DIFFERENCES IN REACTION FORCE-TIME CHARACTERISTICS EXPERIENCED BY FEMALES WHEN RUNNING ON A TRACK AT DIFFERENT SPEEDS

Harper E. Stewart[1] and Jill L. McNitt-Gray[1,2]

Department of Biomedical Engineering[1], Department of Biological Sciences[2], University of Southern California, Los Angeles, USA

Elite collegiate runners are susceptible to sustaining lower extremity stress related injuries. Ground reaction forces (GRFs) were analyzed to understand differences in mechanical loading at steady state 5.5 and 7 min/mile paces. We hypothesized GRF magnitudes would increase with speed while horizontal GRFs during braking would be unique to each participant. GRFs, inertial measurement units, and high speed video were collected during outdoor over ground running. Group differences were observed that were not always significant within participant. As speed increased, average horizontal GRF during braking (-0.25 to -0.29 BWs) decreased while peak vertical GRF increased (2.75 to 2.91 BWs). The unique pattern of the sagittal plane resultant GRF orientation was maintained during initial braking phase which may indicate this orientation is a nervous system control priority.

KEYWORDS: biomechanics, reaction force orientation, running, contact duration

INTRODUCTION: Elite runners at the collegiate level are particularly susceptible to running related injuries. Endurance athletes are a specifically vulnerable population for sustaining lower extremity stress fractures which have incidence rates ranging from 3.9-31.3% depending on the sport (Bennell et al., 1996; Snyder et al., 2006). Lower extremity fractures typically occur in the tibia or metatarsal, but femur and pelvis fractures also occur frequently (Koenig et al., 2008; Nusselt et al., 2010; Tenforde et al., 2018). Our overarching aim is to determine how mechanical loading experienced during running at different paces affects mechanical loading experienced by the lower extremity to indicate the likelihood of an individual developing an injury. This study sought to validate a novel outdoor data collection environment to quantify loads in realistic running environments and characterize differences in reaction force-time characteristics experienced by individual collegiate mid-distance female runners at different speeds. We hypothesized that GRF magnitudes would increase, foot contact duration would decrease with speed, the percent of contact time spent in braking would remain the same, and that the orientation of the resultant reaction force in the sagittal plane would become more vertical with speed.

METHODS: Female collegiate and post-collegiate National Collegiate Athletic Association Division I runners (n=8) volunteered and provided informed consent in accordance with the institutional review board. Participants ran at steady state 7 and 5.5 minutes per mile (3.83 m s^{-1} and 4.92 m s^{-1}) on a level track wearing the shoes they typically wear during training. Photoelectric cells (Brower Timing Systems Draper, UT USA) were placed 10 feet (3.048 m) apart on either side of the force platform at hip height approximating center of mass to ensure trials were within 11% of the selected speeds. Two portable 0.6 m x 0.4 m, 3D force plates (Kistler, Amherst, NY, USA Type 9286BA) were oriented end to end along the runway to avoid tendencies to target the force plates. Ground reaction forces were measured (1200 Hz) for 10 foot contacts on each leg at two speeds. Kinematic data were acquired using inertial measurement units (500 Hz, APDM, Portland, OR) and high speed video (240Hz, Panasonic GH5S Osaka, Japan).

Contact time was defined as the period of time when vertical GRF first exceeded (initial contact) and was less than (final contact) 16 N (Munro et al., 1987). Braking duration was defined from initial contact to the time when the anterior-poster GRF shifted from braking (posterior directed reaction force) to propulsion phase (0 crossing) and is expressed as a percent of total contact time. GRFs measured during contact were used to characterize horizontal and vertical components of the reaction force and changes in CM velocities. The angle of the resultant force in the sagittal plane throughout the stance phase was defined as the angle of the resultant GRF projected into the sagittal plane (vertical defined as 0°). The "initial" contact phase was defined as the instance on the force time curve where the last local minimum occurs before the GRF angle consistently increases to a positive value during propulsion. A percentile bootstrap method for medians was used to test for group differences. Pairwise differences within participant were tested using mean percentile bootstrapping methods and were adjusted using the Benjamini-Hochberg method (Wilcox, 2017).

