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*Original Research*

# Stance Time and Impact Loading Rates are Significant Predictors of Critical Speed During a 3-Minute All-Out Running Test

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ABSTRACT

***International Journal of Exercise Science 17(4): 115-128, 2024.*** The addition of wearable technology during a 3-minute all-out overground running test (3MAOT) could provide additional insights to guide training and coaching strategies. The purpose of this study was to explore the relationships between critical speed (CS) and biomechanical parameters (cadence, stride length, vertical oscillation, stance time, form power, leg spring stiffness, and impact loading rate), and changes in biomechanical parameters throughout the 3MAOT. Sixty-three (male, n=37, female, n=26) recreationally active college-aged (23.4±3.9 years) subjects completed a 3MAOT while wearing a Stryd foot-pod. The correlations between CS and biomechanical parameters were evaluated using Pearson coefficients. Stepwise multiple linear regressions were used to test if biomechanical parameters could predict CS. Stance time and impact loading rate explained 69% and 63% of the variance in CS, respectively ($R^2$=0.69, $p<0.05$; $R^2$=0.63, $p<0.05$). Step-wise multiple linear regression analysis indicated that vertical oscillation, stance time, form power, leg spring stiffness, and impact loading rate explained 90% of the variance in CS ($R^2$=0.90, $p<0.05$). Throughout the 3MAOT, changes in cadence (-29%), stride length (57%), vertical oscillation (-8%), stance time (82%), form power (-5%), leg spring stiffness (-24%), and impact loading rate (-48%) were observed. Interventions such as auditory cueing or training designed to improve CS should focus on maintaining large impact loading rates and short stance times, and efforts should be made to enhance an athlete's ability to maintain cadence, leg spring stiffness, vertical oscillation, and form power throughout the 3MAOT.

KEY WORDS: Critical power, endurance performance, kinematics, fatigue, accelerometer, wearable technology

## INTRODUCTION

The key performance indicators of endurance running are considered to be a high maximal oxygen consumption ($VO_2$ max), the capacity to maintain a high maximum metabolic steady state, and superior running economy [17]. The gold standard for measuring the maximum metabolic steady state of running is considered to be critical speed (CS) [15], which can be derived from a 3-minute all-out test (3MAOT) [30, 36]. During the 3MAOT, participants begin at an all-out sprint around a track and maintain the highest possible running speed for 3 minutes without pacing [30]. As athletes fatigue, their running speed over time graphically displays a hyperbola, where the asymptote is considered to be CS [30, 36]. When estimated from a 3MAOT, CS is calculated as the average running speed in the final 30 seconds of the test [30]. CS represents a fatigue threshold that separates the heavy and severe exercise domains because running intensities above CS evoke the $VO_2$ slow component, which is associated with the development of fatigue due to a loss of muscular efficiency and the accumulation of metabolic byproducts ($H^+$) [16, 18, 29, 31]. In contrast, the physiological responses to exercise stimuli below CS can be stabilized [31]. D′ (pronounced D prime) can also be derived from the 3MAOT and is estimated as the distance covered at speeds above CS which represents a fatigability constant [36]. Once calculated, CS and D′ can be utilized to model maximal performance capacity at several race distances, allowing for the determination of maximal running speed for a given distance or within a given time limit [29]. The CS concept can also be utilized to inform racing strategy. For example, individuals with a superior CS would perform better with a front-running strategy that involves running faster splits throughout the race rather than trying to save energy for a kick at the end of the race [29]. In contrast, an athlete with a superior D′ would perform best by running slower splits throughout the race, saving energy for a big finish [29]. In summary, the 3MAOT represents a valuable and time-efficient test to predict endurance performance across a spectrum of race distances.

Recent technological advances in wearable sports technology have allowed the quantification of biomechanical variables in the field that are otherwise limited to laboratory-based settings. These portable and low-cost inertial measurement units (IMUs) allow researchers and practitioners to observe key biomechanical performance indicators of endurance running performance in sport-specific environments [26]. Wearable IMUs that utilize Bluetooth technology attached to the shoe can be used to monitor biomechanical metrics in real-time, such as pace, speed, horizontal running power, vertical running power, cadence, stride length, vertical oscillation, stance time, and leg spring stiffness. As such, changes in pace, work, and biomechanical parameters can be measured during performance tests, and in response to training interventions [27]. Even more, these devices can be worn during the competition (i.e., national championship cross-country and road running events [19] and provide information about biomechanical parameters and running technique under specific conditions (i.e., trail running [23, 28]), and in turn, provide real-time kinematic feedback to optimize motor learning and development for enhanced performance [10]. Thus, real-time data collection during a 3MAOT could provide additional insights that could guide training and coaching strategies (e.g. verbal cueing) to improve endurance performance.

