I TF-XC team. Controls' inclusion criteria consisted of being physically active ≥ 3 days/week (engaging in recreational aerobic, resistance, and/or plyometric training), not a current member of an NCAA sanctioned athletic team, and matching an enrolled athlete for sex, age (± 2 years; but not younger than 18 years old), and body mass (± 2.5 kg). All subjects were excluded if they were currently undergoing radiation treatment or if they were a female who was pregnant. An *a priori* power analysis using effect sizes derived from total body BMD¹⁹, and vastus lateralis subcutaneous fat-corrected muscle echogenicity and knee extensor isometric peak force production²⁰ measures, with an alpha level of $\alpha=0.050$ indicated a sample size range between 14 and 26 subjects per group for 80% power. A total of 30 TF-XC athletes ($n=21$ female; $n=9$ male) and 30 controls participated in this study. All testing was completed during the NCAA Division I Fall TF-XC pre-season in late summer.

Questionnaires and Anthropometrics

All subjects completed questionnaires regarding sport competition history, current physical training habits, and MSKI history. The competition history questionnaire identified event designation and years competing for athletes, and type and duration of sport participation in high school for controls. Subjects then reported weekly averages of frequency and intensity of aerobic, resistance, and plyometric training, in addition to weekly running mileage, within the physical training questionnaire. For the injury questionnaire, subjects disclosed previous lower-body injuries to bone, muscle, tendon, and ligamentous tissues throughout their competitive high school and collegiate careers for athletes, and since high school for controls. Following completion of questionnaires, subjects'

height and body mass were collected via stadiometer and scale (Health o meter Professional, McCook, IL, USA).

Dual-energy X-Ray Absorptiometry

Following the collection of anthropometrics, subjects underwent a series of Dual-energy X-Ray Absorptiometry (DXA) scans, assessing total body and lower body regional bone mineral indices, body composition, and hip structural analyses (HSA) as previously described²¹. In summary, before scanning, subjects provided a urine sample to ensure normal hydration status (1.004-1.028 USG)²² and negative pregnancy status for females. A Hologic Horizon A model DXA (Apex Software V 5.6.1.2 rev 009, Hologic Inc., Marlborough, MA, USA) was used to complete total body and proximal femora scans. Outcome variables of bone mineral density (BMD; g/cm³), BMD Z-Scores, bone mineral content (BMC; g), bone-free lean body mass (BFLBM; g), fat mass (g), and BFLBM-to-BMC ratios (BFLBM:BMC) were evaluated. Proximal femora scans were further analyzed using HSA to measure cross-sectional area (CSA; cm²), cross-sectional moment of inertia (CSMI; cm⁴), subperiosteal width (SPW; cm), endocortical width (ECW; cm), section modulus (SM; cm³), and buckling ratio (BR) of the narrow neck, intertrochanteric, and femoral shaft regions. Additionally, custom region of interests (ROIs) were created, encompassing the shank from the crest of the tibial plateau to below the foot, segmenting the upper leg and shank bilaterally, as previously described by Redinger et al.²¹ as shown in Figure 1. Outcome variables of BMD, BMC, BFLBM, fat mass, and BFLBM:BMC were provided for each ROI. These measures were then subtracted from the total leg value to obtain upper leg region measures. The Interclass Correlation Coefficients (ICCs) for ROI creation were ≥ 0.998 . All DXA positioning and analyses were conducted by the same certified technicians, using the same DXA machine. All laboratory (machine + technician) coefficients of variation for bone, BFLBM, and fat indices are $< 1.0\%$ ²¹. DXA data extraction was completed using the automated DXA² software to eliminate transcription errors²³.

Diagnostic Musculoskeletal Ultrasonography

After DXA scans, subjects underwent diagnostic B-mode musculoskeletal ultrasonography of the bilateral upper leg and shank musculature, evaluating muscle size, echogenicity, and architecture as previously described^{24,25}. To summarize these methods, transverse panoramic and longitudinal still images of the bilateral medial and lateral gastrocnemius and tibialis anterior muscles, and longitudinal stills of the vastus lateralis muscles were acquired using a GE LOGIQ S8 (General Electric, Boston, MA) ultrasound imaging device with a multi-frequency linear-array transducer (ML6-15L; 4-15MHz; 50.0mm field of view) in conjunction with GE LOGIQ S8 software (Gastrocnemius and Tibialis Anterior: Gain: 50, Frequency: 12.0, Depth: 4.0; Vastus Lateralis: Gain: 50, Frequency: 12.0, Depth: 6.0). Subjects

first laid supine for ten minutes to reduce lower extremity fluid pooling, during which probe positioning marks were made. Medial and lateral gastrocnemius and tibialis anterior positioning marks were made at the proximal 33% distance from the medial and lateral tibial epicondyles and malleoli, respectively. Vastus lateralis marks were made at the 50% distance from the anterior superior iliac spine to the superior border of the patella. Water-soluble transmission gel was applied to the skin to reduce near-field artifacts and enhance acoustic coupling, minimal pressure was applied during scanning to reduce image compression, and gain, frequency, and depth were kept consistent for all subjects. Panoramic sweeps from the medial to lateral muscle border of each respective gastrocnemius and tibialis anterior muscles assessed anatomical cross-sectional area (aCSA; cm²) and raw echogenicity (indicative of contractile tissue concentration and muscle quality; AU). Still images taken at the thickest point of the muscle belly assessed subcutaneous fat and muscle thickness (cm) and fascicular pennation angle (°) across all muscles.

All ultrasound imaging analyses were performed using ImageJ software (Version 1.53t, National Institutes of Health, Bethesda, MD, USA), as shown in Figure 1. Each image was scaled from pixels to cm using cm marks inlaid within the ultrasound image. aCSA and raw echogenicity were measured using the polygon function, which encompassed the entire muscle and excluded fascia. Muscle thickness was quantified as the vertical distance between deep and superficial aponeuroses. Subcutaneous fat thickness was quantified as the vertical distance between the superficial muscle and deep dermal aponeuroses. Fascicular pennation angle was determined by tracing an individual fascicular bundle to its deep aponeurosis and then along the deep aponeurosis to the fascicular midpoint. This measurement was taken at individual 1/3rd horizontal distances of each muscle and then averaged, quantifying total muscle fascicular pennation angle. Subcutaneous fat-corrected echogenicity was also calculated using the conversion equation from Young et al.²⁶. Mean combined gastrocnemius aCSA were calculated by summing each gastrocnemius muscle's aCSA and averaging the value between each leg. Mean muscle and subcutaneous fat thickness, fascicular pennation angle, and echogenicity were calculated by averaging the measures of each respective gastrocnemius muscle and then by each limb, respectively. All image acquisition and analyses were completed by the same trained technicians using the same ultrasound device, with ICCs ranging from 0.946 to 0.999 for all outcome variables across all muscles, respectively, as presented in Supplemental Content Table 1.

