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Original article

Muscle activity and kinematics of forefoot and rearfoot strike runners

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Abstract

Background: Forefoot strike (FFS) and rearfoot strike (RFS) runners differ in their kinematics, force loading rates, and joint loading patterns, but the timing of their muscle activation is less clear.
Methods: Forty recreational and highly trained runners ran at four speeds barefoot and shod on a motorized treadmill. "Barefoot" runners wore thin, five-toed socks and shod runners wore neutral running shoes. Subjects were instructed to run comfortably at each speed with no instructions about foot strike patterns.
Results: Eleven runners landed with an FFS when barefoot and shod and eleven runners landed with an RFS when barefoot and shod. The 18 remaining runners shifted from an FFS when barefoot to an RFS when shod (shifters). Shod shifters ran with a lower stride frequency and greater stride length than all other runners. All FFS runners landed with more plantarflexed ankles and more vertical lower legs at the beginning of stance compared to RFS runners. FFS runners activated their plantarflexor muscles 11% earlier and 10% longer than RFS runners.
Conclusion: This earlier and longer relative activation of the plantarflexors likely enhances the capacity for the passive structures of the foot and ankle to store elastic energy, and may also enhance the performance of the active muscle by increasing the storage of elastic strain energy in the cross-bridges and activated titin.

Keywords: Barefoot; Forefoot strike; Gastrocnemius; Muscle activity; Rearfoot strike; Running

1. Introduction

In modern times, runners usually land on their heels using cushioned running shoes to absorb the impact.[1−3] The differences in foot position during landing are used to classify various running styles; "toe-heel-toe" running or forefoot strike (FFS), "flat-footed" running with a midfoot strike (MFS), or "heel-toe" running with a rearfoot strike (RFS).[4−6] The majority of habitual barefoot runners FFS or MFS, while the majority of habitual shod runners RFS.[5−9] Due to the lower occurrence of both FFS and MFS runners (5%−25%), they are often grouped together as an FFS running style, where the point of impact of the foot occurs anterior to the ankle joint.[5,7,8] These FFS and MFS running styles will result in similar dorsiflexion torques about the ankle and presumably similar muscle activation patterns to absorb that impact.

FFS runners experience no impact peak and lower loading rates of the ground reaction force compared to RFS runners.[3,5,10−12] Despite the higher load rate and magnitude of the impact peak during RFS running, RFS runners are more prevalent in modern times due to the development of the running shoe with a cushioned heel.[1] Before the cushioned heel in running shoes, humans ran without this protection and likely ran more often on the balls of their feet reducing the

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landing impact[5,11−14] and enhancing the storage and release of energy by the elastic structures in the leg and foot.[3,9,13,15]

Although most runners have a habitually preferred style, they can generally convert from an RFS style to an FFS style or *vice versa*, when requested.[9,15−17] For example, some habitually shod RFS runners can readily convert to an FFS style when running barefoot to reduce the pressure on their heels using similar kinematics and mechanics as habitual FFS runners.[12,17−19]

General gait kinematics (stride length and stride frequency) have been well studied when examining FFS and RFS running. FFS runners run with shorter stride lengths, higher stride frequencies, and shorter contact times with the ground.[11,16,20] FFS runners flex their knees more at strike, shortening their stride.[5,16,19] Bending the knees shortens the stride length during FFS running, which correspondingly increases the stride frequency.[2] Additionally a higher stride frequency means each stride takes less time resulting in shorter contact times with the ground.[11] Shorter stride lengths during FFS running also allow the runners to land with a more plantarflexed ankle and flatter foot to allow for the toe-heel-toe running style.[3,11−14,19]

Although the kinematics and landing forces have been well studied, the muscle activation patterns of barefoot or FFS running have been less commonly examined.[19,20] Habitual RFS runners activate their calf muscles differently in amplitude between barefoot and shod running.[20] For example, the pre-activation amplitude of the medial and lateral gastrocnemius muscles (MG and LG) are 24% and 14% greater, respectively, when barefoot compared to the shod condition using an RFS style.[20] The EMG amplitude of the gastrocnemius jumps to 400%−450% for the pre-activation, increases by only 28% during the stance phase, and are similar during the take-off phase during FFS running compared to that of RFS running.[19] The pre-activation of the plantarflexor muscles before landing would increase tension in the Achilles tendon allowing absorption of the impact of landing.[2,19,21] Furthermore, the activation of the plantarflexor muscles will stretch the tendons in the shank and foot, allowing for enhanced storage of energy in these elastic structures.[9,20] Instead of muscle activation amplitude, the current study focuses on the timing of the plantarflexor activation during FFS and RFS running.

We hypothesize that consistent FFS runners will activate their gastrocnemii muscles earlier than consistent RFS runners in order to stiffen the ankle,[12,16] resist the ground reaction forces acting to dorsiflex the ankle,[13,19,22] and lessen the internal ankle forces.[18] We also hypothesize that runners who switch between FFS and RFS styles depending on their footwear condition will change their muscle activity patterns as they switch between running styles to accommodate the different stride and joint kinematics during FFS *vs.* RFS running.[3,12,13,16,18,19] The current study aims to determine the muscle activity and stride patterns used to compensate for the different impact forces of barefoot and shod running, allowing insight into how FFS and RFS running styles influence the activity patterns of the gastrocnemii muscles and joint kinematics.

2. Materials and methods

2.1. Subjects

Forty runners (20 males and 20 females, ages 18−56, mean age = 29.0 ± 11.9 years) were recruited from Harvey Mudd College and the surrounding community. The subjects measured 1.72 ± 0.10 m in height and 65.15 ± 10.74 kg in weight. Of the 40 subjects, 21 were recreational runners who ran at least 8 miles per week for more than 1 year, while 19 subjects trained regularly and ran competitively, including ultramarathons. Four subjects self-reported using minimal running shoes, two subjects self-reported using Vibram Five-Finger shoes, and all other subjects used typical running shoes. The subjects were instructed to run comfortably at all speeds, with no instructions to use or convert to any particular foot strike pattern. All experiments were performed with Institutional Review Board approval from Harvey Mudd College and the Claremont Graduate University.

2.2. Running regimen

Subjects ran on a motorized treadmill at 2.5, 2.8, 3.2, and 3.5 m/s while wearing five-toed lightweight toesocks (45 g; Injinji, San Diego, CA, USA), which we considered to simulate being "barefoot", and in a neutral running shoe (Asics GEL-Cumulus).[5,9,23] Subjects wore thin toesocks during the "barefoot" condition to hold in place and protect the pressure sensors as well as to prevent injury to the runners from the textured treadmill belt (see Section 2.3; Fig. 1). Since running in unloaded diving socks and Vibram FiveFinger shoes adequately imitate the mechanics and energetics of running barefoot, wearing lightweight five-toed socks should also adequately mimic barefoot running even though the sensory feedback may differ slightly.[9,11,13] The order of speeds while barefoot or shod was randomized. Each subject first ran at a self-selected comfortable speed for 2 min. Then, the subjects ran for 1 min to become adjusted to the new speed before a 30-s data collection period.

