Exerted running results in altered impact mechanics and footstrike patterns following gait retraining. <https://doi.org/10.1080/02640414.2020.1868089>

Erin E. Futrell, PT, MPT, PhD^{1,2}
K. Douglas Gross, DPT, ScD³
David R. Mullineaux, PhD⁴
Irene S. Davis, PT, PhD^{2,5}

¹Springfield College, Springfield, MA

²Spaulding National Running Center, Cambridge, MA

³MGH Institute of Health Professions, Boston, MA

⁴University of Lincoln, Lincoln, Lincolnshire, United Kingdom

⁵Harvard Medical School, Boston, MA

Address correspondence to:

Erin Futrell

Springfield College Department of Physical Therapy

263 Alden Street

Springfield, MA 01109-3797

efutrell@springfieldcollege.edu

This investigation was approved by the Institutional Review Board of the Spaulding Rehabilitation Network Research Institute.

This trial is registered at clinicaltrials.gov. Registration number: NCT02987517. Protocol available at: <https://clinicaltrials.gov/show/NCT02987517>.

Acknowledgements

We would like to thank Matt Ruder, Steve Jamison, and Pratham Singh for their assistance with this project. We would like to thank the AMTI Force and Motion Foundation for the scholarship that funded this research and Noraxon USA for the use of their equipment.

This study was funded through a scholarship awarded by the AMTI Force and Motion Foundation and a footwear donation from Inov-8LLC

Disclosure of Interest Statement

The authors report they have no conflicts of interest.

Word count: 4624

Abstract

Exertion may alter running mechanics and increase injury risk. Effects of exertion following gait-retraining are unknown. **Objectives:** To determine how exertion effects load-rates, footstrike, and cadence in runners following a transition to forefoot strike (FFS) or increased cadence (CAD) gait-retraining. **Methods:** 33 (9M, 24F) healthy rearfoot strike runners were randomized into CAD or FFS groups. All runners received strengthening exercises and gait-retraining. 3D kinetic and kinematic motion analysis with instrumented treadmill at self-selected speed was performed at baseline & 1-week post-intervention, including an exerted run. Exertion was ≥ 17 on Borg's Rating of Perceived Exertion scale or voluntary termination of running. **Results:** Within group comparisons between fresh and exerted running: Cadence not affected in either group. Foot angle at contact became less plantarflexed in FFS (-2.2° , ± 0.4) and was unchanged in CAD. Both groups increased vertical average load-rate (FFS +16.9%, CAD +13.6%). CAD increased vertical stiffness (+8.6 kN/m). FFS reduced ankle excursion (1.8°). ($p \leq 0.05$ for all values listed)

Conclusion: Both FFS and CAD exhibited increased load-rates with exertion. Variables that may have increased load-rates were different for each group. CAD runners had increased vertical stiffness while FFS runners had reduced plantarflexion at contact and reduced ankle dorsiflexion excursion.

Key Words: fatigue, exertion, vertical load rates, physical therapy, running injury

INTRODUCTION

Increased rates of vertical impact loading may result in injury to the musculoskeletal system.^{20,44} Load rates that occur in running are highly influenced by the way the foot contacts the ground.²³ A recent study suggests that 95% of recreational runners strike the ground with their heel first and are classified as rearfoot strikers (RFS).² Typically, RFS runners have an impact peak in the vertical ground reaction force (VGRF) curve shortly after initial contact of the foot with the ground. The associated rapid rate of vertical loading with this impact peak has been related to specific running injuries such as tibial stress fractures and plantar fasciitis.^{26,33,44} Several gait retraining studies have shown short and long-term effects that may reduce risk of tibial stress fractures, patellofemoral pain, and overall injury.^{6,7,30,37,42} Therefore, interventions that can produce *lasting* reductions in excessive vertical impact forces and load rates have become popular clinical strategies to reduce the risk of running-related injuries.^{20,44}

Two interventions aimed at reducing vertical load rates are increasing cadence by 5-10% (while maintaining a consistent speed) and transitioning from a RFS to a forefoot strike pattern.^{7,42} Although both of these gait-retraining strategies have been shown to reduce impact loads^{39,42,14}, evidence is lacking regarding if gait changes persist as a runner is further exerted. Higher levels of exertion have been found to alter neuromuscular coordination and influence the runner's ability to attenuate loading.²⁷ Thus, when exerted, runners may increase the risk of impact-related injuries. Specifically in the lower limb, exertion leads to imbalances in muscle contraction along with increased shock acceleration, a combination that can lead to increased tibial stress

fracture risk.²⁷ Along with tibial stress fractures, excessive loading has also been linked to specific running injuries such as patellofemoral pain and plantar fasciitis^{24,26,33}. Because runners often reach an exerted state, it is important to understand if injury prevention strategies, such as gait-retraining to reduce load rates, have lasting effects under these conditions.