IMUs have been used to collect instantaneous speed data during the running 3MAOT to estimate CS [7, 35]. However, the biomechanical parameters that account for differences in CS during the 3MAOT have not been reported. Thus, the measurement of biomechanical parameters with an IMU during the 3MAOT could reveal which parameters (i.e., leg stiffness, vertical oscillation) relate to CS in real-time. Furthermore, changes in biomechanical parameters throughout a 3MAOT are yet to be reported and may provide insights into superior endurance running performance. This knowledge, along with CS and D′, can be used to optimize coaching strategies and training interventions. Therefore, the purpose of this study was to explore the relationships between CS, changes in biomechanical parameters throughout the 3MAOT, and biomechanical parameters in the final 30 seconds of the 3MAOT. We hypothesized that CS will be related to stance time, vertical oscillation, form power (vertical metabolic cost of running), and leg spring stiffness and that athletes with smaller changes in biomechanical parameters throughout the 3MAOT would have a higher CS.

## METHODS

*Participants*

Sixty-three recreationally active college students (male, n=37, female, n=26) voluntarily participated in the study. Subject demographic and anthropometric characteristics can be found in Table 1. All participants completed a medical history, which was used to stratify risk [11] and determine activity level. Recreationally active was functionally defined as participating less than or equal to twice a week in aerobic activity and less than or equal to twice a week in resistance training. Inclusion criteria included: being between the ages of 18-34 years, free of neurological, orthopedic, and/or cardiovascular disorders, medical clearance from their physician, and literacy in English. After being informed of the study procedures, purpose, and risks, informed consent was obtained from all individual participants before the start of the study, which was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of the University of Hawaiʻi (#2022-00631) for studies involving humans.

**Table 1.** General Participant Characteristics.

| | N | Age (years, mean ± SD) | Mass (kg, mean ± SD) | Height (cm, mean ± SD) |
|---|---|---|---|---|
| Male | 36 | 24.8 ± 4.3 | 86.0 ± 15.4 | 177.0 ± 9.2 |
| Female | 27 | 21.7 ± 2.5 | 62.7 ± 17.7 | 161.8 ± 8.5 |
| Overall | 63 | 23.4 ± 3.9 | 75.9 ± 20.1 | 170.4 ± 11.7 |

*Protocol*

In this cross-sectional study, correlations, and forced entry step-wise regression modeling were used to explore relationships between biomechanical parameters derived from a Stryd foot pod (cadence, stride length, stance time, vertical oscillation, form power, leg spring stiffness, impact loading rate) and CS derived from a 3MAOT. The timeline of the current study is presented in Figure 1. All measurements were performed in February of 2023. This research was carried out fully in accordance with the ethical standards of the International Journal of Exercise Science [24].

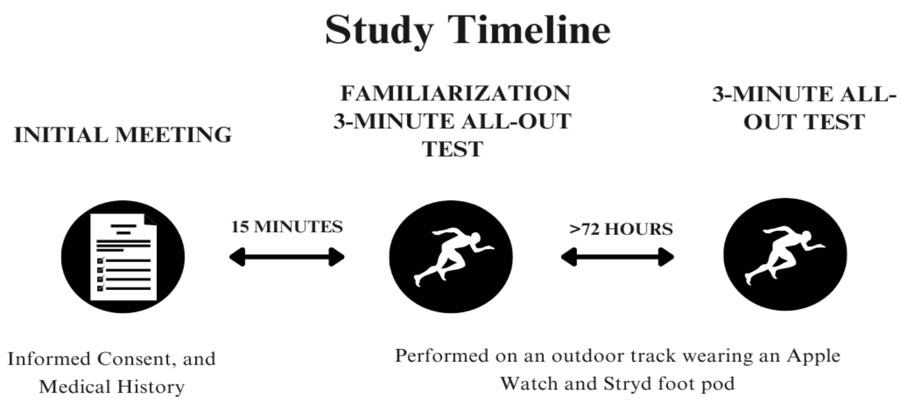


**Figure 1.** Study timeline.

Explorations upon the validity and reliability of Stryd have shown measures of pace, running power, form power, leg stiffness, and vertical oscillation during trail running have shown a coefficient of variation of less than 10% and meet the intraclass correlation threshold of r=0.70, and 95% confidence intervals [23]. When compared with the Optogait system, Stryd provides almost identical standard measurement error with accurate and reliable measures of stride frequency and stride length for running speeds 8-20 km/hour on a treadmill but underestimates stance time (0.5-8%) [9]. However, the stance time derived from Stryd does not show any significant differences with gold standard reference measurements from force plates [13].

