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Title: The importance of duration and magnitude of force application to sprint performance during the initial acceleration, transition and maximal velocity phases

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Preferred running head. Key performance indicators in sprinting

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Abstract

Successful sprinting depends on covering a specific distance in the shortest time possible. Although external forces are considered a key to sprinting, less consideration is given to the duration of force application, which influences the impulse generated during ground contact. This study explored relationships between sprint performance measures and external kinetic and kinematic performance indicators. Data were collected from the initial acceleration, transition and maximal velocity phases of a sprint. Relationships were analysed between sprint performance measures and kinetic and kinematic variables. A commonality regression analysis was used to explore how independent variables contributed to multiple regression models for sprint phases. Propulsive forces play a key role in sprint performance (normalised horizontal power) during the initial acceleration and transition phases (r=0.95 ± 0.03 and r=0.74 ± 0.19, respectively), while braking duration plays an important role during the transition phase (r=-0.72 ± 0.20). Contact time, vertical force and peak propulsive forces represented key determinants (r=-0.64 ± 0.31, r=0.57 ± 0.35 and r=0.66 ± 0.30, respectively) of maximal velocity phase performance (step velocity), with peak propulsive force providing the largest unique contribution to the regression model for step velocity. These results clarified the role of force and time variables on sprinting performance.

Keywords: Biomechanics, kinetics, impulse, running, contact time

Introduction

To investigate the determinants of sprinting, studies have previously aimed to determine the association between ground reaction forces (GRF) and performance during the acceleration,[1–8] and maximal velocity phases[4,9] of sprinting. Performance during the acceleration phase is influenced by the ability to continue to produce an anteriorly directed GRF during ground contact.[2–5,7,8] Sprinters need to generate large propulsive forces during the initial acceleration phase[1,2,4,5,7,8] and minimise braking forces during the transition and maximal velocity phases.[4,5,7] Furthermore, although the association between acceleration performance and average vertical forces during the initial acceleration and transition phases remains less clear, larger average vertical forces relative to bodyweight appear to be key determinants to faster running velocities during the maximal velocity phase (i.e. upright running phase).[4,9] Neither Rabita et al.[3] nor Colyer et al.[5] found any significant correlations between sprint performance and vertical forces during the acceleration phase, while Nagahara et al.[4,8] reported that smaller average and peak vertical forces were beneficial to performance during the acceleration phase. Previous authors[6,8,9] have suggested that during the initial acceleration and transition phases, vertical forces should be sufficiently large to provide an appropriate flight time and provides time to prepare for the next stance phase. Any further increases in vertical force beyond this would likely negatively influence acceleration performance by resulting in longer flight times which, with all other things being equal, could result in lower step frequency.

More successful sprinters generate larger net anteroposterior impulses throughout the whole acceleration phase[4,6,10] by applying larger propulsive impulses during initial acceleration[4,6,10,11] in addition to smaller braking impulses and larger propulsive impulses during the transition phase.[4] However, since impulse depends on both magnitude of force and duration of force application, it is currently unclear what influence contact time and duration of braking and propulsive force application have on sprint performance. Nagahara et al.[4] found that braking impulses were a significant predictor of running velocities between 75 to 95% of maximal velocity, whereas average braking forces were only predictive of running velocity at 75%, while neither propulsive forces nor braking forces were significant predictors of performance at 85% of maximal velocity. This inconsistency between force and impulse results may be due to the influence that the duration of force application has on the impulses generated.[4] For example, while average braking forces might be similar across participants from different performance levels, differences in braking duration could play an important role in the braking impulses generated during the transition and maximal velocity phases. Similarly, it is unclear to what extent propulsive time plays an important role in determining propulsive impulses during sprinting.

As sprinters need to cover a certain distance in the shortest time possible, the combination of force production and duration of force application during the sprint must be considered to enhance understanding of contributors to performance. This study aimed to explore the relationships of external kinetic and kinematic key performance indicators with initial acceleration, transition and maximal velocity sprinting performance. Specifically, we aimed to investigate the importance of force application magnitude and duration on sprinting performance.

Methods

Participants

Twenty-eight trained sprinters were convenience sampled to participate in this study. They provided written informed consent to participate after institutional ethical approval was obtained. The sample consisted of 18 male (height: 1.76 ± 0.05 m; body mass: 73.7 ± 5.9 kg; 60 m PB: 6.92 ± 0.13 s) and 10 female (height: 1.69 ± 0.08 m; body mass: 63.8 ± 5.6 kg; 60 m PB: 7.71 ± 0.18 s) sprinters. Participants were injury free throughout testing.