2.3. Gait kinematics

The timing of the stride cycles was determined from plantar pressures measured on the bottom of the foot. These plantar pressure forces were collected at 4000 Hz with a wireless data logger and four circular, 0.5″-diameter force sensing resistors placed below the metatarsal heads of the 1st, 4th, and 5th toes and the heel pad (Fig. 1; Myomonitor IV; Delsys Inc., Natick, MA, USA; Interlink Electronics, Camarillo, CA, USA).[24] The pressure sensor system allowed for immediate collection and processing of 20−30 sequential steps.[11,20] The pressure sensors were protected and held in place by five-toed socks (Injinji). Plantar pressure recordings were used to determine the average stride frequency, which in combination with running speed, further provided average stride length. The fraction of the stride period, where plantar pressure was measurable, underestimated the stance phase, because the

Fig. 1. Locations of pressure sensors on the bottom of the right foot (yellow circles). The sensors were placed underneath the 1st, 4th, 5th metatarsal heads and the middle of the heel pad and adhered with paper tape to the lightweight toesock.

plantar pressures did not include the last portion of stance between when the pressure is generated from the balls of the feet to the toes.

The duty cycle, or the fraction of the stride during which one foot was on the ground, was determined from the light video (208 fps; AVT Pike 032C Camera, Allied Vision Technologies, Newburyport, MA, USA).

2.4. Foot strike angle (FSA) determined running style

To determine the running style (FFS *vs*. RFS) used by each runner, FSA was measured at each speed under both barefoot and shod conditions (Fig. 2). FSA, the angle between the horizontal and the line from the ankle to the 5th toe at the time of contact between the runner's foot and the horizontal, was corrected for the rest angle (Fig. 2).[6] Runners were recorded with a high-speed light camera for 6 s of the 30 s recording period (208 fps). Each video trial included at least seven complete strides of running at each speed for each condition. To categorize each trial, FSA $< 8°$ represented an FFS trial and FSA $> 8°$ represented an RFS trial (NIH ImageJ; Fig. 2).[6] The average FSA across the four speeds for each subject determined if the individual ran with an FFS or RFS style when barefoot and when shod. Consistently FFS (CFFS) runners always used an FFS style and consistently RFS (CRFS) runners used an RFS style during both footwear conditions. Runners in the "shifter" group used an FFS when barefoot and an RFS when shod.

2.5. Measuring activity (electromyographical) patterns of the calf muscles

Surface electromyography (sEMG) determined the activity patterns of the medial and lateral gastrocnemii muscles with a wireless data logger and a laptop computer (Myomonitor IV; EMGworks, Delsys Inc.) The subjects wore the myomonitor around their waist with the provided adjustable belt. Over the surface of each muscle, the hair was shaved, if necessary, and the skin surface was lightly exfoliated to increase electrode conductance. Bipolar electrodes (Delsys) were adhered lengthwise along the medial and lateral gastrocnemii muscles one-third of the way down the tibia and at the midpoint of the muscle based on measurements made by a B-mode, real-time ultrasound machine (210DX; 7.5 MHz linear transducer, Medasonics, Mountain View, CA, USA).[25] The wires between the right foot and hip were secured to the leg with self-adherent athletic wrap to minimize movement artifact in the sEMG signal. The Myomonitor, used for collecting sEMG and plantar pressure data, acquired signals at 4000 Hz for 30 s intervals at each speed with recording started by a manual trigger (EMGworks).

Three maximum voluntary contractions (MVC) were recorded by having subjects perform a series of 1 s, maximal-effort seated calf raises at a calf raise weight machine (background of Fig. 2). The sEMG amplitude of the MVC was used to normalize the sEMG amplitudes of the gastrocnemii muscles for each individual. The contractions were isometric, if the subject could not lift the weights, or maximally concentric contractions, if the subject could lift all the weights.

To relate muscle activation to the start of each stride, the plantar pressure recordings were used to quantify the timing of the foot contact with the ground (foot strikes) for each stride, and these time points were used to distinguish the start of each stride in the sEMG patterns. An average stride was generated for each subject at each speed and footwear condition, by overlaying and averaging the sEMG patterns for each stride using custom-written software (MATLAB; Mathworks, Natick, MA, USA). As with the kinematics, the initial contact determined by the plantar pressure recordings was corrected for the initial contact determined by high-speed light video (208 fps).

The sEMG signals were filtered using a second order Butterworth band-pass filter from 20 to 400 Hz with a 60 Hz notch filter. The signal was then rectified and smoothed using a moving average filter (MATLAB). The MVC signals were filtered and recorded in the same way as the running sEMG data. The sEMG amplitude of each speed was determined by averaging the strides to create an average signal at each speed then finding the maximum value from the average stride.[25] Each sEMG signal was also binned and averaged based on a percentage of the gait cycle to determine the timing of the muscle activation patterns for each speed. Custom-written MATLAB software was used to quantify the onset and offset of each sEMG signal. The timing of the smoothed sEMG signal was determined to have a positive or negative

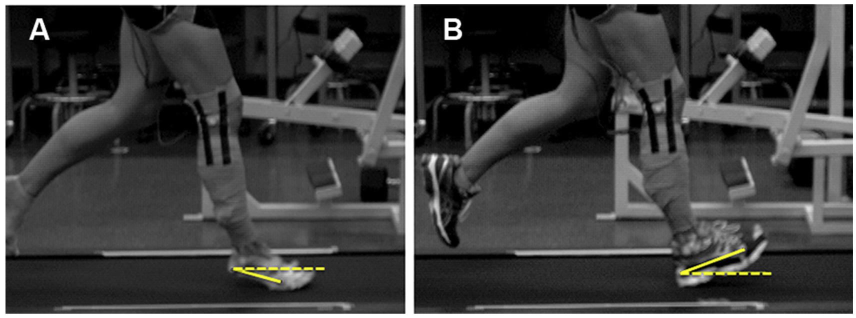

Fig. 2. Foot strike angle (FSA) determined the two strike types differentiated during running. A representative shifter running at 3.2 m/s with a positive FSA (yellow) during a forefoot strike while barefoot (A), and a negative FSA during a rearfoot strike while shod (B). The FSA was measured as the angle between the line from the 5th metatarsal marker to the heel marker (solid yellow) and the horizontal (dashed yellow) at the beginning of stance.

first derivative for onsets and offsets, respectively, and exceeded the threshold of two standard deviations beyond the average noise of the relaxed muscle.