Vertical oscillation is considered to be an important biomechanical factor related to running economy [4]. The Stryd foot pod is also considered to be a reliable and valid tool for measuring vertical oscillation with a standard error of the mean of 0.3 cm [34]. Stryd's proprietary form power measure, which seems to be related to the metabolic cost of vertical oscillation, presents a clear and substantial positive relationship with running economy for both self-selected cadence and lowered cadence [3]. These preliminary findings suggest that Stryd's form power may be a valid indicator of running economy [3]. Lastly, Stryd provides a relatively accurate estimate of leg spring stiffness [13] when compared to estimated leg spring stiffness values derived using force plates and motion capture following McMahon's Method [20], as 90-96% of changes in leg stiffness are accounted for by changes in stance time [21]. However, the direct relationship between a true measurement of leg spring stiffness and Stryd's estimation has not been reported. The Stryd foot pod provides researchers and practitioners with a valid and reliable tool for measuring biomechanical parameters in field-based settings.

All participants attached the Stryd foot pod (Stryd Summit Power Meter, Boulder, CO, USA) to the right foot using shoelaces and manufacturer recommendations. To avoid premature cessation of the test, participants were instructed that the test was over after 3 minutes and 5 seconds [30]. The Stryd foot pod was paired with an Apple Watch SE (Version 9.3, Cupertino, CA, USA) on the right wrist, which was used to start and complete data collection using the

Stryd application. Data obtained from the foot pod was analyzed within the Stryd application (www.stryd.com/powercenter).
The following parameters were obtained from the Styrd foot pod: running speed, cadence, stride length, stance time, vertical oscillation, form power, leg spring stiffness, and impact loading rate. Biomechanical parameters were recorded at 1 Hz. Speed is defined as the rate of change of position and was measured in meters/second. Cadence was measured as the number of steps taken each minute assuming symmetry between the limbs, since only one Stryd foot pod is attached to the right shoe. Stride length represents the distance (meters) between each stride from the initial ground contact to the subsequent initial contact of the same foot, and also assumes symmetry. Stride length was adjusted to become a relative variable as a percentage of height. Stance time was defined as the duration of foot-ground contact, from initial contact to toe-off of the right foot. Vertical oscillation was reported as the vertical distance the center of mass traveled between strides. Form power was defined as vertical power, or the metabolic work (watts) required to move the center of mass vertically between strides. Leg spring stiffness (KN/m) was estimated as the maximum vertical force a person generates in a step divided by the displacement during ground contact time. The impact loading rate was calculated as the initial rate of increase in vertical (or perpendicular) force as a runner contacts the ground with their foot and is reported in the units of body weight per second (bw/sec).

To determine CS, the 3MAOT was performed. All subjects completed a familiarization 3MAOT before completing the test used for data analysis. Before the 3MAOT, all subjects completed a 10-minute standardized dynamic warm-up that followed the RAMP protocol (Table 2) [22].

**Table 2.** Standardized Dynamic Warm-Up.

| |
|---|
| Duck Walks & Backwards Duck Walks |
| Lunge Walk & Side Lunge Walk |
| Step-Pull & A-March |
| Side to Side Easy & Side to Side medium |
| Carioca easy & Carioca medium |
| High Knees & Butt Kickers |
| High Knees to Stride & High Knees to Sprint |
| A Skips to Back Pedal & B Skips to Back Pedal |
| Stride to Sprint |

Once the dynamic warm-up was completed, a verbal script was read to ensure test reliability. Each subject was told that the 3MAOT would last 3 minutes and that they were to accelerate to maximum running speed as soon as the test began. To ensure participants gave maximal effort at the onset of the 3MAOT, they were also instructed that this maximum running speed was one of the primary variables we are measuring. The 3MAOT [30, 36] was conducted on a synthetic outdoor track at the same time of day (± 1 hour) and in similar environmental conditions (26-

28°C, 60-65% humidity, wind < 8 km/hour, and the UV index was 6-8). To prevent pacing and increase motivation, loud verbal cheering was provided to all participants without sharing the duration remaining in the test. CS was the average speed between 150 and 180 seconds [24].

