

Effects of Multi-Day Gobi Endurance Trekking on Foot Morphology in Male Adolescents

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Abstract

Background

Multi-day outdoor endurance sports are increasingly popular among adolescents, whose feet endure repeated mechanical loading and are prone to morphological deformation. Most relevant studies focus on urban road running, while few have explored foot changes induced by long-distance trekking on harsh Gobi terrain. This study investigated the immediate effects of multi-day Gobi endurance trekking on foot morphology in male adolescents.

Methods

Ten healthy male amateur runners aged 10–18 years were recruited as research subjects based on a three-day, two-night 72-kilometer Gobi endurance race. Foot morphological parameters under weight-bearing standing posture were collected using a 3D laser foot scanner one day before the race and immediately after each daily race stage. Simultaneous measurements included the rating of perceived exertion (RPE), handgrip strength, countermovement jump (CMJ) height, visual analogue scale (VAS) for pain, and sleep duration. Repeated-measures analysis of variance was applied to analyze the temporal variation patterns of all indicators.

Results

During the three-day Gobi endurance cycle, no significant temporal alterations were observed in bony foot contour metrics including bilateral foot length, metatarsal width and forefoot width ($P>0.05$).

Bilateral heel center-to-heel length increased significantly after the initial stage, with this elevated distance sustained across most of the event, with a progressive widening trend detected in left heel width ($P<0.05$).

Bilateral medial longitudinal arch height decreased continuously with race progression, accompanied by gradual elongation of the right medial longitudinal arch, indicating progressive functional flattening of the medial longitudinal arch ($P<0.05$). Participants simultaneously presented progressive accumulation of subjective fatigue, decreased upper and lower limb muscle strength, aggravated exercise-induced pain, and shortened sleep duration.

Conclusions

Multi-day Gobi endurance trekking did not induce significant changes in external foot contour dimensions reflecting the underlying bony framework, but induced heel soft tissue edema and functional collapse of the medial foot arch. These findings suggest that synergistic interactions between localized foot soft-tissue deformation and systemic fatigue and pain may contribute to the elevated foot injury risk observed during the race. These findings provide empirical evidence for foot health protection and safety management among adolescents participating in wilderness endurance events.

Introduction

Driven by rising public health awareness and shifting recreational lifestyles, wilderness sports have undergone rapid global expansion and gained immense popularity among outdoor enthusiasts. Participants are no longer limited to professional athletes but extend to ordinary people spanning diverse age groups and occupations,

fueling sustained expansion of the wilderness recreation industry. Adolescent participation in wilderness endurance sports has increased steadily in recent years [1, 2]. Unlike single-day exercise, multi-day endurance trekking imposes consecutive days of sustained mechanical loading with limited recovery, making the feet—especially the still-maturing adolescent foot—more susceptible to fatigue-related deformation.

Multi-day Gobi endurance challenge events represent a typical extreme wilderness competition format. The Xuanzang Road International Adolescent Gobi Challenge, a multi-day Gobi endurance event for adolescents in China, adopts a three-day, two-night long-distance format staged within the Moheyanqi Gobi in Gansu Province. This region features classic Gobi landforms with sparse vegetation and extensive gravel and coarse sand coverage, distinguishing its geomorphology from typical desert and loess terrains. Strong winds and frequent sandstorms prevail during the competition period, accompanied by extreme diurnal temperature fluctuations ranging from 6°C to 30°C. Coupled with intense solar radiation, these conditions collectively create a harsh athletic environment [3, 4].

To date, relevant empirical work has largely adopted single-day, short-distance urban road running as the experimental setting, and no investigations have characterized foot morphological alterations in adolescents completing multi-day Gobi endurance exercise. Furthermore, single-day study designs cannot capture the cumulative effects of consecutive competition days—including progressive fatigue accumulation and escalating pain—that may interact with foot deformation over time and correlate with elevated risk of foot injury [5–8]. The medial longitudinal arch enables elastic energy storage and shock absorption during running through its arched structure; once deformed, it disrupts lower-extremity biomechanics, alters plantar pressure distribution, and precipitates foot pathologies such as plantar fasciitis [9, 10]. We hypothesized that multi-day Gobi trekking would induce progressive soft-tissue swelling and medial longitudinal arch deformation, and that these changes would track alongside accumulating systemic fatigue and exercise-induced pain across consecutive race days. Accordingly, this study characterized the dynamic effects of a 72-kilometer, three-day-two-night Gobi endurance event on foot morphological profiles in adolescent recreational runners, alongside their associations with perceived fatigue, muscular function, and pain perception, providing evidence for safety management of adolescent endurance events in extreme environments.