2.6. Joint kinematics of the leg

Three-dimensional (3D) joint kinematics, or joint angle patterns, were collected while subjects ran on the treadmill using three high-speed cameras (Oqus, 148 Hz; Qualisys Motion Capture System; Deerfield, IL, USA). Two-cm, spherical, reflective markers were adhered on the right side of each subject centered on the axis of rotation of five joints (greater trochanter of the femur (hip), the lateral condyle of the femur (knee), the lateral malleolus (ankle), and the first and fifth MTP) to determine the major joints angles of the leg. An additional marker was placed on the lateral surface of the calcaneus (heel) over the sock or the shoe to obtain the FSA (Fig. 2). When barefoot, the calcaneus and MTP markers were placed above the sock; when shod, these markers were placed on their corresponding locations on the shoes. The cameras emit and measure only infrared light. Therefore, each marker simulates the joints and is used to create a computer generated 3D-model that tracks the movement of each subject (Qualisys Motion Caption System).

The 3D position of each marker was used to quantify the joint angle patterns (Qualisys Motion Caption System). The timing of each heel strike from the pressure sensors was used to divide the 30-s trial into gait cycles (MATLAB). The gait cycles were then averaged to determine a typical stride for each joint at each speed under both conditions per subject. Because the plantar pressure sensors determined the onset of pressure of the middle of the heel or the base of the MTP joints, the average gait cycle was then corrected for the initial contact as determined by high-speed light video (208 fps).

2.7. Statistics

Timing (sEMG onset, offset, duration) and amplitude of muscle activation were compared between the FFS, RFS, and shifter groups to examine the variability between the three running styles. The muscle activity and kinematic variables were analyzed using analysis of variance (ANOVA), paired and unpaired t tests. Values from the groups were considered significantly different when $p < 0.05$. All values are reported as mean $\pm$ SD. To minimize clutter, we present the values for the representative speed of 3.2 m/s periodically.

3. Results

3.1. Three categories of runners

The CFFS runners included individuals who always landed with an FFS under both barefoot and shod conditions, and consisted of 11 individuals: five men and six women; six recreational and five competitive runners. The CRFS runners included 11 individuals who always landed on their heels when barefoot and shod: six men and five women; six recreational and five competitive runners. The shifter group included 18 individuals who ran with an FFS when barefoot and an RFS when shod: 10 men and eight women; seven recreational and 11 competitive. There were no differences between the runners of the three groups in age, weight, height, and hip height ($p > 0.05$). The joint kinematics for two shifters (1 male, 1 female; 1 recreational, 1 competitive) were unusable and omitted from the dataset.

3.2. FSA, stride frequency, and stride length increased with running speed for all runners

When not considering footwear condition or type of runner, FSA increased slightly with speed ($p < 0.05$; $n = 40$; Table 1). FSA, however, varied considerably within each speed and more with footwear condition than with speed (see Section 3.3; Figs. 2–4). Overall, stride frequency increased by 0.09 Hz per 1 m/s ($p < 0.05$; $n = 39$; Table 1; Fig. 3). Average stride length also increased with speed, with an increase of 0.6 m with each 1 m/s ($p < 0.05$; $n = 40$; Table 1; Fig. 3). Average duty cycle for the runners decreased by 7.8% per 1 m/s increase in speed ($p < 0.05$; $n = 39$; Table 1).

3.3. Barefoot runners tend to FFS

Overall, runners generally landed more on their forefeet when barefoot (FSA $= -0.2° \pm 10.0°$; $n = 40$) and they

Table 1
Foot strike angles and gait kinematics at different running speeds (mean ± SD).

Variable	Condition	Speed (m/s)			
		2.5	2.8	3.2	3.5
Foot strike angles (°)	All combined	5.9 ± 11.7	6.7 ± 12.1	7.5 ± 12.7	7.3 ± 12.9
	All barefoot	0.7 ± 10.3	0.5 ± 10.3	0.5 ± 11.4	−0.4 ± 10.1
	All shod	12.7 ± 9.0	13.0 ± 10.4	14.5 ± 9.84	14.9 ± 10.6
Stride frequency (Hz)	All runners	1.4 ± 0.1	1.4 ± 0.1	1.5 ± 0.1	1.5 ± 0.1
Stride length (m)	All runners	1.8 ± 0.1	2.0 ± 0.1	2.2 ± 0.1	2.4 ± 0.1
Duty cycle (%)	All runners	44.7 ± 11.8	40.8 ± 3.2	38.6 ± 3.2	36.5 ± 2.6

landed more on their heels when shod at each speed (FSA = 13.4°± 9.9°; $n = 40$; $p < 0.05$). CFFS runners always landed on their forefeet when barefoot and shod and CRFS runners always landed on their heels whether barefoot or shod ($p < 0.05$; Table 2). Shifters tended to land on their forefeet when barefoot and on their heels when shod (Table 2; Fig. 2). The FSA of barefoot shifters was similar to those of CFFS runners and the FSA of shod shifters was similar to that of CRFS runners ($p > 0.05$). Overall, barefoot runners tended to land on their forefeet and shod runners generally landed on their heels (Table 1; $p < 0.05$; $n = 40$).

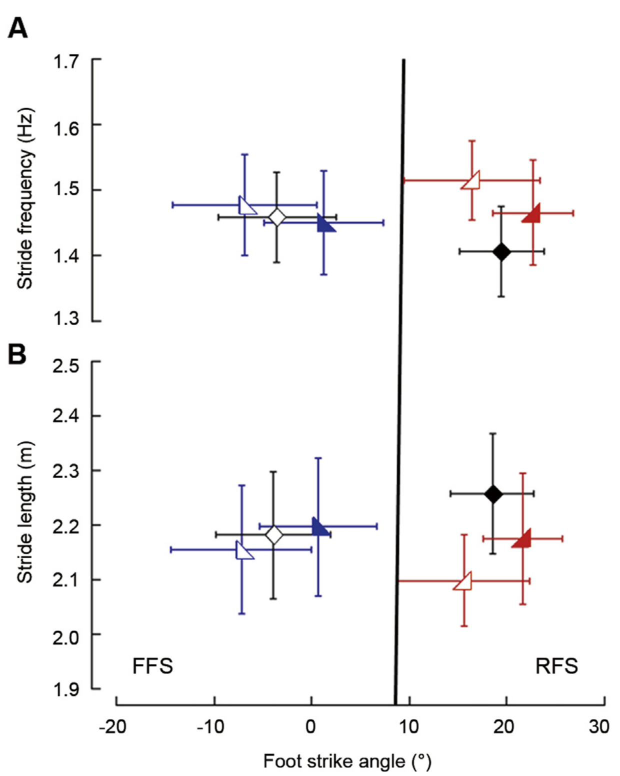

Fig. 3. Stride frequency and stride length of the three groups of runners at 3.2 m/s. Open symbols represent the barefoot condition, while solid symbols represent shod. Symbols and error bars represent the mean ± SD of the consistently forefoot strike (CFFS; blue), consistently rearfoot strike (CRFS; red), and shifter (black) groups. Vertical line indicates the foot strike angle division between FFS (<8°) and RFS (>8°) runners.[6] (A) Barefoot runners use higher stride frequencies. When grouped, CFFS (blue, left-biased triangles), CRFS (red, right-biased triangles), and barefoot shifters (open black diamonds) run with similar stride frequencies. Shod shifters (closed black diamonds) run with lower stride frequencies. (B) Barefoot runners use longer stride lengths. When grouped, CFFS, CRFS, and barefoot shifters run with similar stride lengths. Shod shifters run with longer stride lengths.