*Statistical Analysis*

The estimated sample size for multiple linear regression with 5 predictors (independent variables: vertical oscillation, stance time, form power, leg spring stiffness, impact loading rate) was calculated using G*Power (Version 3.1.9.7) [5]. While considering a medium (0.15) Cohen's $f2$ effect size, with a 5% type I error, 80% power, and 5 predictors, the estimated sample size was 55 participants.

Changes (Δ%) for running speed, cadence, stride length, vertical oscillation, form power, leg spring stiffness, and impact loading rate were calculated as (Mean during CS - Maximum)/Maximum. Δ (%) for stance time was calculated as (Mean during CS - Minimum)/Minimum. Data normality was assessed using the Shapiro-Wilk test. Preliminary relationships between CS and temporospatial parameters were explored using Pearson's correlation coefficients and simple linear regression. Correlations were considered trivial, small, moderate, and large when R squared was 0.1, 0.1-0.3, 0.3-0.5, and >0.5, respectively [33]. Stepwise multiple linear regression was applied to systematically evaluate the prognostic characteristics of temporospatial parameters in predicting CS. A variable inflation factor (VIF) of >5 was used as the cut-off value to identify multicollinearity [12]. The stepwise inclusion criterion for the addition of independent variables to the model was an increase in $R^2$ without a concomitant increase in VIF above the aforementioned cut-off value (>5). The initial multiple linear regression model (Model 1) was designed to include all biomechanical variables that present trivial relationships with CS. The remaining variables were then sequentially added to the multiple linear regression model from least to greatest $R^2$, based on the respective preliminary $R^2$ with CS. Significance was set at $P < 0.05$ for Pearson correlations and significance was adjusted to < 0.0166 (0.05/3=0.0166) to account for multiple comparisons and reduce the chance of type 2 error. Data were analyzed using GraphPad Prism (Version 9.2 for MacOS, GraphPad Software, San Diego, California, USA).

## RESULTS

Table 3 provides the mean ± SD critical speed and average biomechanical parameters from 150-180 seconds of the 3MAOT, and changes (Δ) in biomechanical parameters throughout the 3MAOT.

Figures 2 and 3 display the average biomechanical metrics for all participants throughout the 3MAOT.

Table 4 displays the results of the Pearson Correlation Analysis between average biomechanical parameters and CS derived from the Stryd foot pod from 150-180 seconds of the 3MAOT. Stance time presented the strongest relationship with CS, explaining 69% of the interindividual variance ($R^2$=0.69, p<0.05). The impact loading rate showed a large and significant positive correlation with CS ($R^2$=0.63, p<0.05). Both cadence and stride length present significant relationships with CS ($R^2$=0.31, $R^2$=0.10, respectively; p<0.05), with cadence having a stronger relationship to CS than relative stride length. Vertical oscillation, form power, and leg spring stiffness were not significantly associated with CS ($R^2$=0.05, $R^2$=0.05, $R^2$=0.001, respectively; p>0.05).

**Table 3.** Critical Speed, Average Biomechanical Parameters from 150-180 seconds of the 3MAOT, and Changes in Biomechanical Parameters throughout the 3MAOT.

| Variable | Males (n=36) | Δ 3MAOT (%) | Females (n=27) | Δ 3MAOT (%) | Overall (n=63) | Δ 3MAOT (%) |
|---|---|---|---|---|---|---|
| Critical Speed (m/s) | 3.5 ± 0.7 | -51.1% | 2.97 ± 0.6 | -50.7% | 3.27 ± 0.7 | -51.0% |
| Cadence (steps/min) | 164.4 ± 9.7 | -31.6% | 164.0 ± 11.4 | -26.5% | 164.3 ± 10.4 | -29.5% |
| Stride length (% height) | 0.7 ± 0.1 | -53.9% | 0.67 ± 0.1 | -61.3% | 0.70 ± 0.1 | -57.0% |
| Vertical Oscillation (mm) | 84.9 ± 9.2 | -6.7% | 78.9 ± 12.5 | -10.1% | 82.4 ± 11.0 | -8.2% |
| Stance Time (ms) | 241.3 ± 35.6 | 81.7% | 263.3 ± 47.4 | 82.6% | 250.5 ± 42.0 | 82.1% |
| Form Power (watts) | 85.4 ± 13.1 | -4.5% | 79.7 ± 13.7 | -7.4% | 83.0 ± 13.5 | -5.7% |
| Leg Spring Stiffness (KN/m) | 11.6 ± 2.0 | -22.8% | 12.1 ± 3.1 | -25.7% | 11.8 ± 2.5 | -24.1% |
| Impact Loading Rate (body weight/s) | 64.3 ± 14.0 | -93.3% | 60.3 ± 14.5 | -114.7% | 62.6 ± 14.2 | -48.5% |