Exertion is a natural component of exercise, but is often accompanied by alterations in mechanics. A number of studies have found that the mechanics associated with exertion may contribute to injury.^{16,26,27} Changes in running mechanics brought about by exertion or fatigue vary in the literature, likely because the levels of exertion vary greatly between study protocols. Further, different methods are used to exert runners, such as altering speed and/or gradient, using physiologic markers such as $\text{VO}_{2\text{max}}$, or simply allowing a runner to report level of exertion. Altered mechanics with exerted running may include altered joint angles, changes in step length, and increased impact loading.^{9,11,12,27} Two large observational studies, in which runners were able to vary their speed, found that runners using mid or forefoot strike patterns tend to adopt a rearfoot strike pattern over the course of a long distance run.^{17,21} Other studies, all of which kept runners at a constant speed, have reported increased plantarflexion at initial contact in RFS runners who were exerted.^{8,9,12} Reports of altered knee angle with exertion have been mixed, despite all studies keeping runners at a constant speed. Some studies have found greater knee flexion or internal rotation at contact^{11,12,28}, while others have found no significant changes in knee kinematics.^{8,9,12} Regarding changes in step length or cadence, some authors have found increased step length (or reduced cadence) with exertion^{13,16,28}, while others have found that step length remains

constant.⁹ Findings regarding the effects of exertion on impact mechanics have been more consistent. Most studies, all of which kept runners at a constant speed, have found increased impact loading with high levels of exertion.^{8,9,11,27} Only one study found reduced loading in female runners who were exerted.¹⁴ These runners were exerted with progressive increases in speed and gradient, but data collected on their “fatigued run” was at self-selected speed. Because excessive impact loads may lead to specific running injuries, and because high levels of exertion increase impact loads, interventions to reduce running impacts need to remain effective under these conditions.

The short and long-term effects of a transition to forefoot strike (FFS) and increased cadence (CAD) gait retraining programs on vertical load rates have been previously published (Results: Appendix Table A1).¹⁴ The purpose of the present study was to determine the effects of exertion on the persistence of the changes in recently retrained mechanics in RFS runners. We hypothesized that both groups would demonstrate greater vertical load rates in an exerted state compared to a fresh state. We hypothesized increased load rates in the exerted state would be due to decreased cadence in the CAD group and a less plantarflexed foot angle at initial contact in the FFS group.

METHODS

The institutional review board of the Spaulding Rehabilitation Network Research Institute approved all activities and subjects provided informed consent before any procedures took place. The gait retraining methods and pre and post gait-retraining measures of primary variables are presented in brief in the Appendix and are fully

published elsewhere.¹⁴

Participants

Participants were healthy recreational runners ages 18-50 years and currently running 8-24 kilometers per week. They were injury-free for the past 3 months, with no history of stress fracture to the foot or ankle and with no conditions that permanently altered gait. Those that met these criteria performed a treadmill screening to determine their habitual cadence and footstrike pattern. Based on visual inspection, subjects who exhibited a RFS and cadence ≤ 170 steps/minute were included. As a result, thirty-three volunteers (9M, 24F) were invited to participate. A single researcher (EF) used a computer-generated block randomization scheme (Microsoft Excel) based on age and sex (block size=4) to assign subjects to a forefoot strike (FFS) or increased cadence (CAD) intervention group (Figure 1). The randomization of age and sex was to create equal distribution in both groups as these factors have been linked with differences in running biomechanics.³² Participants in the FFS and CAD groups were similar in age, speed, distance, and anthropometrics at the baseline analysis (Table 1).

Data Collection

Subjects underwent a baseline gait analysis wearing laboratory neutral cushioned shoes (Nike Air Pegasus) to determine their habitual mechanics. They were fitted with 70 retroreflective markers (44 tracking, 26 anatomical), on the head, trunk, upper, and lower extremities. Calcaneal markers were placed directly on the skin through holes cut into the shoes. Participants performed a static alignment trial, followed by a running analysis. They ran on an instrumented treadmill (AMTI, Watertown, MA, USA) for a 3-minute warm up and speed was adjusted to their self-selected long run pace. 3D motion capture was

performed using an 8-camera system sampled at 250Hz (Vicon, Oxford, United Kingdom), and an instrumented treadmill sampled at 1500Hz. Kinetic and kinematic data were recorded for 20 seconds and 10 consecutive right footstrikes were used for data analysis. In addition, high speed cameras recorded footstrike, and these were visually confirmed and compared with kinetic and kinematic data.

Interventions

Following baseline analysis, participants were given a 4-week independent strengthening program to prepare musculoskeletal tissues for demands of a new running gait. The FFS group were provided minimal shoes (Inov-8 Bare XF 210) as part of their intervention, as this has been found to further encourage a forefoot strike landing. Numerous studies have found minimal footwear is necessary to produce a correct forefoot strike pattern.^{19,31,36,40} The CAD group received neutral traditional cushioned shoes (Inov-8 Road Claw 275), as footstrike was not expected to change with increased cadence gait retraining.^{1,18} Gait retraining consisted of 8 sessions in a 2-3 week period depending on participants' availability. This schedule was chosen based on previous gait retraining studies.^{7,10,30,43} Auditory feedback with a faded-feedback design was used for both groups. Over the 8 sessions, run time was gradually increased from 10-30 minutes while auditory feedback was systematically reduced.^{30,37,43} Runners had continuous feedback for the first 4 sessions, then progressively reduced feedback at the beginning, middle, and end of the run for the last 4 sessions. The CAD group was instructed to match their footstrikes to the beat of an auditory metronome to increase cadence by 7.5% above their initial screening measure. The FFS group wore a wireless accelerometer on the distal medial tibia (Noraxon USA, Scottsdale, AZ). The accelerometer provided an auditory

signal if the acceleration signal indicated that subjects landed on their heel with a RFS pattern, or exhibited an uncontrolled heel descent. When all sessions of gait retraining were complete, subjects were encouraged to use their new gait independently and were given written instructions on how to safely progress running distance.