Table 1: Summary table of major findings. Stance time and anterior-posterior GRF findings, S.D. indicated in parentheses. * Indicates statistically significant results.

	Contact Time *(ms)*	***Braking Duration*** *(% Contact Time)*	***Peak*** GRF_{VERT} *(BW)*	**Avg** GRF_{HORIZ} **during Braking** (BW)	ΔVel_{VERT} ***during Contact*** *(m/s)*	ΔVel_{HORIZ} **during Braking** (m/s)
3.83 m/s *(7 min/mi)*	208 (15)	49 (2)	2.74 (0.21)	-0.25 (0.04)	1.35 (0.19)	-0.24 (0.03)
4.92 m/s *(5.5 min/mi)*	179 (15)	48 (2)	2.91 (0.25)	-0.29 (0.05)	1.41 (0.17)	-0.24 (0.04)
Group Significance	($p < 0.001$)*	($p = 0.723$)	($p < 0.001$)*	($p < 0.001$)*	($p = 0.199$)	($p = 0.829$)

RESULTS: Contact duration significantly decreased with increases in speed. Significant differences in contact duration were observed between speeds for the group and each individual runner (Table 1). As a group, no significant differences in percent time in braking phase were seen across speeds (Table 1). Within-participant comparisons of braking phase duration between speeds indicated 6 of 8 participants also exhibited no significant differences. As a group, participants experienced significantly greater peak vertical GRFs and average horizontal GRFs during braking when running at the faster pace (Table 1). Within-participant analysis revealed 6 of the 8 participants experienced greater peak vertical GRFs at the faster pace and 7 of the 8 participants experienced greater average horizontal GRFs during braking at the faster pace (Fig 1, 2).

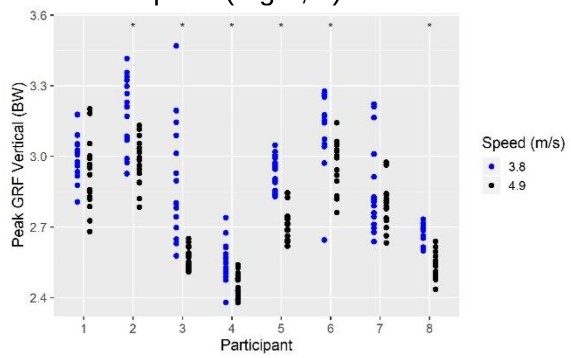

Figure 1: Comparison of the peak vertical GRF during contact by trial for each participant across speeds and normalized to body weight (BW). * Indicates significant differences within participant across speeds.

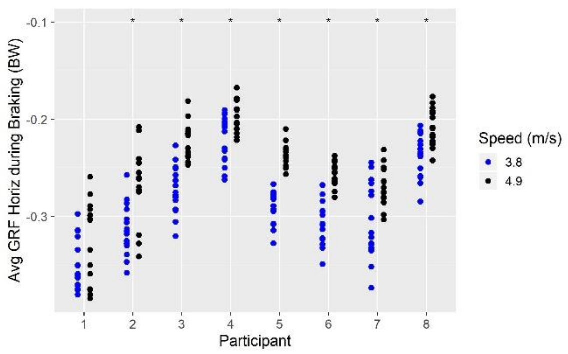

Figure 2: Comparison of the average horizontal GRF during the braking phase by trial for each participant across speeds and normalized to body weight (BW). Negative values indicate a posteriorly directed GRF. * Indicates significant differences within participant across speeds.

As a group and within-participant, no significant differences in change in horizontal CM velocity during braking were observed between speeds (Table 1). This indicates that as steady state running speed increases, the velocity lost during the braking phase is not changing within participant. As a group, no significant differences in change in vertical CM velocity during contact were observed between speeds although 5 of 8 participants experienced greater changes in vertical CM velocity at the faster pace. The representative trials show how contact time decreased, peak vertical GRF increased, and braking duration remained the same (Fig 3).

