Speed-Dependent Changes in Vertical Ground Reaction Force Characteristics During $\dot{V}O_{2max}$ Testing in Trained 5k Runners

Original Research

Kaela M. Hierholzer[1], Kimitake Sato[2], G. Monique Mokha[3], Michael Ramsey[4], John C. Abbott[5], & Michael H. Stone[4,6]

[1]*Department of Sport and Health Sciences, Catawba College, Salisbury, NC, USA*
[2]*Peak Force International, Taichung, Taiwan*
[3]*College of Health Care Services, Nova Southeastern University, Fort Lauderdale, FL, USA*
[4]*Department of Exercise and Sport Sciences, East Tennessee State University, Johnson City, TN, USA*
[5]*Sport Science, Atlanta United FC, Atlanta, GA, USA*
[6]*Institute for Sport, Physical Education and Health Sciences (ISPEHS), The University of Edinburgh, Edinburgh, Scotland, UK*

Open Access

RESEARCH in STRENGTH and PERFORMANCE

Submitted: May 6, 2026
Accepted: June 3, 2026
Published: June 16, 2026

Research in Strength and Performance: *2026, Volume 6 (Issue 1): 18*

ISSN: 3069-0765

Abstract

Introduction: Vertical ground reaction force (vGRF) characteristics have been well documented across sprint speeds; however, limited research has examined these variables during incremental maximal aerobic tests ($\dot{V}O_{2max}$) in distance runners. The purpose of this study was to investigate the effects of increasing speeds on biomechanical parameters during an incremental $\dot{V}O_{2max}$ test.

Methods: Twelve trained college cross-country and triathlon athletes (8 females, 4 males) completed a graded treadmill protocol to volitional fatigue. Descriptive statistics, percent change, correlation matrices, and regression analysis were conducted to examine relationships between biomechanical parameters (independent variable) and $\dot{V}O_2$ (dependent variable).

Results: Running speed demonstrated a near-perfect negative correlation with contact time ($r = -0.99$, $p < .001$) and strong positive correlations with vGRF ($r = 0.986$, $p < .001$) and loading rate ($r = 0.965$, $p < .001$). Additionally, vGRF was strongly associated with loading rate ($r = 0.965$, $p < .001$) and inversely related to contact time ($r = -0.982$, $p < .001$). Regression analysis revealed excellent reliability across speeds (ICC = 0.98–1.00), with the highest reliability observed at 20.4 and 21.7 km/h (ICC = 1.00). In contrast, asymmetry demonstrated weak, non-significant relationships with all variables. In trained distance runners, increasing speed is associated with greater vGRF and loading rate, and reduced contact time. Furthermore, vGRF and contact time were significantly related to oxygen consumption.

Conclusions: These findings demonstrate consistent, speed-dependent biomechanical changes during incremental $\dot{V}O_{2max}$ testing and suggest that this may provide information for examining interactions between mechanical and metabolic responses to increasing exercise intensity.

Key Words: biomechanics, asymmetry, graded exercise test, performance, distance runners

Corresponding author: Kaela M. Hierholzer; khierhol22@catawba.edu

Introduction

Collegiate cross-country and triathlon athletes may be required to perform at a wide range of speeds during competition.[1] Due to the demand of their sport, it is important for sport coaches and practitioners to understand their athlete's performance metrics and potential injury risk associated with their sport. Numerous kinetic variables can be collected in a lab setting to analyze an athlete's performance; however, there are specific parameters that have been previously researched demonstrating their importance. Previous research has reported that vertical ground reaction forces (vGRF), as well as loading rate can be related to running injuries and performance.[2]

Vertical ground reaction forces during running can change depending on factors such as speed.[3] Previous research has reported vGRF among recreational males averaged 2.46 ± 0.33 BW and females, an average vGRF of 2.28 ± 0.32 BW;[4] indicating athletes undergo substantial stress during running. More important than vGRF, is the degree to which asymmetry takes place during activity. Kinetic asymmetry has been associated with increased risk of injury, therefore, the larger amount of kinetic asymmetry the higher the risk of injury.[1] Bailey, et al.,[5] reported that strength seems to play a large role in decreasing the amount of asymmetry between limbs. Therefore, asymmetry may be an indication of relative weakness among athletes.