Exerted Run Protocol

One week after the final gait retraining session, participants returned for a follow-up gait assessment. The first portion of this analysis was considered the “fresh state”, and was identical to the set up and running speed performed at the baseline analysis. Runners were then allowed to rest for 5 minutes. Because recreational runners rarely work to exhaustion or maximal effort, a submaximal effort was purposeful in the design of the exerted run. Analyzing runners in a submaximal exerted state, typical of a training run, may be more ecologically valid for the majority of running this population engages in. For the exerted run, speed was increased by 10% above the self-selected speed performed during the fresh state. While running at the increased speed, runners were asked to report a number from Borg’s Rating of Perceived Exertion Scale (RPE) every 5 minutes.³ A runner was considered adequately exerted if they achieved a score ≥ 17 (“very hard”; score range 6-20) on the RPE scale, or if they were unable to maintain the run speed and asked to slow down to their original speed. Once exertion was reached for either reason, runners were returned to their original self-selected run speed for two minutes before 20 seconds of running data were recorded for the “exerted state”. Time to exertion and heart rate at time of exertion were also recorded.

Data Processing

Researchers were blinded to intervention group and performed data processing

using Visual3D software (C-motion, Germantown, MD) and customized MATLAB code (MathWorks, Natick, MA). Kinetic and kinematic data were filtered using a 4th order, low pass Butterworth filter with cut-off values of 50Hz and 12Hz respectively.

The primary variables of interest were cadence, foot angle at initial contact, and vertical average and instantaneous load rates (VALR, VILR). Cadence was defined as step frequency (i.e., left-right), and was determined from the number of contacts per minute derived from the vertical ground reaction force data. Foot angle was determined by the angle between the lateral foot and the laboratory coordinate system, with zero degrees being the value obtained during the static trial. A negative angle (plantarflexion) indicated a FFS, a positive angle (dorsiflexion) indicated a RFS, and an angle of zero indicated a midfoot strike. Vertical load rates were calculated using a previously published method.^{14,15} There were three different types of vertical ground reaction force curves produced by running subjects: one with an impact peak, one with an impact transient (with no local maxima), and one with neither an impact peak nor a transient. For each type of curve, a point of interest (POI) was identified to determine the area over which the load rate was calculated. The POI was the point just before the slope reduced by 15 body weights per second and had to exceed a subject's body weight. The slope of the most linear portion of the curve from footstrike to the POI was considered the vertical load rate zone. The vertical average load rate (VALR) was defined as the average slope of the VGRF curve in the region 20-80% of the curve from footstrike to POI. The vertical instantaneous load rate (VILR) was defined as the steepest slope of two consecutive points on the VGRF curve in the region 20-100% of the curve from footstrike to POI.

After the primary results were obtained, a secondary analysis was conducted to

seek an explanation for these results. The secondary variables were selected as they are likely factors that may influence load rates. Secondary variables of vertical stiffness during initial loading (VSIL) and sagittal plane knee and ankle excursions from initial loading to the first 50% of stance of gait were assessed. Knee flexion excursion was calculated as the difference between peak knee flexion in the first 50% of stance and knee flexion at initial contact. Ankle dorsiflexion excursion was calculated as the difference between the minimal dorsiflexion angle (or peak plantarflexion angle in the FFS group) and peak dorsiflexion angle in the first 50% of stance. As vertical stiffness is related to load rate, it was also calculated in the region of initial loading, which corresponded to the VALR region of the VGRF curve. Vertical stiffness was calculated as the ratio of the maximum VGRF (in the VALR region) to the maximum vertical displacement of the center of mass (COM) in the VALR region. COM excursion was determined by double integration of the vertical ground reaction force. This method is similar to that used in a study regarding vertical stiffness during a single leg hop test.⁴¹ The COM displacement was referenced to the COM position at initial contact.

Statistical Analysis

Statistical analysis was performed using SPSS Version 25. The *a priori* power analysis for the current investigation considered the variable with the least expected change (load rates with exertion) to calculate the minimum number of participants necessary to be recruited. Results indicated to achieve 0.90 power, with alpha set at $p < 0.05$ and a moderate effect (Cohen's $d > 0.70$), at least 14 cases per group for a total of 28 cases would be necessary. To account for a potential 15% participant attrition, a total of 34 participants was the aim of recruitment. Statistical outliers for each variable of

interest were removed using the “median absolute deviation” (MAD) method of Leys et al²², and modified based on Mullineaux and Irwin²⁹, using a more conservative t-statistic for scaling, resulting in detection of fewer outliers. This method is more statistically robust than using the more common standard deviation-based outlier removal methods (e.g. mean $\pm$ 3 standard deviations). Where outliers were detected, the t-statistic was adjusted between 0.01 and 0.001 so there were 2 or fewer outliers removed in each analysis. The number of subjects included for each variable’s analysis is listed in the Appendix. Vertical load rates (VILR, VALR), cadence, and foot angle at initial contact changes between fresh and exerted running were assessed within each intervention group using paired sample t-tests. In addition, difference scores of VALR and cadence in the CAD group and VALR and foot angle in the FFS group were analyzed.

RESULTS

No differences were noted in the subject baseline characteristics (Table 1). The variables relating to exertion were also generally similar between groups (Table 2). Time to exertion and level of exertion were similar between groups. However, more subjects stopped the exerted run due to an RPE ≥ 17 in the FFS group, while in the CAD group more stopped the exerted run due to having to reduce speed. Changes between fresh state and exerted state running within each group in the kinematic and kinetic variables are seen in Figures 2-5, with data for the means (SD), p values, and effect sizes provided in the Appendix (Table A2).