Isometric Dynamometry and Electromyography

Subjects concluded testing with bilateral knee extension maximal voluntary isometric contractions, coinciding with surface bipolar electromyography (EMG), evaluating muscle force and gross electrical activity characteristics.

Table 1. Group comparison of anthropometrics, questionnaires, and DXA measures.

	TF-XC (n=30)	Controls (n=30)	Ind. <i>t</i> -test (p)	Cohen's <i>d</i>
Anthropometrics (corrected $\alpha=0.0125$)				
Age (years)	20.4±1.7	20.5±1.5	0.874	0.04
Weight (kg)	60.1±7.8	60.6±7.8	0.834	0.05
Height (m)	1.7±0.7	1.7±0.8	0.222	0.03
BMI (kg/m ²)	20.6±1.8	21.4±2.3	0.132	0.39
Questionnaire Responses (corrected $\alpha=0.006$)				
Running (Miles/Wk)	49.8±35.5	1.3±2.1	<0.001 ^a	1.93
AT Sessions/Wk	8.0±2.6	3.3±2.2	<0.001 ^a	1.98
AT Intensity (0-10)	5.2±1.8	5.3±2.1	0.789	0.08
RT Frequency (Days/Wk)	2.5±1.3	3.4±1.5	0.006 ^a	0.63
RT Intensity (0-10)	5.7±1.1	6.8±0.9	0.029	0.65
PT Frequency (Days/Wk)	1.7±0.4	1.8±0.4	0.356	0.24
# Lower Body MSKIs	3.3±2.9	1.1±1.5	<0.001 ^a	0.96
# Shank MSKIs	1.9±2.2	0.8±1.4	0.024	0.60
Total Body DXA Measures (corrected $\alpha=0.010$)				
BMD (g/cm ²)	1.142±0.079	1.083±0.079	0.005 ^a	0.75
BMD Z-Score	0.2±1.0	-0.6±0.8	0.008 ^a	0.81
BMC (kg)	2.3±0.3	2.1±0.3	0.052	0.51
BFLBM (kg)	47.5±7.4	43.7±6.8	0.041	0.54
Fat Mass (kg)	10.8±2.7	15.2±3.9	<0.001 ^a	1.30

Data are shown as means ± standard deviations, and ^a indicates significant group differences after Bonferroni correction. Mann-Whitney U tests were used for running mileage and RT frequency. DXA bone mineral indices data are adjusted for total body BFLBM. Abbreviations – BMI: Body Mass Index; AT: Aerobic Training; RT: Resistance Training; PT: Plyometric Training; MSKI: Musculoskeletal Injury; BMD: Bone Mineral Density; BMC: Bone Mineral Content; BFLBM: Bone-Free Lean Body Mass.

Contractions were conducted using an isokinetic dynamometer (KinCom 125AP, IsoKinetic International, East Ridge, TN, USA) with concurrent EMG recordings being taken through surface bipolar electrodes (Trigno Wireless Biofeedback System, Delsys Inc., Natick, MA, USA) placed on the vastus lateralis quadriceps muscle at the 50% measurement site used for ultrasound imaging. Subjects were positioned in the dynamometer according to the manufacturer's guidelines for knee joint extension. In summary, all subjects were seated upright with a hip and knee flexion angle of 90° in the dynamometer with the lever arm fulcrum placed in line with the femoral condyle, and secured with Velcro straps across the working shank, waist, and shoulders. The dynamometer load cell was positioned and secured 2cm proximal to the lateral malleolus for all subjects. Before EMG sensor placement, the surface of the skin was prepared by shaving the sensor area, removing superficial dead skin with adhesive tape, and sterilizing with a 70% isopropyl alcohol wipe. Subjects were then instructed to conduct four consecutive isometric contractions at self-perceived 25%, 50%, 75%, and 100% maximal effort with five seconds of rest between contractions, serving as protocol familiarization and warm-up, and allowing for signal quality determination. Following

this, subjects were instructed to complete three consecutive five-second maximal effort contractions, with strong verbal encouragement, with 90 seconds of rest between bouts. All testing was completed on the right leg first, followed by the identical protocol being conducted on the left leg.

Signal Acquisition and Processing

All signal acquisition was acquired through the use of a National Instruments four-channel simultaneous input voltage module housed within a compact chassis (NI-9215, cDAQ-9171, Austin, TX, USA). Force and EMG signals were synchronously sampled at 1,926 Hz per the Trigno unit's proprietary sampling rate. Offline processing occurred via custom LabVIEW programming (LabVIEW v19.0, National Instruments, Austin, TX, USA). Force signal epochs (N) were smoothed with a 12.5-ms moving average, and EMG signal amplitudes (μ V) were digitally filtered using a band-pass filter (4th order Butterworth) at 10-500Hz. Rate of force development (RFD; N/s⁻¹) was collected for the first 0-250ms of force onset through automatic detection (rise of amplitude greater than 1SD from baseline). EMG Root Mean Squared amplitude time domains (EMG_{RMS}; μ V) were calculated with the root mean square function corresponding

Table 2. Group comparison of mean lower body regional Dual-energy X-Ray Absorptiometry (DXA) bone mineral indices and body composition measures.