Loading rate is also a kinematic metric that has been associated with performance and injury risk analysis.[2,6] Loading rate is derived from the slope of vGRF over a period of time and is known to be affected by running speed.[7] With the increase in running speed, there is also typically a shift in running mechanics that takes place. Collegiate runners display increased loading rates; likely due to running at increased speeds, and their running mechanical differences compared to recreational runners.[8] Interestingly, despite increased loading rate being correlated with increased injury risk, collegiate runners have not been shown to experience an increase in injury risk due to a shift in their running mechanics, compared to recreational runners.[8]

Ground contact time has also been shown to be a gait analysis variable that would allow practitioners to learn more about their athlete's performance. Ground contact time is indicative of an athlete's running economy. Previous research conducted on female Kenyan runners found that a shorter ground contact time was associated with higher running economy and therefore, improved performance.[9] Improved running economy, stemming from optimal ground contact time, can occur, which results in the athlete being able to utilize a lower percentage of their $\dot{V}O_{2max}$ at a given running speed.[9] Specifically, if ground contact time is shorter, this indicates that an athlete is spending less time during the braking force.[10]

The purpose of this study was to examine how progressively increasing running speeds influence biomechanical parameters during an incremental $\dot{V}O_{2max}$ test. This investigation provides a more detailed awareness of the mechanical responses of collegiate cross-country and triathlon athletes resulting from increasing running speed and intensity. This type of information may provide preliminary insight to coaches and athletes in optimizing a strength and sport-specific training integrated process aimed at improving performance. This investigation aimed to characterize mechanical responses to increasing physiological demand within a controlled laboratory setting and to provide preliminary insight into how these responses may be used to monitor changes in running mechanics across exercise intensities. It was hypothesized that progressively increasing running speed during the incremental $\dot{V}O_{2max}$ test would result in: a) increased vGRF and loading rate, b) decreased ground contact time, and c) increased lower-limb asymmetry at higher running speeds due to greater mechanical and physiological demands associated with fatigue.

Methods

Participants

The subjects were 12 trained male (n = 8) and female (n = 4) collegiate cross-country and triathlon athletes, ranging from age 18 to 25 years old. The athletes' demographics are shown in Table 1; tests were part of an ongoing athlete monitoring program. Athletes had clearance by the university's sports medicine staff to take part in the monitoring program. Prior to the start of the study, all participants were informed about study aims and procedures, and they signed the informed consent document. This study was approved by the Institutional Review Board at East Tennessee State University.

Protocol

The study was designed to assess the relationship between running speed and biomechanical parameters during a $\dot{V}O_{2max}$ test. Twelve D-1 and D-2 cross-country and triathlon collegiate subjects ran on a specially instrumented treadmill with increasing speed to volitional exhaustion. A correlation matrix was created to quantify the relationships between running speed, biomechanical parameters, and oxygen consumption across progressively increasing exercise intensities. Additionally, regression analysis was applied to further define the relationship between ground reaction forces, loading rate, contact time and $\dot{V}O_2$.

Table 1. Athlete demographics.

Variable	All Athletes (n=12)	Males (n=4)	Females (n=8)
Age (years)	19.92 ± 1.56	19.40 ± 1.52	20.29 ± 1.60
Height (cm)	167.55 ± 7.23	169.62 ± 10.12	166.07 ± 4.64
Weight (kg)	65.7 0± 9.85	70.02 ± 12.28	62.61 ± 7.13

Note: cm: centimeters; kg: kilograms

A flow chart of the basic procedures is shown in Figure 1. Upon reporting to the laboratory athletes were tested for hydration status. Hydration testing consisted of athletes providing a urine sample and several drops of urine were tested using a digital refractometer (PAL 10S, Atago USA, Inc) to obtain a urine specific gravity value. If the urine specific gravity was ≥ 1.020, athletes were required to drink water and retested approximately thirty minutes after the initial test. Athletes with a urine specific gravity of <1.020 were classified as adequately hydrated and were allowed to continue the testing session.