3.4. Gait kinematics differed for barefoot and shod running

In general, barefoot running increased stride frequency compared to shod running by 1.5%−4.5% (Table 2; $n = 40$; $p < 0.05$). When grouped, the stride frequencies of CFFS runners were similar to those of the CRFS runners. Both CFFS and CRFS runners ran with stride frequencies similar to barefoot shifters (Table 2; $p > 0.05$; Fig. 3A; $n = 18$). By contrast, the shod shifters (RFS) ran with a lower stride frequency than all the other groups, including the barefoot shifters (FFS) (Table 2; $p < 0.05$; Fig. 3A). These trends were consistent at all four speeds, at which shod shifters ran with lower stride frequencies than barefoot shifters, CFFS runners, and CRFS runners ($p < 0.05$).

Shod shifters (RFS) ran with longer strides (i.e., more overstride) than CFFS runners, CRFS runners, and barefoot shifters (FFS) (Table 2; $p < 0.05$; Fig. 3B). Additionally, within each of the three groups, running barefoot shortened stride lengths compared to running shod by 1.5%−4.9% ($n = 40$; $p < 0.05$).

At each speed, shifters ran with 4.2%−6.7% lower duty cycles when barefoot than shod. CRFS runners also used lower duty cycles when barefoot than when shod (Table 2; $p < 0.05$). By contrast, the duty cycle for CFFS runners remained constant between barefoot and shod conditions (Table 2; $p > 0.05$). Shod CFFS runners used 7.4%−11.1% lower duty cycles than shod CRFS runner (Table 2). When shod, those in the CFFS group ran with lower duty cycles than those in the CRFS group (Table 2; $p < 0.05$). When barefoot, the two groups ran with similar duty cycles (Table 2; $p > 0.05$).

3.5. Shank angle at initial contact varied similarly

The landing or shank angle relative to the vertical (λ in Fig. 4C) at initial contact in CFFS runners (2.4° ± 3.2°) was slightly more vertical compared to CRFS runners (8.4° ± 4.1°; $n = 11$ each; $p < 0.05$; Fig. 4B). Barefoot shifters (FFS) (3.6° ± 2.9°) landed with the shank similarly vertical like CFFS runners, whereas shod shifters (RFS) (8.3° ± 4.0°) landed with their legs positioned like CRFS runners (Fig. 4B;

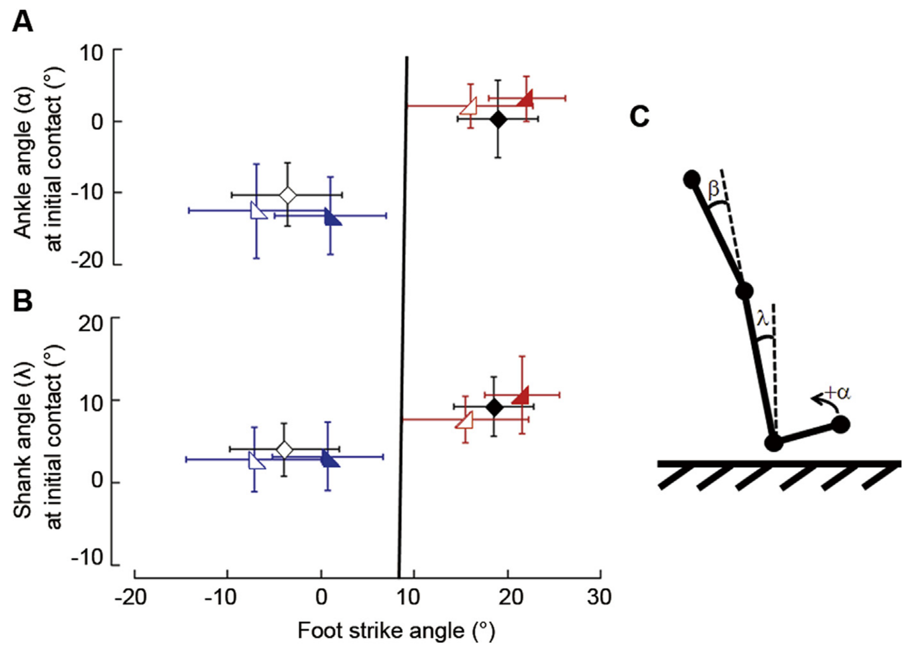

Fig. 4. Ankle and lower leg kinematics at the beginning of stance for the three groups of runners at 3.2 m/s. Open symbols represent the barefoot conditions, while solid symbols represent shod. Symbols and error bars represent the mean ± SD of the consistently forefoot strike (blue), consistently rearfoot strike (red), and shifter (black) groups. Vertical line indicates the foot strike angle (FSA) division between a forefoot strike (<8°) and a rearfoot strike (≥8°) runners.[6] Ankle (A) and shank (B) angles at the initial contact for the three groups of runners increase with FSA. (C) The ankle (α), knee (β; not plotted; see text), and shank (λ) angles examined. The ankle angle is determined relative to a 90° angle, where positive denotes dorsiflexion. The knee angle is determined relative to a straight leg and the shank angle is relative to the vertical.

$n = 16$; $p < 0.05$). The landing angle within CFFS and CRFS groups was similar between barefoot and shod conditions ($p > 0.05$; Fig. 4B). In all, FFS runners landed with a more vertical shank, indicating less overstride, than RFS runners who landed with their foot angled farther in front of them (Fig. 4B). The landing angle at initial contact remained constant across all speeds for all groups.

CFFS runners landed with their knee more flexed (16.0° ± 4.5°) than did CRFS runners (9.5° ± 6.5°; $n = 11$ each; $p < 0.05$). Both CFFS and CRFS runners did not alter their knee kinematics when barefoot compared to when shod ($p > 0.05$). However, barefoot shifters (FFS) (12.7° ± 4.2°) landed with more flexed knees compare to shod shifters (RFS) (8.71° ± 5.9°; $n = 16$ subjects at four speeds under two conditions; $p < 0.05$). For the knee angle at landing, barefoot shifters (FFS) did not differ from CFFS runners and shod shifters (RFS) did not differ from CRFS runners ($p > 0.05$). Knee angles at initial contact did not change with speed for all groups.