Increased Cadence Group

The CAD group increased VALR significantly (13.6%) when in the exerted state. For VILR, the CAD group’s increase (7.7%) did not reach significance (p=0.06, effect size

0.4). Within the CAD group, cadence was not significantly changed with exerted running (Figure 3A). For secondary variables, there were no changes in knee or ankle excursion angles with exertion for CAD runners (Figure 4, Table A2). However, VSIL was significantly increased with exertion (Figure 5, Table A2).

Forefoot strike group

The FFS group increased VALR significantly (16.9%) when in the exerted state (Figure 2, Table A2). VILR also increased significantly (14.8%) in the FFS group. In the FFS group, foot angle at initial contact became less plantarflexed by 2.2° ($p=0.01$), which was associated with a moderate effect size ($d=0.5$) (Figure 3B, Table A2). Two runners fully transitioned to a RFS while all others had a reduced plantar flexion angle. In addition, ankle excursion significantly reduced with exerted running for the FFS group, but knee flexion was not (Figure 4, Table A2). There were no significant changes in VSIL for the FFS group (Figure 5, Table A2).

Individual subject data within groups

The increase in VALR for the CAD group with exerted running, in the absence of a change in cadence, led us to look more closely at individual subject data within this group. We observed no relationship between CAD and VALR. We noted both increases and decreases in cadence during exertion for CAD runners (Figure 6A). These changes were also accompanied by a wide range of load rate changes. In contrast, individual subject data within the FFS group did not display a wide range of load rate changes. The FFS group exhibited a significant positive correlation between VALR and foot strike angle. Specifically, the foot became more dorsiflexed with exerted running and this was associated with an increase in the load rates (Figure 6B).

DISCUSSION

The purpose of this study was to examine whether newly retrained gait patterns of increasing cadence and transitioning to a forefoot strike pattern persisted under exerted conditions. It was hypothesized that the new patterns would degrade with exertion. Specifically, it was anticipated that the CAD group would reduce their cadence and the FFS group would reduce their plantarflexed foot angle at initial contact. As a result of these alterations in mechanics, we expected both groups would exhibit increases in vertical load rates.

Contrary to our hypothesis, the CAD group experienced no significant changes in cadence between fresh and exerted running. Therefore, cadence was not responsible for the increases in vertical load rates with exerted running in this group. As can be seen in Figure 7, some individuals increased their cadence, while others decreased their cadence. However, there was a wide range of change in load rates across the subjects. In fact, the individual with the largest change in VALR (+25.9 BW/s) with exertion had *no change in cadence* (166 steps/min) between fresh and exerted running. Further, individuals with the greatest increase and greatest decrease in cadence while exerted (-16.7 steps/min and +14.4 steps/min) had similar increases in VALR (+19.3 BW/s and +18.0 BW/s respectively). This underscores the lack of relationship between cadence and load rates, as has been reported previously¹⁵, and suggests other factors are at play.

In support of our cadence findings, Clansey et al (2012)⁹ and Derrick et al (2002)¹¹ found no significant changes in step length (inversely related to cadence) when runners were exerted. This is likely due to similar levels of exertion experienced in our runners and these previous studies. For instance, our runners and those of Clansey et al reported

similar RPE scores (16-17 “hard” to “very hard”) during an exerted, or “fatiguing” run. Derrick et al had participants “run until volitional exhaustion”, defined as, “prevented them from continuing”. Although we did not instruct runners to exert themselves to exhaustion, nearly half of the participants in our study (n=14) terminated their exerted run when they felt they could no longer continue at the increased speed of the exerted run. In contrast to our findings, Dutto and Smith¹³ noted a decrease in stride rate with fatigue and reported this was strongly correlated with a decrease in stiffness ($r=0.85$, $p<0.01$). However, Dutto and Smith had runners work to exhaustion (based on 80% of peak oxygen consumption), while our runners reached a submaximal state of exertion. In addition, Dutto and Smith’s runners ran for 31-90 minutes, while our runners did not exceed 20 minutes, indicating a likely lower level of exertion. Speed was controlled for our runners, which was also the case in these other studies. Thus, differences between our results and Dutto and Smith’s is likely due to differences in level of exertion.

As we hypothesized, foot angle at initial contact significantly reduced in the FFS group with the exerted state compared to the fresh state. This was accompanied by a significant reduction in ankle excursion. This is consistent with the findings of Larson et al²¹ who reported that the majority of runners who were forefoot and midfoot strikers at the 10km point in a race reduced their foot angles (became less plantarflexed) at the 32km point, with a large percentage transitioning to a rearfoot strike. Larson et al attributed the change in footstrike to fatigue of the plantarflexor muscles. As the FFS group’s mean foot angle with exerted running was -0.71 degrees, our FFS runners, on average, did not fully transition to a RFS pattern. Only two individuals transitioned to a RFS during exerted running. The greater number of runners transitioning to a RFS pattern

in Larson et al may be related to the longer distance and more competitive nature of their run. This likely led to greater levels of exertion. In addition, runners observed by Larson were engaged in in-field running and likely varied their speed, while our runners maintained continuous speed. Controlled speed may lead to more subtle changes in gait.

RFS runners also demonstrate changes in their foot angle with exertion, but in the opposite direction. Both Christina et al⁸ and Clansey et al⁹ have reported that RFS runners exhibited less dorsiflexion at initial contact during running likely due to fatigue of the ankle dorsiflexor muscles. Interestingly, our CAD runners, who were habitual RFS did not experience a significant change in foot angle with exertion. However, Christina et al induced a local fatigue of the ankle dorsiflexor with exercises prior to a controlled speed treadmill run, which may have influenced the foot angle at contact. Clansey et al had subjects perform two 20-minute fatiguing runs with consistent speed determined by lactate threshold. Therefore, local muscle fatigue in these previous studies may have been greater than that experienced by runners in the current study.

