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original research

High-Intensity Running and Plantar-Flexor Fatigability and Plantar-Pressure Distribution in Adolescent Runners

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Context: Fatigue-induced alterations in foot mechanics may lead to structural overload and injury.

Objectives: To investigate how a high-intensity running exercise to exhaustion modifies ankle plantar-flexor and dorsiflexor strength and fatigability, as well as plantar-pressure distribution in adolescent runners.

Design: Controlled laboratory study.

Setting: Academy research laboratory.

Patients or Other Participants: Eleven male adolescent distance runners (age = 16.9 ± 2.0 years, height = 170.6 ± 10.9 cm, mass = 54.6 ± 8.6 kg) were tested.

Intervention(s): All participants performed an exhausting run on a treadmill. An isokinetic plantar-flexor and dorsiflexor maximal-strength test and a fatigue test were performed before and after the exhausting run. Plantar-pressure distribution was assessed at the beginning and end of the exhausting run.

Main Outcome Measure(s): We recorded plantar-flexor and dorsiflexor peak torques and calculated the fatigue index. Plantar-pressure measurements were recorded 1 minute after the start of the run and before exhaustion. Plantar variables (ie, mean area, contact time, mean pressure, relative load) were determined for 9 selected regions.

Results: Isokinetic peak torques were similar before and after the run in both muscle groups, whereas the fatigue index increased in plantar flexion (28.1%; $P = .01$) but not in dorsiflexion. For the whole foot, mean pressure decreased from 1 minute to the end (–3.4%; $P = .003$); however, mean area (9.5%; $P = .005$) and relative load (7.2%; $P = .009$) increased under the medial midfoot, and contact time increased under the central forefoot (8.3%; $P = .01$) and the lesser toes (8.9%; $P = .008$).

Conclusions: Fatigue resistance in the plantar flexors declined after a high-intensity running bout performed by adolescent male distance runners. This phenomenon was associated with increased loading under the medial arch in the fatigued state but without any excessive pronation.

Key Words: ankle, medial longitudinal arch, isokinetic exercise, pronation

Key Points

- High-intensity running to exhaustion affected resistance to fatigue of the ankle plantar flexors in adolescent male athletes.
- Loading increased under the medial arch in the fatigued state without excessive pronation.
- Mechanisms underpinning fatigue-induced pronation should be interpreted with caution because these adaptations are complex and multifactorial.

Researchers have reported changes in plantar-pressure distribution, including increased peak plantar-pressure and impulse values in the forefoot and concomitant reductions under the toe areas, among individuals running in a fatigued state.[1,2] A top-down theory,[3] in which the proximal musculature (weakness or fatigue) at the hip may be contributing to the changes in distal joint mechanics, may be a plausible framework. This shift in load from the toes to the metatarsal heads also may arise from fatigue in the lower limb and foot musculature (ie, the toe flexor muscles[2] or the ankle plantar flexors[1]) and may be explained by reductions in the stretch-shortening capabilities of the plantar flexors, subsequently leading to reduced toe-off efficiency.[4] Researchers[5,6] have proposed 2 other mechanisms. First, in fatigued conditions, participants may change from a heel-toe to midfoot landing strategy.[5] Second, increased first metatarsal loading may reflect an increase in foot pronation induced by fatigue of the musculature responsible for controlling this movement.[6,7] In the last decade, dynamic plantar pressure has been used widely to assess the pressure distribution under the feet of participants with pathologic conditions and under normal feet. Although no direct link between plantar pressure and joint motion has been established, investigators[8,9] think that some changes in plantar-pressure distribution, such as excessive peak plantar pressure under the medial forefoot and midfoot or a decrease in peak plantar pressure under the lateral forefoot and midfoot, reflect excessive pronation. Overall, changes in subtalar alignment during the stance phase (ie, excessive pronation) lead to subsequent changes in plantar-pressure distribution.[8,9]

Fatigue due to high-intensity running can lead to alterations in lower limb biomechanics, including increased impact forces[7] and increased rear-foot motion.[10] These alterations may result in overload of the bony structures in the legs and feet, increasing the potential for overuse injury,[1] especially in adolescent distance runners with immature skeletal development.[10] Indeed, in adolescent athletes, endurance sports that involve recurrent, regular cyclic stressing of the lower extremities may lead to stress fractures in the metatarsal bones.[10]

Isokinetic dynamometry assessments, which involve calculating changes in peak torque from pre-exercise to postexercise, are relevant for assessing muscle-force changes in muscle function after fatiguing exercise.[11] Specific isokinetic protocols to assess muscle fatigability have been proposed and involve a predetermined number of reciprocal maximal concentric contractions at a given angular velocity.[12–14] Despite the emergence of such tests, isokinetic measures have rarely been used to assess the torque changes induced by a running bout.[4,15] Moreover, to our knowledge, the relationship between lower limb muscle fatigability and alterations in plantar-pressure distribution during a run to exhaustion has not been investigated. Therefore, the purpose of our study was to determine the extent to which running to exhaustion modified plantar-flexor and dorsiflexor strength and fatigability and plantar-pressure distribution. We hypothesized that (1) running-induced fatigue would result in loss of plantar-flexor and dorsiflexor strength and endurance and (2) changes resulting from localized calf-muscle fatigue may be associated with abnormal loading (eg, increased peak plantar pressure at the medial forefoot and midfoot).

