

A Comparison of Negative Joint Work and Vertical Ground Reaction Force Loading Rates in Chi Runners and Rearfoot-Striking Runners

The majority of runners analyzed as part of biomechanical research have demonstrated a rearfoot-strike (RS) pattern.^{21,29,31} Recently, alternative running styles, such as Chi running, have become popular because their proponents claim that these running styles are a safer alternative to

RS running. The founder of Chi running, Danny Dreyer, credits the origins of this running form to the discipline of

Tai Chi.¹⁶ This method of running is described as the alignment of body, mind, and forward movement. Runners are



instructed to avoid heel strike and to land with an initial foot strike anterior to the heel. The body leans forward slightly, and the strides are shorter, with a focus on relaxing the legs. Dreyer¹⁶ recommends but does not require that runners discard more traditional heavily padded running shoes and use a more minimalist running shoe with thin sole material and limited supportive features.

Recent injury-prevention efforts that have matched traditional running-shoe prescription to foot morphology have not been effective,²⁵⁻²⁷ leading several investigators to examine other factors that may contribute to injury. Two biomechanical variables recently associated with increased injury risk for conditions such as tibial stress fracture,⁴⁰ patellofemoral pain,¹³ and plantar fasciitis⁴⁵ are the presence of a vertical ground reaction force impact peak and ground reaction force loading rate. Running with an initial foot strike anterior to the heel has been shown to reduce knee loading⁵ and reduce initial vertical loading rates,³¹ and may decrease injury incidence rates.¹⁸ Typically, striking the ground anterior to the heel is associated with a shorter stride length^{12,18,35,44}

● **STUDY DESIGN:** Observational.

● **OBJECTIVES:** To compare lower extremity negative joint work and vertical ground reaction force loading rates in rearfoot-striking (RS) and Chi runners.

● **BACKGROUND:** Alternative running styles such as Chi running have become a popular alternative to RS running. Proponents assert that this running style reduces knee joint loading and ground reaction force loading rates.

● **METHODS:** Twenty-two RS and 12 Chi runners ran for 5 minutes at a self-selected speed on an instrumented treadmill. A 3-D motion analysis system was used to obtain kinematic data. Average vertical ground reaction force loading rate and negative work of the ankle dorsiflexors, ankle plantar flexors, and knee extensors were computed during the stance phase. Groups were compared using a 1-way analysis of covariance for each vari-

able, with running speed and age as covariates.

● **RESULTS:** On average, RS runners demonstrated greater knee extensor negative work (RS, -0.332 J/body height \times body weight [BH-BW]; Chi, -0.144 J/BH-BW; $P < .001$), whereas Chi runners demonstrated more ankle plantar flexor negative work (Chi, -0.467 J/BH-BW; RS, -0.315 J/BH-BW; $P < .001$). RS runners demonstrated greater average vertical ground reaction force loading rates than Chi runners (RS, 68.6 BW/s; Chi, 43.1 BW/s; $P < .001$).

● **CONCLUSION:** Chi running may reduce vertical loading rates and knee extensor work, but may increase work of the ankle plantar flexors. *J Orthop Sports Phys Ther* 2013;43(10):685-692. Epub 9 September 2013. doi:10.2519/jospt.2013.4542

● **KEY WORDS:** ankle, barefoot, impact, knee, minimalist

¹US Army-Baylor University Doctoral Program in Physical Therapy, Fort Sam Houston, TX. ²Division of Physical Therapy, Program in Human Movement Science, University of North Carolina at Chapel Hill, Chapel Hill, NC. This study was approved by the Institutional Review Boards at the University of North Carolina at Chapel Hill and Womack Army Medical Center, Fort Bragg, NC. The opinions and assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Departments of the Army or Defense. The authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the article. Address correspondence to LTC Don Goss, 3599 Winfield Scott Road, Suite 1301, Fort Sam Houston, TX 78234. E-mail: donald.l.goss.mil@mail.mil • Copyright ©2013 *Journal of Orthopaedic & Sports Physical Therapy*®

and increased stride frequency.^{15,23,38}

Although proponents of Chi running claim that this method of running reduces injuries by reducing knee joint loading and vertical ground reaction forces, the authors are unaware of any biomechanical evaluations of this running style to support that claim. Therefore, the purpose of this study was to compare lower extremity negative work at the ankle and knee joints and average vertical ground reaction force loading rates (AVLRs) in Chi runners and RS runners.