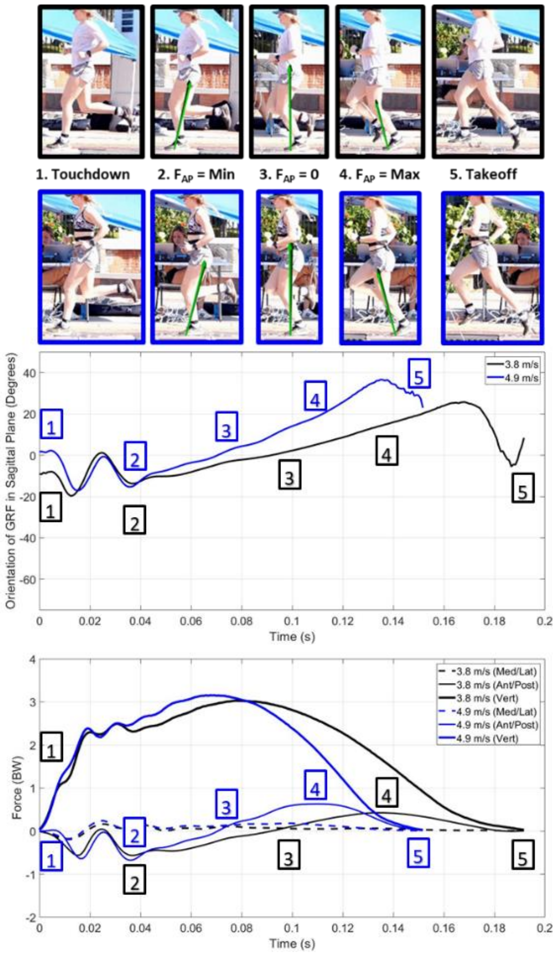

Figure 3: Comparison of two representative trials for Participant 6 at 3.8 m/s (black) and 4.9 m/s (blue). (Top) Filmstrips show the GRF (green) in the sagittal plane relative to the participant. Numbers 1-5 correspond to takeoff, minimum A-P force, zero crossing of the A-P force, maximum of the A-P force, and takeoff, respectively. (Middle) Orientation of force angle relative to vertical during contact. (Bottom) Component forces during contact in BW units.

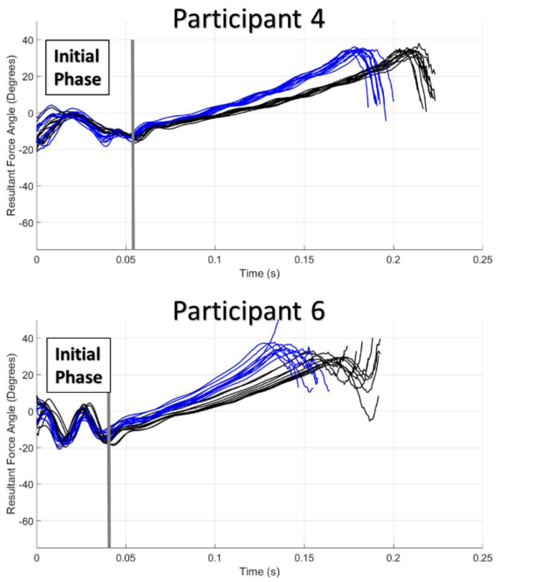

Figure 4: Comparison of GRF orientation in the sagittal plane for two exemplar participants during contact where 0° corresponds to vertical orientation of the resultant vector. The resultant force angle in the sagittal plane for all left foot trials at 7 min pace (black) and 5.5 min pace (blue) demonstrate consistency across trials within and between speeds. Initial phase indicated by the region proceeding the vertical line.

Finally, the results of this study show that the orientation of the reaction force during the initial phase did not change within subject as speed increased (Fig 4). This phenomenon can be seen in the consistency of the GRF orientation in the sagittal plane for multiple trials (Fig 4). The two participants demonstrate different GRF orientation patterns during the initial phase but are internally consistent between speeds. Amount of time spent in the initial phase did not change despite the increase in speed as indicated by the placement of the grey vertical line (Fig 4).The consistency of the resultant force angle in the sagittal plane during the initial phase indicates forces in the anterior-posterior (A-P) and vertical directions are increasing proportionally with speed. Therefore, changes in the vertical and anterior-posterior GRF between speeds are due to the magnitude of forces rather than orientation during the initial phase.