METHODS

Participants

Based on the results of a previous study,[16] we used a priori analyses to determine sample sizes. Assuming a difference in means of 10 N·m in ankle peak-torque measurements, a sample size of 8 to 11 was required for an α level of .05 and statistical power of 0.8. Therefore, 11 male adolescent distance runners (age = 16.9 $\pm$ 2.0 years, height = 170.6 $\pm$ 10.9 cm, mass = 54.6 $\pm$ 8.6 kg, maximal aerobic speed = 18.7 $\pm$ 1.5 $km \cdot h^{-1}$) were recruited and completed the study. We conducted this study in a sports academy located in the Middle East and tested only male adolescents. The average competitive experience of these male adolescent distance runners was 4 years. All participants were healthy and pain free during the testing period, had no history of musculoskeletal dysfunction or injuries of the lower limbs in the 2 months preceding testing, and were registered on the academy middle-distance running team for at least 3 seasons. These athletes had participated in previous experiments involving treadmill running, in-shoe dynamic-pressure measurement, and isokinetic testing.

Before the experiment, the participants were familiarized with the purpose and importance of the study and safety measures regarding the experimental setup. All participants and their parents or guardians provided written informed consent, and the study was approved by the ASPIRE Academy for Sports Excellence Ethics Committee.

Experimental Protocol

Three testing sessions were organized and separated by 1 week. A familiarization protocol was conducted a few days before the first session to introduce the experimental procedures to the participants (Figure 1). In this session, we focused on explaining the testing protocol and demonstrating and having the participants practice the isokinetic testing (ie, 2 sets of 6 contractions in concentric and eccentric modes) while avoiding compensations. At the first session, participants completed an incremental test to exhaustion on a treadmill (h/p/cosmos, Nussdorf-Traunstein, Germany) to define their velocities at maximal oxygen uptake ($v\dot{V}O_2max$). The second session was performed with the participants in a nonfatigued state using a bicycle ergometer (model Cyclone 530C; Cybex International, Medway, MA) and a treadmill for the warm-up (Figure 1A). Next, we obtained isokinetic measurements. For the third session, participants performed in a fatigued state. This session included constant-pace running exercise to exhaustion (T_{lim}) and, within 3 minutes of completion, isokinetic measurements and blood lactate sampling (Figure 1B).

Determination of Velocity at Maximal Oxygen Uptake

The first testing session consisted of an initial 1-minute workload of 8 $km \cdot h,^{-1}$ followed by increases of 1 $km \cdot h^{-1}$ every minute at a 1% slope. Gas exchange was measured using a breath-by-breath analyzer (model Oxycon Pro; Jaeger, Hoechberg, Germany). Maximal oxygen uptake was 63.3 $\pm$ 4.4 $mL \cdot min^{-1} \cdot kg^{-1}$ and its associated velocity was 18.7 $\pm$ 0.9 $km \cdot h^{-1}$.

Running Exercise to Exhaustion

The third testing session consisted of a T_{lim} at 95% $v\dot{V}O_2max$ on a 1% slope on a treadmill. The participants ran until they had to terminate the run due to fatigue. During the T_{lim}, the rate of perceived exertion (RPE) was recorded every minute.[17] After 3 minutes, the lactate concentration was determined from a capillary blood sample using the same procedure as for the $v\dot{V}O_2max$ determination test.[18] We measured the lactate value to confirm the high levels of exercise intensity and exhaustion.