Methods

Participants

A total of 10 healthy male adolescents aged 10–18 years were included in this study (mean $\pm$ SD: age, 14.50 $\pm$ 2.59 years; body mass index, 19.54 $\pm$ 2.08 kg·m⁻²). Eligible participants were recreational endurance runners with good physical health, unrestricted daily activities and no definite exercise contraindications, who had no history of severe trauma, fractures or major sports injuries within six months prior to testing and did not use foot orthoses or custom arch-support insoles in daily life. Individuals were excluded if they had congenital foot structural abnormalities or evident lower limb malalignment, chronic illnesses including cardiovascular, cerebrovascular, respiratory, metabolic and neurological diseases or any exercise contraindications, received surgical procedures within six months before testing, took medications that may affect exercise performance, or suffered from cognitive or communication disorders that prevented cooperation with foot scanning, physical fitness tests and questionnaire completion. Written informed consent was obtained from all participants and

their legal guardians. The experimental protocol was reviewed and approved by the Ethics Committee of Peking University Third Hospital (Ethics Approval No. M2024512-4.0).

Study Design

All participants were tested one day before the Gobi endurance event and immediately after the race on Day 1, Day 2 and Day 3. All measurements were carried out inside the medical tents at the Gobi campsite and administered by uniformly trained on-site staff following a standardized protocol.

Experimental Procedures

Questionnaire Survey

All participants wore their daily running shoes throughout all testing sessions without additional orthotic arch supports. Standardized questionnaires were administered to collect demographic data, medical history, prior sports injury records, and sleep status. The Visual Analogue Scale (VAS) was used to quantify pain intensity, and the 6–20 Borg rating of perceived exertion (RPE) scale was adopted to measure subjective fatigue.

Handgrip Strength Measurement

Digital hand dynamometers were utilized to quantify maximal handgrip strength. Participants stood with feet hip-width apart and toes oriented forward. The dominant hand gripped the dynamometer with the upper arm abducted at 45°, elbow fully extended, and palm facing the thigh. Participants exerted maximal compressive force for 2 s; the procedure was repeated three times per hand with a minimum 60 s rest interval between trials. The maximum value across trials was recorded in kilograms to one decimal place. Handgrip strength served as an indicator of whole-body and upper-extremity muscular capacity [11].

Countermovement Jump (CMJ) Test

Participants stood with feet shoulder-width apart on a contact mat, maintaining hands fixed on the hips for the entirety of each jump. Each trial commenced with a rapid descent to approximately 90° of knee flexion, followed immediately by a maximal vertical jump without pause. Both feet must land entirely within the boundary of the contact mat upon landing. Three maximal jump attempts were completed, and the highest jump height (recorded in centimeters to one decimal place) was retained for analysis. Jump height was used to evaluate lower-extremity neuromuscular function and fatigue status [12–14].

Three-Dimensional Foot Morphology Assessment

Foot morphological parameters were captured using an XSOL 3D laser foot scanner (Kangzhilai, Wenzhou, China) and its proprietary supporting analysis software. All scanning procedures were conducted inside shaded rest tents at the competition campsite to eliminate artifacts induced by direct light exposure under stable ambient temperature ranging from 23°C to 26°C. During scanning, participants stood barefoot under full weight-bearing load. The target foot was placed flat on the scanning platform, while the contralateral foot rested on a

stationary auxiliary board. Participants stood with feet shoulder-width apart and evenly distributed body mass across both feet, with naturally aligned feet oriented such that the midline of each foot bisected the space between the second and third toes. A single-foot sequential scanning mode was applied, with the contralateral foot scanned following completion of the first foot (Fig. 1). The reconstructed 3D foot models were post-processed via XSOL analytical software to extract bilateral morphological metrics: foot length, metatarsal widths 1–5, medial and lateral longitudinal arch lengths, heel center-to-heel length, forefoot width, heel width, hallux valgus angle, and medial and lateral longitudinal arch height and length. Baseline measurements of all testing outcomes were acquired one day prior to race commencement. Full repeated measurements of all indices were performed immediately upon the conclusion of each daily race stage.

Statistical Analysis

All statistical analyses were performed using SPSS 24.0 software. Normally distributed continuous variables are presented as mean $\pm$ standard deviation, non-normally distributed data were expressed as median (P25, P75). Repeated-measures analysis of variance was performed for normally distributed continuous variables measured at multiple time points, and the Friedman test was applied for non-normally distributed data with the significance threshold set at $\alpha = 0.05$. Effect sizes are reported as partial eta squared (η^2) for repeated-measures ANOVA and Kendall's W for the Friedman test.