CFFS runners landed with their ankles (−13.0° ± 5.8°) in more plantarflexion than did CRFS runners (1.9° ± 3.7°; $n = 11$ each; $p < 0.05$; Fig. 4A). Barefoot shifters (FFS) (−10.5° ± 4.4°) landed with their ankles similarly plantarflexed like CFFS runners, whereas shod shifters (RFS) (0.0° ± 5.3°) landed with their ankles positioned similarly to that of CRFS runners ($n = 16$; $p < 0.05$; Fig. 4A). The ankle angle at initial contact in CFFS runners was similarly plantarflexed when barefoot compared to shod ($p > 0.05$; $n = 11$; Fig. 4A). This angle in CRFS runners was similarly dorsiflexed when barefoot and shod ($p > 0.05$; $n = 11$; Fig. 4A). In all, FFS runners, regardless of group, landed with a more plantarflexed ankle joint than RFS runners, regardless of group. Ankle angle at initial contact remained constant across all speeds for all groups.

The clearest difference in joint kinematics was the movement of the ankle joint just after the initial contact (Fig. 5). All FFS runners, including barefoot shifters, landed with more plantarflexed ankle joints, and then dorsiflexed during the first half of the stance phase (Fig. 5A). All RFS runners, including shod shifters, landed with more dorsiflexed ankles, then immediately plantarflexed the beginning of stance (Fig. 5C).

Table 2
Foot strike angles and gait kinematics of the groups when barefoot *vs*. shod (mean ± SD).

Variable	Group	*n*	Barefoot	Shod
Foot strike angles (°)	CFFS	11	6.3 ± 0.9	−0.2 ± 1.0
	CRFS	11	13.9 ± 1.3	21.3 ± 2.2
	Shifter	18	−4.7 ± 0.6	17.8 ± 0.8
Stride frequency (Hz) at 3.2 m/s	CFFS	11	1.49 ± 0.06	1.46 ± 0.06
	CRFS	11	1.51 ± 0.08	1.46 ± 0.08
	Shifter	18	1.46 ± 0.08	1.41 ± 0.07
Stride length (m) at 3.2 m/s	CFFS	11	2.15 ± 0.12	2.20 ± 0.13
	CRFS	11	2.10 ± 0.08	2.17 ± 0.12
	Shifter	18	2.18 ± 0.10	2.26 ± 0.11
Duty cycle (%) at 3.2 m/s	CFFS	11	36.6 ± 2.7	37.3 ± 4.1
	CRFS	11	38.7 ± 2.6	40.8 ± 2.3
	Shifter	18	38.1 ± 2.6	39.7 ± 3.2

Abbreviations: CFFS = consistently forefoot strike; CRFS = consistently rearfoot strike.

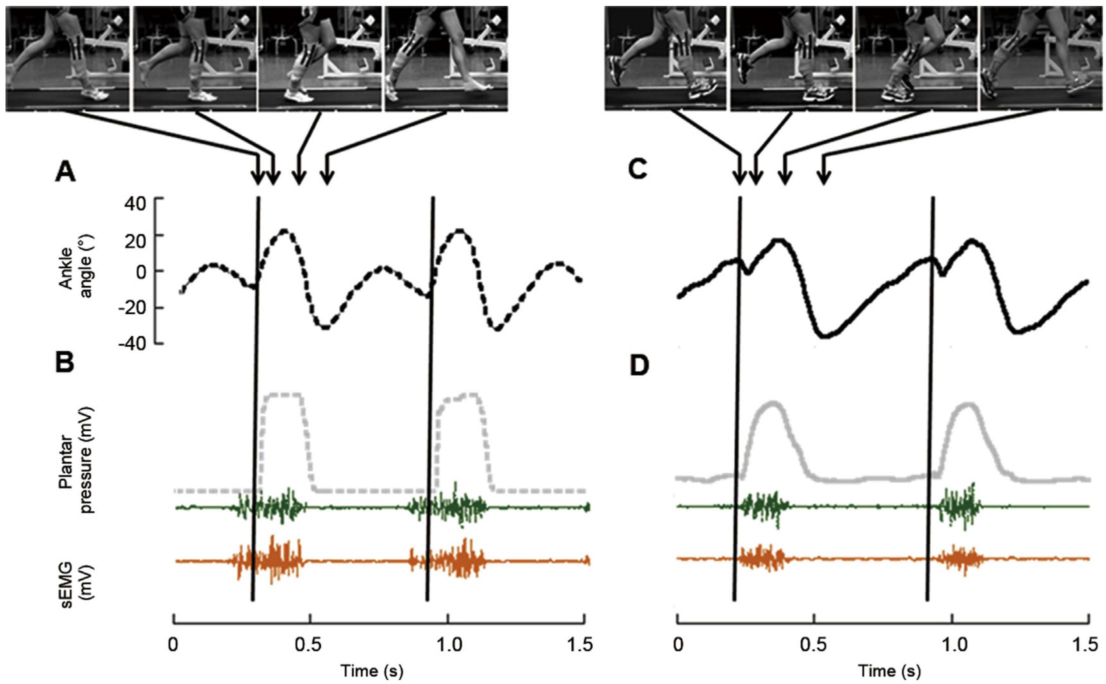

Fig. 5. Ankle kinematics, plantar pressures, and muscle activity patterns of a representative shifter where the vertical lines represent the beginning of stance while running at 3.2 m/s. In each series of arrows, the first arrow indicates the initial contact and the 4th arrow indicates the end of stance. These recordings were obtained from the same representative individual as shown in Fig. 2. (A) When barefoot, the ankle dorsiflexes immediately upon landing. (C) When shod, the RFS runner lands on their heels and immediately plantarflexes after heel strike. (B), (D) The activity patterns of the lateral gastrocnemius (green, upper) and medial gastrocnemius (orange, lower) muscles of the forefoot strike runner activate earlier than that of the rearfoot strike runner.

3.6. Running speed altered muscle activity patterns of calf muscles

All runners activated and deactivated both medial (MG) and lateral gastrocnemii (LG) muscles earlier in the stride as they ran faster (Table 3; Fig. 6; $n = 40$; $p < 0.05$). The changes in the timing of activation patterns of the gastrocnemii with speed were similar amongst runners regardless of strike type or footwear condition ($n = 40$, Fig. 6). The MG and LG activated and deactivated at similar times at each speed (Table 3; $p > 0.05$; Fig. 6). The activation durations for the MG and LG did not vary with speed (Table 3; $p > 0.05$; Fig. 6).