Maximal Isokinetic Strength and Fatigue-Resistance Tests

Plantar-flexor and dorsiflexor maximal voluntary isokinetic concentric contraction and maximal voluntary isokinetic eccentric contraction strength and fatigue resistance were evaluated for the right ankle on the Humac Norm System dynamometer (CSMI, Soughton, MA; Figure 1C). Good levels of validity and reliability have been reported for this equipment.[19] We elected to test participants only in the concentric mode to minimize the risk of

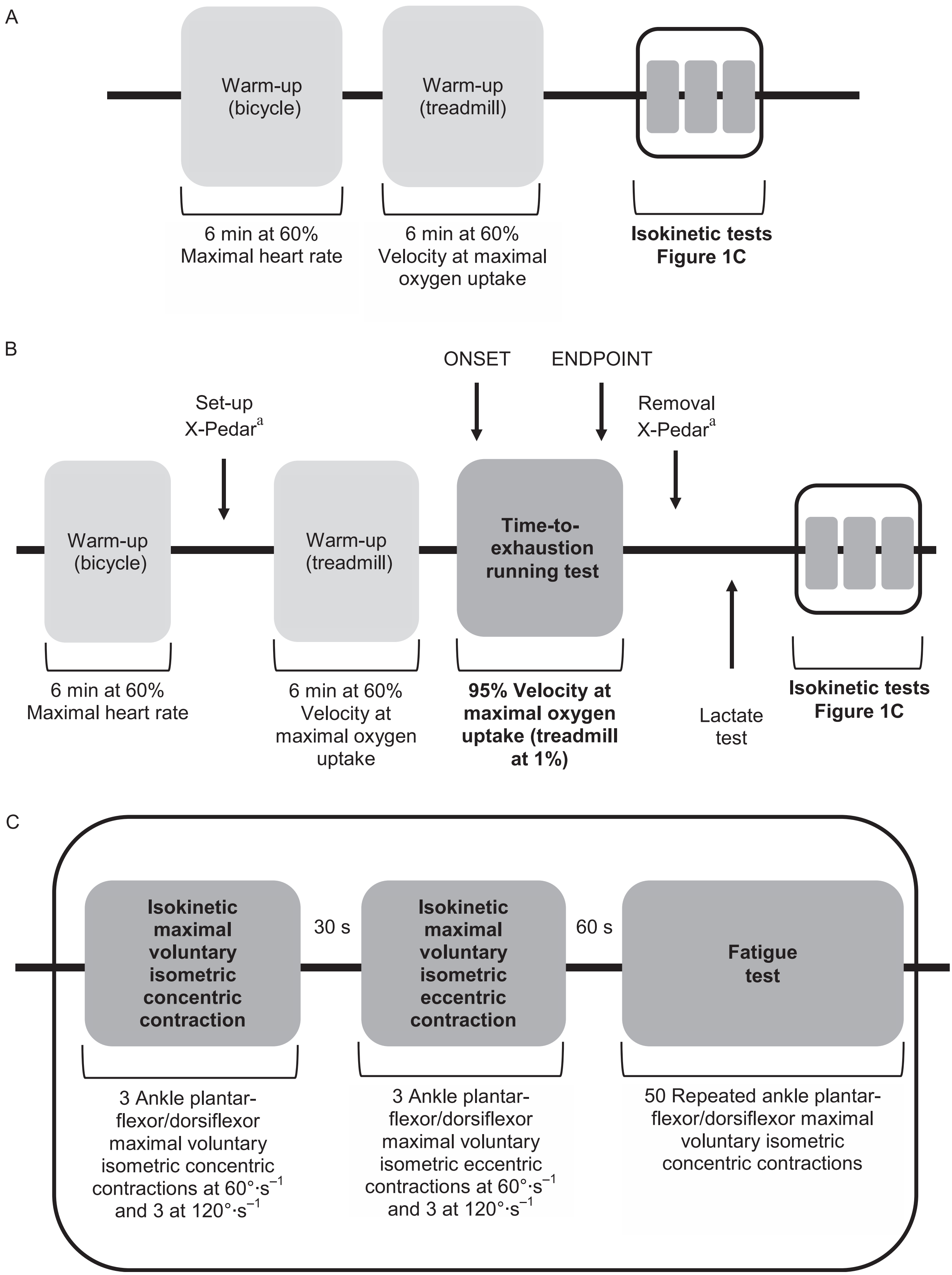

Figure 1. Experimental protocol performed before and after the running bout to exhaustion. A, Testing session 2 in the nonfatigued state. B, Testing session 3 in the fatigued state. C, Detailed procedure of the isokinetic testing. [a] X-Pedar Mobile System (Novel GmbH, Munich, Germany).