Results

Exercise-Related Symptoms and Discomforts

Temporal alterations in cumulative case counts of all exercise-related discomforts and injuries throughout the three-day race are illustrated in Fig. 2. Collectively, muscle soreness and exercise-induced plantalgia constituted the two most prevalent adverse conditions, with their cumulative case counts rising progressively alongside race progression. The number of participants reporting muscle soreness increased steadily from 5 on Day 1 to 10 on Day 3. Exercise-induced plantalgia affected 6 athletes on Day 1, rose to 9 on Day 2, and remained unchanged through Day 3; these two pathologies represented the dominant injury burdens among adolescent competitors. Plantar blisters were documented in 2 participants on Day 1, with no further increases observed over the subsequent two days, yielding stable cumulative prevalence. Cumulative cases of deltoid ligament strain and tendinopathy remained low, ranging only from 1 to 2 across all race stages without evident upward trends. Shoulder discomfort associated with backpack strap compression was mild during the first two competition days, and declined to zero by Day 3. This observation indicates that a subset of participants developed progressive local adaptation to mechanical pressure from backpack loads, with corresponding subjective discomfort alleviated as the event proceeded.

Temporal Variations in Subjective Fatigue, Muscular Strength, Perceived Pain and Sleep Duration

Comparisons of pre-race baseline and post-daily-race RPE, handgrip strength, CMJ height, VAS pain scores and sleep duration revealed highly significant main effects of time for all five metrics ($P < 0.01$). Post-hoc multiple comparison outcomes are detailed below:

RPE scores measured after each race day were markedly elevated relative to pre-race baseline ($P < 0.01$). Mean RPE increased from a baseline value of 7.70 ± 2.21 to 15.80 ± 3.39 on Day 3, demonstrating a continuous upward trajectory and indicating robust fatigue accumulation induced by three consecutive days of Gobi endurance exercise. Handgrip strength declined progressively across race stages, day 3 handgrip strength was additionally reduced relative to Day 1 and Day 2 ($P < 0.05$), reflecting cumulative muscular strength attenuation. CMJ height exhibited substantial continuous reduction throughout the event. All three post-race jump heights were significantly suppressed compared with pre-race baseline ($P < 0.01$). Day 2 and Day 3 values were further lower than Day 1 ($P < 0.01$), and Day 3 height was significantly diminished relative to Day 2 ($P < 0.01$). The Friedman's test revealed that time had a significant main effect on VAS. The VAS score after each daily exercise were significantly higher than the baseline ($P < 0.01$). Sleep duration decreased sequentially over the three race days. Recorded sleep times on Day 1 and Day 3 were significantly shorter than pre-race baseline ($P < 0.05$ and $P < 0.01$, respectively), while Day 3 sleep duration was markedly reduced relative to Day 1 and Day 2 ($P < 0.01$), exhibiting a consistent progressive decline. Comprehensive statistical outputs are summarized in Table 1.

Table 1
Changes in fatigue, muscular strength, pain and sleep duration

RPE	Before	Day1	Day2	Day3	F/ χ^2	P	η_p^2 /W
	7.70 $\pm$ 2.21	14.80 $\pm$ 2.25**	14.00 $\pm$ 3.30**	15.80 $\pm$ 3.39**	17.95	<0.01	0.67
grip strength(kg)	34.02 $\pm$ 11.47	33.20 $\pm$ 10.92	32.10 $\pm$ 10.23#	31.15 $\pm$ 10.59***#\$	4.67	<0.01	0.34
CMJ height(cm)	44.23 $\pm$ 8.40	34.98 $\pm$ 7.60**	22.47 $\pm$ 10.6***##	18.14 $\pm$ 10.46***##\$\$	34.89	<0.01	0.80
VAS score	0(0,0)	5.00(3.25,6.00)**	6.00(2.50,7.00)**	6.00(5.00,7.25)**	23.38	<0.01	0.78
Sleep duration(min)	475.50 $\pm$ 8.78	414.80 $\pm$ 37.79*	449.70 $\pm$ 28.71	351.20 $\pm$ 57.33***#\$	14.67	<0.01	0.62

* $P < 0.05$, ** $P < 0.01$ vs. Before; # $P < 0.05$, ## $P < 0.01$ vs. Day 1; \$ $P < 0.05$, \$\$ $P < 0.01$ vs. Day 2.

Alterations in Weight-Bearing Foot Morphological Parameters

Repeated-measures ANOVA outputs for global foot length, forefoot width and other fundamental morphological metrics are provided in Table 2. No statistically significant main effects of time were detected for bilateral foot length, metatarsal widths 1–5, forefoot width, and hallux valgus angle throughout the three-day competition cycle ($P > 0.05$). These results indicate that three consecutive days of Gobi endurance exercise failed to induce significant shifts in overall foot length and transverse forefoot width among adolescents, with the gross bony framework of the foot remaining comparatively stable.

Significant main effects of time were identified for bilateral heel center-to-heel length ($P < 0.01$). Post-hoc testing revealed that left heel center-to-heel length was significantly elevated on Day 1 and Day 2 relative to pre-race baseline ($P < 0.05$); the corresponding right-side metric was significantly higher than baseline on Day 1 and Day 3

($P < 0.05$). Collectively, this parameter increased acutely post-race and sustained elevated values during subsequent competition stages.