Note: Data is presented as mean ± SD; 3MAOT = 3-minute all-out test; Δ 3MAOT (%) for running speed, cadence, stride length, vertical oscillation, form power, leg spring stiffness, and impact loading rate was calculated as (Mean during CS - Maximum)/Maximum. Δ 3MAOT (%) for stance time was calculated as (Mean during CS - Minimum)/Minimum.

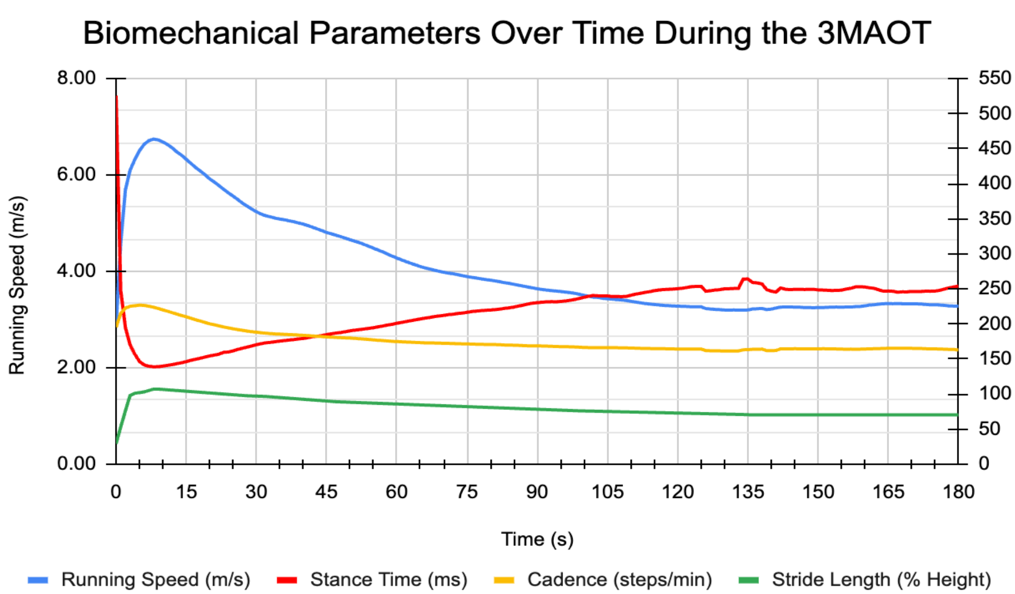


**Figure 2.** Biomechanical parameters over time during the 3MAOT.

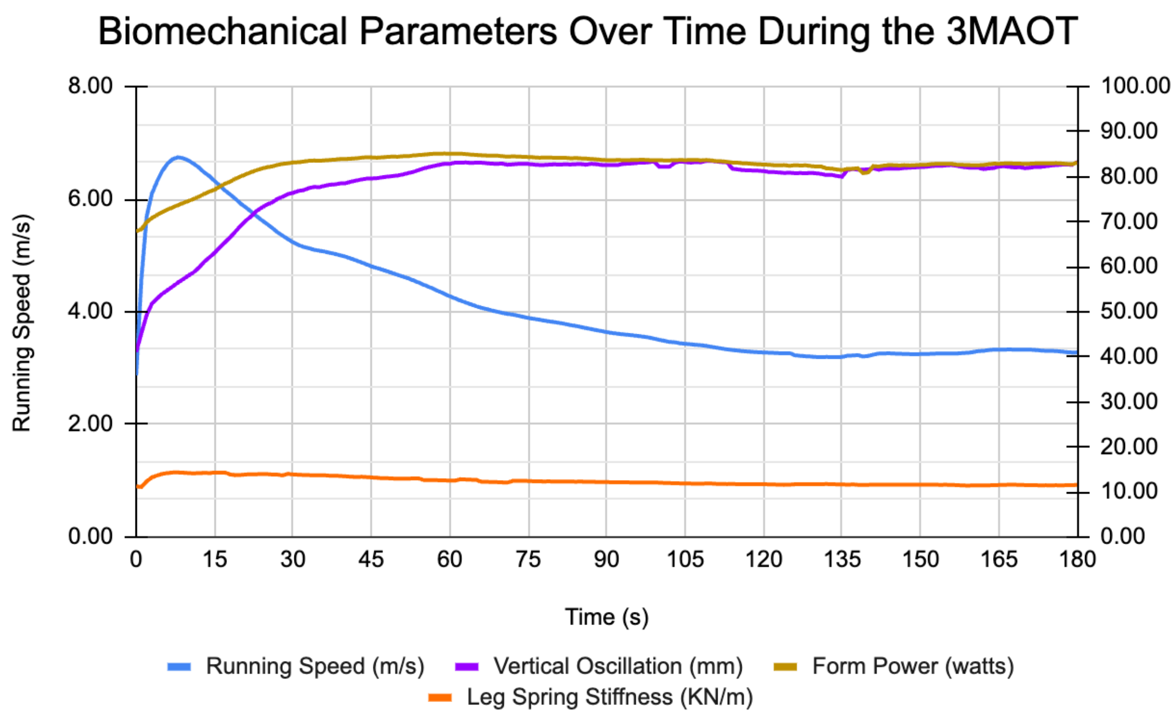


**Figure 3.** Biomechanical parameters over time during the 3MAOT.

**Table 4.** Pearson Correlation Analysis Between Biomechanical Parameters and Critical Speed (n=63).

| | Variable | r | 95% confidence interval | R squared | P Value |
|---|---|---|---|---|---|
| Critical Speed (m/s) | Cadence (steps/min) | 0.55 | 0.35 to 0.71 | 0.31 | <0.0001* |
| | Stride length (% height) | 0.32 | 0.06 to 0.54 | 0.10 | 0.016* |
| | Vertical Oscillation (mm) | 0.22 | -0.04 to 0.45 | 0.05 | 0.099 |
| | Stance Time (ms) | -0.83 | -0.89 to -0.73 | 0.69 | <0.0001* |
| | Form Power (watts) | 0.23 | -0.02 to 0.46 | 0.05 | 0.076 |
| | Leg Spring Stiffness (KN/m) | 0.04 | -0.22 to 0.29 | 0.001 | 0.776 |
| | Impact Loading Rate (body weight/s) | 0.80 | 0.67 to 0.87 | 0.63 | <0.0001* |

Note: CS = critical speed. 3MAOT = 3-minute all-out test. Biomechanical parameters correlated with CS are calculated as the average of each metric during seconds 150-180 of the 3MAOT. 3MAOT Δ (%) for running speed, cadence, stride length, vertical oscillation, form power, leg spring stiffness, and impact loading rate was calculated as (Mean during CS - Maximum)/Maximum. 3MAOT Δ (%) for stance time was calculated as (Mean during CS - Minimum)/Minimum. * = P<0.05.