Table 1. Maximal Isokinetic Strength and Fatigue Tests in Plantar Flexion and Dorsiflexion Before and After the Running Exercise to Exhaustion

Movement	Measurement	Velocity,[a] Mode	Running to Exhaustion (Mean ± SD) Before	After	*P* Value	Effect Size
Plantar flexion	MVIC, N·m	$60° \cdot s^{-1}$, Concentric	50.5 ± 14.3	52.2 ± 11.4	.87	1.23, Large
		$120° \cdot s^{-1}$, Concentric	38.5 ± 11.1	40.9 ± 11.2	.61	0.22, Small
		$60° \cdot s^{-1}$, Eccentric	87.0 ± 23.3	87.8 ± 28.4	.93	0.03, Trivial
		$120° \cdot s^{-1}$, Eccentric	80.9 ± 22.2	74.5 ± 22.0	.56	0.29, Small
	Fatigue index, %[b]	Concentric	−23.8 ± 6.0	−30.5 ± 4.7	.01[a]	1.30, Large
Dorsiflexion	MVIC, N·m	$60° \cdot s^{-1}$, Concentric	20.6 ± 6.2	21.5 ± 5.5	.81	0.14, Trivial
		$120° \cdot s^{-1}$, Concentric	15.6 ± 3.5	16.4 ± 3.7	.84	0.23, Small
		$60° \cdot s^{-1}$, Eccentric	41.6 ± 11.4	41.2 ± 12.0	.91	0.04, Trivial
		$120° \cdot s^{-1}$, Eccentric	44.0 ± 13.3	44.8 ± 12.6	.98	0.06, Trivial
	Fatigue index, %	Concentric	−27.6 ± 6.9	−32.0 ± 5.4	.12	0.73, Moderate

Abbreviation: MVIC, maximal voluntary isokinetic contraction.

[a] Where applicable.

[b] $t_{20} = 2.93$, $P = .01$.

muscle injury associated with delayed-onset muscle soreness. Force-generation decrements associated with delayed-onset muscle soreness may persist beyond 1 week,[20] although our testing protocol only permitted 1 week between isokinetic tests.

Despite the importance of some ankle invertor-evertor muscles (eg, tibialis posterior) in controlling pronation, we did not test these muscle groups. The inability of the isokinetic dynamometer axis to match the alignment of the true axis of the eversion-inversion rotation and the risk of excessively lengthening our protocol by adding several testing trials convinced us not to assess these muscle groups.

Each participant lay supine with the hip and knee flexed to 60° and the lower leg supported in the horizontal position, as described in the owner's manual of the Humac Norm System and in previous research.[21,22] The axis of the dynamometer was aligned with the plantar-flexion–dorsiflexion axis of the ankle joint. We used straps to stabilize the ankle, leg, knee, pelvis, and chest. Handles were set and adjusted on both sides of the seat, allowing more participant stability. Oral encouragement instructed participants to push as hard as possible. The gravity-correction mode was activated in the software of the isokinetic device before testing. We set ankle range of motion to 10° of dorsiflexion and 20° of plantar flexion during familiarization and testing. The 90° position of the ankle was defined as the neutral 0° position.

Plantar-flexor and dorsiflexor maximal voluntary isokinetic concentric contraction and maximal voluntary isokinetic eccentric contraction were recorded at $60° \cdot s^{-1}$ and $120° \cdot s^{-1}$ over 3 contractions, as in previous studies (Figure 1C).[21–23] We obtained the peak torque (PT) of each contraction for the plantar flexors and dorsiflexors and used the highest value among the 3 contractions for further analysis.

Isokinetic fatigue resistance (ie, prefatigability and postfatigability) was assessed over 50 maximal voluntary isokinetic concentric contractions at $30° \cdot s^{-1}$ for the plantar flexors and at $120° \cdot s^{-1}$ for the dorsiflexors. We chose different velocities for isokinetic contractions of the plantar-flexor and dorsiflexor muscles to reach similar times to fatigue for both muscle groups as in previous studies.[12,23] Based on the changes in torque over 50 contractions, a fatigue index was calculated for the plantar flexors and dorsiflexors as follows[13]:

$$\text{Fatigue index} = \left(100 \times \left[\frac{\text{total PT}}{\text{ideal PT}}\right]\right) - 100,$$

where total PT is the sum of PT over 50 contractions and ideal PT is the product of the number of contractions and the best PT.

Plantar-Pressure–Distribution Measures

During the T_{lim}, insole plantar-pressure distribution was recorded using the X-Pedar Mobile System (Novel GmbH, Munich, Germany). Each pressure insole consisted of a 2-mm-thick array of 99 capacitive pressure sensors. Before data collection, we calibrated new insoles according to the manufacturer's guidelines. One insole was placed under the right foot of all participants, who wore the same type of neutral running shoes (Supernova sequence; Adidas AG, Herzogenaurach, Germany). The data logger for data storage was in a harness on the back of the participant. Plantar pressures were sampled at 50 Hz.[24,25] Plantar-pressure data were recorded over a 30-second period on 2 occasions: (1) 1 minute after exercise started (ONSET) and (2) as soon as the participant reported an RPE of 18, which corresponded to 78 to 84 steps (ENDPOINT). This 30-second window ended in a range of 25 to 45 seconds before exhaustion. We performed a regional analysis using 9 separate "masks" (Groupmask Evaluation; Novel GmbH) or areas of the foot: medial and lateral heel; medial and lateral midfoot; medial, central, and lateral forefoot; and hallux and lesser toes.[26] Mean area (cm^2), contact area (cm^2), contact time (milliseconds), maximal force (N), mean force (N), mean pressure (kPa), peak pressure (kPa), and relative load (ie, the force-time integral in each region divided by the force-time integral for the total plantar-foot surface; %) were determined for the 9 selected regions.