METHODS

Subjects

WE RECRUITED RS RUNNERS (N = 22) and potential Chi runners (n = 23) for this study. The RS runners and Chi runners were experienced in their respective running styles for at least 6 months prior to participation. Videos of the 22 RS runners were viewed by 2 physical therapists with over 40 years of combined experience. The 2 therapists were in 100% agreement that all 22 runners demonstrated a strike pattern in which the rear one third of the shoe made initial contact with the treadmill.

Chi runners had to demonstrate an anterior foot-strike pattern (ie, non-heel-strike pattern). Chi runners also completed a training course with a certified Chi running instructor. Videos of their running form were evaluated by Danny Dreyer, whose evaluation methods are summarized in **TABLE 1**. Mr Dreyer selected runners for inclusion in the Chi running group if they met the first 5 criteria outlined in **TABLE 1**. Twelve of 23 potential Chi runners were identified as demonstrating proper Chi running form and were included in the Chi running group. To establish reliability, Mr Dreyer assessed the 23 videos 17 months after his initial assessment. Despite being blinded to his initial evaluations, he selected the same 12 runners as using proper Chi running form and confirmed that the remaining 11 runners were not using proper Chi running form ($\kappa = 1.0$).

TABLE 1

VISUAL CRITERIA USED TO DETERMINE CHI RUNNING STYLE*

1. Postural alignment in midstance: shoulders, hips, and ankles aligned
2. Hips slightly ahead of feet in midstance
3. Knees bent on impact: no heel striking or dorsiflexion
4. No contraction of calves in terminal stance: no toe-off
5. Lifting ankles, not knees: knees are bent but not lifted
6. Pelvic rotation more prevalent than upper-body rotation
7. Arm swing rearward
8. Elbows bent 90°: not pumping
9. Not bending at the waist in midstance

*Chi runners were required to demonstrate the first 5 criteria.

TABLE 2

DESCRIPTIVE STATISTICS FOR SUBJECTS

	RS (n = 22)*	Chi (n = 12)*	Tests of Significance†
Gender, n (%)			$\chi^2 = 0.64, df = 2, P = .80$
Male	12 (54.5)	6 (50)	
Female	10 (45.5)	6 (50)	
Age, y	34.6 ± 10.7	41.6 ± 8.0	t = 2.16, P = .04‡
Height, m	1.73 ± 0.09	1.74 ± 0.10	t = 0.23, P = .82
Mass, kg	69.1 ± 12.3	75.0 ± 12.6	t = 1.16, P = .25
Time using current running style, mo	91.1 ± 61.2	29.8 ± 23.1	t = 3.18, P = .003‡
Reported weekly mileage, mi/wk	25.5 ± 14.4	22.7 ± 14.1	t = 0.65, P = .52
Reported training pace, min/mi	8:56 ± 1:18	9:10 ± 1:34	t = 0.49, P = .63

Abbreviations: Chi, certified Chi runners; RS, rearfoot-striking runners.

*Values are mean ± SD unless otherwise indicated.

†Chi-square analysis was performed for gender proportions, and independent t tests were performed for other descriptive statistic variables to establish group differences.

‡Statistical significance.

Each subject's running shoes were classified as being "traditional" or "minimalist." Traditional shoes were defined as motion-control, stability, or cushioning shoes, with a drop of 10 mm or greater from heel height to forefoot height. Minimalist shoes were defined as any shoe that was very flexible, contained minimal supportive features, and had a heel-to-forefoot drop of 4 mm or less. The principal investigator made the determination of shoe type based on the manufacturer's specifications and examination of the shoes. For example, shoes that were easily folded in half and twisted along their longitudinal axis with minimal resistance to deformation were classified as

minimalist. All 22 RS runners wore traditional running shoes. Chi runners wore a combination of traditional (n = 7) and minimalist footwear (n = 5).

Potential subjects were screened for inclusion and exclusion criteria prior to enrollment. Participants ranged in age from 18 to 50 years and reported running a minimum of 19.2 km/wk (12 mi/wk) (**TABLE 2**). Subjects were free of lower extremity injuries and low back pain that would limit lower extremity function for the 3 months preceding participation in the study. All runners expressed familiarity with treadmill running.