The activation amplitudes of the MG and LG increased with running speed in all runners (Table 3; $p < 0.05$; $n = 39$). Unlike the other activation parameters, activation amplitude did not differ between barefoot and shod conditions. In all, the amplitudes of the MG exceeded that of the LG at the two lower speeds ($p < 0.05$), but matched at the two higher speeds.

3.7. FFSs activate calf muscles earlier

CFFS runners activated their MG muscles 7.7%−16.3% of the gait cycle earlier than CRFS runners at 2.5, 2.8, 3.2, and 3.5 m/s (Table 3; $p < 0.05$; Fig. 6). Barefoot shifters (FFS) also activated their MG at the four speeds (Figs. 5 and 6) earlier than shod shifters (RFS) ($p < 0.05$). CFFS runners, when both barefoot and shod, activated the MG muscles at similar times to the barefoot shifters (Fig. 6). Correspondingly, CRFS runners when barefoot and shod activated their muscle at similar times to the shod shifters (RFS) at the four speeds ($p > 0.05$; Fig. 6).

The timing of LG activation followed the same trends as that of the MG for all runners (Fig. 6). CFFS runners activated their LG muscles 7.7%−13.1% of the gait cycle earlier than CRFS runners at all speeds ($p < 0.05$; Fig. 6). Barefoot shifters (FFS) activated their LG earlier than shod shifters (RFS) at all speeds (Table 3; $p < 0.05$). Barefoot and shod CFFS runners activated their LG muscles at similar times to the barefoot shifters (FFS) at all speeds (Fig. 6). Correspondingly, barefoot and shod CRFS runners activated their LG at similar times to shod shifters (RFS) (Table 3; $p > 0.05$; Fig. 6).

3.8. Calf muscle deactivation time did not depend on running style

All runners deactivated their calf muscles similarly regardless of footwear condition or strike type ($p > 0.05$; Table 3). In all, runners have similar MG offset times when barefoot (42.4% ± 6.0% gait cycle) and when shod (44.6% ± 5.8% gait cycle; $p > 0.05$; $n = 40$). In all, runners have similar LG offset times when barefoot (42.7% ± 7.7% gait cycle) and when shod (44.7% ± 7.9% gait cycle; $p > 0.05$; $n = 40$).

3.9. FFSs activate calf muscles longer

CFFS runners activated their MG muscles on average 9.7% of the gait cycle longer than CRFS runners ($n = 11$ each;

Table 3
Muscle activity patterns at different running speeds (mean ± SD) (n = 40).

Variable	Group and condition	Speed (m/s)			
		2.5	2.8	3.2	3.5
MG activation amplitude (% MVC)	All runners	78.0 ± 31.6	81.2 ± 34.0	86.7 ± 35.1	92.1 ± 37.9
LG activation amplitude (% MVC)	All runners	63.8 ± 22.6	71.2 ± 24.9	77.5 ± 25.4	86.1 ± 26.6
MG activation phase (% gait cycle)	All barefoot	−4.1 ± 9.3	−4.6 ± 9.0	−4.8 ± 8.8	−7.1 ± 8.2
	All shod	2.5 ± 9.2	0.5 ± 9.0	1.0 ± 9.1	−2.4 ± 7.9
	CFFS combined	−6.3 ± 8.0	−7.5 ± 7.9	−7.3 ± 8.3	−8.0 ± 8.1
	CFFS barefoot	−4.9 ± 7.8	−6.1 ± 8.4	−6.5 ± 7.6	−7.6 ± 8.4
	CFFS shod	−7.4 ± 8.4	−8.8 ± 7.6	−8.8 ± 7.6	−8.1 ± 9.3
	CRFS combined	7.6 ± 6.1	6.0 ± 4.8	5.5 ± 4.7	1.3 ± 6.1
	CRFS barefoot	6.4 ± 7.2	5.5 ± 5.6	5.0 ± 4.6	0.2 ± 7.1
	CRFS shod	8.9 ± 4.7	6.6 ± 4.1	6.1 ± 4.8	2.4 ± 5.1
	Shifter barefoot (FFS)	−9.9 ± 5.2	−9.9 ± 5.4	−9.8 ± 6.3	−11.2 ± 5.4
	Shifter shod (RFS)	4.7 ± 6.8	2.3 ± 11.0	3.3 ± 7.1	−1.6 ± 7.1
LG activation phase (% gait cycle)	All barefoot	−0.60 ± 8.3	−1.4 ± 8.0	−2.4 ± 7.0	−3.5 ± 7.6
	All shod	3.4 ± 7.4	2.1 ± 9.2	2.9 ± 9.4	1.2 ± 8.0
	CFFS combined	−4.7 ± 6.5	−4.2 ± 6.8	−5.0 ± 7.6	−6.4 ± 7.5
	CFFS barefoot	−5.1 ± 7.0	−3.5 ± 6.9	−4.5 ± 6.5	−7.2 ± 6.1
	CFFS shod	−4.3 ± 6.2	−4.9 ± 6.9	−5.5 ± 8.8	−5.5 ± 8.8
	CRFS combined	8.4 ± 3.4	6.8 ± 4.3	4.5 ± 4.8	3.8 ± 4.5
	CRFS barefoot	7.9 ± 3.1	5.7 ± 4.7	3.3 ± 4.9	3.4 ± 5.0
	CRFS shod	8.8 ± 3.8	7.9 ± 3.7	6.1 ± 4.5	4.3 ± 4.1
	Shifter barefoot (FFS)	−3.1 ± 7.4	−4.4 ± 7.6	−4.7 ± 6.6	−5.4 ± 7.2
	Shifter shod (RFS)	4.8 ± 5.8	2.7 ± 10.2	6.1 ± 8.9	3.3 ± 7.2
MG deactivation phase (% gait cycle)	All barefoot	43.9 ± 5.4	43.3 ± 6.9	41.9 ± 6.6	40.4 ± 5.2
	All shod	46.7 ± 6.0	45.2 ± 6.0	44.0 ± 5.5	42.4 ± 5.8
	CFFS barefoot	44.2 ± 6.2	43.0 ± 7.6	43.1 ± 9.3	39.9 ± 6.5
	CFFS shod	44.9 ± 6.3	44.0 ± 6.8	43.3 ± 6.0	39.8 ± 4.2
	CRFS barefoot	45.9 ± 4.9	46.2 ± 6.7	42.9 ± 4.7	42.8 ± 5.2
	CRFS shod	48.8 ± 5.8	47.3 ± 5.9	44.8 ± 3.1	44.5 ± 4.9
	Shifter barefoot (FFS)	42.5 ± 5.0	41.7 ± 6.2	40. ± 5.6	39.2 ± 4.0
	Shifter shod (RFS)	46.5 ± 5.8	44.6 ± 5.6	44.0 ± 6.5	42.7 ± 6.6
LG deactivation phase (% gait cycle)	All barefoot	44.2 ± 7.6	43.2 ± 7.7	41.9 ± 7.7	41.4 ± 7.9
	All shod	46.0 ± 7.6	44.4 ± 7.5	44.7 ± 7.8	43.6 ± 8.6
	CFFS barefoot	45.4 ± 10.0	42.9 ± 10.2	43.1 ± 10.2	42.5 ± 9.8
	CFFS shod	41.4 ± 7.6	40.5 ± 9.7	43.1 ± 9.6	40.1 ± 6.9
	CRFS barefoot	44.1 ± 6.5	44.4 ± 6.6	43.3 ± 7.5	42.1 ± 7.6
	CRFS shod	48.2 ± 6.6	47.0 ± 6.1	46.2 ± 6.6	45.1 ± 6.5
	Shifter barefoot (FFS)	43.5 ± 6.9	42.7 ± 7.0	40.3 ± 6.1	40.3 ± 7.1
	Shifter shod (RFS)	47.4 ± 7.4	45.2 ± 5.9	44.7 ± 7.6	44.7 ± 10.3
MG duration (% gait cycle)	All barefoot	48.0 ± 10.2	47.9 ± 11.6	46.7 ± 11.3	47.5 ± 9.4
	All shod	44.2 ± 11.0	44.7 ± 12.4	43.1 ± 9.9	44.8 ± 9.9
	CFFS barefoot	49.1 ± 12.1	49.1 ± 13.6	49.6 ± 13.6	47.5 ± 12.8
	CFFS shod	52.3 ± 13.0	52.8 ± 12.6	51.4 ± 12.5	48.2 ± 10.4
	CRFS barefoot	39.5 ± 8.0	40.7 ± 9.5	37.9 ± 5.6	42.6 ± 6.0
	CRFS shod	39.9 ± 5.7	40.6 ± 5.6	38.7 ± 4.2	42.2 ± 6.6
	Shifter barefoot (FFS)	52.4 ± 6.7	51.6 ± 9.8	50.3 ± 10.0	50.4 ± 7.9
	Shifter shod (RFS)	41.8 ± 9.9	42.2 ± 13.5	40.7 ± 7.9	44.3 ± 11.2
LG duration (% gait cycle)	All barefoot	44.8 ± 12.7	44.6 ± 12.9	44.3 ± 11.8	44.9 ± 11.7
	All shod	42.6 ± 10.6	42.4 ± 11.5	41.8 ± 10.6	42.4 ± 12.0
	CFFS barefoot	45.4 ± 10.0	42.9 ± 10.2	43.1 ± 10.2	42.5 ± 9.8
	CFFS shod	41.4 ± 7.6	40.5 ± 9.7	43.1 ± 9.6	40.1 ± 6.9
	CRFS barefoot	44.1 ± 6.5	44.4 ± 6.6	43.3 ± 7.5	42.1 ± 7.6
	CRFS shod	48.2 ± 6.6	47.0 ± 6.1	46.2 ± 6.6	45.1 ± 6.5
	Shifter barefoot (FFS)	43.5 ± 6.9	42.7 ± 7.0	40.3 ± 6.1	40.3 ± 7.1
	Shifter shod (RFS)	44.4 ± 7.4	45.2 ± 5.9	44.7 ± 7.6	44.7 ± 10.3