Statistical Analysis

We calculated means and standard deviations for all variables of interest. The effect size (ES) was determined for each test to assess the magnitude and practical relevance of the findings that were different and was interpreted as *trivial* (<0.2), *small* (0.2–0.6), *moderate* (0.6–1.2), *large* (1.2–2.0), *very large* (2.0–4.0), or *nearly perfect* (>4.0).[27] An independent-samples *t* test was used to examine the differences in plantar-loading variables for the whole foot between the ONSET and ENDPOINT conditions (percentage change from ONSET values) and in plantar-flexor– and dorsiflexor-strength and fatigue-resistance variables between pre-T_{lim} and post-T_{lim} (as a percentage change from pre-T_{lim} values). A large number of comparisons led to an inflated type I error in an analysis-of-variance test. Therefore, we applied the Holm correction, which consists of progressive adjustments in the α level based on the number of comparisons and the desired experimental error rate.[28] We also calculated the fatigue-resistance values over the first 30 contractions only as recommended[10] and compared the findings with the values calculated over 50 contractions. A 2-way repeated-measures analysis of variance was performed with condition (ONSET, ENDPOINT) and foot regions (masks 1–9) as the repeated factors and the plantar-loading variables designated as dependent variables. This analysis revealed the global effect of foot region and the interaction between the ONSET and ENDPOINT conditions and foot regions. When we observed main effects, we used post hoc Tukey analyses to identify differences among means. Pearson product moment correlation coefficients were used to examine the relationships between isokinetic values pre-T_{lim} and changes in plantar-pressure variables from ONSET to ENDPOINT. The statistical analyses were performed using SigmaStat software (Jandel Corporation, San Rafael, CA). The α level was set at .05. Statistical power was calculated for an α level of .05 and a β level of .2.

RESULTS

Running Performance

The mean running speed during T_{lim} was 17.8 ± 1.4 km·h^{-1}. Participants ran at that speed for 8.8 ± 3.4 minutes until exhaustion. The mean lactate level was 104.50 ± 24.3 mg·dL^{-1} (11.6 ± 2.7 mmol·L^{-1}), and the mean RPE before exhaustion was 19.3 ± 0.6.

Maximal Isokinetic Strength and Fatigue-Resistance Tests

The coefficient of variation between maximal-strength trials ranged from 4% to 7%. The highest degree of reproducibility was in the isokinetic torque measurements at slow speed in the concentric mode (60°·s^{-1}), whereas the lowest value was at high speed in the eccentric mode (120°·s^{-1}). The maximal voluntary isokinetic concentric and eccentric contractions remained unchanged from pre-T_{lim} and post-T_{lim} in both muscle groups (Table 1).

The fatigue index calculated over 50 repetitions was reduced in the plantar flexors but not in the dorsiflexors (Table 1). Over the first 30 repetitions, the index was also reduced in the plantar flexors (29.7%; $P = .04$, power = 0.49, ES = 1.09) but not in the dorsiflexors (17.3%; $P = .16$, power = 0.17, ES = 0.64). Therefore, we found no

Table 2. Area, Force, Pressure, Relative Load, and Contact Time for Each Foot Region at the Beginning (ONSET) and End (ENDPOINT) of the Running Exercise to Exhaustion