For heel width: a significant main effect of time was observed for left heel width ($P < 0.01$), which widened progressively with race progression. Left heel width measured on Day 2 and Day 3 was significantly greater than baseline ($P < 0.05$ and $P < 0.01$, respectively), and Day 3 width was markedly increased relative to Day 1 ($P < 0.05$), demonstrating unambiguous cumulative widening. No significant temporal variation was detected for right heel width ($P > 0.05$).

Table 2
Changes in weight-bearing foot morphological parameters

Left foot length (mm)	Before	Day1	Day2	Day3	F	P	η_p^2
	252.38 ± 12.76	252.75 ± 13.49	252.92 ± 13.88	253.11 ± 12.58	0.55	0.65	0.06
Right foot length (mm)	252.40 ± 13.49	252.71 ± 13.69	252.64 ± 14.42	253.01 ± 13.15	0.72	0.55	0.07
Left 1–5 metatarsal width (mm)	66.52 ± 3.85	66.64 ± 3.29	66.92 ± 3.93	66.80 ± 4.41	0.29	0.83	0.03
Right 1–5 metatarsal width (mm)	66.56 ± 3.36	67.18 ± 2.15	67.45 ± 2.83	67.76 ± 3.29	1.73	0.19	0.16
Left heel center-to-heel length (mm)	30.33 ± 1.81	32.94 ± 1.76*	33.04 ± 1.79*	32.30 ± 2.46	5.04	<0.01	0.36
Right heel center-to-heel length (mm)	30.26 ± 2.60	32.70 ± 1.67*	32.60 ± 1.94	33.46 ± 2.19*	5.93	<0.01	0.40
Left forefoot width (mm)	95.26 ± 6.09	95.45 ± 4.93	94.95 ± 5.79	95.24 ± 5.92	0.21	0.89	0.02
Right forefoot width (mm)	95.40 ± 4.18	96.05 ± 3.78	96.06 ± 3.92	96.10 ± 3.89	1.16	0.34	0.11
Left heel width (mm)	60.48 ± 2.79	60.72 ± 2.37	61.39 ± 2.86*	61.48 ± 2.54** [#]	4.63	<0.01	0.34
Right heel width (mm)	60.05 ± 3.49	60.89 ± 2.79	60.99 ± 3.06	60.89 ± 2.47	1.90	0.15	0.18
Left hallux valgus angle (°)	7.10 ± 3.75	9.17 ± 3.25	7.22 ± 2.20	7.58 ± 3.57	2.01	0.14	0.18
Right hallux valgus angle (°)	8.48 ± 2.51	8.65 ± 3.77	7.66 ± 3.95	8.36 ± 3.68	0.34	0.80	0.04

* $P < 0.05$, ** $P < 0.01$ vs. Before; # $P < 0.05$, ## $P < 0.01$ vs. Day 1; \$ $P < 0.05$, \$\$ $P < 0.01$ vs. Day 2.

Morphological Modifications of Arch Architecture

Repeated-measures ANOVA outputs for bilateral longitudinal arch length and height are presented in Table 3.

For longitudinal arch length: a significant main effect of time was detected for right medial longitudinal arch length ($P < 0.01$). Post-hoc comparisons demonstrated that Day 3 length was significantly elongated relative to pre-race baseline and Day 1 (both $P < 0.01$), as well as Day 2 ($P < 0.05$), consistent with progressive lengthening. No significant temporal effects were observed for left medial longitudinal arch length or bilateral lateral longitudinal arch lengths ($P > 0.05$).

For longitudinal arch height: bilateral medial longitudinal arch height declined continuously over race progression. A significant main effect of time existed for left medial longitudinal arch height ($P = 0.03$), with Day 3 height markedly reduced compared with baseline ($P < 0.05$). Linear trend analysis yielded statistical significance for right medial longitudinal arch height ($P = 0.04$); values recorded on Day 1 and Day 3 were significantly lower than baseline ($P < 0.05$ and $P < 0.01$, respectively). No significant main effect of time was detected for bilateral lateral longitudinal arch height ($P > 0.05$). Collectively, these data confirm that multi-day consecutive Gobi endurance exercise reduces medial longitudinal arch height in adolescents, driving a progressive arch collapse deformation pattern.