Table 5 displays the stepwise multiple regression analysis performed to maximize the $R^2$ value when estimating CS from biomechanical parameters (cadence, stride length, vertical oscillation, stance time, form power, leg spring stiffness, and impact loading rate) derived from the Stryd foot pod. Both cadence and stride length were excluded from the models due to their impact on the variable inflation factor, indicating the presence of collinearity. The initial overall regression (Model 1) including vertical oscillation, form power, and leg spring stiffness was not statistically significant ($R^2$ = 0.07, F(3, 60) = 1.515, p>0.05). However, Model 1 presented a significant parameter estimate of CS (p<0.05) explaining 7% of the interindividual variance in CS, but no single predictor was significant (p>0.05). When the impact loading rate was added to the model (Model 2) 66% of the variance in CS was explained and the overall model became significant ($R^2$ = 0.66, F(3, 60) = 26.07, p<0.05). In Model 2, only impact loading rate was a significant predictor of CS (β=0.04, p<0.05). The addition of stance time in Model 3 further improved the goodness of fit, presenting a significant overall regression model ($R^2$ = 0.90, F(3, 60) = 93.43, p<0.05) with all parameter estimates (vertical oscillation, stance time, form power, leg spring stiffness, impact loading rate) becoming significant predictors of CS (p<0.05).