			Foot Region								
Variable (Mean ± SD)	Measure	Whole Foot	Medial Heel 1	Lateral Heel 2	Medial Midfoot 3	Lateral Midfoot 4	Medial Forefoot 5	Central Forefoot 6	Lateral Forefoot 7	Hallux 8	Lesser Toes 9
Area, cm^2	ONSET	115.3 ± 7.4	11.1 ± 2.5	7.5 ± 3.8	15.7 ± 2.6	18.7 ± 1.7	11.7 ± 1.4	13.3 ± 1.1	13.1 ± 0.8	8.9 ± 0.7	15.2 ± 1.5
	ENDPOINT	117.5 ± 9.2[a]	11.3 ± 2.1	7.8 ± 4.0	17.2 ± 3.1[b]	19.2 ± 2.3	11.9 ± 1.3	13.4 ± 1.0	12.9 ± 1.1	8.8 ± 0.7	14.9 ± 1.3
Force, N	ONSET	1020.2 ± 163.3	72.7 ± 35.3	50.2 ± 38.8	77.5 ± 20.9	146.5 ± 36.3	152.9 ± 44.6	167.7 ± 60.2	124.5 ± 37.3	106.1 ± 16.5	120.4 ± 24.7
	ENDPOINT	991.9 ± 170.6	71.6 ± 25.0	48.3 ± 30.9	80.8 ± 20.3	145.4 ± 41.0	146.2 ± 42.2	161.4 ± 64.4	119.8 ± 41.6	100.3 ± 16.3	116.7 ± 26
Pressure, kPa	ONSET	119.8 ± 18.1	96.8 ± 36.6	95.9 ± 40.2	66.7 ± 17.3	110.7 ± 22.8	203.9 ± 47.1	197.2 ± 56.6	143.4 ± 32.2	176.7 ± 28.6	111.7 ± 20.7
	ENDPOINT	115.8 ± 18.5[c]	102.8 ± 31.9	99.3 ± 31.7	64.9 ± 14.5	110.2 ± 23.6	200.8 ± 45.2	193.7 ± 60.6	142.4 ± 35.6	175.1 ± 36	113.9 ± 25.2
Relative load, %	ONSET	Not applicable	7.3 ± 3.5	4.9 ± 3.4	7.8 ± 2.4	14.4 ± 2.9	14.9 ± 3.4	16.2 ± 3.9	12.1 ± 2.4	10.5 ± 1.6	12.0 ± 2.3
	ENDPOINT	Not applicable	7.5 ± 2.9	4.9 ± 3.1	8.3 ± 2.3[b]	14.6 ± 2.9	14.7 ± 3.3	15.9 ± 3.8	11.9 ± 2.6	10.3 ± 1.8	11.9 ± 2.4
Contact time, ms	ONSET	180.4 ± 13.1	128.9 ± 27.1	126.4 ± 26.7	178.1 ± 14.1	177.6 ± 13.6	169.2 ± 9.8	176.4 ± 12.3	179.6 ± 13.6	166.1 ± 13.5	174.3 ± 9.7
	ENDPOINT	193.2 ± 20.4	144.3 ± 42.4	146.5 ± 41.4	190.6 ± 22.0	191.6 ± 21.5	186.7 ± 20.9	191.0 ± 21.1[d]	192.3 ± 20.8	182.0 ± 27.1	189.8 ± 20.5[b]

[a] Difference between ONSET and ENDPOINT ($t_{20} = -1.63$, $P < .05$).
[b] Difference between ONSET and ENDPOINT ($P < .01$).
[c] Difference between ONSET and ENDPOINT ($t_{20} = 1.52$, $P = .003$).
[d] Difference between ONSET and ENDPOINT ($P < .05$).