Abbreviations: MG = medial gastrocnemius; LG = lateral gastrocnemius; CFFS = consistently forefoot strike; CRFS = consistently rearfoot strike; FFS = forefoot strike; RFS = rearfoot strike; MVC = maximum voluntary contraction.

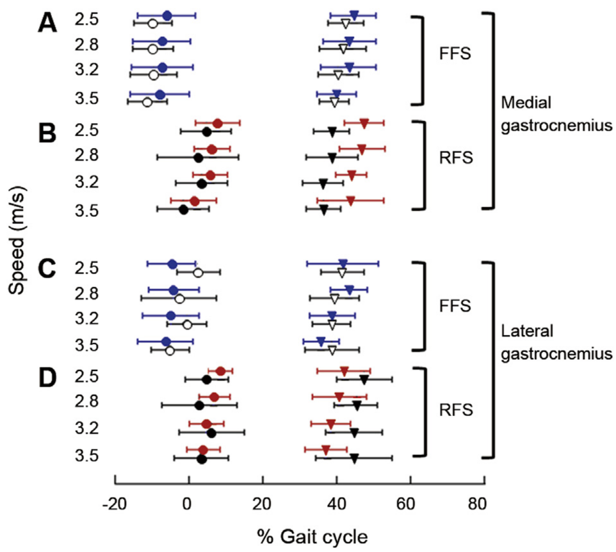

Fig. 6. Muscle activity patterns of the medial gastrocnemius (MG) (A, B) and the lateral gastrocnemius (LG) (C, D) during the gait cycle, where 0 represents the beginning of stance. Symbols (mean ± SD) represent the normalized onset (circles) and offset (triangles) times of the muscle activity patterns. Vertical axis for the four panels indicates speed. (A) MG activity patterns during running for forefoot strike (FFS) runners, which include consistently forefoot strike (CFFS; blue) and barefoot shifters (open black). (B) MG activity patterns during running for rearfoot strike (RFS) runners, which include consistently rearfoot strike (CRFS; red) and shod shifters (closed black). (C) LG activity patterns during running for FFS runners, which include CFFS (blue) and barefoot shifters (open black). (D) LG activity patterns during running for RFS runners, which include CRFS (red) and shod shifters (closed black).

$p < 0.05$; Fig. 6). Barefoot shifters (FFS) activated their MG muscles longer than shod shifters (RFS) at each speed ($n = 18$; $p < 0.05$). MG activation in CFFS runners lasted similar durations when barefoot and shod, and similar to that of barefoot shifters (FFS) ($p > 0.05$). CRFS runners, when both barefoot and shod, activated their MG activation in similar duration to the shod shifters (RFS) ($p < 0.05$; Fig. 6). Overall, runners activated their MG muscles longer when landing with an FFS than with an RFS (Fig. 6).

Similarly, CFFS runners activated their LG muscles 6.3%–14.3% of the gait cycle longer than CRFS runners at the four speeds (Table 3; $p < 0.05$; Fig. 6). CFFS runners, when both barefoot and shod, activated their LG for durations similar to that of barefoot shifters (FFS) ($n = 11$). Shifters activated the LG muscles longer when barefoot (FFS) than when shod (RFS). CRFS runners, when both barefoot and shod, activated their LG for durations similar to the shod shifters (RFS) ($n = 11$, Fig. 6). In general, runners activated their LG muscles longer when running with an FFS style than when running with an RFS style (Table 3; Fig. 6).