Exclusion criteria included a history of any lower extremity surgical procedure,

lumbar spine surgery, balance problems, or pregnancy in the previous 6 months. All subjects were briefed on the study requirements and asked to sign an informed consent form approved by the Institutional Review Boards at the University of North Carolina at Chapel Hill and Womack Army Medical Center, Fort Bragg, NC.

Data Collection

Data for each subject were collected during a single visit lasting approximately 1 hour. Subjects were asked to wear their preferred running shoes for data collection. Height was measured with a tape measure. Mass was obtained from a static measurement of weight on the instrumented treadmill. Additional descriptive data were collected from each subject, including shoe type, running mileage, and length of time using their particular running style.

Subjects had 39 reflective markers affixed to their shoes and the following locations: medial and lateral ankles, lower legs, medial and lateral knees, posterior thighs, greater trochanters, iliac crests, and sacrum.³⁰ The subjects were asked to stand still on the treadmill for 1 second while a static calibration trial was obtained. After the calibration trial, 14 anatomical markers were removed for the data-collection running trials, and only the tracking markers remained.³⁰

During data collection, subjects were asked to run for 5 minutes on the treadmill at a self-selected speed. During the first 4 minutes of running, the subjects were allowed to accommodate themselves to the treadmill,^{14,19,24} and during the final minute of running data were collected in 5 three-second periods.²⁷ To reduce measurement bias, subjects were blinded to the data-collection times.

Running was performed on the right belt of a split-belt, instrumented treadmill (Bertec Corporation, Columbus, OH), with force plates sampling data at 1200 Hz.^{24,33} Three-dimensional kinematic data were captured using an 8-camera Vicon Nexus MX40+ system (OMG

plc, Oxford, UK) at 240 Hz.^{3,4,6,17,21,32,33,43} A Handycam HDR-CX150 (Sony Corporation, Tokyo, Japan), sampling at 60 Hz, was positioned perpendicular to the treadmill to obtain a lateral view of the subjects. The video recordings from the Sony camera were used to confirm foot-strike patterns and to certify that Chi runners were using appropriate Chi running form.

Data Reduction

The data-smoothing methods and smoothing parameters for the ground reaction forces and coordinates of center-of-pressure data were selected after an analysis of the noise-to-signal ratios, frequency spectra, and signal patterns.⁴⁷ Data processing and reduction were performed using a customized computer program (MS3D 2010; MotionSoft, Chapel Hill, NC).

The coordinates of reflective markers and the virtual landmark were filtered using a second-order, recursive Butterworth digital filter at a cutoff frequency of 15 Hz.⁴⁷ Ground reaction forces during each stance phase were filtered using a second-order, recursive Butterworth digital filter at cutoff frequencies of 20 Hz, 20 Hz, and 100 Hz for anterior/posterior, medial/lateral, and vertical ground reaction force, respectively. The coordinates of the center-of-pressure data were filtered using a third-order polynomial.

Data were averaged across 5 strides for each subject, then averaged with other runners in the same group. After the initial data processing, average joint angles, joint angular velocities, ground reaction forces, internal net joint moments, and joint net power files were created from normalized individual trial data. Normalization was conducted on the first 5 right-stance phases captured from the 5 three-second running periods. Force data were normalized to body weight (BW). Moment data were normalized to the product of body height (BH) and BW (BH·BW). Power was normalized to watts per BH·BW. Work was normalized to joules per BH·BW.

The Euler sequence for segment rotations was sagittal plane flexion/extension, abduction/adduction, and internal/external rotation. Hip joint centers were defined as being 25% medial to the distance between greater trochanter markers.⁴⁶ Knee and ankle joint centers were defined as the midpoint between the medial and lateral knee and ankle markers, respectively. Internal moments at the ankle and knee were quantified using inverse dynamic equations. Angular work (J) was determined by integrating the joint power curve throughout the stance phase. Joint power (W) was defined as the product of the internal joint moment and the joint angular velocity.