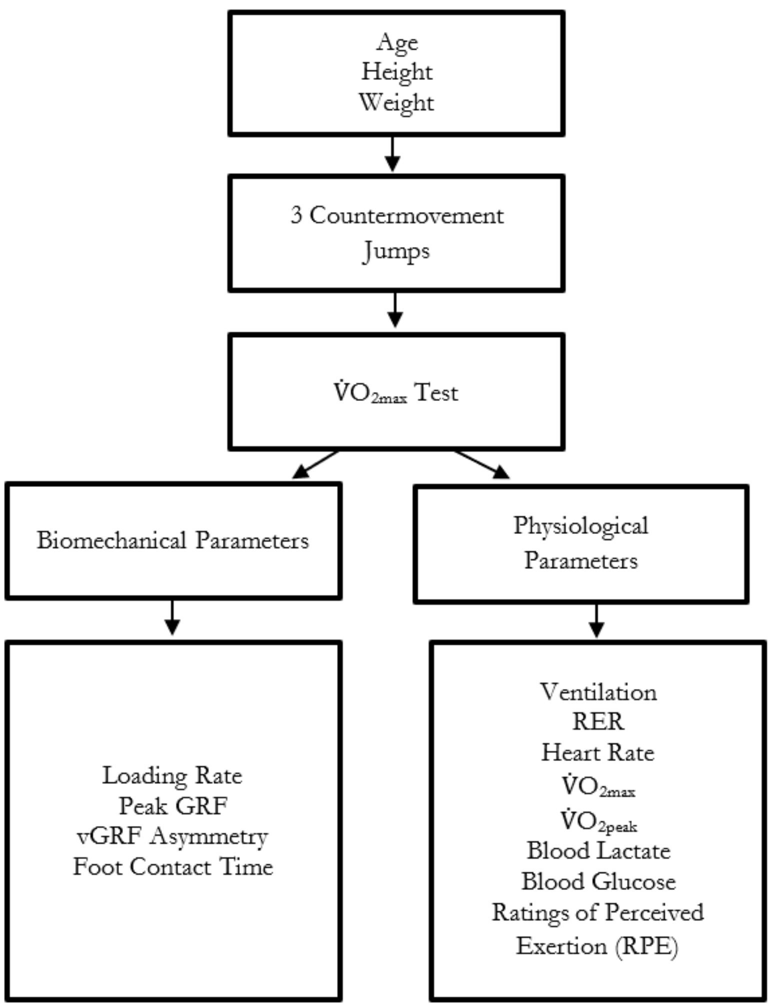

Figure 1. Flow chart of testing procedures.

Each athlete's age, body mass, and height were recorded prior to testing. Before the $\dot{V}O_{2max}$ test, the athletes performed three unweighted countermovement jumps on PASCO Force Plates (Roseville, CA) that were analyzed using ForceDecks Software (VALD Performance, Brisbane, Australia). Previous investigation in our laboratory and others,[11,12] established PASCO portable force plates as a reliable tool for collecting intra and inter-session jump data. Following the jump test, athletes performed a $\dot{V}O_{2max}$ test, until volitional fatigue. Gas exchange was monitored with a Parvo Medics TrueOne 2400 Metabolic Cart (Sandy, UT). The $\dot{V}O_{2max}$ protocol had been consistently used for athlete monitoring by the team strength and conditioning coach/sport scientist for the triathlon and cross-country teams, thus maintaining consistency.[13] Prior to starting the test, each athlete's baseline measurements were recorded. The protocol used in this study was not typical compared to other studies. The majority of $\dot{V}O_{2max}$ tests follow the Balke or Bruce protocol.[14] Both of these protocols not only increase in speed, but also grade with each stage.[13] However, the study protocol consisted of each athlete starting at a speed of 10.1 km/h. The speed increased by 1.28 km/h every 2 minutes until the subject reached an RER of 1.00. Thereafter, the speed increased 1.28 km/h every 1 minute until cessation of the test. This was performed to achieve a true $\dot{V}O_{2max}$ test and max lactate concentration, while keeping the total test time as close to 12 minutes as possible, which is the preferred duration.[14] Throughout the $\dot{V}O_{2max}$ test, a grade of 0% was maintained to properly collect and compare vGRF data from the force plates. During the $\dot{V}O_{2max}$ test, the athlete's blood lactate (2 measurements each time) was measured using a Nova Medical Lactate Plus analyzer (Waltham, MA). The Lactate Plus device has good reliability and accuracy when compared to an in-laboratory based blood lactate analyzer.[15] Blood glucose (2 measurements each time) was measured using an Accu-Chek Aviva Plus meter (Roche, Indianapolis, IN), and when portable blood glucometers were compared to an in-laboratory analyzer it was reported that 82% of the readings met the International Organization of Standardization's criteria for clinical accuracy.[16] Ratings of perceived exertion (RPE) were also collected at the end of each stage. To collect this data, the athlete stepped off the belt and onto the treadmill's running board. Then the athlete returned to the treadmill belt for the next stage of the test. All athletes were equipped with a Garmin heart rate monitor chest strap (Olathe, KS) to monitor changes in heart rate throughout the test. Garmin was chosen to maintain consistency with what the athletes use during training. While the athlete was running, their vGRF was being recorded using four load cells (Rice Lake, WI) collecting at 1,000 hertz (Hz) placed beneath the Tuff Tread treadmill belt (Conroe, TX) and the LabView 2018 software (National Instruments, Austin, TX) for the entirety of the $\dot{V}O_{2max}$ test. All testing ceased when the athlete ended the $\dot{V}O_{2max}$ test by stepping off the treadmill belt and onto the side platform on their own.

Statistical Analysis
Data were analysed using Microsoft Excel (Microsoft Corporation, Redmond, WA, version 16.25) to calculate average and percent change. SPSS (IBM Corporation, Armonk, NY, version 26) was used to create a correlation matrix of the average values to establish relationships between variables. SPSS was also used to perform a regression analysis between biomechanical parameters (independent variable) and $\dot{V}O_2$ (dependent variable). Intraclass correlation (ICC) and coefficient of variation (CV) were used to analyse reliability of the treadmill load cell data using Microsoft Excel and a spreadsheet developed for analysis of reliability.[17]

Results
Table 2 displays the percent change in each biomechanical parameter from speed to speed. The largest increase in vGRF for all athletes occurred from speed 19.1 km/h to 20.4 km/h (4.31%). Loading rate had the largest percent change from 19.1 km/h to 20.4 km/h with an increase of 15.28%. For contact time, the largest percent change was a decrease from 12.7 km/h to 14.0 km/h (-5.99%).