Measure	TF-XC (n=30)	Controls (n=30)	Ind. t-test (p)	Cohen's <i>d</i>
Total Leg (corrected $\alpha=0.010$)				
BMD (g/cm ²)	1.247±0.102	1.127±0.109	<0.001 ^a	1.14
BMC (g)	446.7±65.8	396.1±68.9	0.141	0.75
BFLBM (kg)	8.2±1.4	7.4±1.2	0.018	0.63
Fat Mass (kg)	2.4±0.8	3.4±1.1	<0.001 ^a	1.20
BFLBM:BMC Ratio	18.3±1.4	18.7±2.0	0.383	0.23
Upper Leg Region (corrected $\alpha=0.010$)				
BMD (g/cm ²)	1.416±0.117	1.304±0.110	0.006 ^a	0.98
BMC (g)	207.4±28.9	183.1±33.9	0.106	0.77
BFLBM (kg)	5.5±0.9	5.2±0.9	0.103	0.43
Fat Mass (kg)	1.6±0.5	2.4±0.7	<0.001 ^a	1.21
BFLBM:BMC Ratio	26.9±2.2	28.7±4.3	0.053	0.52
Shank ROI Region (corrected $\alpha=0.010$)				
BMD (g/cm ²)	1.132±0.108	1.012±0.111	0.001 ^a	1.09
BMC (g)	239.2±39.1	213.0±36.8	0.271	0.69
BFLBM (kg)	2.6±0.5	2.1±0.4	<0.001 ^a	0.96
Fat Mass (kg)	0.8±0.2	1.1±0.3	<0.001 ^a	1.11
BFLBM:BMC Ratio	10.9±1.1	10.3±1.4	0.063	0.49
Total Hip (corrected $\alpha=0.025$)				
BMD (g/cm ²)	1.097±0.119	0.982±0.106	0.004 ^a	1.02
BMC (g)	39.1±7.3	33.3±6.9	0.061	0.82
Femoral Neck (corrected $\alpha=0.025$)				
BMD (g/cm ²)	0.997±0.116	0.903±0.125	0.065	0.78
BMC (g)	5.1±0.8	4.4±0.9	0.059	0.82
Greater Trochanter (corrected $\alpha=0.025$)				
BMD (g/cm ²)	0.809±0.095	0.728±0.082	0.006 ^a	0.91
BMC (g)	8.9±1.6	7.8±1.7	0.194	0.68

Data are shown as means ± standard deviations, and ^a indicates significant group differences after Bonferroni correction. DXA bone mineral indices are adjusted for mean leg BFLBM. Abbreviations: BMD: Bone Mineral Density; BMC: Bone Mineral Content; BFLBM: Bone-Free Lean Body Mass; BFLBM:BMC: Bone-Free Lean Body Mass-to-Bone Mineral Content ratio.

with force epochs at peak force and the 0-250ms RFD increment. Additionally, all RFD and EMG_{RMS} epochs were normalized to the 25-ms epoch corresponding with peak force and EMG_{RMS} amplitude at peak force, respectively.

Statistical Analysis

All statistical procedures were performed using IBM SPSS (v26, Armonk, New York), and significance was set at $p \leq 0.050$. All data are reported as means ± standard deviations in tables and means ± standard errors in figures. Independent t-tests with domain-specific Bonferroni corrections were used to assess all measures between athletes and controls. Additional analyses of covariance (ANCOVAs) were conducted for musculoskeletal and neuromuscular analyses. Total body BFLBM was used as a

covariate for total body BMD and BMC, and mean total leg BFLBM served as a covariate for all mean total leg, regional leg, and regional hip BMD and BMC measures, in addition to all HSA indices. Shank ROI BFLBM was a covariate for all mean shank ultrasonography measures, and mean vastus lateralis subcutaneous fat thickness was used as a covariate for all electromyography analyses. ANCOVA assumptions for outcome measure and covariate normality, linear relationships, homogeneity of regression slopes, and homogeneity of variance were tested and met for all respective musculoskeletal and neuromuscular analyses. Mann-Whitney U non-parametric analyses were conducted for questionnaire responses that were not normally distributed. Lastly, Cohen's effect sizes (*d*) were calculated and interpreted as small ($d=0.2$), moderate ($d=0.5$), or large ($d=0.8$)²⁷.

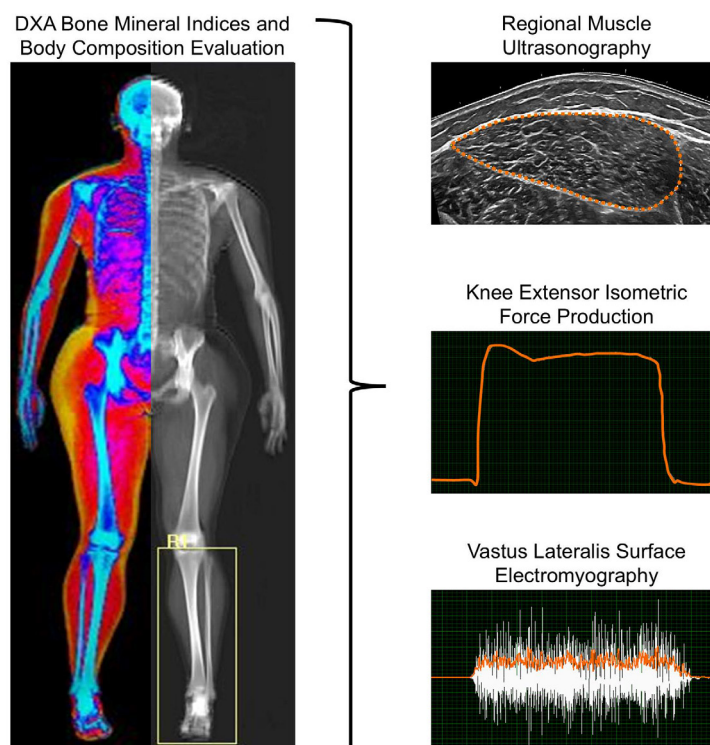


Figure 1. Methodological diagram of musculoskeletal and neuromuscular evaluation. Dual-energy X-Ray Absorptiometry (DXA) total body scan with shank custom region of interest, allowing for assessment of whole and regional lower body bone mineral indices and body composition (LEFT). Panoramic ultrasonography sweeps with ImageJ analyses evaluating muscle size, architecture, and echogenicity (RIGHT-TOP). Isometric dynamometry coinciding with surface bipolar electromyography with LabVIEW analyses, assessing knee extensor force characteristics (RIGHT-MIDDLE) and vastus lateralis gross electrical activity (RIGHT-BOTTOM). Created in <https://BioRender.com>