Mean vertical ground reaction force, joint excursion, joint moment, and joint power curves were quantified for each runner's stance phase, and time was normalized with respect to stance phase (100 points). Loading rates and angular work variables were computed using nonnormalized time data. Negative work values were obtained by integrating the negative portion of the power curve. The negative work for the ankle dorsiflexors and plantar flexors was considered separately for the RS runners. Average vertical loading rate was defined as the slope of the vertical ground reaction force curve from 20% to 80% of the nonnormalized stance time from initial contact to impact peak, or, in the absence of an impact peak, from 3% to 12% of the stance phase (FIGURE 1).^{8,9,37}

Additional variables obtained to aid in the interpretation of the lower extremity joint work and vertical ground reaction force variables were as follows: running speed, ankle and knee joint excursion, step frequency, stance time, maximum vertical ground reaction force, and maximum braking force. Total ankle and knee range-of-motion values were calculated from peak flexion/extension values obtained from the kinematic time-series data. Step frequency was obtained from the smoothed ground reaction force data by dividing the total time for 5 steps by 5, then dividing that mean step-interval value into 60 seconds to obtain steps per

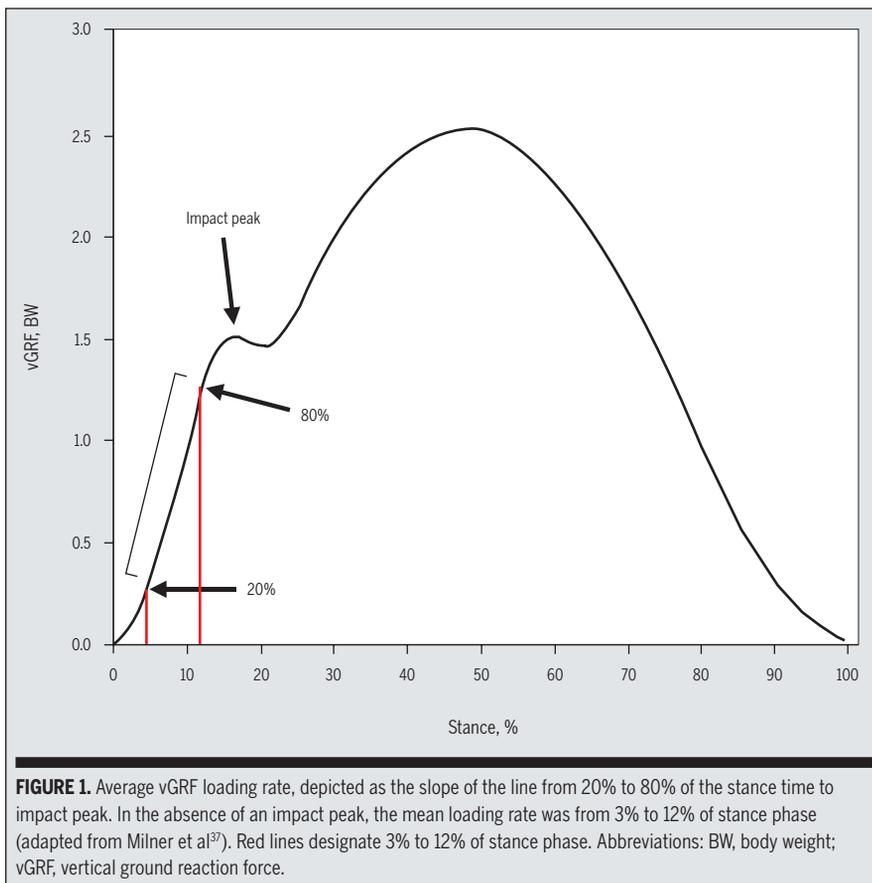


FIGURE 1. Average vGRF loading rate, depicted as the slope of the line from 20% to 80% of the stance time to impact peak. In the absence of an impact peak, the mean loading rate was from 3% to 12% of stance phase (adapted from Milner et al³⁷). Red lines designate 3% to 12% of stance phase. Abbreviations: BW, body weight; vGRF, vertical ground reaction force.

minute (eg, 5 steps in 1.67 seconds would equal 0.334 seconds per step, or 179.64 steps per minute). A custom MATLAB code was used to obtain maximum vertical ground reaction force and maximum braking force values from normalized averaged ground reaction force files for each runner (MATLAB 7.12 R2011a; The MathWorks, Inc, Natick, MA).