Design

Data were collected at the National Indoor Athletics Centre in Cardiff. Data collections were completely noninvasive and were undertaken during the athletes' regular speed training sessions. To investigate the determinants of sprinting across different phases in sprinting, data from the initial acceleration, transition and maximal velocity phases were collected from steps 3, 9 and 19 of a maximal sprint.[12] These sprint phases, which align with the definitions used in coaching literature,[e.g.13] were defined based on breakpoint steps (steps 4 – 6 and steps 14 -17) previously identified to separate a sprint into individual phases based changes in kinematics [12,14] and external kinetics.[15] To avoid any confounding effects of fatigue and step-to-step variations, data for the different steps were collected across multiple data collections and always from the same leg (rear leg in the blocks) for all analysed steps. The data were collected in December (before the indoor season) and in March-May (before the outdoor season) which aligned with when the sprinters were in their acceleration and maximal speed training phases respectively. As such, it was not possible to collect data from all three steps from all 28 participants. Step 3, 9 and 19 data were collected from 28, 20 and 13 individual athletes, respectively, with 12 participants completing all three steps.

Participants performed three to six maximal effort sprints from blocks over distances up to 40 m with a minimum of five minutes recovery. To ensure that the required step contacted the force plates without any need for targeting, the starting blocks were placed at a predetermined distance from the capture area.

Methodology

Sagittal plane kinematics were collected using one DV Digital Camera (Sony Z5, Sony Corporation, Tokyo, Japan) set-up perpendicular to the running lane and with a 5.5 m horizontal field of view. The camera was positioned a minimum of 15.0 m from the running lane and 1.0 m above the ground and recorded in HD (1440 × 1080 pixels) at 200 Hz. The iris was fully open and the shutter speed was 1/600 s. To facilitate calibration of a 4.00 m × 1.90 m plane, a pole with six known-location markers was moved sequentially through five locations in the camera view. Reconstruction accuracies ranged from 0.001-0.002 m during the different data collections.

Two force plates (type 9287BA and 9287CA, Kistler Instruments Corporation, Winterthur, Switzerland) placed in series were embedded within the running lane at the centre of the camera's horizontal field of view and covered with the same Mondo surface as the surrounding track. The GRF data were collected at 1000 Hz using Codamotion analysis (version 6.68/MPx30, Charnwood Dynamics Ltd, Leicester, UK). GRF and kinematic data were synchronised to within 0.001 s using a series of illuminating LEDs (Wee Beastie, UK). Videos were digitised in MATLAB (The MathWorks Inc., USA, version R2014a) using an open source digitising package.[16] Digitising commenced 10 frames prior to toe-off of steps 2, 8 and 18 and ended 10 frames after the touchdown of steps 4, 10 and 20, respectively. Eighteen points on the human body (vertex, C7, and hip, shoulder, elbow, wrist, knee, ankle and MTP joint centres, and the distal end of the sprinting spikes) were digitised. A further frame was marked to identify the instant of touchdown of the subsequent step (i.e. touchdown of steps 4, 10 and 20). This touchdown event was used to calculate flight and step times. Trials were reconstructed using a 9 parameter 2D DLT function[12,17] which accounted for lens distortion.[18] Following an autocorrelation analysis,[19] kinematic data were filtered at 26 Hz using a fourth-order Butterworth digital filter.[20] Whole-body centre of mass (CM) was calculated[20] from both unfiltered and filtered coordinates. The unfiltered CM coordinates were later used to calculate step velocity and touchdown velocity. Data from de Leva[21] was used to calculate the inertia data for all the segments except the two-segment foot, for which data from Bezodis et al.[22] was used with the inclusion of each participant's shoe mass. The mass of the shoe was divided according to the two-segment foot proportions and added to the respective foot segments.