Table 3
Changes in foot arch structural parameters

Left medial longitudinal arch length (mm)	Before	Day1	Day2	Day3	F/ χ^2	P	η_p^2 /W
	181.53 ± 8.97	182.12 ± 9.94	181.96 ± 9.86	182.22 ± 9.45	0.88	0.47	0.09
Right medial longitudinal arch length (mm)	181.57 ± 9.70	181.95 ± 9.72	181.95 ± 10.18	183.18 ± 9.63 ^{***\$}	6.28	<0.01	0.41
Left lateral longitudinal arch length (mm)	159.07 ± 8.07	159.26 ± 8.49	159.11 ± 8.76	159.48 ± 7.85	0.45	0.72	0.05
Right lateral longitudinal arch length (mm)	158.99 ± 8.83	159.45 ± 8.80	159.04 ± 8.80	159.49 ± 8.52	1.42	0.26	0.14
Left medial longitudinal arch height (mm)	8.80 ± 4.37	7.60 ± 5.54	8.50 ± 5.84	7.30 ± 5.21 [*]	3.34	0.03	0.27
Right medial longitudinal arch height (mm)	9.00 ± 5.52	6.80 ± 3.74 [*]	8.10 ± 6.66	7.30 ± 5.66 ^{**}	5.87	0.04	0.39
Left lateral longitudinal arch height (mm)	0(0,0)	0(0,0)	0 (0,0.50)	0(0,0)	6.00	0.11	0.20
Right lateral longitudinal arch height (mm)	0(0,0)	0(0,0)	0(0,0)	0(0,0)	2.00	0.57	0.07

* $P < 0.05$, ** $P < 0.01$ vs. Before; # $P < 0.05$, ## $P < 0.01$ vs. Day 1; \$ $P < 0.05$, \$\$ $P < 0.01$ vs. Day 2.

Discussion

This study recruited adolescent male non-professional runners participating in a three-day, two-night 72-kilometer Gobi endurance event to systematically observe the acute effects of consecutive multi-day endurance

exercise in extreme environments on foot morphological characteristics. Results revealed that short-duration high-intensity Gobi exercise induced no statistically significant alterations to the gross bony framework of the foot, yet triggered localized morphological changes including posterior heel soft tissue edema and progressive medial longitudinal arch collapse. These morphological shifts exhibited strong synchronous synergies with cumulative whole-body subjective fatigue, reduced upper and lower extremity muscle strength, and exacerbated exercise-induced pain. For the first time, this study characterizes foot morphological responses of adolescents exposed to multi-day extreme Gobi environments, filling a critical gap in biomechanical research on adolescent feet within wilderness endurance sports. The findings provide empirical evidence for injury prevention in comparable events and the safe delivery of outdoor endurance training for adolescents.

This study additionally observed that participants' daily sleep duration fell far below the 8–10 h sleep recommendation for adolescents [15]. Sleep deprivation impairs muscular fatigue recovery and elevates injury susceptibility [16], consistent with prior investigations of adolescent runners. The prior cohort consisted predominantly of elite athletes, among whom 29.23% sustained severe exercise-related injuries and 12.13% experienced ankle sprains, with insufficient sleep linked to elevated injury risk [16]. The present cohort comprised non-elite adolescents; approximately 20% presented ankle injuries, with no severe musculoskeletal trauma documented. This discrepancy may stem from more conservative pacing and movement strategies adopted by non-professional adolescent runners, which mitigate the risk of severe injury.

With regard to fatigue and muscular performance, participants maintained persistently high subjective fatigue scores following daily race stages without marked single-day fluctuations, indicating a sustained high-load fatigue state. Grip strength, a proxy for baseline muscular capacity, declined significantly on the final race day, demonstrating that global muscular attenuation represents a lagged outcome of cumulative multi-day endurance loading. CMJ height exhibited continuous progressive reduction across the event timeline: this trend signals gradual deterioration of neuromuscular control and deepening lower-extremity fatigue, and correlates with exercise-induced plantar pain. Pain-mediated inhibitory effects further attenuate lower-limb explosive force output.

No statistically significant temporal changes were detected in bony foot contour metrics across bilateral feet, including total foot length, widths of the first to fifth metatarsals, forefoot width, and hallux valgus angle, confirming high structural stability of the adolescent gross foot skeleton under short-term multi-day high-intensity exertion. Comparable observations have been reported following other long-distance running modalities; marathon completion fails to elicit meaningful shifts in global foot dimensions such as foot length [17]. Physiologically, the bony architecture, tendons, and associated muscle complexes of the human foot possess robust mechanical rigidity and structural integrity. Functional foot dysfunction typically arises from elevated impact loading and compromised dynamic supporting structures—soft tissues, fascia, and musculature—rather than skeletal deformation [18]. Cumulative short-term exercise loading is insufficient to alter global bony foot geometry. Although adolescent foot epiphyseal plates remain unfused and skeletal maturation incomplete, the 72-kilometer three-day race constitutes an acute short-duration load that does not exceed the mechanical threshold required to remodel gross foot skeletal morphology. This indirectly indicates that consecutive multi-day Gobi endurance competition exerts minimal impact on the overall bony structure of adolescent feet.