DISCUSSION: To better understand how runner-specific mechanical loading differs at different training paces, reaction forces experienced during multiple running cycles performed outside on the track were analyzed and compared within participant. The participants in this study exhibited shorter contact times and greater peak vertical GRFs which were consistent with

previous findings (Kipp et al., 2018; Munro et al., 1987). As a group, contact duration decreased with speed while peak vertical ground reaction force and average horizontal reaction force during braking increased. Not all participants exhibited significant differences observed for the group. Orientation of the GRF in the sagittal plane was unique to each participant but the pattern remained the same within individual during the initial phase regardless of speed. These preliminary results suggest maintaining reaction force orientation during initial foot contact may reflect nervous system control priorities across speed.
Changes in CM vertical velocity between speeds were not found to be significantly different indicating that oscillations of the CM within participant may not change with speed. Interestingly, the magnitude of the braking impulse normalized by body mass was not found to be significantly different between speeds yet when normalized by braking phase duration, the average horizontal GRF experienced increased with speed. The orientation of the GRF in the sagittal plane was internally consistent within participants across speed suggesting increases in GRF with speed occurs proportionally in the vertical and horizontal directions. Increasing sample size and further validation of lower extremity segment kinematic data will further elucidate how GRF magnitudes and orientation affect mechanical load distribution across the lower extremity of individuals when running. Extending this research will aid to help screen and prevent stress related injuries in endurance athletes. This work demonstrates the value of in-field studies where athletes train and experience regular loading conditions.

CONCLUSION:
Consistent with running research conducted in a lab and on an instrumented treadmill, contact duration decreased while peak vertical GRF and average horizontal GRF during braking increased with speed. Not all participants exhibited significant differences observed for the group. The internal consistency of the orientation of the GRF in the sagittal plane within subjects during the initial phase of contact provides insight to advance understanding of nervous system control priorities while navigating landing during steady state running. This field-based research approach provides avenues for characterizing mechanical loading during running and to screen and prevent stress related lower extremity injuries in endurance athletes.

REFERENCES

Bennell, K.L., Malcolm, S.A., Thomas, S.A., Wark, J.D., Brukner, P.D., 1996. The incidence and distribution of stress fractures in competitive track and field athletes: A twelve-month prospective study. *Am. J. Sports Med*. 24, 211–217. https://doi.org/10.1177/036354659602400217

Kipp, S., Grabowski, A.M., Kram, R., 2018. What determines the metabolic cost of human running across a wide range of velocities? *J. Exp. Biol*. 221. https://doi.org/10.1242/jeb.184218

Koenig, S.J., Toth, A.P., Bosco, J.A., 2008. Stress fractures and stress reactions of the diaphyseal femur in collegiate athletes: an analysis of 25 cases. *Am. J. Orthop.* (Belle Mead. NJ). 37, 476–480.

Munro, C.F., Miller, D.I., Fuglevand, A.J., 1987. Ground reaction forces in running: A reexamination. *J. Biomechanics.* 20, 147-155.

Nusselt, T., Klinger, H.M., Schultz, W., Baums, M.H., 2010. Fatigue stress fractures of the pelvis: A rare cause of low back pain in female athletes. *Acta Orthop*. Belg. 76, 838–843.

Snyder, R.A., Koester, M.C., Dunn, W.R., 2006. Epidemiology of Stress Fractures. *Clin. Sports Med.* 25, 37–52. https://doi.org/10.1016/j.csm.2005.08.005

Tenforde, A.S., Carlson, J.L., Sainani, K.L., Chang, A.O., Kim, J.H., Golden, N.H., Fredericson, M., 2018. Sport and triad risk factors influence bone mineral density in collegiate athletes. *Med. Sci. Sports Exerc*. 50, 2536–2543. https://doi.org/10.1249/MSS.0000000000001711

Wilcox, R., 2017. Modern Statistics for the Social and Behavioral Sciences. Chapman and Hall/CRC. https://doi.org/10.1201/9781315154480

ACKNOWLEDGEMENTS: This study is supported by the PAC12 Student-Athlete Health & Well-Being Grant Program. Work by this author was also partially supported by the Los Angeles Chapter of ARCS and USC WiSE.