Results

Anthropometrics, Questionnaire Responses, and DXA

A total of 30 athletes (females $n=21$, males $n=9$) and 30 matched controls were included in the analyses. Athletes reported 9.0 ± 2.9 years of competitive experience with 2.3 ± 1.6 years at the collegiate level specifically, and 77% of all athletes identified participation in ≥ 3 events. 80% of athletes presented with a history of ≥ 2 lower body musculoskeletal injuries throughout their high school and collegiate competitive career, and 56% reported ≥ 2 shank musculoskeletal injuries. When delineating between hard and soft tissue injuries, 73% of injured athletes reported ≥ 1 bone-specific overuse injury, 60% indicated ≥ 1 soft-tissue (muscle, tendon, or ligament) overuse injury, and 50% incurred injuries to multiple tissues. 80% of controls reported participating in ≥ 1 high school sport, with an average competition age of 3.3 ± 1.1 years during that time frame. Regarding control's habitual aerobic training characteristics, 50% primarily trained in weight-supported exercises (swimming and cycling), 27% engaged in low-to-

moderate impact activities (brisk walking and light jogging), and 23% indicated no active participation in aerobic training. 93% of controls reported progressive compound resistance training utilizing free weights (barbell and dumbbell) and/or weight-loaded machines, and 7% trained with compound bodyweight movements. Additionally, 83% of controls indicated engaging in aerobic and resistance training concurrently.

In Table 1, subject demographics, questionnaire responses, and total body DXA measures are shown. Athletes and controls were similar for age, height, body mass, and BMI (all $p \geq 0.132$; d : 0.04-0.39). While athletes presented higher weekly running mileage and greater average weekly aerobic training sessions, controls resistance trained at a higher frequency and intensity, as presented in Table 1. However, only resistance training frequency was statistically different after Bonferroni correction. Prior to correction, total body and mean total leg BFLBM were higher in athletes compared to controls (both $p \leq 0.041$; d : 0.54-0.96); though after correction, these differences no longer met the new alpha. Nonetheless, total

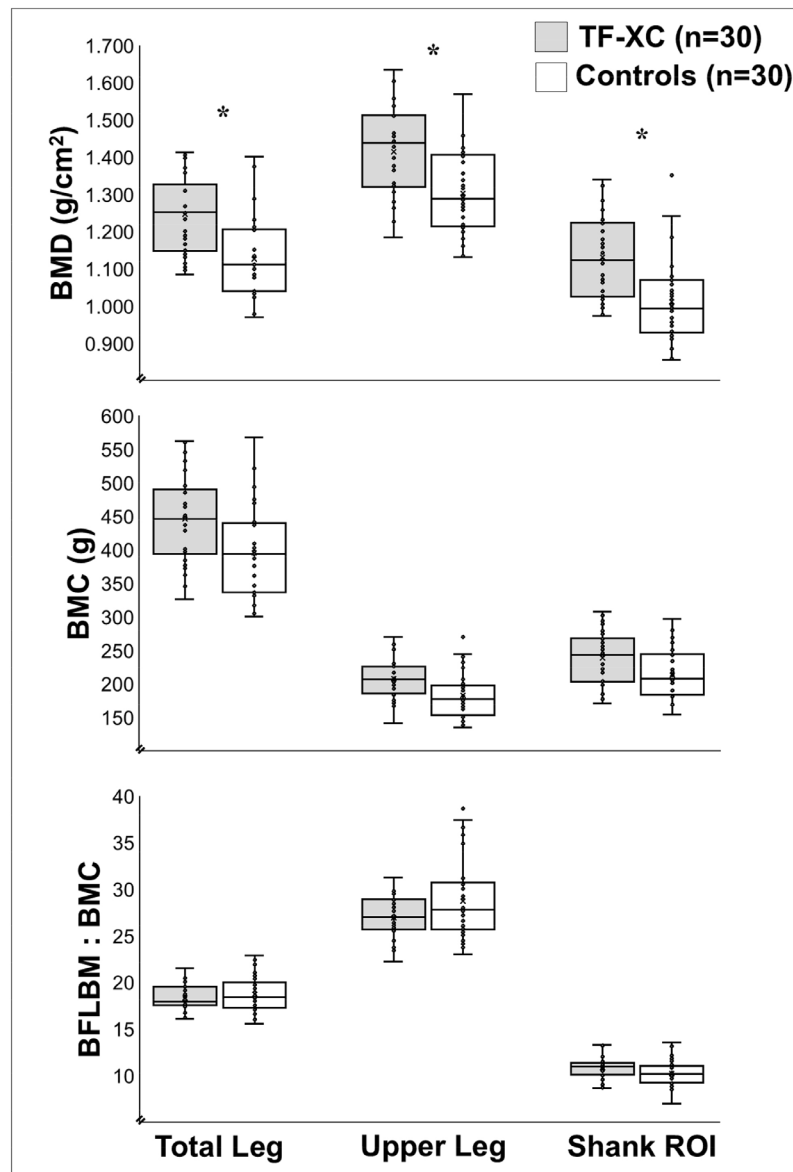


Figure 2. Comparison of Track and Field and Cross-Country (TF-XC) athletes and controls' mean total, upper leg, and shank bone mineral density (BMD), bone mineral content (BMC), and bone-free lean body mass to bone mineral content (BFLBM:BMC) ratios. Athletes demonstrated significantly greater BMD at all anatomical sites after controlling for Bone-Free Lean Body Mass (BFLBM), and after Bonferroni correction (corrected $\alpha=0.010$) (*all $p \leq 0.006$; d : 0.98-1.14; TOP). Athletes and controls presented similar BMC across all regions (all $p \geq 0.106$; d : 0.69-0.77; MIDDLE) and similar BFLBM:BMC ratios (all $p \geq 0.053$; d : 0.23-0.53; BOTTOM) after controlling for BFLBM.

body and mean total leg BFLBM were still used as covariates for total body and regional leg and hip bone mineral indices analyses, respectively, due to their anatomical and physiological influences. Despite athletes reporting a 3-fold higher incidence of lower body MSKI compared to controls ($p < 0.001$; $d = 0.96$), they presented higher total body BMD and BMD Z-Scores after controlling for total

body BFLBM (Table 1). Additionally, athletes' BMD across all leg regions was greater than controls after controlling for mean leg BFLBM (Figure 2), with significance for these measures meeting the new alpha after correction. However, athletes and controls demonstrated similarities across all leg regions for BMC (after controlling for leg BFLBM) and BFLBM:BMC, as presented in Figure 2. When evaluating