**Table 5.** Stepwise Multiple Linear Regression Using Temporospatial Parameters for Determining Critical Speed.

| | | | | | | 95% CI for coefficient | |
|---|---|---|---|---|---|---|---|
| Model | Variable | Coefficient | SE | t-value | p-value | Lower to Upper | VIF |
| Model 1 ($R^2$ = 0.07; SEE = 0.79 m/s) | (constant) | 1.98 | 0.79 | 2.45 | 0.01 | 0.39 to 3.55 | |
| | Vertical Oscillation (mm) | 0.01 | 0.01 | 1.14 | 0.26 | -0.008 to 0.02 | 1.44 |
| | Form Power (watts) | 0.007 | 0.01 | 0.88 | 0.38 | -0.009 to 0.02 | 1.84 |
| | Leg Spring Stiffness (KN/m) | -0.01 | 0.04 | 0.28 | 0.78 | -0.09 to 0.07 | 1.50 |
| Model 2 ($R^2$ = 0.66; SEE = 0.49 m/s) | (constant) | 1.17 | 0.50 | 2.35 | 0.02 | 0.17 to 2.17 | |
| | Vertical Oscillation (mm) | -0.003 | 0.01 | 0.66 | 0.51 | -0.01 to 0.007 | 1.49 |
| | Form Power (watts) | 0.007 | 0.004 | 1.59 | 0.12 | -0.002 to 0.01 | 1.83 |
| | Leg Spring Stiffness (KN/m) | -0.05 | 0.03 | 1.81 | 0.08 | -0.09 to 0.004 | 1.54 |
| | Impact Loading Rate (body weight/s) | 0.04 | 0.004 | 9.78 | <0.0001 | 0.02 to 0.04 | 1.08 |
| Model 3 ($R^2$ = 0.90; SEE = 0.64 m/s) | (constant) | 7.64 | 0.64 | 11.91 | <0.0001 | 6.35 to 8.93 | |
| | Vertical Oscillation (mm) | -0.01 | 0.003 | 4.29 | <0.0001 | -0.02 to -0.007 | 1.61 |
| | Form Power (watts) | 0.02 | 0.003 | 7.262 | <0.0001 | 0.01 to 0.02 | 2.21 |
| | Leg Spring Stiffness (KN/m) | -0.14 | 0.02 | 8.74 | <0.0001 | -0.17 to -0.11 | 2.15 |
| | Impact Loading Rate (body weight/s) | 0.007 | 0.003 | 2.29 | 0.02 | 0.0009 to 0.01 | 2.79 |
| | Stance Time (ms) | -0.01 | 0.001 | 11.16 | <0.0001 | -0.01 to -0.01 | 3.37 |

Note: * = P < 0.05, SE= standard error, VIF= variable inflation factor, CI = confidence intervals.

## DISCUSSION

The findings of the present study suggests that biomechanical parameters (vertical oscillation, form power, leg spring stiffness, impact loading rate, and stance time) derived from a Stryd foot pod during the final 30 seconds of a 3MAOT explain 90% of the variance in CS. Average stance time displayed a large significant negative relationship with CS and accounted for 69% of the interindividual variance. In contrast, the impact loading rate presents a large and significant positive correlation with CS and independently accounts for 63% of the variance. Together, these findings suggest that shorter stance times and larger impact loading rates are the primary predictors of CS during the final 30 seconds of the 3MAOT. Throughout the 3MAOT impact loading rates decreased by -48% and stance times increased by 82% with a concomitant -29% decrease in cadence. Thus, interventions (e.g. training or verbal cueing) designed to improve CS should prioritize enhancing the ability to maintain biomechanical parameters (impact loading rate and stance time) in a fatigued state, such as in the final 30 seconds of the 3MAOT.

Running speed is a product of stride length and cadence [5]. Although these variables were not incorporated in Model 3, the multiple regression model that explained the greatest variance in CS, stride length and cadence are important considerations in running performance. Our findings suggest that cadence and stride length relative to height are significant independent predictors of CS, which was expected. However, average stance time during the final 30 seconds of the 3MAOT displayed the strongest independent relationship with CS when compared to all other biomechanical variables. This makes sense, as stance time has clear and substantial relationships with running speeds, cadence, and stride length [5, 33]. As running speed increases, stance time decreases, which requires large impulses to be applied to the ground during short stance times [33]. Stride length is mostly correlated with the impulse produced during stance time since more forceful ground contacts will result in larger flight times [8, 14].