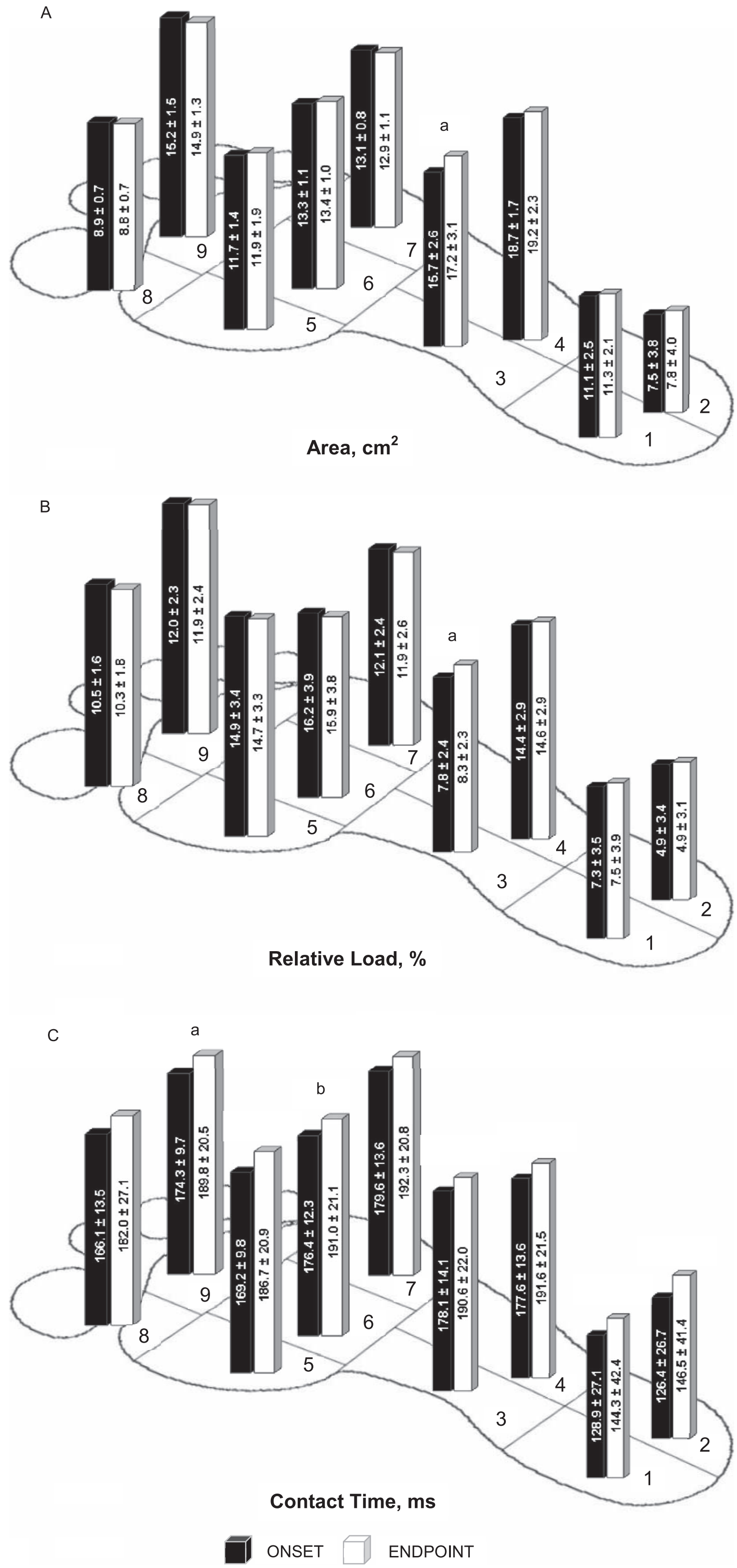

Figure 2. A, Mean area (mean ± SD). B, Relative load. C, Contact time for each foot region at the start (ONSET) and at the end (ENDPOINT) of the running bout to exhaustion. [a] Indicates difference between ONSET and ENDPOINT ($P < .01$). [b] Indicates difference between ONSET and ENDPOINT ($P < .05$).

difference when comparing fatigue-resistance values calculated over 30 and 50 contractions.

Plantar-Pressure–Distribution Measures

Plantar-pressure measures for each foot region at the ONSET and ENDPOINT are presented in Table 2. For the whole foot, mean pressure was reduced at the ENDPOINT when compared with the ONSET (t_{20} = 1.52, P = .003, power = 0.93, ES = 0.22). We noted interaction (condition × region) effects on plantar-pressure distribution in mean area ($F_{8,10}$ = 36.57, $P < .001$), relative load ($F_{8,10}$ = 16.67, $P < .001$), and contact times ($F_{8,10}$ = 37.18, $P < .001$). Post hoc comparisons showed an increased mean area (P = .005, power = 0.90, ES = 0.52) and relative load (P = .009, power = 0.80, ES = 0.21) during fatigued conditions (Figure 2A and B), whereas contact time increased under the central forefoot (P = .01, power = 0.77, ES = 0.85) and the lesser toes (P = .008, power = 0.83, ES = 0.97; Figure 2C).

The percentage change in the fatigue index for the plantar flexors was negatively correlated with the percentage change in mean pressure under the whole foot (r = –0.68, P = .02) and the percentage change in mean area at the toes (r = –0.62, P = .04) but was positively correlated with the percentage change in mean area at the medial midfoot (MLA; r = 0.68, P = .02). The T_{lim} duration was correlated with the percentage changes in the contact area from the ONSET to the ENDPOINT at the MLA (r = 0.74, $P < .01$).

DISCUSSION

We wanted to determine the extent to which a running exercise to exhaustion modified plantar-flexor and dorsiflexor strength and fatigability and plantar-pressure distribution. In this group of adolescent middle-distance runners, isokinetic strength was not lost in either the plantar flexors or dorsiflexors from pre-T_{lim} to post-T_{lim}. However, the fatigue index calculated over 50 repetitions was reduced in the plantar flexors but not in the dorsiflexors. Interestingly, these results were not different when calculated over the first 30 contractions only (plantar flexors: 29.7%, P = .04, power = 0.49, ES = 1.09; dorsiflexors: 17.3%, P = .16, power = 0.17, ES = 0.64), as recommended,[10] versus the values we calculated over 50 contractions. These changes affecting only the plantar flexors are in line with previous studies in which the plantar flexors of adults were subjected to fatigue after prolonged[29,30] or shorter-term (ie, 13-minute) running.[1] As suggested,[5] one may assume that, to manage fatigued conditions at such a high running speed, the participants unconsciously engaged a midfoot landing strategy, which consequently altered the loading demands on the plantar flexors. Overall, high-intensity, running-induced fatigue appears to lead to different adaptations in the plantar flexors and dorsiflexors in terms of fatigue resistance. This imbalance between the plantar flexors and dorsiflexors may compromise the protective action of these muscles on the lower leg and affect foot-loading patterns.[31]