Bilateral heel center-to-rear length increased significantly immediately post-stage and remained elevated throughout the event, while left heel width demonstrated progressive cumulative widening across race days, identifying the posterior heel as the primary site of soft tissue edema during multi-day Gobi running. The

underlying pathophysiological mechanism is well characterized: rearfoot striking represents the dominant foot strike pattern for most endurance runners, independent of biological sex [19], and heel pain and swelling rank among the most prevalent exercise-related symptoms [20]. Furthermore, heel pain and edema constitute hallmark clinical manifestations of plantar fasciitis in adolescent endurance athletes [21]. As the primary weight-bearing structure, the heel undergoes repetitive ground reaction forces and vertical compressive loading, eliciting congestion of the heel fat pad and interstitial fluid accumulation within soft tissues, which manifests as morphological bulging. Running surface topography additionally modulates lower-extremity biomechanical profiles: impact magnitudes during foot strike are substantially greater on hard, coarse terrain relative to soft, smooth surfaces [22]. The Gobi landscape is blanketed with gravel and coarse sand, yielding rigid, uneven ground that amplifies impact loading during heel contact compared with urban paved surfaces. Repetitive mechanical stimulation exacerbates interstitial fluid extravasation and local edema. Prolonged exertion also elevates intra-shoe temperature, augmenting plantar blood perfusion and subcutaneous vasodilation to further amplify soft tissue swelling [6].

Reduced medial longitudinal arch height and elongated longitudinal arch length constitute the core findings of this investigation, with the full cohort demonstrating unambiguous progressive arch collapse that accumulates linearly with successive race days. Analogous trends have been documented in separate cohorts of elite and recreational male marathon runners, who exhibit sustained reductions in longitudinal arch height from immediately post-race through 60 min of recovery [17]. A secondary study of 11 recreational runners reported significant declines in longitudinal arch height and arch stiffness index following a 10-kilometer run [23]. Direct numerical comparison between studies is limited by differences in measurement devices and protocols, but the directional consistency across marathon, 10-kilometer, and multi-day Gobi settings supports the robustness of exercise-induced arch deformation.

Medial longitudinal arch integrity depends on coordinated static and dynamic support mechanisms. Static support is conferred by connective tissues including the plantar fascia and ligaments; prolonged multi-day tensile loading may induce fatigue-mediated laxity and diminished tissue tension, potentially eroding static arch stability. Dynamic stabilization is mediated by intrinsic foot muscles, triceps surae, and tibialis posterior. Cumulative multi-day exertion induces widespread lower-extremity muscular fatigue, and diminished muscle strength may reduce the capacity to sustain normative arch geometry [9, 24, 25]. Compounding these effects, the heterogeneous Gobi terrain mandates continuous postural adjustment of the foot to negotiate uneven ground, requiring frequent arch deformation for shock attenuation and balance maintenance and accelerating functional deterioration of supportive soft tissue and musculotendinous structures.

Progressive medial arch collapse carries robust clinical injury-prediction value. Temporal alignment exists between longitudinal arch height reduction and cumulative incidence of exercise-related plantar pain, which rose to nine documented cases on Day 2 and persisted through Day 3. Arch collapse may disrupt normative plantar pressure distribution, driving focal overload at the metatarsal heads and heel; chronic exposure elevates risk of plantar fasciitis and metatarsal stress fractures. Arch collapse may additionally induce medial shift of lower-extremity kinetic alignment, altering mechanical loading at the ankle and knee and indirectly increasing prevalence of muscular soreness and articular injury across the lower limb [9]. Relative to adult cohorts, adolescent medial arches remain in developmental maturation, with inferior muscular and ligamentous tensile strength and reduced tolerance to sustained loading, rendering this population disproportionately susceptible to

functional arch collapse. This identifies adolescents as a high-risk group for arch-associated overuse injuries [26].

Asymmetrical bilateral shifts in heel width and medial longitudinal arch length may reflect several factors. Biologically, gait asymmetry, dominant-limb differences, and uneven backpack load distribution could contribute to unilateral morphological changes. Statistically, the limited sample size ($n = 10$) provides insufficient power to detect small bilateral differences; notably, contralateral limbs exhibited congruent directional trends that failed to meet statistical significance thresholds. Future work with larger cohorts is needed to validate these unilateral observations and determine whether bilateral asymmetry reflects true physiological variation or statistical noise.

Subjective fatigue, muscular performance, pain, and sleep metrics all displayed progressive temporal trajectories that correlated tightly with foot morphological remodeling, demonstrating that localized foot deformation does not occur in isolation but engages bidirectional synergistic interactions with global physiological deterioration.

Diminished lower-extremity muscle strength represents a key correlate of medial arch collapse [27]. Continuous marked declines in countermovement jump height reflect global deterioration of lower-limb neuromuscular function; fatigued lower-extremity musculature loses capacity to provide dynamic arch stabilization, directly accelerating arch flattening. Progressive grip strength reduction indexes cumulative systemic fatigue, which impairs gait precision and indirectly exacerbates aberrant plantar loading patterns.