A significant inverse relationship between impact loading rate and vertical impulse has been reported [2]. The findings of this study suggest that as fatigue accumulated throughout the 3MAOT, relative stride length decreased 29%, concomitant with a -48% decrease in impact loading rate and an 82.09% increase in stance time. Cadence is a function of stance time and flight time. Most of the variance in cadence can be explained by differences in stance time, as faster runners consistently display shorter stance times than slower runners [5], and a faster repositioning of the lower limbs during flight time contributes little to faster-running speeds [37]. We observed that cadence decreased -29% concomitant with an 82% increase in stance time throughout the 3MAOT. In the present study, larger impact loading rates and shorter stance times were related to faster CS. Since athletes can only propel themselves during ground contact, efforts to improve CS should focus on maintaining large impact loading rates and short stance times while fatigued in the final 30 seconds of a 3MAOT. The average observed cadence during CS was 164 steps per minute, which is considered to be below the theoretical optimal (most economical) cadence of 180 steps per minute [32]. Therefore, the implementation of a modality such as a metronome may have the capacity to influence the decrement of cadence throughout the 3MAOT, thereby having the potential to increase CS. Cueing to increase cadence has been shown to decrease vertical oscillation, and ground contact time [1], which are associated with higher CS in the present study.

Our study suggests that throughout the 3MAOT, leg spring stiffness decreased by -24%. These findings are consistent with recent research, suggesting that leg spring stiffness decreases with fatigue, and may have implications for performance [6]. However, leg spring stiffness alone was not a significant predictor of CS. The relationship between leg spring stiffness and performance is suggested to function via the non-linear relationship between leg spring stiffness and running economy [6]. Factors that affect running economy include but are not limited to vertical oscillation, muscles' capacity to store energy, fatigue, gender, and environmental conditions [25].

In the present study, both average form power and vertical oscillation in the final 30 seconds of the 3MAOT independently explained 5% of the variance in CS. Throughout the 3MAOT, average form power, and vertical oscillation decreased by -5% and -8%, respectively. When included in a multiple regression model, leg spring stiffness, vertical oscillation, and form power significantly predicted CS. These findings may indicate that subjects who resisted decrements in leg spring stiffness, form power, and vertical oscillation possess higher running economies at CS in the final 30 seconds of the 3MAOT, which may have allowed for higher performance levels. When cadence is manipulated by auditory cues such as metronomes, the effect on stance time appears to result in a direct increase in leg spring stiffness. In the present study, leg spring stiffness decreased by -24%, which may be influenced by conscious focus being allocated toward cadence in the final 30 seconds of the 3MAOT.

The scope of this study is limited to recreationally active college-aged adults. The primary limitation of this research is the assumption of symmetry, as the Stryd foot pod is a single IMU that was placed on the right shoe. The sample rate of the Stryd foot pod (1 Hz) is also a limitation of the findings presented herein, as the maximum and minimum values used to calculate percent changes throughout the 3MAOT may have been affected. Another limitation is the utilization of IMUs with Bluetooth technology which may be affected by environmental settings, such as a track within a stadium where the measurements were observed. A limitation of this study (and nearly all exercise testing studies) is the subject's motivation for the 3MAOT. This study also utilized a cross-sectional design, which does not allow the establishment of a cause–effect relationship.

Conclusion: In summary, biomechanical parameters (vertical oscillation, form power, leg spring stiffness, impact loading rate, and stance time) derived from a Stryd foot pod during the final 30 seconds of a 3MAOT explain 90% of the variance in CS. Stance time presents a large inverse relationship with CS, whereas the impact loading rate presents a large positive relationship. Each biomechanical parameter obtained from an IMU during a 3MAOT should be evaluated individually while considering the relationships among the variables. For example, auditory cueing to increase cadence while in a fatigued state (such as in the final 30 seconds of the 3MAOT) could enhance running performance by decreasing stance time and vertical oscillation. Thus, the addition of an IMU to a 3MAOT allows coaches and athletes to hone in on specific kinematics aspects during a race and more importantly, know which running characteristic they need to focus on as fatigue sets in. Since the kinematic metrics reported in this study predict endurance running performance, evaluation of these measurements can be useful to assess performance over a training session, or during competition. Findings from the present study suggest that the overall goal for the optimization of running performance is to maintain cadence, leg spring stiffness, vertical oscillation, and form power throughout a 3MAOT.

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