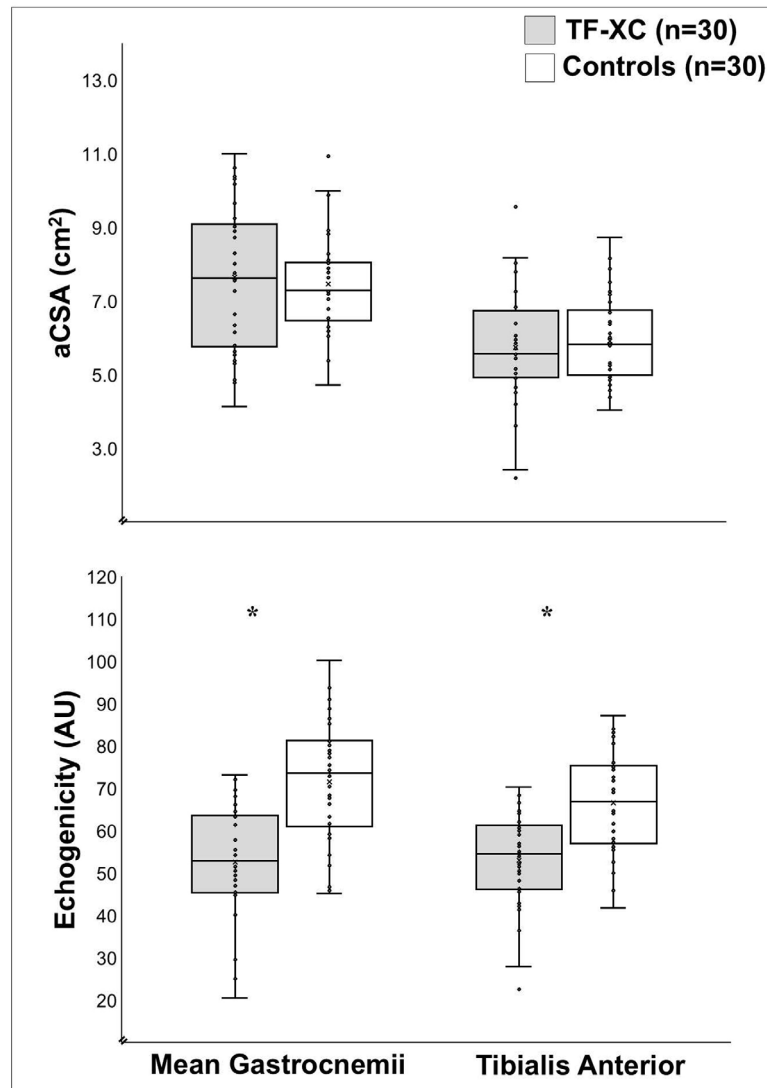


Figure 3. Comparison of Track and Field and Cross-Country (TF-XC) athletes and controls' mean combined gastrocnemius and tibialis anterior muscle anatomical cross-sectional area (aCSA) and subcutaneous fat corrected echogenicity. Athletes and controls were similar for aCSA for the combined gastrocnemii muscles after controlling for shank ROI Bone-Free Lean Body Mass (BFLBM) ($p=0.127$; $d=0.11$; TOP). Controls presented a significantly larger aCSA for the tibialis anterior after controlling for shank ROI BFLBM ($p=0.016$; $d=0.23$; TOP). However, significance was not maintained after Bonferroni correction was applied (corrected $\alpha=0.010$). Athletes demonstrated significantly lower subcutaneous fat corrected echogenicity for the combined gastrocnemius and tibialis anterior compared to controls, after controlling for shank ROI BFLBM, and after Bonferroni correction (corrected $\alpha=0.010$) (*both $p\leq 0.004$; $d: 1.13-1.36$; BOTTOM).

mean hip regions, athletes presented higher BMD at the total hip and greater trochanter, after controlling for mean leg BFLBM (both $p\leq 0.006$; $d: 0.91-1.02$). However, athletes and controls were similar for BMD at the femoral neck, BMC at all sites (Table 2), and all HSA measures except for mean intertrochanteric endocortical width, as indicated in Supplementary Table 2.

Muscle Morphological, Force, and Electromyographical Evaluation

Shank muscle ultrasonography analyses showed that athletes had lower subcutaneous fat-corrected echogenicity (indicative of greater contractile tissue concentration and better muscle quality) for both the mean combined gastrocnemii and mean tibialis anterior muscle compared

Table 3. Group comparison of mean lower body musculoskeletal ultrasonography measures.

Measure	TF-XC (n=30)	Controls (n=30)	Ind. <i>t</i> -test (p)	Cohen's <i>d</i>
Combined Gastrocnemius (corrected $\alpha=0.010$)				
aCSA (cm ²)	15.3±3.9	14.9±2.7	0.127	0.11
Subcutaneous Fat Thickness (cm)	0.3±0.2	0.6±0.2	0.017	1.16
Average Pennation Angle (°)	19.2±2.4	17.1±2.1	0.008 ^a	0.94
Raw Echogenicity (AU)	40.1±9.3	49.1±8.1	0.013	1.05
sFAT Corrected Echogenicity (AU)	52.6±13.2	71.6±14.6	0.001 ^a	1.36
Tibialis Anterior (corrected $\alpha=0.010$)				
aCSA (cm ²)	5.6±1.9	5.9±1.2	0.016	0.23
Subcutaneous Fat Thickness (cm)	0.2±0.1	0.3±0.1	0.002 ^a	1.22
Average Pennation Angle (°)	9.8±1.9	9.3±1.9	0.435	0.24
Raw Echogenicity (AU)	45.1±11.4	53.5±9.7	0.048	0.79
sFAT Corrected Echogenicity (AU)	53.1±11.6	66.6±12.3	0.004 ^a	1.13
Vastus Lateralis (corrected $\alpha=0.010$)				
Muscle Thickness (cm)	2.0±0.3	2.1±0.3	0.204	0.35
Subcutaneous Fat Thickness (cm)	0.4±0.2	0.9±0.5	<0.001 ^a	1.30
Average Pennation Angle (°)	16.4±3.5	16.7±3.0	0.753	0.09
Raw Echogenicity (AU)	39.8±8.7	36.3±7.9	0.130	0.42
sFAT Corrected Echogenicity (AU)	54.8±14.1	72.4±25.1	0.002 ^a	0.87
<i>Data are shown as means ± standard deviations, and ^a indicates significant group differences after Bonferroni correction. Combined gastrocnemius and tibialis anterior ultrasonography measures are adjusted for shank ROI BFLBM (Bone-Free Lean Body Mass). Abbreviations: aCSA: Anatomical Cross-sectional Area; sFAT: Subcutaneous Fat.</i>				

Table 4. Group comparison of mean knee extensor isometric dynamometry and vastus lateralis surface electromyography measures.