Although not directly measured in this study, the observed arch collapse may be mechanistically linked to plantar fascia fatigue. Prior biomechanical work demonstrates that variance in plantar fascia fatigue status explains approximately 70% of total variability in arch collapse metrics [28]. This supports a potential causal cascade wherein fascia fatigue elevates in vivo tensile strain during running; excessive fatigue may generate microtears within the plantar fascia, potentially precipitating exercise-induced plantar pain and eventual clinical plantar fasciitis [10], a pathophysiological sequence consistent with the observational data reported herein. Systemic fatigue further degrades gait precision and distorts foot strike kinematics and pressure distribution, amplifying soft tissue edema and arch deformation. Arch collapse itself constitutes an established risk factor for running-related musculoskeletal injury [29]; mechanically aberrant plantar fascia and secondary arch flattening propagate abnormal biomechanical loading to adjacent articular structures, elevating peripheral injury risk. This mechanistic pathway is corroborated within the present cohort: two of ten participants sustained deltoid ligament injuries, and one experienced an ankle sprain. Pain and morphological remodeling may establish a self-amplifying vicious cycle: plantar edema and aberrant pressure distribution generate nociception, which elicits protective compensatory gait patterns that exacerbate arch collapse and focal soft tissue compression. Reciprocally, arch deformation and soft tissue swelling may amplify localized mechanical loading to potentiate pain perception. This fatigue–deformation–pain positive feedback loop may underpin the progressive elevation of foot injury risk observed throughout multi-day endurance competitions.

This study enriches the library of foot biomechanical datasets collected under extreme wilderness conditions and expands the investigative scope of sports morphological research. Based on these results, several directions for future investigation and event practice are proposed. Future studies may evaluate whether post-stage three-dimensional foot scanning can serve as a routine daily health surveillance tool to screen at-risk participants via rapid morphological quantification or simplified anthropometric measurement. Future interventional studies may test whether dedicated foot recovery strategies—including ice therapy, plantar fascia release protocols, and lower-limb elevation—can mitigate soft tissue edema and slow the accumulation of arch fatigue. Footwear

optimization for adolescent competitors warrants empirical evaluation: race shoes with volumetric forefoot and heel clearance may accommodate exercise-induced swelling and avoid constrictive fit that exacerbates soft tissue trauma, while custom arch-support insoles may augment external static load bearing to reduce mechanical strain and collapse risk. Finally, pre-event conditioning regimens integrating intrinsic foot muscle and lower-limb stabilizer training, alongside structured uneven-terrain locomotion drills, may improve arch fatigue resistance and gait control on heterogeneous surfaces, potentially mitigating injury susceptibility via baseline neuromuscular adaptation.

Several limitations exist in the present study. Firstly, constrained by field environmental conditions, the sample size recruited in this research was relatively small. Only male adolescents were enrolled, with no female participants or subgroups stratified by pubertal developmental stage included, which restricts the generalizability of the findings. Secondly, only static weight-bearing standing foot morphology was quantified; synchronous dynamic plantar pressure distribution, three-dimensional gait kinematics, and surface electromyography data were not acquired. Direct causal inference linking morphological shifts to biomechanical loading cannot be established, and mechanistic underpinnings require further empirical validation.

Conclusion

Three-day, two-night Gobi endurance trekking did not induce significant changes in external foot contour dimensions reflecting the underlying bony framework, but induced heel soft tissue edema and functional collapse of the medial foot arch, accompanied by cumulative effects of systemic fatigue, reduced muscle strength, and exercise-related pain. Synergistic interactions between localized foot soft-tissue deformation and systemic fatigue and pain may constitute a critical mechanism underlying elevated foot injury risk during the race, and represent a core target for on-site injury prevention in such wilderness endurance events. The present dataset expands the body of physiological evidence characterizing adolescent physical exertion under extreme wilderness conditions, delivering substantial practical guidance for safety management and health promotion for adolescent Gobi endurance events.

Abbreviations

CMJ
countermovement jump
RPE
rating of perceived exertion
VAS
visual analogue scale

Declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of Peking University Third Hospital (approval No. M2024512-4.0) and complied with the latest revision of the Declaration of Helsinki. Written informed consent was obtained from all participants and their legal guardians.

Clinical trial number

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

JWang, JZ, HL and SR designed the study, and JWang led the project. JWang, SJ, TX, JWei and TS recruited participants, conducted tests and collected data. JWang and SJ performed all statistical analyses. JWang wrote the first draft of the manuscript. All authors contributed to the manuscript revision and read and approved the final version.

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Data Availability

All data sets analyzed for the current investigation will be provided by the corresponding author to any researcher who makes a reasonable formal request.