4. Discussion

Runners were categorized into three groups based on the strike type when running barefoot and shod. Of the 40 subjects, 11 individuals (27.5%) were CFFS runners, landing only on their forefeet whether running barefoot or shod, whereas CRFS runners landed only on their heels when barefoot and shod ($n = 11$; 27.5%). The remaining subjects ($n = 18$; 45%) used an FFS style when barefoot and then shifted to an RFS style when shod. Runners who CRFS or CRFS when both barefoot and shod have been studied previously.[5,9,14,16,17] However, almost half of the runners in the current study shifted their running style between an RFS when shod and an FFS when barefoot.[12]

Within a given group or footwear condition, an increase in speed increases both stride length and stride frequency (Table 1).[11,15,20] Barefoot runners generally run with shorter stride lengths and higher stride frequencies and are more likely to FFS than shod runners (Fig. 3).[3,11,15,16,20] Shorter stride lengths attenuate the shock wave caused by the heel strike at initial contact[2] and may also reduce decelerations that occur within running strides, due to more vertical ground reaction forces.[26] Interestingly, CFFS and CRFS runners used similar stride lengths and frequencies at a given speed and footwear condition (Fig. 3). Shod shifters, however, use longer stride lengths and higher stride frequencies and duty cycles than all other groups (Fig. 3). Runners who change their running style also modulate their stride length and stride frequency. Notably, runners with consistent styles, whether FFS or RFS, have stride lengths, stride frequencies and duty cycles similar to each other across groups. The similar stride lengths, frequencies, and duty cycles between CFFS and CRFS runners may relate more to training level than foot strike pattern. Sometimes, training shortens stride lengths[27,28] but elite training lengthens stride lengths.[29] In our subjects, even though the level of training and mileage did not differ between the three groups, these effects may mask differences in stride length. When training level is controlled (e.g., in the shifters), FFS barefoot runners shorten their stride lengths compared to the RFS shod runners (Fig. 3).[11,16,20] Only the shod shifters ran with longer stride lengths (Fig. 3). These shod runners may be using the cushioning of the shoe to attenuate the increased shock experienced through the leg and decrease energy absorption when running with longer stride lengths.[2]

Shorter strides during FFS running also correlate with more vertical landing angles (less overstride; Fig. 4).[3] FFS runners land with their shank more vertical (2°) compared to RFS runners (8°). Barefoot RFS runners also land with a more vertical shank compared to shod RFS runners.[16] This vertical landing angle in FFS runners likely functions to minimize ankle moments.[2]

FFS runners slightly plantarflex (−12.5°) their ankle joints at impact, RFS runners slightly dorsiflex their ankle joints (1.2°; Figs. 4 and 5),[3,11–14,19] while shifters alter their kinematics to correspond to the two styles of running. Typically, running involves a quick plantarflexion at heel contact before dorsiflexion,[2,4,16,26,30–32] but only for RFS runners (Fig. 4).[3,5] The ankle may passively plantarflex due to the "toe-down" torque generated by the heel contact posterior to the ankle joint.[33] The plantarflexion immediately after heel contact is possibly passive because the fast-twitch plantarflexors are likely not generating force yet (Fig. 5; see Section 3.7). By contrast, FFS runners only dorsiflex upon initial contact at the beginning of stance (Figs. 4 and 5).[3,5,9,17,22,34] The foot strike style seems to determine not only the ankle angle at initial contact, but also the direction of the ankle rotation during the first half of stance (Fig. 4).[3,9,19] In fact, the ankle movement during the first half of the stance phase could be used as a method to determine whether a runner uses an FFS or an RFS style using only joint kinematics (Fig. 5).[5]

CFFS runners activate their gastrocnemii muscles earlier by ∼11% of the stride duration and longer by ∼10% of the stride duration relative to CRFS runners, as hypothesized (Fig. 6). Again, shifters adjust their muscle activity patterns based on their footwear condition conforming to the patterns of the consistent or "habitual" runners of a single style. The muscle activity patterns and joint kinematics of the barefoot shifters (FFS) are indistinguishable from those in the CFFS and shod shifters (RFS) are indistinguishable from CRFS runners (Figs. 4−6).

Earlier activation of the plantarflexor muscles will not only plantarflex the ankle joint to prepare for landing, but also increase the capacity of the passive structures to store elastic energy at the beginning of stance.[5,9,15] When the gastrocnemii muscles activate, the muscle fibers contract and begin to shorten the muscle just before initial contact of the foot. During an FFS, if the muscles were passive, dorsiflexion at the initial contact would stretch the gastrocnemii muscles (Fig. 5). In FFS runners, the force of landing is immediately counteracted by the earlier and longer contractions of their plantarflexor muscles, which stabilizes the ankle joint and smoothens the tendon force development.[35] The pre-activation of the gastrocnemii muscles also increases the immediate storage capacity of the elastic tissues in the shank by stretching the Achilles tendon before landing.[36,37] If the tendon is in tension before landing, then the force of landing would stretch the tendon more, allowing for greater storage of elastic energy. Increased storage of elastic energy in the connective tissue of the tendon and aponeurosis will increase the force output of the plantarflexors during the latter, energy-producing phase of stance.[26,36,37]

Earlier activation of plantarflexors before dorsiflexion at initial contact also enhances the performance of the active components operating at the ankle. For example, the elastic energy can be stored in the activated cross-bridge springs within the sarcomeres during the first 20%−25% of the stance phase when the gastrocnemii operate nearly isometrically.[31,38] Active pre-stretch enhances work generated in muscle[39] or amplifies power production from a joint system.[21] Finally, titin stiffness varies with activation level.[40] Increased activation of titin will lead to the storage additional elastic energy to enhance force after active lengthening.[41] Several active mechanisms in muscle could function independently or in concert to enhance plantarflexion during the latter, energy-producing phase of stance during running.

Longer activation of the plantarflexors in FFS running implies greater plantarflexor forces and possibly an increase in energetic cost when using this style. Studies have shown varied results, however. Barefoot running can lower the energetic cost of running by 2.8% when compared to shod running, but this increase in energetic cost may be caused by the extra weight of the shoe.[13] When controlled for mass, barefoot FFS running increases metabolic cost of running by 3%−4% compared to shod FFS running.[42] Alternatively, FFS running can be more 2.4% more economical than RFS running in minimal shoes.[9] Finally, there can be no difference between FFS and RFS running either in minimal shoes or with standard shoes.[15] The increased cost of increased activation may or may not be negated by the elastic energy stored in and subsequently returned by the foot arch, the Achilles tendon, and/or the plantarflexors.

Habitual runners of one style may convert temporarily to using different foot strike patterns to adequately mimic the mechanical loading condition.[17,18] However, the difference of the muscle activation patterns in FFS running compared to RFS running indicates possible re-training of the motor pattern for a runner.[43,44] Transitioning from an RFS to an FFS style can require many months to build the proper musculature to minimize injury and include modifying one's muscle activation and kinematic patterns.

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