Figure 2 shows the right and left leg vGRF at each speed for all athletes. The data indicates that as the speed increased during the $\dot{V}O_{2max}$ test, the vGRF of both the left and right leg also increased until the final speed of 21.7 km/h where there is a slight decrease.

Table 3 displays the vGRF asymmetry between the right and left legs at each speed that was depicted above in figure 2. It was noted that the largest asymmetry occurred at 21.7 km/h (2.95%), while the smallest asymmetry occurred at 17.8 km/h (0.62%).

Table 2. Percent change from speed to speed for biomechanical parameters for all athletes.

Speed (km/h)	vGRF (BW)	vGRF (% Change)	Loading Rate (BW/ms)	Loading Rate (% Change)	Contact Time (ms)	Contact Time (% Change)
10.1 (n=12)	2.38	-	0.02	-	251.20	-
11.4 (n=12)	2.49	4.27%	0.02	8.07%	237.98	-5.55%
12.7 (n=12)	2.56	2.63%	0.02	5.40%	226.16	-5.23%
14.0 (n=12)	2.62	2.34%	0.03	5.57%	213.39	-5.99%
15.2 (n=12)	2.66	1.78%	0.03	5.13%	202.76	-5.24%
16.5 (n=11)	2.69	1.11%	0.03	3.92%	194.86	-4.05%
17.8 (n=9)	2.76	2.32%	0.03	8.26%	185.63	-4.97%
19.1 (n=7)	2.83	2.63%	0.03	10.29%	179.23	-3.57%
20.4 (n=4)	2.96	4.31%	0.04	15.28%	172.43	-3.95%
21.7 (n=4)	2.92	-1.46%	0.04	2.73%	165.97	-3.89%

Note: km/h: kilometers/hour; vGRF: vertical ground reaction force; BW: body weight; ms: millisecond

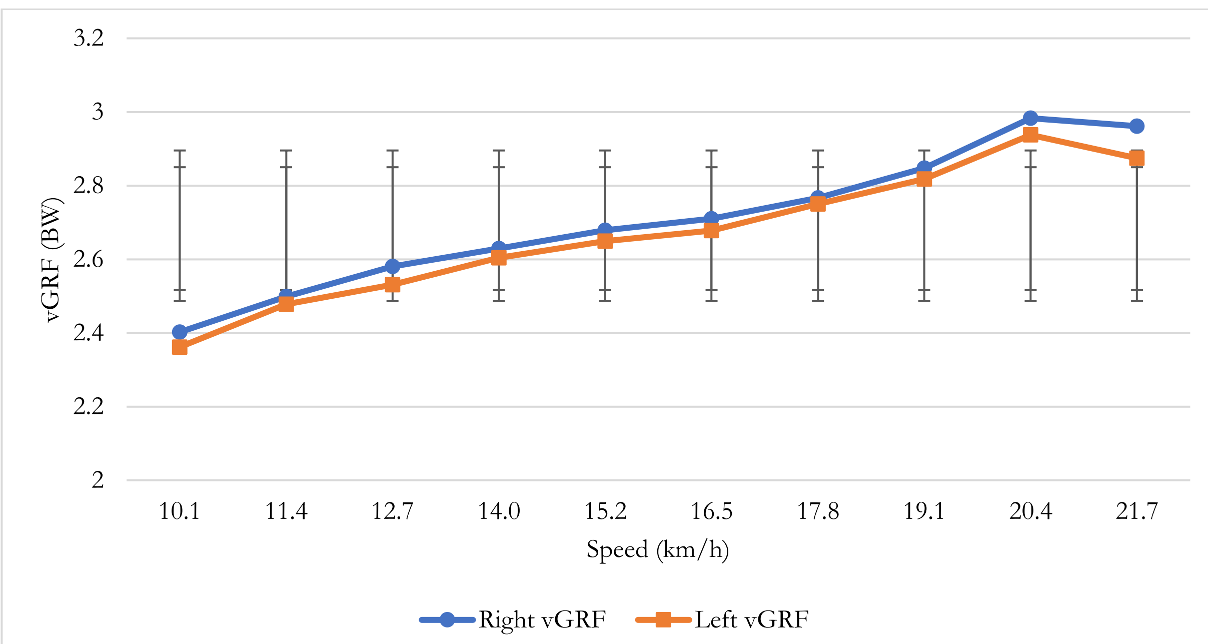

Figure 2. Right and left leg vGRF at each speed for all athletes.

Table 3. vGRF asymmetry between right and left leg for all athletes at each speed.