Raw vertical GRF data were used to identify ground contact using a 10 N threshold. The GRF data were then individually filtered at cut-off frequencies (~170 Hz), determined using the autocorrelation method.[19] Filtered GRF data were used to calculate: peak force (braking, propulsive, vertical and resultant); average anteroposterior and vertical forces during the ground contact phase and separately during the braking and propulsive phases; ratio of forces (RF),[2] expressed as a percentage; braking, propulsive, net anteroposterior and vertical (bodyweight removed) impulses calculated using the trapezium rule integration method and expressed relative to the participant's body mass to reflect the change in velocity of the centre of mass; contact time: the difference between touchdown and toe-off time; braking time: the duration during which a braking (negative) force was acting; propulsive time: the duration during which a propulsive (positive) force was acting; horizontal external power: the product of instantaneous anterior-posterior velocity at touchdown[23] and horizontal force. Horizontal external power across the contact phase was subsequently averaged and normalised to calculate normalised average horizontal external power (NAHEP).[23] All force variables were normalised to body weight.

Kinematic variables included: step characteristics [i.e. step velocity (m/s), step length (m), step frequency (Hz), flight time (s), step time (s)],[12] touchdown velocity: the instantaneous anterior-posterior velocity at touchdown used to calculate NAHEP was calculated by fitting a 1st order polynomial through the unfiltered CM displacement data from the preceding flight phase[23] and average centre of mass angle (°): the angle between the vector connecting the centre of pressure and the filtered CM coordinates relative to the forward horizontal, averaged across stance.

Statistical Analysis

Since power production is of critical importance to sprint acceleration,[5,23] NAHEP was used as the key performance measure in steps 3 and 9. For step 19, in the maximal velocity phase, step velocity was used as the key performance measure. Whilst the time taken to complete a sprint is the standard performance criterion, without comprehensive biomechanical data from every step within a sprint, it is not possible to fully determine all of the factors that contribute to this overall performance metric. Therefore, an individual-step based approach might be preferable. During the initial acceleration and transition phases, the athlete's goal is to increase their running velocity to the greatest extent possible in the shortest possible time. The external power produced during just the step of interest is, therefore, an appropriate variable to quantify performance independently from the influence of prior steps.[23] By the maximum velocity phase of the sprint, the change in velocity within each step is, by definition, small to null. At this point, the key performance criterion is how fast the athlete is running, hence step velocity is an appropriate dependent variable for step 19. The best step 3, 9 and 19 trials for each athlete (based on these performance measures) were selected for further analysis. An interclass correlation coefficient (ICC; model 3, 1) with a 90% confidence interval[24] for NAHEP (the performance measure used to determine the best trial) confirmed good reliability[25] of the measure (ICC 0.85, CI: 0.76-0.91).

Descriptive statistics (mean ± SD) were calculated for all variables. Pearson correlation coefficients were calculated to assess the relationships between the performance measures, force and kinematic variables. Male and female athletes were combined into one group as the relationships between the performance measures and the mechanics (e.g. force production) of the skill were not considered to be influenced by sex. Therefore, while the overall performance output may differ between male and female participants, the mechanical variables that determine their performance are the same. For all correlation coefficients, a threshold of 0.10 was set for the smallest worthwhile effect, and 90% confidence intervals (CI) were used to make inferences about the magnitude of the correlation.[26] Determinants of sprinting performance were explored using multiple linear regression analyses. Independent variables were selected based on previous literature[1–6,9] except for peak propulsive force which was included in the multiple regression model for step velocity following the results of the correlation analysis in this study. For steps 3 and 9, NAHEP was used as the dependent variable and average braking force, average propulsive force, braking time and propulsive time were entered as the independent variables as these have previously been linked to better performance during the initial acceleration and transition phases.[e.g.3,10] For step 19, step velocity was used as the dependent variable (as explained above) and contact time, average vertical force and peak propulsive force were entered as the independent variables. Contact time and vertical force were included as these have previously been linked to better performance during the maximal velocity phase,[4,9] whilst peak propulsive force was included based on the correlation with step velocity found in this study. A commonality analysis[27,28] was performed to identify the unique (variance uniquely attributed to independent variable) and common (shared variance between two or more independent variables) effects which each predictor contributed to the variance (r^2) of the multiple regression models. Furthermore, the commonality analysis also revealed the presence of suppressor effects (i.e. negative commonality coefficients) when some of the independent variables affected each other in opposite directions.[27,28] All regression analyses were performed in SPSS (v.24.0). The significance level was set at $P<0.05$. For all multiple-regression regression models, the 95% CI was calculated for the β-coefficients, normality of the residuals were confirmed (Shapiro-Wilk; Step 3: $p=0.174$; Step 9: $p=0.652$, Step 19: $p=0.373$), autocorrelation was minimal (Durbin–Watson statistic between 1.4 and 2.6) and multicollinearity was within acceptable limits (variance inflation factors: 1.4 and 3.7).[29]

Results

All participants generated a positive anteroposterior impulse on each step (Table 1). Braking impulses increased, and propulsive impulses decreased, between steps 3, 9 and 19.