We observed increases in the relative load and the mean area under the MLA when participants neared exhaustion. The MLA is a deformable structure that can flatten up to 10 mm and change its length approximately 4 mm during midstance.[32] It plays an important role in transferring ground reaction forces through the foot to the rest of the body.[33] According to the literature[8,9] regarding the relationship between excessive peak-plantar pressure at the MLA and pronation, our results showing that peak plantar pressure under the MLA in a fatigued state did not change indicated that, although more loaded, the MLA did not really collapse and the foot-ankle region did not fall into excessive pronation. Our findings suggest that the MLA maintained its mechanical properties as a load-absorbing structure.

The positive correlation between exercise duration and the percentage changes in contact area from the ONSET to the ENDPOINT at the MLA tended to confirm that MLA changes make an important contribution to load absorption when a runner becomes fatigued.

Interestingly, the greater posttest fatigability of the plantar flexors (ie, increased fatigue index from pre-T_{lim} to post-T_{lim}) was positively correlated with a larger mean contact area under the MLA. This finding points to a close and inverse relationship between the plantar flexors and the MLA. Recently, Kelly et al[34] reported that running with foot orthoses for 60 minutes led to reductions in ankle plantar-flexor fatigue. They hypothesized that the increased foot pronation might lead to fatigue in the ankle plantar flexors. More precisely, they suggested that a compliant MLA (ie, increased pronation) may diminish the quality of force transmission through the foot in the stance phase. Therefore, the plantar flexors may have to produce more work to maintain a constant running velocity. This proposal also aligns well with our finding that participants who had increased foot pronation at the end of their runs also displayed increased ankle plantar-flexor fatigue. Weist et al[1] proposed an alternative viewpoint: that with decreased plantar-flexor activity during fatigue, the supinatory action of these muscles is reduced and the pronation is more pronounced, resulting in increased loading under the MLA. Moreover, mean pressures decreased under the whole foot from pre-T_{lim} to post-T_{lim}, which is in opposition to earlier findings[1,2,35] regarding plantar distribution in the fatigued state. Even if the underlying mechanisms are unclear and probably unconscious, this phenomenon appears to constitute a beneficial and protective adaptation of the plantar patterns of adolescent runners. It may partially prevent the bony structures from the overload usually sustained while running in a fatigued state.

We also observed an increase in the contact times under the central forefoot and the lesser toes. Researchers[4,36] have reported that such an increase in contact times may result from an altered stretch-shortening cycle. However, increased contact times likely allowed the participants to maintain a constant horizontal impulse despite the decrease in neuromuscular capacity due to fatigue.[37]

Our experiment had strengths, such as the uniqueness of the population, the validity of the protocol, and the relationships between the lower capacities of some muscles and plantar-pressure distribution. Nevertheless, it also had limitations that need to be considered. For instance, the small sample size most likely affected the strength of the statistical analysis according to the power and ES.

Practically, our findings demonstrated increased loading under the MLA in a fatigued state but without any increase in peak plantar pressure, which may indicate an absence of excessive pronation. It could be that the relative load increase under the MLA constitutes the first step of a pronation process, resulting ultimately in a degree of excessive pronation that was not reached in our study, probably due to the shorter running time in our experiment compared with previous studies.[1,2,35] Therefore, reinforcing the structures that control pronation may be helpful to postpone or minimize excessive pronation. This may assist in preventing numerous lower extremity pathologic conditions that are related to excessive pronation[38] and occur frequently in adolescent athletes.[39] The augmented compliance of the MLA under fatigue may result in an increased plantar-flexor workload, leading to localized fatigue. Improving the strength or endurance of all the muscles controlling pronation, especially the tibialis posterior, should be a priority to prevent pronation-related injuries. In light of our findings, we also recommend implementing exercises to strengthen the calf muscles and intrinsic foot musculature, especially in the fatigued state. Electromyostimulation of the abductor hallucis has been described as a promising technique,[38,40] but this modality must be applied carefully in immature adolescent athletes.

CONCLUSIONS

Ankle plantar-flexor resistance to fatigue was affected by a high-intensity running exercise to exhaustion. This phenomenon was associated with increased loading under the MLA in a fatigued state but without excessive pronation. Caution is needed when interpreting the mechanisms underpinning fatigue-induced pronation, as these adaptations are complex and multifactorial.

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