Data Analysis

Demographic variables between groups were compared using independent *t* tests. Gender proportions among groups were compared using a chi-square analysis. Reported training pace was compared to self-selected running speed on the treadmill using a paired-samples *t* test.

Univariate analyses of covariance were conducted on all biomechanical variables of interest, with potential covariates identified by preliminary independent *t* tests. Because group running speed approached statistical significance

between groups and age differed significantly between groups (TABLES 2 and 3), we used speed and age as covariates. R Version 2.7.2⁴¹ (R Foundation for Statistical Computing, Vienna, Austria) statistical software was used for the analysis.

RESULTS

DESCRPTIVE STATISTICS FOR THE PARTICIPANTS in our study are presented in TABLE 2. Gender proportions, height, and mass did not differ between groups. Chi runners were significantly older than RS runners. RS runners reported using their running style for a greater length of time than Chi runners. Reported weekly mileage did not differ between groups, and reported training pace averaged approximately 9 min/mi for both groups.

Kinematic Variables

The results of the analysis of covariance for kinematic variables of interest are

presented in TABLE 3. Reported training pace (3.01 m/s) was greater than the self-selected running speed during testing (2.69 m/s). Step frequency was significantly greater for the Chi group when covaried for speed and age. Stance times were not significantly different between the 2 groups.

No significant difference was observed in ankle excursion between the RS and Chi groups. A difference in ankle joint position occurred at initial contact, with the RS group contacting the ground with the ankle in dorsiflexion ($-2.60^\circ \pm 4.04^\circ$), whereas the Chi group contacted the ground in plantar flexion ($1.55^\circ \pm 4.12^\circ$, $t = 2.82$, $P = .008$) (FIGURE 2). The RS group demonstrated greater total knee excursion during stance phase ($25.9^\circ \pm 5.2^\circ$) than the Chi group ($21.2^\circ \pm 4.9^\circ$, $F = 4.86$, $P = .03$) (FIGURE 3).

Kinetic Variables

Analysis of covariance results for the kinetic variables of interest appear in TABLE 3. The RS group demonstrated a greater AVLR than the Chi group (RS, 68.55 BW/s; Chi, 43.15 BW/s; $P < .001$). RS runners demonstrated ankle dorsiflexor negative work (ADNW), whereas Chi runners demonstrated no ADNW (RS, -0.004 J/BH·BW; Chi, 0 J/BH·BW). RS runners also exhibited greater knee extensor negative work (KENW) than Chi runners (RS, -0.332 J/BH·BW; Chi, -0.144 J/BH·BW; $P < .001$). Chi runners demonstrated greater ankle plantar flexor negative work (APNW) than RS runners (Chi, -0.467 J/BH·BW; RS, -0.315 J/BH·BW; $P < .001$). While no difference was detected between groups for maximum vertical ground reaction force, the RS group demonstrated significantly greater maximum braking forces compared to the Chi group (RS, -0.072 BW; Chi, -0.027 BW; $P = .01$).

DISCUSSION

SIGNIFICANTLY GREATER NEGATIVE work of the ankle dorsiflexors and knee extensors was demonstrated

by the RS runners compared to the Chi group. Because the RS runners demonstrated a greater maximum braking force at impact, the resultant ground reaction force vector was positioned more posterior to the knee joint center. This more posteriorly positioned ground reaction force vector created an external knee flexion moment that was countered by an internal knee extensor moment. In addition, the greater knee excursion of the RS runners contributed to their having to generate greater KENW and attenuating vertical ground reaction forces through the knee joint instead of through the ankle joint, as did the Chi runners. This finding is consistent with Arendse et al,¹ who reported reduced KENW and greater APNW in a group of Pose runners who used a forefoot-strike pattern compared to runners who used either a midfoot-strike or RS pattern.