Speed (km/h)	Right vGRF (BW)	Left vGRF (BW)	Asymmetry (%)
10.1 (n=12)	2.402	2.361	1.69%
11.4 (n=12)	2.498	2.477	0.85%
12.7 (n=12)	2.580	2.530	1.93%
14.0 (n=12)	2.629	2.604	0.96%
15.2 (n=12)	2.678	2.649	1.09%
16.5 (n=11)	2.710	2.678	1.18%
17.8 (n=9)	2.766	2.749	0.62%
19.1 (n=7)	2.847	2.817	1.06%
20.4 (n=4)	2.983	2.937	1.52%
21.7 (n=4)	2.961	2.874	2.95%

Note: km/h: kilometers/hour; vGRF: vertical ground reaction force; BW: body weight

Figure 3 displays the change in vGRF from speed to speed for all athletes. The figure displays that the average vGRF increases as the speed increases. It is indicated that the largest increase occurred between 19.1 km/h and 20.4 km/h (4.31%), while the smallest increase occurred from 15.2 km/h to 16.5 km/h (1.11%). A decrease in vGRF occurred from 20.4 km/h to 21.7 km/h by 1.46%.

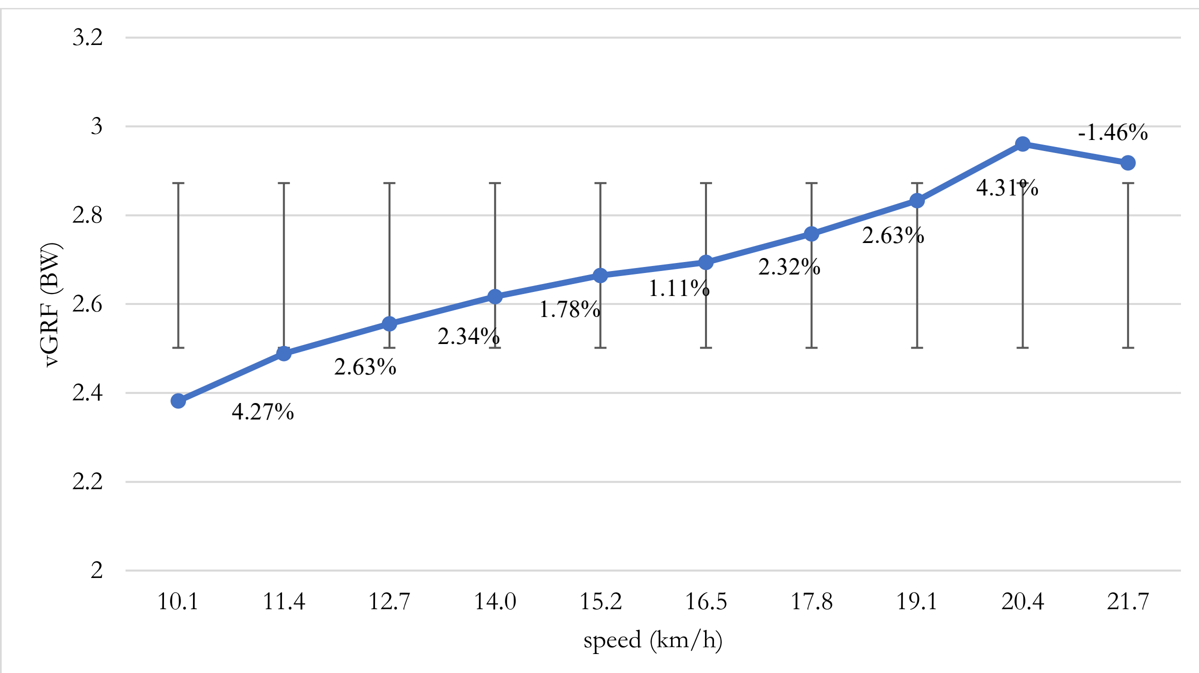

Figure 3. Change in vGRF from speed to speed for all athletes.

A Pearson correlation was performed on all variables to estimate relationships. Table 4 below displays the relationships between the biomechanical parameters of this study. The highest correlation was between speed and contact time with an *r* value of -0.991, indicating a strong, negative correlation. Other notable relationships are between speed and vGRF ($r = 0.986$, $p = 0.000$), between loading rate and vGRF ($r = 0.965$, $p = 0.000$), and between vGRF and contact time ($r = -0.982$, $p = 0.000$). However, asymmetry had weak correlations with all other variables.

Table 4. Biomechanical parameter correlation matrix.

Variable	Speed (km/h)	vGRF (BW)	Asymmetry (%)	Loading Rate (BW/ms)	Contact Time (ms)
Speed (km/h)	-	0.986*	0.291	0.965*	-0.991*
vGRF (BW)	0.986*	-	0.242	0.965*	-0.982*
Asymmetry (%)	0.291	0.242	-	0.430	0.201
Loading Rate (BW/ms)	0.965*	0.965*	0.430	-	-0.927*
Contact Time (ms)	-0.991*	-0.982*	-0.201	-0.927*	-

Notes: *denotes significant correlation, $p<0.05$; km/h: kilometers/hour; vGRF: vertical ground reaction force; BW: body weight; ms: millisecond

Table 5 shows the results from a regression analysis conducted using $\dot{V}O_2$ (L/min) as the dependent variable and all biomechanical variables as the independent variables. vGRF ($p = 0.012$) and contact time ($p = 0.047$) were statistically significant with $\dot{V}O_2$. However, there was no statistical significance with loading rate.