Measure	XCTF (n=30)	Controls (n=30)	Ind. <i>t</i> -test (p)	Cohen's <i>d</i>
Isometric Dynamometry (corrected $\alpha=0.017$)				
Peak Force Epoch (N)	460.3±104.1	467.2±111.6	0.808	0.06
0-250ms RFD (Ns ⁻¹)	2686.8±922.2	3488.9±788.7	0.001 ^a	0.93
Normalized 0-250ms RFD	5.7±2.5	7.9±2.8	0.003 ^a	0.82
Surface Electromyography (corrected $\alpha=0.012$)				
Peak EMG _{RMS} (μV)	1404.3±667.0	1175.2±680.2	0.096	0.34
Peak Force EMG _{RMS} (μV)	922.3±428.4	666.9±401.3	0.200	0.62
0-250ms EMG _{RMS} (μV)	677.0±370.9	507.1±244.5	0.576	0.55
0-250ms Normalized EMG _{RMS}	0.5±0.1	0.5±0.1	0.280	0.14
<i>Data are shown as means ± standard deviations, and ^a indicates significant group differences after Bonferroni correction. Surface electromyography measures are adjusted for vastus lateralis subcutaneous fat thickness. Abbreviations – RFD: Rate of Force Development; EMG_{RMS}: Electromyography Root Mean Square.</i>				

to controls, after controlling for ROI BFLBM (all $p \leq 0.004$; d : 1.13-1.36); with significance for these measures being maintained after correction. Additionally, although athletes presented similar mean combined gastrocnemii aCSA compared to controls, controls' tibialis anterior aCSA was larger, after controlling for shank ROI BFLBM, as presented in Figure 3. However, significance for tibialis anterior aCSA

was not maintained after correction. Furthermore, after controlling for shank ROI BFLBM, athletes' mean combined gastrocnemius fascicular pennation angle was greater compared to controls ($p=0.008$; $d=0.94$), though group similarities were present for the tibialis anterior ($p=0.435$; $d=0.24$). Regarding vastus lateralis ultrasonography, athletes demonstrated lower corrected echogenicity and

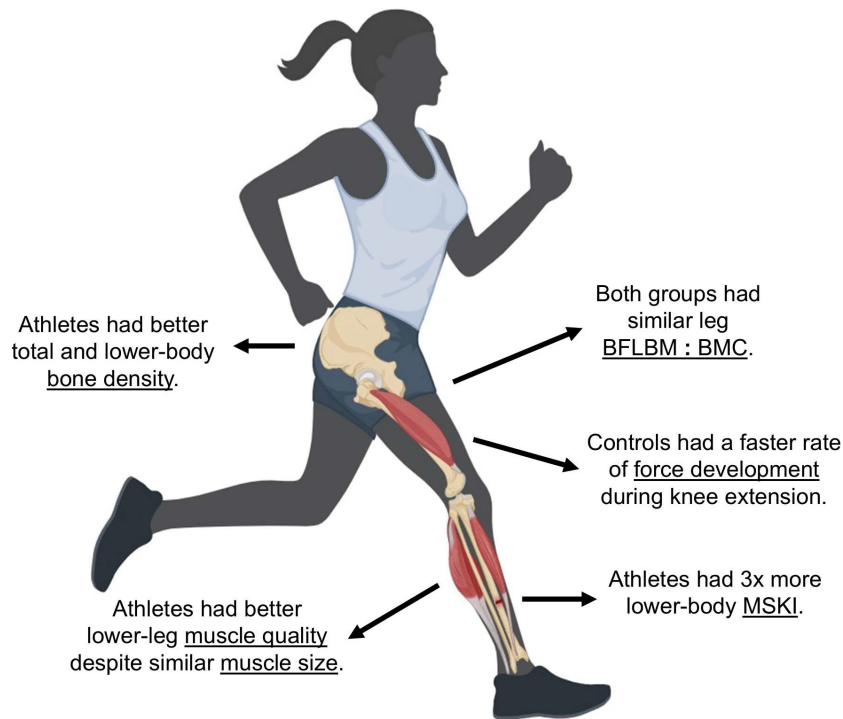


Figure 4. Highlighted key findings between NCAA Division I Track and Field and Cross-Country (TF-XC) athletes and physically active sex, age, and body mass matched non-athlete controls. Athletes presented greater bone mineral density (BMD) and BMD Z-Scores, but three times higher musculoskeletal injuries (MSKI) compared to controls. Athletes' bone-free lean body mass to bone mineral content (BFLBM:BMC) ratios and regional muscle anatomical cross-sectional area (aCSA) was similar compared to controls. Athletes demonstrated lower muscle echogenicity (indicative of better muscle quality) than controls; however, they produced slower rate of force development. Created in <https://BioRender.com>

subcutaneous fat thickness compared to controls, which was maintained after correction. However, muscle thickness and fascicular pennation angle were similar between groups, as indicated in Table 3. Isometric dynamometry showed that athletes and controls produced similar peak force; although, controls demonstrated higher raw and normalized rate of force development, as presented in Table 4. Additionally, the significance of both rate of force development measures was maintained after correction. When evaluating vastus lateralis electromyography, athletes and controls had similar EMG_{RMS} at both the peak force epoch and during the 0-250ms rate of force development epoch after correcting for vastus lateralis subcutaneous fat thickness (both $p \geq 0.492$; d : 0.14-0.62).

Discussion

The purpose of this investigation was to evaluate physical training, MSKI history, and musculoskeletal and

neuromuscular profiles of NCAA Division I TF-XC athletes and physically active, non-athlete, matched controls. It was found that athletes consistently presented better bone health measures and muscle quality but reported 3 times more musculoskeletal injuries, and demonstrated similar muscle size, peak force production, and gross electrical activity, compared to physically active, non-athlete controls.