Greater KENW implies greater force generation by the quadriceps muscle group, which may lead to greater compressive forces at the tibiofemoral and patellofemoral joints. However, running with greater trunk flexion, as the Chi runners did, has been shown to reduce patellofemoral contact stress.⁴⁵ Increased contact pressure at these joints may lead to articular cartilage wear and is consistent with the greater prevalence of knee injuries reported in RS runners.²⁰

RS runners also demonstrated significantly greater maximum braking forces and reduced step frequency compared to the Chi runners. This finding is consistent with the work of Heiderscheit et al,²² who observed reduced braking impulses when runners increased step rates by 5% and 10%. Greater braking forces may be problematic, as Milner et al³⁶ observed greater braking forces in a sample of runners with a history of tibial stress fracture compared to matched controls. Furthermore, Zifchock et al⁴⁹ observed greater braking forces in the previously injured limb of females with a history of tibial stress fracture when compared to their uninjured side. The greater braking forces observed in the RS runners also

TABLE 3

SUMMARY OF ANALYSIS OF COVARIANCE RESULTS FOR THE KINEMATIC AND KINETIC VARIABLES OF INTEREST

Variable	RS*	Chi*	P Value
Running speed, m/s	2.78 ± 0.45	2.53 ± 0.48	.14
Step frequency, steps/min	180.18 ± 7.70	185.26 ± 10.22	.01†
Stance time, s	0.258 ± 0.02	0.255 ± 0.04	.08
Ankle ROM, deg	19.84 ± 3.26	21.38 ± 3.47	.13
Knee ROM, deg	25.88 ± 5.18	21.17 ± 4.97	.03†
Ankle DF negative work, J/BH-BW	-0.004 ± 0.001	0.0 ± 0.0	NA
Ankle PF negative work, J/BH-BW	-0.315 ± 0.139	-0.467 ± 0.100	<.001†
Knee extensor negative work, J/BH-BW	-0.332 ± 0.138	-0.144 ± 0.078	<.001†
Loading rate, BW/s	68.55 ± 15.45	43.15 ± 10.20	<.001†
Maximum vGRF, BW	2.28 ± 0.21	2.22 ± 0.30	.61
Maximum braking force, BW	-0.072 ± 0.001	-0.027 ± 0.001	.01†

Abbreviations: BH, body height; BW, body weight; Chi, certified Chi runners; DF, dorsiflexor; NA, not available; PF, plantar flexor; ROM, range of motion; RS, rearfoot-striking runners; vGRF, vertical ground reaction force.

*Values are mean ± SD, covaried for age and gender.

†P<.05.

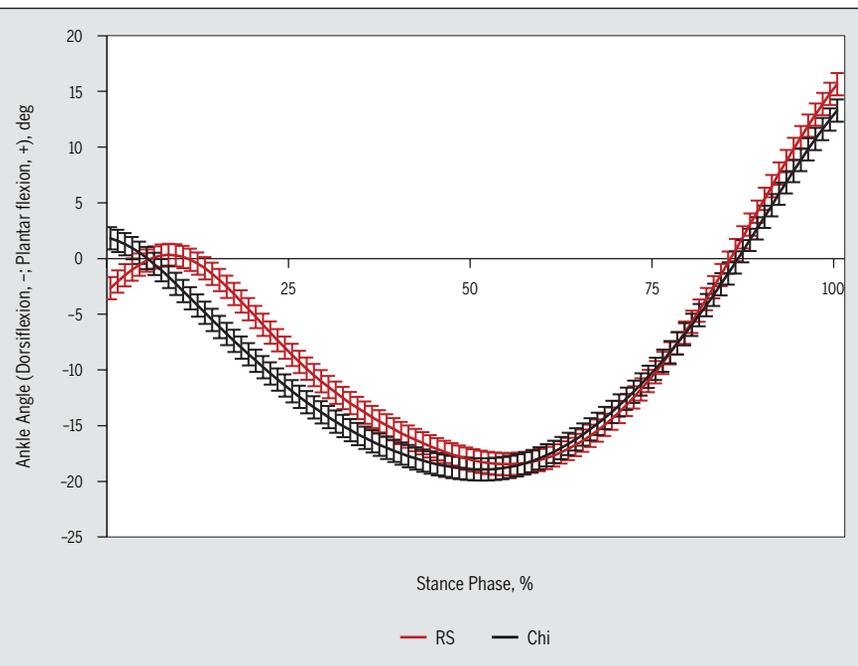


FIGURE 2. Comparison of ankle excursion during the stance phase of running. Abbreviations: Chi, Chi runners; RS, rearfoot-striking runners.

might have contributed to the increased KENW performed in this group.