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Figures

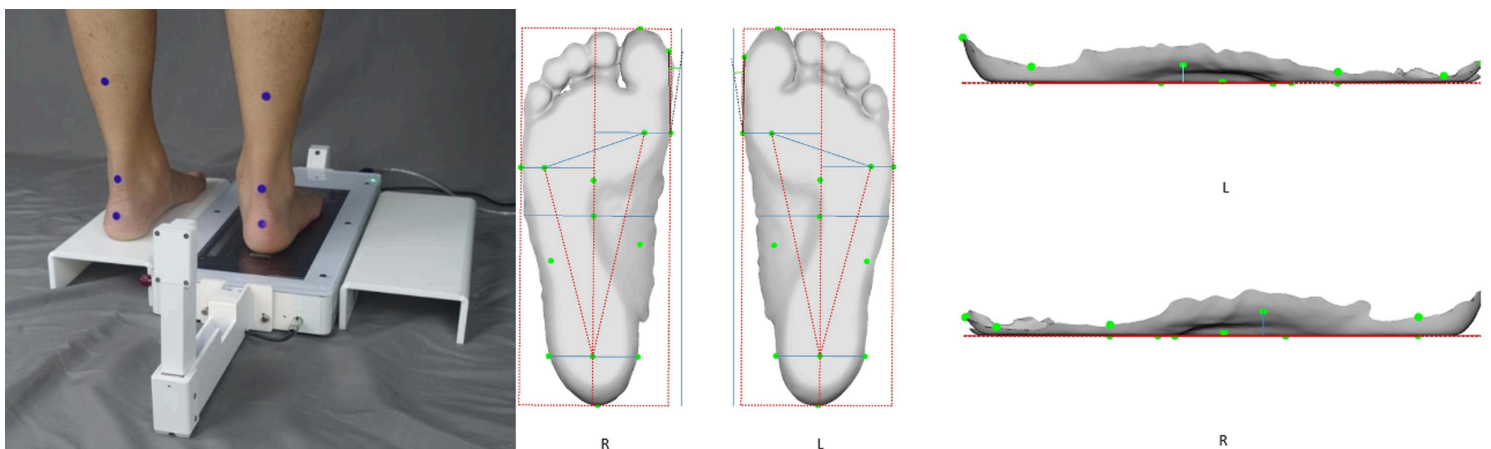


Figure 1

Scanning setup and reconstructed foot morphology generated by the 3D foot scanner

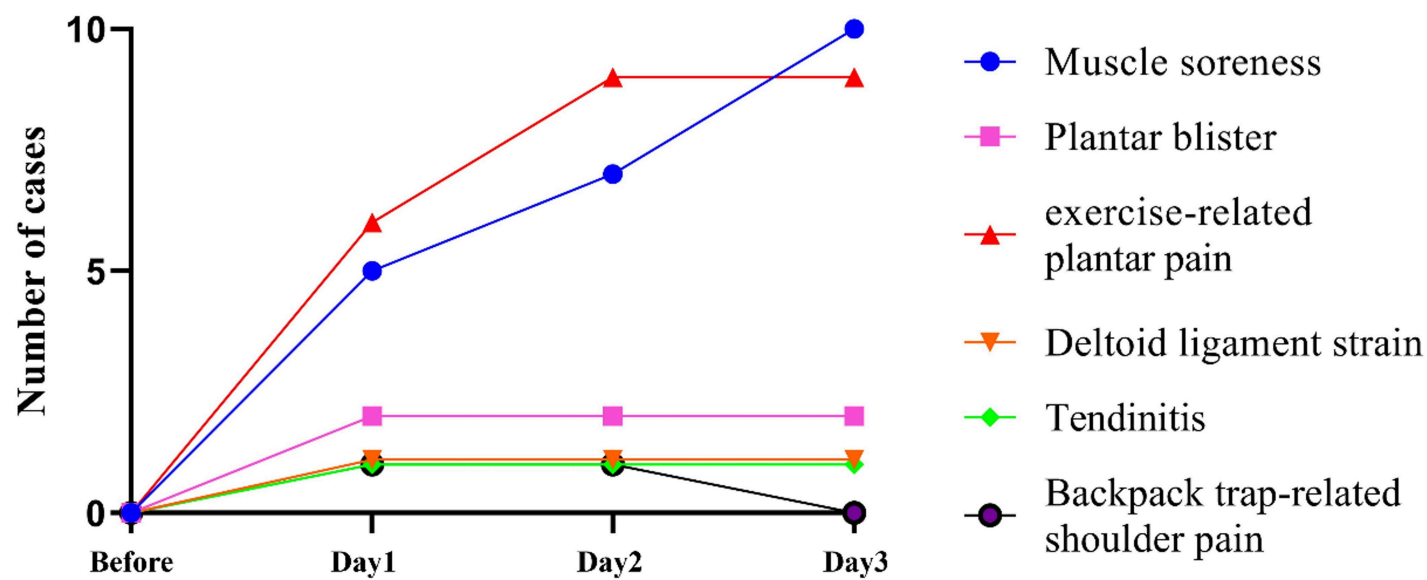


Figure 2

Temporal trends of exercise-related Symptoms and Discomforts

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