Table 5. Regression analysis of biomechanical parameters with $\dot{V}O_2$.

Variable	P-Value
vGRF (BW)	0.012*
Loading Rate (BW/ms)	0.376
Contact Time (ms)	0.047*

Notes: *denotes significant correlation, $p<0.05$; vGRF: vertical ground reaction force; BW: body weight; ms: millisecond

Table 6 displays the results from intraclass correlation and coefficient of variation statistics for the treadmill load cell peak force data. The results indicate a change in both ICC and CV as the speed increases. The ICC indicated excellent reliability at all speeds. The highest ICC occurred at 20.4 km/h and 21.7 km/h (1.00). However, CV tended to be large for the middle speeds. The highest CV occurred at 17.8 km/h (22.59%), while the lowest occurred at 20.4 km/h and 21.7 km/h (7.58%).

Discussion

With the sport demands for collegiate runners and triathletes, it is important for sport coaches and practitioners to understand their athlete's performance metrics and injury risk associated with their sport. Therefore, the purpose of this study was to examine the effects of increasing speeds on biomechanical parameters during an incremental $\dot{V}O_{2max}$ test. The present findings partially supported the study hypotheses. As hypothesized, vGRF and loading rate increased, while contact time decreased, as running speed increased. However, contrary to the hypothesis, asymmetry did not systematically increase at higher running speeds. Instead, asymmetry fluctuated across speeds and remained relatively low overall. These findings suggest that trained collegiate runners maintain symmetrical movement patterns despite increasing mechanical demands, potentially due to training adaptations and familiarity with higher running intensities.

Table 6. Intraclass correlation and coefficient of variation for treadmill load cell data.

Speed (km/h)	10.1	11.4	12.7	14.0	15.2	16.5	17.8	19.1	20.4	21.7
Intraclass Correlation (ICC)	0.98	0.98	0.98	0.98	0.98	0.98	0.99	0.99	1.00	1.00
Lower Confidence Limit	0.97	0.97	0.97	0.96	0.96	0.96	0.98	0.97	1.32	1.30
Upper Confidence Limit	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.01	1.01
Coefficient of Variation (CV) (%)	18.43 %	19.11 %	20.03 %	20.33 %	19.92 %	20.32 %	22.59 %	21.29 %	7.58 %	7.81 %

Note: km/h: kilometers/hour

Aligning with previous research,[18,19,20] a primary finding indicates that vGRF increased as the speed increased. This increase in vGRF may be, in part, related to the increase in force production required to support an individual's body weight as the speed increases. Interestingly, previous research reported similar responses in both recreational and trained runners, despite there being methodological differences.[4] It is important to note that there was a slight decrease in vGRF displayed by some subjects when running at the highest speed. This could reflect individual differences in running mechanics due to the higher speeds, such as a reduction in ground contact time.

Unlike vGRF, asymmetry did not increase as running speed increased. Instead, a large amount of fluctuation was noted in the asymmetry values depending on the speed. For example, some faster speeds resulted in a reduction in running asymmetry compared to some of the slower speeds during the beginning stages of the test. It was expected that asymmetry would increase with an increase in running speed, however, this did not occur. Although, the asymmetry results did not follow a linear trend with speed, it is possible that the variations in asymmetry may be due to certain speeds being more closely related to the athlete's training pace, making them more efficient and symmetrical at those specific paces. It appears that the subjects in this study had higher levels of asymmetry at the slower speeds; likely a pace they do not frequently used during training. At the higher running speeds that were achieved, there were small increases in vGRF that were observed. This may not have been caused directly by inefficiency in running mechanics, but perhaps fatigue had started to impact performance.[21]

Previous research suggests that an increase in asymmetry may be associated with increased risk of injury.[1] However, since the level of asymmetry in this study remained relatively small overall, it may not be enough to lead to an increased risk of injury. However, it is important to note that even a small amount of asymmetry may accumulate over repeated running cycles. While more advisory as opposed to predictive, the accumulation of even small asymmetry differences could contribute to a summation of uneven mechanical stress during a prolonged training session or competition that may result in injury.