Historically, TF-XC athletes have presented elevated overuse injury rates to muscle and bone^{7,8}, with the greatest proportion of injuries occurring in the lower body²⁸. Factors such as high sport-specific training volume, repetitive mechanical loading, and underlying musculoskeletal deficiencies such as poorer bone health (≤ -1.0 Z-Score) and reduced bone mineral and lean mass indices have shown pertinent relationships to musculoskeletal overuse injury risk^{5,6}. However, our findings provide some interesting divergent findings to consider. Despite 80% of our TF-XC cohort reporting a history of multiple musculoskeletal injuries and 73% of athletes reporting bone-specific

overuse injuries, they presented total body bone health Z-Scores (TF-XC mean = 0.2) above both a clinical⁵ (≤ -2.0) and far stricter²⁹ (≤ 0.0) at-risk threshold. This, coinciding with greater regional bone mineral and lean mass indices compared to physically active, college-aged non-athletes, may pose a unique injury etiological conundrum. While athletes' high weight-bearing training volume can induce increased rates of bone and muscle accrual, their frequent repetitive loading and lack of novel mechanical stimulus may be chronically overtaxing these tissues. Additionally, group similarities of lean mass to bone mineral content ratio may raise a further interesting point regarding load attenuation. Shinkel-Ivy et al.³⁰ identified that this ratio plays a potentially crucial role in intrinsic skeletal shock absorption, indicating that reduced ratios may impact injury risk in repetitive loading endurance athletes. Given such similarities and coinciding elevated athlete injury rates, it may be theorized that TF-XC tissue loading attenuation may not be optimally protective given their rigorous demands. Thus, while TF-XC presented musculoskeletal health and density measures that deviate from traditional injury risk factors, their elevated injury rates and potentially disadvantageous tissue loading ratios warrant further evaluation of soft tissue structure and quality.

Though sport-related physical training has been shown to develop muscle morphological traits more so than recreational training³¹, TF-XC's chronic repetitive mechanical demands may hinder these benefits. Traditionally, larger muscle cross-sectional area, lower echogenicity (indicative of better muscle quality), and smaller fascicular pennation angles have been associated with better performance and reduced injury risk in athletes^{32,33}. However, morphological characteristics, such as smaller muscle size and increased pennation angle, can both result from injury and may increase re-injury risk^{10,34}. This potential increased risk can be due in part to decreased load distribution area¹⁰ and slower fascicular contractile speed³³. While the current TF-XC cohort did present lower muscle echogenicity compared to non-athletes, they demonstrated similar anatomical cross-sectional areas, agreeing with Cabre et al.³⁵ who found similar muscle morphological traits between collegiate Cross-Country athletes and recreationally active non-athletes. These findings may suggest that the chronic aerobic nature of TF-XC might lend to habitual utilization of intramuscular fat as an immediate regional energy source and increase contractile tissue density, but it may also attenuate the muscles' hypertrophic capabilities. Though TF-XCs' greater gastrocnemius pennation angles conflict with Phillips et al.³², who reported smaller medial and similar lateral gastrocnemius pennation angles in Achilles tendinopathic distance runners compared to uninjured runners, it agrees with Timmins and colleagues³⁴, who found increased pennation angles in the injured biceps femoris muscle compared to the contralateral uninjured muscle within ballistics and endurance athletes. Findings from Timmins et al.³⁴ proposed that the combination of injury and repetitive loading of a chronically taxed muscle

may reduce the number of in-series sarcomeres, which may manufacture larger pennation angles and increase reinjury risk. Given TF-XC's great mechanical demands, their muscle size and architectural profiles may theoretically be insufficient to rapidly attenuate and appropriately distribute chronic loading forces. This, coinciding with lower muscle echogenicity, which may limit utilization of regional energy stores and potentially alter contractile function³⁶, could create a detrimental musculoskeletal overloading triad and potentially increase injury risk. Due to these potentially inadequate morphological traits and high injury rates, assessment of neuromuscular characteristics is vital to understand functional factors that may further contribute to TF-XC injury risk.

While collegiate sport training can amplify neuromuscular performance progression, TF-XC's aerobic training emphasis and lack of mechanical stimuli variation may blunt muscle force and electrical characteristics^{11,37}. For instance, whereas Tillin et al.³⁸ identified that short-distance running and jumping event track athletes, who emphasize power training, produced greater knee extension rate of force development compared to non-athletes, whereas the current TF-XC cohort, which is comprised primarily of middle- to long-distance athletes, produced slower values. Additionally, Degens et al.¹¹ found that endurance runners produced similar knee extensor peak force compared to recreationally active non-athlete controls, which agrees with the results of the present study. These neuromuscular characteristics may present both performance and etiological insights. Historically, higher force production and coinciding electromyographic amplitudes, and faster rate of development have been associated with favorable performance traits such as increased running economy, faster race times, and lower MSKI risk^{11,12,39}. These neuromuscular characteristics have also shown a positive relationship with muscle morphological characteristics such as larger muscle size and better muscle quality (lower muscle echogenicity)⁴⁰⁻⁴². Though the present TF-XC cohort demonstrated better muscle quality compared to non-athletes, their similar peak force production and slower rate of force development pose a unique muscle morphological and functional disconnect. While reduced muscle echogenicity suggests greater contractile tissue density, the composition of such contractile tissue can be reliant on physical training style⁴³. For instance, it may be theorized that the chronic endurance demands of TF-XC may elicit hypertrophy of slow-twitch fibers, which can reduce intramuscular fat concentration and echogenicity⁴⁴, and consequently dampen force production and development³⁷. However, such morphological and neuromuscular traits may be both a product and, potentially, a benefit for TF-XC-specific performance^{45,46}. From an epidemiological perspective, a history of MSKI can potentially evoke a slower rate of force development⁴⁷. This, in turn, may play a pertinent role regarding increased re-injury risk through diminished capacity for rapid regional muscle load attenuation¹¹. A

possible interventional target to assist with neuromuscular development, specifically rate of force development, could be greater incorporation of resistance and plyometric training. These training styles have shown improvements to force production, rate of force development, and increased electromyographic amplitude during contraction in TF-XC athletes^{48,49}; potentially leading to reduced injury risk within this susceptible cohort, but to date, little longitudinal data exists. Though TF-XC's sport-specific training habits and elevated injury rates coincided with better bone health indices and body composition, their potentially inadequate musculoskeletal loading ratios, morphological traits, and performance features may pose as pertinent factors possibly influencing injury risk and serve as interventional targets.