VALR and VSIL are related measures as they both incorporate a change in vertical force over the impact phase of landing. However, this change is referenced to a change in time for VALR, but to a change in center of mass excursion with VSIL. While both groups exhibited an increase in VALR with the exerted run, only the CAD group exhibited higher VSIL. Interestingly, this was found in the absence of reductions in knee and ankle excursions which might have explained the greater stiffness. Further assessment of joint kinetics may provide more insight into the cause of the increased vertical stiffness. Regardless of the cause, the increased stiffness with exertion suggests that runners using the increased cadence gait style may need to augment their retraining with a program to

increase their lower extremity compliance during running. This may be accomplished with activities such as eccentric-emphasized strengthening exercises in the hip, knee and ankle extensors to mimic the loading response of running. The FFS runners exhibited a reduction in ankle dorsiflexion excursion with exertion. This is consistent with observations by Larson et al, in which recreational runners using a FFS pattern adopted a RFS by the end of a long distance run.²¹ This change reduces the time over which the force can be dissipated leading to the increased load rates during running. Runners receiving FFS gait retraining may need further emphasis on muscular endurance in the plantar flexors in order to better dampen the effects of muscle fatigue experienced during exerted running.

The increases with exerted running within both our groups were lower than that observed by Clansey et al⁹ in VILR (+18.1%) and VALR (+17.3%) during a fatiguing run in habitual RFS runners. The lower increase in our study may be due to the retraining programs that these runners had just undergone to reduce their load rates. Additionally, the runners in the present study performed a 4-week foot and ankle-strengthening program in addition to gait retraining, while the runners in Clansey et al received no interventions. These muscles are important in helping to dampen impact during loading. The strengthening program performed by our subjects may have helped to mitigate the effects of the local muscle fatigue, resulting in an overall smaller increase in load rates. Finally, differences in running protocols between Clansey et al and our study could explain differences in load rates results. Clansey et al based each subject's fatiguing run speed upon measures of their lactate threshold as opposed to a 10% increase in self-selected speed chosen for our study. Their runners were required to run at the lactate

threshold speed for two 20-minute bouts. Although level of exertion was similar between their runners and ours (RPE scores 16-17, “hard” to “very hard”), it is possible running at lactate threshold speed may have influenced local muscle fatigue, and therefore, effected loading rates.

In contrast, Gerlach et al¹⁶ found load rates *decreased* by 11.8% in females who performed a treadmill run to voluntary exhaustion. Surprisingly, this decrease was accompanied by an increased step length and slower running cadence, which are thought to increase load rates. However, there is perhaps a difference in runners’ level of exertion from Gerlach et al and the present study. Gerlach used a fatiguing protocol that increased both speed and gradient of the treadmill until voluntary exhaustion. This protocol may have resulted in changes in increased joint excursions or decreased vertical stiffness that could result in lower impacts compared to those seen with our exerted run protocol.

Limitations

The subjects included in this study were healthy recreational runners with relatively low weekly mileage. Therefore, results cannot be extrapolated to injured, elite, or long-distance runners. The runners in our study underwent the exerted run 1 week after the completion of their gait retraining intervention. It is arguable they did not have enough time to adapt to their new gait pattern, and therefore, their performance during the exerted run may be different had the analysis been at a later date. However, gait analysis during the exerted had to occur fairly soon after gait retraining to maintain equal experience using the new gait pattern for all of the runners. In addition, the exerted running analysis was performed on a treadmill using a consistent speed. Although we utilized a subject-

selected speed, runners in the field likely vary their speed under exerted conditions which may result in different alterations in mechanics.³⁸

CONCLUSION

These results suggest that exertion increases vertical load rates in runners who have recently undergone gait retraining to either increase their cadence or transition to a forefoot strike pattern. However, the factors contributing to increased load rates with exertion were different in each of the two gait retraining interventions. During an exerted run, FFS runners demonstrated a decrease in plantarflexion at initial contact with an associated reduction in ankle dorsiflexion excursion, while CAD runners exhibited an increased vertical stiffness. Levels of running exertion or fatigue vary widely across the literature; therefore, comparing biomechanical changes in these conditions is difficult.

Key Points

Findings: Runners who received gait retraining for increasing cadence or transitioning to forefoot strike had differing responses to exerted running. Exerted running resulted in reduced plantarflexion at initial contact and reduced ankle excursion for FFS runners. Exertion did not influence changes in running cadence, but resulted in increased vertical stiffness in CAD runners. Vertical load rates increased with exerted running for all runners, but to a lesser extent as in previous studies, perhaps due to the newly retrained patterns aimed at reducing load rates.

Implications: Interventions aimed at reducing impact loading may help mitigate the negative effects of exerted running on newly trained gait patterns. FFS retrained

433 runners may need additional plantarflexor endurance training, while CAD retrained
434 runners may need lower extremity compliance training such as quadricep eccentric-
435 emphasized strengthening.

436 **Caution:** This investigation included healthy recreational runners with low weekly
437 mileage. Extrapolating these results to injured or elite runners should be done with
438 caution.