****INSERT TABLE 1 NEAR HERE****

Average anteroposterior impulse (Figure 1) and force (Figure 2) showed strong relationships with NAHEP during steps 3 and 9 (r=0.76 ± 0.14 to 0.99 ± 0.01) and the relationship between NAHEP and average propulsive force slightly decreased from step 3 (r=0.95 ± 0.03) to 9 (r=0.74 ± 0.19). Similarly, while the relationships between NAHEP and contact times were strong during steps 3 and 9 (Figure 3; r=-0.82 ± 0.11 to -0.89 ± 0.09), the strength of the relationship increased between NAHEP and braking time (Step 3: -0.31 ± 0.29; Step 9: -0.72 ± 0.20) and decreased between NAHEP and propulsive time (Step 3: -0.80 ± 0.12; Step 9: -0.54 ± 0.28) as the sprint progressed.

****INSERT FIGURE 1 NEAR HERE****

****INSERT FIGURE 2 NEAR HERE****

****INSERT FIGURE 3 NEAR HERE****

Step 3 average propulsive force uniquely contributed 28% of the variance in the regression model and average propulsive force and propulsive time together contributed 61% of the variance (Figure 4c). On step 9, the largest unique contribution was due to braking time (40%) while the largest common contribution resulted from the combination of average propulsive force and propulsive time (30%, Figure 4d).

****INSERT FIGURE 4 NEAR HERE****

With step velocity as the dependent variable for step 19, average vertical force (r=0.57 ± 0.35), average resultant force (r=0.58 ± 0.34), peak propulsive force (r=0.66 ± 0.30), contact time (r=-0.64± 0.31) and touchdown CM velocity (r=0.98 ± 0.03) showed the strongest relationships (Figure 5).

****INSERT FIGURE 5 NEAR HERE****

During step 19, total variance (shared + unique) contributed by peak propulsive force, contact time and average vertical force was 79%, 75% and 59% (Figure 6b), respectively. Contact time and peak propulsive force provided the largest unique contribution to the variance of the regression model with 8% and 24%, respectively. Contact time and average vertical force shared 13% of the variance and contact time and peak propulsive force shared 9% of the variance of the regression model. Finally, contact time, average vertical forces, and peak propulsive forces shared 44% of the variance.

****INSERT FIGURE 6 NEAR HERE****

Pearson correlation coefficients were also calculated between step velocity and braking time. The relationship between braking time and step velocity was likely meaningful for step 3 (r=-0.34 ± 0.28, p = 0.07; R^2=0.12), unclear for step 9 (r=-0.03 ± 0.38; p = 0.90; R^2=0.00) and likely meaningful for step 19 (r=-0.46 ± 0.40, p = 0.11; R^2=0.21).

Discussion

This study explored the relationships of GRF and contact time variables with sprint performance during the initial acceleration, transition and maximal velocity phases. In addition to supporting previous studies which identified that average propulsive forces are a key to sprint acceleration performance,[1,2,4,5,7,8] the results of this study demonstrate the importance of braking time to sprint acceleration performance during the transition phase. During the maximal velocity phase, contact times, average vertical forces and peak propulsive forces showed the largest meaningful correlations with step velocity, with peak propulsive force having the largest predictive capability as identified by the commonality regression analysis.

The regression analysis showed that net anteroposterior and propulsive impulses were most likely correlated with NAHEP on steps 3 and 9 (r between 0.70 ± 0.21 to 0.93 ± 0.06), while braking impulse was very likely correlated with NAHEP on step 9 (r=0.58 ± 0.27; Figure 1). These partly contrast with the findings relating to the relationships between GRF and NAHEP (Figure 2). Here, net anteroposterior (step 3: r=0.97 ± 0.02; step 9: r=0.99 ± 0.01) and propulsive forces (step 3: r=0.95 ± 0.03; step 9: r=0.74 ± 0.19) were most likely correlated with NAHEP while the correlations between braking forces and NAHEP (step 3: r=0.21 ± 0.31; step 9: r=-0.28 ± 0.35) were not meaningful. These contrasting findings of the associations between braking impulse and NAHEP and braking force and NAHEP align with previous research.[4] This could result from the participants' ability to attenuate the braking forces towards the end of the braking phase[5,7] and therefore have shorter braking times. In this study, participants who generated propulsive forces earlier (i.e. had shorter braking times) generated smaller braking impulses. Therefore, the duration of the braking phase plays an important role in the generation of braking impulses during the transition phase of sprinting.