This study presents several strengths and limitations to consider. While a comprehensive evaluation of collegiate TF-XC training, injury, musculoskeletal, and neuromuscular characteristics provides potential insight into injury etiology, the cross-sectional nature of this study and the heterogeneity of our TF-XC group may limit the generalizability and impact of possible interventional strategies, as they are merely speculative based on available literature. Though DXA and ultrasonography are valid, precise, reliable, and clinically relevant for assessing musculoskeletal health and structure, future investigations may consider the inclusion of skeletal microarchitecture and serum biomarker evaluation. The addition of these mechanistic measures could provide more comprehensive etiological insight for this at-risk cohort than macro-scale imaging alone. The assessment of knee extensor force and electromyographical characteristics identified pertinent neuromuscular performance traits of a joint that is heavily utilized in TF-XC. However, ankle-joint specific force and electrical evaluation, coinciding with regional DXA and ultrasonography, may allow for a more poignant mechanical understanding of this injury-prone region. This study utilized questionnaires to determine behavioral physical training profiles, and though these can be easily implemented for large-scale data collections, they present limitations when objectively determining exercise intensity and loading parameters. TF-XC participants in the current study reported competing in a variety of events, distances, and disciplines. As such, a technical consideration for future researchers and practitioners alike may be the incorporation of wearable load-tracking sensors to precisely quantify athlete mechanical loading profiles, allowing for more nuanced interpretation of results.

In conclusion, this study indicates that despite better musculoskeletal health and density, TF-XC athletes present elevated injury risk, possibly due to their high injury incidence, and musculoskeletal loading ratios, muscle morphological size and architecture, and neuromuscular characteristics, which may be potentially inadequate for loading demands. These characteristics may serve as pertinent interventional targets for coaches, practitioners, and clinicians to reduce injury risk within this susceptible population.

Ethics approval

Approval for this cross-sectional study was granted by the Oklahoma State University Institutional Review Board (#22-112-STW) and was in accordance with the Declaration of Helsinki 1964 and its later amendments.

Consent to participate

Voluntary written informed consent was obtained for all subjects prior to participation.

Authors' contributions

ALR, TKD, and BSB contributed to the conception and design of this investigation. ALR, SMFA, SAM, NJS, OKA, and CIG contributed to data collection. ALR, MAT, and BSB contributed to the analysis and interpretation of the data. ALR, SMFA, SAM, NJS, OKA, CIG, TKD, MAT, and BSB approve of the final version of this manuscript and take responsibility for the integrity of the data presented.

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Supplementary Table 1. Intraclass Correlation Coefficients (ICCs) for Dual-energy X-Ray Absorptiometry (DXA) shank region of interest (ROI) and lower body muscle ultrasonography measures.

DXA Measure	Bone Mineral Content				
Shank ROI	0.998				
Ultrasonography Muscle	Muscle Thickness	Echogenicity	Pennation Angle	aCSA	Subcutaneous Fat Thickness
Tibialis Anterior	0.999	0.996	0.947	0.978	0.998
Lateral Gastrocnemius	0.997	0.962	0.946	0.989	0.991
Medial Gastrocnemius	0.996	0.994	0.948	0.949	0.990
Vastus Lateralis	0.968	0.978	0.986	0.998	0.992

Data are shown as intraclass correlation coefficients (ICCs). Abbreviations – ROI: Region of Interest; aCSA: Anatomical Cross-sectional Area.

Supplementary Table 2. Group comparison of Dual-energy X-Ray Absorptiometry (DXA) mean expanded proximal femora hip structural analyses (HSA) measures.

Measure	TF-XC (n=30)	Controls (n=30)	Ind. f-test (p)	Cohen's d
Narrow Neck Region (corrected $\alpha=0.007$)				
Subperiosteal Width (cm)	3.2±0.3	3.1±0.2	0.636	0.28
Endocortical Width (cm)	2.7±0.3	2.7±0.2	0.456	0.12
Cross-sectional Area (cm ²)	3.7±0.5	3.3±0.6	0.197	0.71
CSMI (cm ⁴)	3.1±0.9	2.6±0.7	0.722	0.57
Section Modulus (cm ³)	1.8±0.4	1.6±0.3	0.576	0.61
Cortical Thickness (cm)	0.2±0.0	0.2±0.0	0.141	0.65
Buckling Ratio	7.3±1.6	7.8±1.5	0.279	0.34
Intertrochanteric Region (corrected $\alpha=0.007$)				
Subperiosteal Width (cm)	5.2±0.5	5.2±0.4	0.012	0.06
Endocortical Width (cm)	4.3±0.5	4.3±0.3	0.004 ^a	0.19
Cross-sectional Area (cm ²)	5.9±0.9	5.1±0.9	0.026	0.89
CSMI (cm ⁴)	14.0±4.2	11.9±3.7	0.909	0.53
Section Modulus (cm ³)	4.6±1.0	3.9±0.9	0.387	0.65
Cortical Thickness (cm)	0.5±0.1	0.4±0.1	0.083	0.73
Buckling Ratio	6.3±1.2	7.0±1.2	0.046	0.61
Femoral Shaft Region (corrected $\alpha=0.007$)				
Subperiosteal Width (cm)	2.9±0.2	2.8±0.2	0.514	0.51
Endocortical Width (cm)	1.7±0.4	1.6±0.4	0.669	0.02
Cross-sectional Area (cm ²)	4.6±0.6	4.1±0.5	0.015	0.93
CSMI (cm ⁴)	3.5±0.9	3.0±0.7	0.460	0.63
Section Modulus (cm ³)	2.3±0.4	2.0±0.3	0.518	0.62
Cortical Thickness (cm)	0.6±0.1	0.6±0.1	0.206	0.53
Buckling Ratio	2.5±0.5	2.6±0.6	0.483	0.22

Data are shown as means ± standard deviations, and ^a indicates significant group differences after Bonferroni correction. DXA HSA measures are adjusted for mean leg BFLBM (Bone-Free Lean Body Mass). Abbreviations – CSMI: Cross-sectional Moment of Inertia.