REFERENCES

1. Allen DJ, Heisler H, Mooney J, Kring R. The effect of step rate manipulation on foot strike pattern of long distance runners. *Int J Sports Phys Ther*. 2016;11(1):54-63.
2. de Almeida MO, Saragiotto BT, Yamato TP, Lopes AD. Is the rearfoot pattern the most frequently foot strike pattern among recreational shod distance runners? *Phys Ther Sport*. 2015;16(1):29-33. doi:10.1016/j.ptsp.2014.02.005
3. *American College of Sports Medicine. Guidelines for Exercise Testing and Prescription*. 6th ed. Lippincott Williams & Wilkins; 2000.
4. Burr DB, Milgrom C, Boyd RD, Higgins WL, Robin G, Radin EL. Experimental stress fractures of the tibia. Biological and mechanical aetiology in rabbits. *J Bone Joint Surg Br*. 1990;72(3):370-375.
5. Burr DB, Milgrom C, Fyhrie D, et al. In vivo measurement of human tibial strains during vigorous activity. *Bone*. 1996;18(5):405-410.
6. Chan ZYS, Zhang JH, Au IPH, et al. Gait retraining for the reduction of injury occurrence in novice distance runners: 1-year follow-up of a randomized controlled trial. *Am J Sports Med*. 2018;46(2):388-395. doi:10.1177/0363546517736277
7. Cheung RTH, Davis IS. Landing pattern modification to improve patellofemoral pain in runners: a case series. *J Orthop Sports Phys Ther*. 2011;41(12):914-919. doi:10.2519/jospt.2011.3771
8. Christina KA, White SC, Gilchrist LA. Effect of localized muscle fatigue on vertical ground reaction forces and ankle joint motion during running. *Hum Mov Sci*. 2001;20(3):257-276. doi:10.1016/S0167-9457(01)00048-3
9. Clansey AC, Hanlon M, Wallace ES, Lake MJ. Effects of fatigue on running mechanics associated with tibial stress fracture risk. *Med Sci Sports Exerc*. 2012;44(10):1917-1923. doi:10.1249/MSS.0b013e318259480d
10. Crowell HP, Davis IS. Gait retraining to reduce lower extremity loading in runners. *Clin Biomech Bristol Avon*. 2011;26(1):78-83. doi:10.1016/j.clinbiomech.2010.09.003
11. Derrick TR, Dereu D, McLean SP. Impacts and kinematic adjustments during an exhaustive run. *Med Sci Sports Exerc*. 2002;34(6):998-1002.
12. Dierks TA, Davis IS, Hamill J. The effects of running in an exerted state on lower extremity kinematics and joint timing. *J Biomech*. 2010;43(15):2993-2998. doi:10.1016/j.jbiomech.2010.07.001
13. Dutto DJ, Smith GA. Changes in spring-mass characteristics during treadmill running to exhaustion. *Med Sci Sports Exerc*. 2002;34(8):1324-1331.

14. Futrell EE, Gross KD, Reisman D, Mullineaux DR, Davis IS. Transition to forefoot strike reduces load rates more effectively than altered cadence. *J Sport Health Sci*. Published online July 17, 2019. doi:10.1016/j.jshs.2019.07.006
15. Futrell EE, Jamison ST, Tenforde AS, Davis IS. Relationships between habitual cadence, footstrike and vertical loadrates in runners. *Med Sci Sports Exerc*. Published online 2017.
16. Gerlach KE, White SC, Burton HW, Dorn JM, Leddy JJ, Horvath PJ. Kinetic Changes with Fatigue and Relationship to Injury in Female Runners: *Med Sci Sports Exerc*. 2005;37(4):657-663. doi:10.1249/01.MSS.0000158994.29358.71
17. Hasegawa H, Yamauchi T, Kraemer WJ. Foot strike patterns of runners at the 15-km point during an elite-level half marathon. *J Strength Cond Res Natl Strength Cond Assoc*. 2007;21(3):888-893. doi:10.1519/R-22096.1
18. Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, Ryan MB. Effects of step rate manipulation on joint mechanics during running. *Med Sci Sports Exerc*. 2011;43(2):296-302. doi:10.1249/MSS.0b013e3181ebedf4
19. Hollander K, Argubi-Wollesen A, Reer R, Zech A. Comparison of minimalist footwear strategies for simulating barefoot running: a randomized crossover study. *PloS One*. 2015;10(5):e0125880. doi:10.1371/journal.pone.0125880
20. Hreljac A. Impact and Overuse Injuries in Runners: *Med Sci Sports Exerc*. Published online May 2004:845-849. doi:10.1249/01.MSS.0000126803.66636.DD
21. Larson P, Higgins E, Kaminski J, et al. Foot strike patterns of recreational and sub-elite runners in a long-distance road race. *J Sports Sci*. 2011;29(15):1665-1673. doi:10.1080/02640414.2011.610347
22. Leys C, Ley C, Klein O, Bernard P, Licata L. Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median. *J Exp Soc Psychol*. 2013;49(4):764-766. doi:10.1016/j.jesp.2013.03.013
23. Lieberman DE, Venkadesan M, Werbel WA, et al. Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature*. 2010;463(7280):531-535. doi:10.1038/nature08723
24. Messier SP, Davis shala E, Curl WW, Lowery RB, Pack RJ. Etiologic factors associated with patellofemoral pain in runners. *Med Sci Sports Exerc*. 1991;23(9):1008-1015.
25. Milgrom C, Radeva-Petrova DR, Finestone A, et al. The effect of muscle fatigue on in vivo tibial strains. *J Biomech*. 2007;40(4):845-850. doi:10.1016/j.jbiomech.2006.03.006