Importantly, along with vGRF, loading rate increased as speed increased with a strong, positive correlation. This is likely due to not only the increase in vGRF, but also the decrease in ground contact time that was observed. As the ground contact times shortened with an increase in running speed, the subjects were required to increase the speed at which they applied force into the ground, leading to an increase in loading rates. Previous research has reported similar results with the increase in loading rates as running speed increased, additionally, it has been suggested that the increase in loading rates may lead to an increase in injury risk.[22,23] At the highest speed collected in this study, loading rates were slightly higher than what has been reported in previous studies, which may be due to either different training status of the subjects or even a difference in testing protocols.[19]

Another important finding for biomechanical parameters was with ground contact time. Ground contact time decreased as the running speed increased. This is consistent with previous research reports in both recreational and trained athletes.[24,19,25,20] Shorter ground contact times at higher running speeds are indicative of an increased reliance on rate of force development (RFD), or how quickly an individual can produce force. Increased RFD would have a substantial effect on loading rate as measured in this study. As an individual reaches a high running speed, typically in the later stages of a $\dot{V}O_{2max}$ test, their ability to produce a high vGRF during a shorter ground contact time becomes extremely important to maintain or increase running speed.[25] The increase in vGRF and decrease in ground contact time the was observed in this study supports the role and importance of RFD as a key factor in high-speed running performance.

This study is not without its limitations. One limitation of this study was the use of treadmill-based testing, which may not accurately reflect the biomechanical and physiological demands of real-world cross-country or triathlon environments. Future studies, though logistically complex, should attempt to improve ecological validity by assessing athletes under more sport-specific conditions. Sport science research is frequently underpowered from a statistical standpoint because of the small sample sizes typical of well-trained and athletic populations.[27] An a priori power analysis was not conducted prior to data collection, which should be considered when interpreting the findings of the present study. Given the relatively small sample size and the challenges associated with recruiting training collegiate endurance athletes, the results are best interpreted as exploratory rather than confirmatory. Although the participants in the present study were all members of a Division I collegiate program, the findings remain constrained by the limited sample, particularly the low representation of female athletes (n = 4). Nevertheless, despite the limited sample, several biomechanical variables demonstrated strong relationships and consistent trends across increasing running speeds, suggesting that the findings may provide useful direction for future investigations with larger cohorts. Exploratory sport science studies remain valuable, as they provide access to high-level athletic data that are rarely obtainable and contribute to a broader epistemic balance within the field.[27,28,29]

The findings of this study emphasize the value of paying attention to how an athlete's mechanics change as running speed increases during incremental testing and high-intensity training. As speed rises, sport coaches, strength and conditioning coaches, and other practitioners should expect higher impact forces and loading rates, along with shorter ground contact times, indicating a greater demand for rapid force production. These changes can increase overall mechanical stress, especially at faster speeds or when fatigue is present, highlighting the importance of managing training load during hard sessions and maximal tests. Importantly, running asymmetry did not consistently increase with speed and was often lowest at speeds closer to an athlete's typical training pace. This suggests that evaluating athletes only at slower or unfamiliar speeds may exaggerate perceived asymmetry or injury risk. Sport coaches, strength and conditioning coaches, and other practitioners may gain more meaningful insight by assessing athletes across a range of sport-specific speeds to better understand running efficiency, fatigue tolerance, and potential injury risk.

Conclusions

This study provides data to show that collegiate cross-country and triathlon athletes can be affected biomechanically by increasing speeds. The athletes in this study were able to maintain relatively low levels of asymmetry across a range of running speeds, even when there was an increase in mechanical load. This could be indicative of the training status of the subjects in this study. Additionally, the results of this study highlight the importance of an individual developing the ability to withstand higher loading rates while producing force at a faster speed as running speed increases. Strength training programs that emphasize bilateral strength development and RFD may help reduce asymmetry and support overall performance.[5,30] In conclusion, with these findings and the addition of strength training programs, athletes could maintain a minimal amount of kinetic asymmetry throughout the $\dot{V}O_{2max}$ test, therefore, keeping their injury risk minimal.

Conflict of Interest. The authors declare no conflicts of interest.

References

1. Furlong LM, Egginton NL. Kinetic asymmetry during running at preferred and nonpreferred speeds. *Med Sci Sports Exerc.* 2018;50(6):1241-1248.
2. Wouda FJ, Giuberti M, Bellusci G, et al. Estimation of vertical ground reaction forces and sagittal knee kinematics during running using three inertial sensors. *Front Physiol.* 2018;9:218.
3. Yu L, Mei Q, Xiang L, et al. Principal component analysis of the running ground reaction forces with different speeds. *Front Bioeng Biotechnol.* 2021;9:629809.
4. Keller TS, Weisberger AM, Ray JL, Hasan SS, Shiavi RG, Spengler DN. Relationship between vertical ground reaction force and speed during walking, slow jogging, and running. Clin Biomech. 1996;11(5):253-259.
5. Bailey CA, Sato K, Burnett A, Stone MH. Kinetic asymmetry and center of mass displacement during jumps. In: *Proceedings of the 33rd International Conference on Biomechanics in Sports*; 2015:776-779.