During stance phase, runners in the Chi group demonstrated no ADNW and greater APNW. As such, striking the ground with the anterior portion of the

foot may be desirable for runners who have a history of anterior compartment syndrome¹³ or knee pathology. If a runner has a history of tibial stress fractures or plantar fasciitis associated with high-impact forces and/or loading rates, an

appropriate recommendation may be to adopt a more anterior foot strike with an increased step rate, in an attempt to land more softly. However, this strategy may not be appropriate for a runner with a history of metatarsal stress fracture, due to the increased loading time of the midfoot when running with this form.³⁹ Furthermore, the increased APNW in the Chi runners is indicative of greater utilization of the gastrocnemius and soleus muscles and may contribute to foot and ankle overuse injuries. At the very least, runners with a history of foot/ankle injuries should use caution when attempting to convert to a running style that uses an anterior foot-strike pattern.

Chi runners demonstrated reduced AVLR compared to RS runners. AVLRs greater than 70 BW/s have been associated with tibial and metatarsal stress fractures.^{48,49} In addition, instantaneous vertical ground reaction force loading rates greater than 100 BW/s have been associated with plantar fasciitis,⁴⁰ and AVLRs of 72 BW/s have been linked to patellofemoral pain syndrome.^{10,11} Previous authors have observed AVLRs ranging between 60 and 70 BW/s in healthy runners.^{10,11,48} While the healthy RS runners in our study demonstrated AVLRs similar to those of healthy runners in other studies, it remains unclear whether reducing loading rates to 43 BW/s, as observed in the Chi runners in our study, would be associated with a reduction in lower extremity overuse injuries. Considering that Chi runners take a greater number of steps per minute, it is possible that the total angular work conducted at various joints may actually increase for a given time or distance.

Several limitations should be considered when interpreting the results of our study. The assessment criteria used to determine acceptable Chi running were subjective. This may limit the ability of an individual to determine whether a runner is using this running form. For the current study, however, the individual who performed this assessment demonstrated perfect intrarater reliability. Asking over-

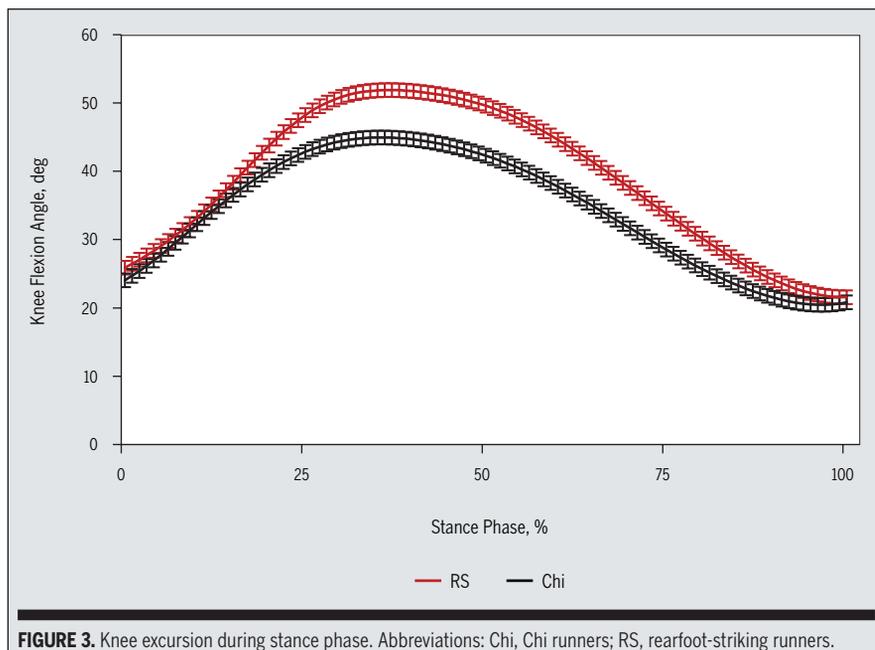


FIGURE 3. Knee excursion during stance phase. Abbreviations: Chi, Chi runners; RS, rearfoot-striking runners.