- 507 26. Milner CE, Ferber R, Pollard CD, Hamill J, Davis IS. Biomechanical factors associated
508 with tibial stress fracture in female runners. *Med Sci Sports Exerc.* 2006;38(2):323-
509 328. doi:10.1249/01.mss.0000183477.75808.92
- 510 27. Mizrahi J, Verbitsky O, Isakov E. Fatigue-Related Loading Imbalance on the Shank in
511 Running: A Possible Factor in Stress Fractures. *Ann Biomed Eng.* 2000;28(4):463-469.
- 512 28. Mizrahi J, Verbitsky O, Isakov E, Daily D. Effect of Fatigue on Leg Kinematics and
513 Impact Acceleration in Long Distance Running. *Hum Mov Sci.* 2000;19:139-151.
- 514 29. Mullineaux DR, Irwin G. Error and anomaly detection for intra-participant time-series
515 data. *Int Biomech.* 2017;4(1):28-35. doi:10.1080/23335432.2017.1348913
- 516 30. Noehren B, Scholz J, Davis I. The effect of real-time gait retraining on hip kinematics,
517 pain and function in subjects with patellofemoral pain syndrome. *Br J Sports Med.*
518 2011;45(9):691-696. doi:10.1136/bjsm.2009.069112
- 519 31. Nordin AD, Dufek JS. Footwear and footstrike change loading patterns in running. *J*
520 *Sports Sci.* Published online May 7, 2020:1-8. doi:10.1080/02640414.2020.1761767
- 521 32. Phinyomark A, Hettinga BA, Osis ST, Ferber R. Gender and age-related differences in
522 bilateral lower extremity mechanics during treadmill running. *PloS One.*
523 2014;9(8):e105246. doi:10.1371/journal.pone.0105246
- 524 33. Pohl MB, Hamill J, Davis IS. Biomechanical and anatomic factors associated with a
525 history of plantar fasciitis in female runners. *Clin J Sport Med Off J Can Acad Sport Med.*
526 2009;19(5):372-376. doi:10.1097/JSM.0b013e3181b8c270
- 527 34. Radin EL, Parker HG, Pugh JW, Steinberg RS, Paul IL, Rose RM. Response of Joints to
528 Impact Loading - III - Relationship Between Trabecular Microfractures and Cartilage
529 Degeneration. *J Biomech.* 1973;6:51-57.
- 530 35. Radin EL, Paul IL. Response of Joints to Impact Loading. I. In Vitro Wear. *Arthritis*
531 *Rheum.* 1971;14(3):356-362. doi:10.1002/art.1780140306
- 532 36. Rice HM, Jamison ST, Davis IS. Footwear matters: Influence of footwear and foot strike
533 on load rates during running. *Med Sci Sports Exerc.* 2016;48(12):2462-2468.
534 doi:10.1249/MSS.0000000000001030
- 535 37. Roper JL, Harding EM, Doerfler D, et al. The effects of gait retraining in runners with
536 patellofemoral pain: A randomized trial. *Clin Biomech Bristol Avon.* 2016;35:14-22.
537 doi:10.1016/j.clinbiomech.2016.03.010
- 538 38. Ruder M, Jamison ST, Tenforde A, Mulloy F, Davis IS. Relationship of Foot Strike
539 Pattern and Landing Impacts during a Marathon. *Med Sci Sports Exerc.*
540 2019;51(10):2073-2079.

- 541 39. Samaan CD, Rainbow MJ, Davis IS. Reduction in ground reaction force variables with
542 instructed barefoot running. *J Sport Health Sci.* 2014;3(2):143-151.
543 doi:10.1016/j.jshs.2014.03.006
- 544 40. Squadrone R, Gallozzi C. Biomechanical and physiological comparison of barefoot and
545 two shod conditions in experienced barefoot runners. *J Sports Med Phys Fitness.*
546 2009;49(1):6-13.
- 547 41. Waxman JP, Ford KR, Nguyen A-D, Taylor JB. Female Athletes With Varying Levels of
548 Vertical Stiffness Display Kinematic and Kinetic Differences During Single-Leg
549 Hopping. *J Appl Biomech.* 2018;34(1):65-75. doi:10.1123/jab.2017-0144
- 550 42. Willy RW, Buchenic L, Rogacki K, Ackerman J, Schmidt A, Willson JD. In-field gait
551 retraining and mobile monitoring to address running biomechanics associated with
552 tibial stress fracture. *Scand J Med Sci Sports.* 2016;26(2):197-205.
553 doi:10.1111/sms.12413
- 554 43. Willy RW, Scholz JP, Davis IS. Mirror gait retraining for the treatment of patellofemoral
555 pain in female runners. *Clin Biomech Bristol Avon.* Published online August 20, 2012.
556 doi:10.1016/j.clinbiomech.2012.07.011
- 557 44. Zadpoor AA, Nikooyan AA. The relationship between lower-extremity stress fractures
558 and the ground reaction force: A systematic review. *Clin Biomech.* 2011;26(1):23-28.
559 doi:10.1016/j.clinbiomech.2010.08.005

APPENDIX

Table A1. Previously published pre and post gait-retraining values for variables of interest.¹⁴ Means (SD). Negative value for foot angle indicates plantarflexion at initial contact. (CAD – increased cadence group, FFS – forefoot strike group, VILR and VALR – vertical instantaneous and average load rates).