6. Schmitz A, Pohl MB, Woods K, Noehren B. Variables during swing associated with decreased impact peak and loading rate in running. *J Biomech.* 2014;47(1):32-38.
7. Schmida EA, Wille CM, Stiffler-Joachim MR, Kliethermes SA, Heiderscheit BC. Vertical loading rate is not associated with running injury, regardless of calculation method. Med Sci Sports Exerc. 2022;54(8):1382-1389.
8. Evans RJ, Moffit TJ, Mitchell PK, Pamukoff DN. Injury- and performance-related biomechanical differences between recreational and collegiate runners. *Biomech Control Hum Mov.* 2023;5:1-8.
9. Mooses M, Haile DW, Ojiambo R, et al. Shorter ground contact time and better running economy: evidence from female Kenyan runners. J Strength Cond Res. 2021;35(2):481-486.
10. Nummela A, Keränen T, Mikkelsson LO. Factors related to top running speed and economy. *Int J Sports Med.* 2007;28(8):655-661.
11. Carroll KM, Wagle JP, Sole CJ, Stone MH. Intrasession and intersession reliability of countermovement jump testing in Division I volleyball athletes. J Strength Cond Res. 2019;33(11):2932-2935.
12. Peterson Silveira R, Stergiou P, Carpes FP, Castro FA, Katz L, Stefanyshyn DJ. Validity of a portable force platform for assessing biomechanical parameters in three different tasks. *Sports Biomech.* 2017;16(2):177-186. doi:10.1080/14763141.2016.1213875
13. Beltz NM, Gibson AL, Janot JM, Kravitz L, Mermier CM, Dalleck LC. Graded exercise testing protocols for the determination of VO_2max: historical perspectives, progress, and future considerations. *J Sports Med.* 2016;2016:3968393.
14. Arena R, Myers J, Williams MA, et al. Assessment of functional capacity in clinical and research settings: a scientific statement from the American Heart Association. Circulation. 2007;116(3):329-343.
15. Tanner RK, Fuller KL, Ross ML. Evaluation of three portable blood lactate analyzers: Lactate Pro, Lactate Scout, and Lactate Plus. Eur J Appl Physiol. 2010;109(3):551-559.
16. Salacinski AJ, Alford M, Drevets K, Hart S, Hunt BE. Validity and reliability of a glucometer against industry reference standards. J Diabetes Sci Technol. 2014;8(1):95-99.
17. Hopkins WG. Spreadsheets for analysis of validity and reliability. *Sportscience.* 2005;9:36-42. Accessed 2015. http://sportsci.org/2015/ValidREly.htm.
18. Jiang X, Biro I, Sarosi J, Fang Y, Gu Y. Comparison of ground reaction forces as running speed increases between male and female runners. Front Bioeng Biotechnol. 2024;12:1378284.
19. De Witt JK, Hagan RD, Cromwell RL. The effect of increasing inertia upon vertical ground reaction forces and temporal kinematics during locomotion. J Exp Biol. 2008;211:1087-1092.
20. Kluitenberg B, Bredeweg SW, Zijlstra S, Zijlstra W, Buist I. Comparison of vertical ground reaction forces during overground and treadmill running: a validation study. *BMC Musculoskelet Disord.* 2012;13:235.
21. Luo Z, Zhang X, Wang J, Yang Y, Xu Y, Fu W. Changes in Ground Reaction Forces, Joint Mechanics, and Stiffness during Treadmill Running to Fatigue. *Applied Sciences*. 2019; 9(24):5493.
22. Dudley RI, Pamukoff DN, Lynn SK, Kersey RD, Noffal GJ. A prospective comparison of lower extremity kinematics and kinetics between injured and noninjured collegiate cross-country runners. *Hum Mov Sci.* 2017;52:197-202.
23. Zifchock RA, Davis I, Hamill J. Kinetic asymmetry in female runners with and without retrospective tibial stress fractures. *J Biomech.* 2006;39:2792-2797.
24. Brughelli M, Cronin J, Chaouachi A. Effects of running velocity on running kinetics and kinematics. J Strength Cond Res. 2011;25(4):933-939.
25. Hayes P, Caplan N. Foot strike patterns and ground contact times during high-calibre middle-distance races. *J Sports Sci.* 2012;30(12):1275-1283.
26. Frederick EC, Hagy JL. Factors affecting peak vertical ground reaction forces in running. *J Appl Biomech.* 1986;2:41-49.
27. Bernards JR, Sato K, Haff GG, Bazyler CD. Current research and statistical practices in sport science and a need for change. *Sports (Basel).* 2017;5(4):87.
28. Murphy J, et al. Estimating the replicability of sports and exercise science research. Sports Med. 2025;55:1-21.
29. Scheel AM, et al. Why hypothesis testers should spend less time testing hypotheses. *Perspect Psychol Sci.* 2021;16(4):744-755.
30. Martinez-Valencia MA, Romero-Arenas S, Elvira JLL, Gonzalez-Rave JM, Navarro-Valdivielso F, Alcaraz PE. Effects of sled towing on peak force, rate of force development, and sprint performance during the acceleration phase. J Hum Kinet. 2015;46:139-148.