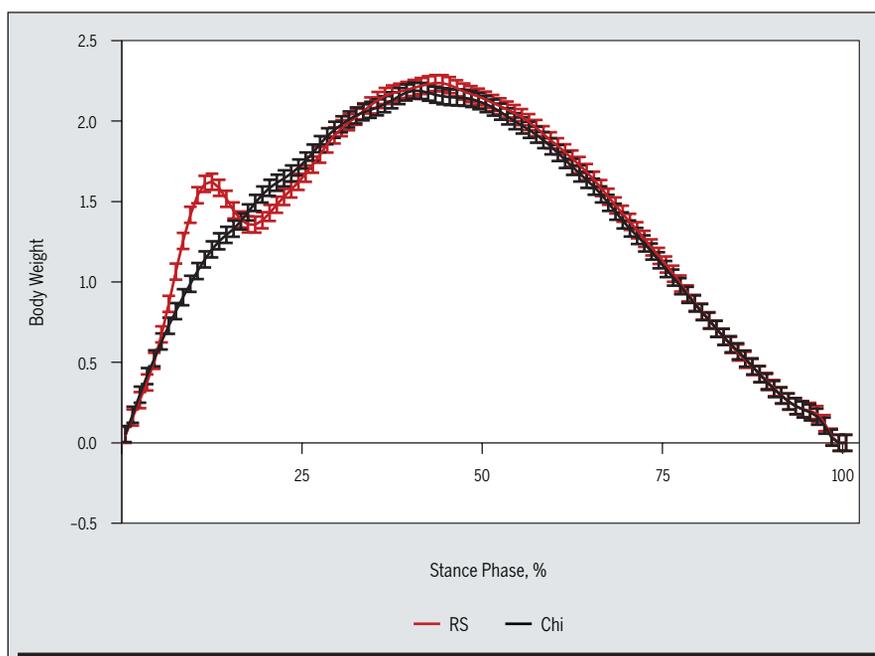


FIGURE 4. Comparison of vertical ground reaction force curves for RS and Chi runners. Abbreviations: Chi, Chi runners; RS, rearfoot-striking runners.

ground runners to run on a treadmill can influence kinematic and kinetic variables. For example, the relatively high step frequencies observed in our study (180-185 steps per min) might have been the result of using a treadmill to obtain data. Typical stride frequencies for tradition-

ally shod rearfoot strikers have been reported to be as low as 150 to 160 steps per minute. Advocates of running styles that emphasize striking the ground with the anterior portion of the foot recommend a stride frequency of approximately 180 steps per minute.^{16,34,42} The greater than

expected step frequency demonstrated by the RS runners in our study might have attenuated the kinetic variables of interest.

A recent study by Kristianslund et al²⁸ demonstrated the importance of considering cutoff frequencies for the filtering of kinetic and kinematic data when using inverse dynamic equations. Kristianslund et al²⁸ observed significant differences in their results when different low-pass cutoff frequencies were used. These authors,²⁸ however, arbitrarily selected cutoff frequencies based on values commonly used by other investigators. Our method of employing different kinetic and kinematic filtering frequencies was based on an analysis of the noise-to-signal ratios and frequency spectra for our data. However, using variable cutoff frequencies for the kinetic and kinematic data might have influenced the findings of this study. We also recognize that the maximum vertical ground reaction force and braking force variables have the potential for error, as they were extracted from an average of the trials for each runner.

To date, it is not known what constitutes “safe” and “potentially injurious” kinetic values. Further research is needed to compare ADNW, APNW, and KENW between healthy runners and runners who have a history of lower extremity injury. In addition, prospective studies of RS and Chi runners are needed to document differences in injury trends. Importantly, prospective studies involving groups of runners using an anterior foot strike are needed to evaluate the injury-prevention claims made by proponents of this running style.

CONCLUSION

CHI RUNNERS DEMONSTRATED NO ADNW, greater APNW, reduced KENW, reduced AVLR, and reduced maximum braking forces when compared to RS runners. Future research is necessary to determine whether these changes translate to reduced injury risk. ●

KEY POINTS

FINDINGS: RS runners demonstrated greater vertical ground reaction force loading rates and negative work of the knee extensors when compared to Chi runners. In contrast, Chi runners demonstrated greater negative work of the ankle plantar flexors.

IMPLICATIONS: Employing a method of running similar to Chi running may reduce knee loading and ground reaction force loading rates.

CAUTION: Data were collected on a laboratory treadmill. As such, the findings may not be applicable to overground running.

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