	VILR		VALR		Cadence		Foot Angle	
	pre	post	pre	post	pre	post	pre	post
CAD	72.8 (24.1)	66.6 (14.2)	57.9 (19.9)	49.8 (9.4)	160.3 (6.1)	171.7 (7.6)	14.0 (2.5)	12.5 (6.5)
FFS	73.1 (25.6)	42.5 (11.3)	58.4 (21.0)	29.4 (5.2)	160.8 (8.5)	170.7 (11.3)	14.3 (4.3)	-3.4 (4.4)

Table A2. Within group comparisons of Fresh vs. Exerted states for primary and secondary variables. Means (SD). n= number of subjects analyzed for each variable. * Indicates significant difference ($p \leq 0.05$) between fresh and exerted running. (IC - initial contact; Knee Flx Exc - knee flexion excursion in sagittal plane, Ankle Exc - ankle excursion in sagittal plane).

Forefoot strike group (FFS)	n	FFS Fresh	FFS Exerted	p-value	Effect size
Primary					
VILR (BW/s)	15	46.9 (15.3)	53.9 (22.2)	0.05*	0.4
VALR (BW/s)	14	30.6 (6.3)	35.8 (11.1)	0.03*	0.6
Cadence (steps/min)	15	172.5 (10.7)	170.0 (6.3)	0.21	0.3
Foot Angle IC (degrees)	16	-2.9 (4.4)	-0.71 (4.8)	0.01*	0.5
Secondary					
Knee Flx Exc (degrees)	16	20.3 (4.2)	20.9 (5.0)	0.30	0.1
Ankle Exc (degrees)	16	29.6 (4.7)	27.8(4.4)	0.01*	0.4
Vertical Stiffness (kN/m)	14	29.2 (5.7)	32.6 (10.1)	0.29	0.4
Increased cadence group (CAD)	n	CAD Fresh	CAD Exerted	p-value	Effect size
Primary					
VILR (BW/s)	17	67.7 (14.2)	72.9 (14.9)	0.06	0.4
VALR (BW/s)	17	52.4 (12.4)	59.6 (12.6)	0.01*	0.6
Cadence (steps/min)	17	170.9 (7.7)	168.8 (5.9)	0.25	0.3
Foot Angle IC (degrees)	16	12.6 (6.7)	11.7 (3.8)	0.17	0.2
Secondary					
Knee Flx Exc (degrees)	17	25.4 (2.8)	24.9 (3.5)	0.49	0.2
Ankle Exc (degrees)	16	18.8 (3.5)	17.6 (2.1)	0.14	0.4
Vertical Stiffness (kN/m)	17	41.8 (8.9)	50.3 (17.9)	0.01*	0.6

TABLE 1. Subject characteristics at baseline. Means (SD). (*FFS – forefoot strike group, CAD – increased cadence group*)

	FFS n=16 (5 male)	CAD n=17 (4 male)
Age (years)	29.7 (4.8)	29.7(6.5)
Height (m)	1.7 (0.06)	1.7 (0.1)
Weight (kg)	70.2 (12.1)	65.0 (11.3)
Average km/week	14.3 (4.9)	15.2 (4.4)
Self-selected speed (m/s)	2.5 (0.2)	2.6 (0.2)

TABLE 2. Variables of exertion for FFS and CAD groups. Means (SD). (*FFS – forefoot strike group, CAD – increased cadence group*)

	FFS (n=16)	CAD (n=17)
10% increased Speed (m/s)	2.7 (0.2)	2.9 (0.2)
Time to Exertion (min)	19.4 (8.2)	20.6 (10.6)
Average RPE at Exertion	16.6 (1.0)	16.5 (1.1)
Average HR at Exertion (bpm)	170.1 (19.0)	171.6 (17.3)
# subjects stopped by RPE ≥ 17	11	8
# subjects stopped due to inability to maintain speed	5	9

FIGURE 1.

FIGURE 2.

FIGURE 3.

FIGURE 4.

FIGURE 5.

FIGURE 6.

Figure 1. Flow diagram of study progression. (*CAD – increased cadence group, FFS – forefoot strike group*)

Figure 2. Fresh and exerted state means for VILR and VALR (error bars SD). *Indicates significant within group difference between fresh and exerted states. (*CAD – increased cadence group, FFS – forefoot strike group, VILR and VALR – vertical instantaneous and average load rates, BW/s – body weights per second*).

Figure 3. Fresh and exerted state means for **A)** cadence in the CAD group, and **B)** foot angle at initial contact in the FFS group (error bars SD). *Indicates significant within group difference between fresh and exerted states. (*CAD – increased cadence group, FFS – forefoot strike group*)

Figure 4. Fresh and exerted state means for sagittal ankle excursion from initial contact to 50% of stance phase (error bars SD). *Indicates significant within group difference between fresh and exerted states. (*CAD – increased cadence group, FFS – forefoot strike group*)

Figure 5. Fresh and exerted state means for vertical stiffness (error bars SD). *Indicates within group significant difference between fresh and exerted states. (*CAD – increased cadence group, FFS – forefoot strike group*)

Figure 6. Individual participant difference scores of VALR between fresh and exerted running for each group. **A) CAD:** There is a large spread of the data across both axes with no relationship between the change in cadence and change in VALR. Note that individual (a) with no change in cadence exhibited the largest increase in VALR with exertion. However, the individuals with the greatest increase in cadence (b) and greatest decrease in cadence (c) had similar changes in VALR with exertion. **B) FFS:** There is a positive relationship between the change in foot angle and change in VALR with an increase in dorsiflexion and increase in VALR with exertion. (*CAD – increased cadence group, FFS – forefoot strike group, VILR and VALR – vertical instantaneous and average load rates*).