Contact times were most likely negatively associated with NAHEP during both steps 3 ($r=-0.82 \pm 0.11$) and 9 ($r=-0.89 \pm 0.09$), while the association with braking time increased and the association between NAHEP and propulsive time decreased between steps 3 and 9 (Figure 3). The commonality regression analysis (Figure 4b) further highlighted that between steps 3 and 9 the unique contribution due to braking time increased from 1% to 40% of the explained variance (step 3: $R^2=0.95$; step 9: $R^2=0.96$). These results show that braking time plays an important role in determining sprint performance during the transition phase and provides some context to findings from a previous study[4] which reported that braking impulse was a significant predictor of performance between 75% - 95% of maximal velocity whereas braking forces only significantly predicted running performance at 75% of maximal running velocity. Braking times may, therefore, play an important role in determining the braking impulse and ultimately influencing sprint performances.

Previous research found that contact time was associated with the sprinter's kinematics (i.e. horizontal velocity, touchdown and toe-off leg angle).[30] Therefore, it could be reasoned that sprinters with shorter braking times either had a higher anterior-posterior velocity or altered kinematics (e.g. shorter anterior-posterior foot to CM distances at touchdown) or both, compared to sprinters with longer braking times. In the current study, step velocity accounted for little of the variation in braking times (<12%) during steps 3 and 9, therefore other kinematic variables may better explain differences in braking times and therefore provide practical solutions to increase performance during the transition phase. One such variable is CM angle (Figure 3), which has previously been linked to acceleration.[31] The results of this study show that smaller average CM angles were associated with larger NAHEP during the initial acceleration and transition phases. The magnitude of the CM angle can be directly influenced by segment orientations at touchdown and toe-off.

During the maximal velocity phase, contact time, vertical force and peak propulsive force showed the strongest association with step velocity in step 19 (Figure 5). The commonality analysis revealed that vertical force contributed a total variance (unique + shared; Figure 6b) of 59% of the model for step velocity (Figure 6). This result supports previous research showing that increasing average vertical force is linked with increases in running velocities across a heterogeneous population (running velocities ranging widely between 6.2 and 11.1 m/s)[9] and within a group of trained sprinters.[4] The current study also found that most of the variance contributed by vertical force (Figure 6b) was shared with contact time and peak propulsive force. This suggests that while vertical forces are important to support the increase in running velocities,[4,9] there is likely an optimal magnitude[6,8] which is directed by a given velocity and contact time combination.

A novel finding relating to the maximal velocity phase (step 19) was the association between step velocity and peak propulsive force ($r=0.66 \pm 0.30$; Figure 5). The commonality analysis revealed that peak propulsive force uniquely contributed 24% of the r^2 for step velocity (Figure 6). Previously Nagahara et al.[8] reported that peak propulsive force was only correlated with acceleration performance in step 9. While the different results of Nagahara et al.[8] and the current study could be related to the different dependent variables used, this result may represent an important capacity in sprinters to ensure suitably large propulsive impulses are generated during maximal velocity sprinting.

Whilst data was only collected from one step per phase across a maximal sprint from blocks, the kinematics and kinetics of those three steps are representative of the initial acceleration, transition and maximal velocity phases respectively.[12,14,15] This is shown by the relative vertical impulse during the braking phase, which was negative on step three and positive on steps 9 and 19. This aligns with research by Nagahara et al.,[15] showing the participants to be in the initial acceleration and transition phases during steps 3 and 9 respectively. In addition, because overall sprint performance is determined by the time taken to cover a specific distance, we had to adopt proxies of sprint performance during each step of interest and we therefore cannot know how our independent variables compare with other performance measures. The use of NAHEP as the performance measure in steps which occurred during the initial acceleration and transition phases (i.e. steps 3 and 9 in the current analysis) is consistent with much contemporary research across these phases[5,23,32–34] as it enables the change in velocity achieved and the time taken to achieve this change to be incorporated into a single outcome measure which corresponds directly to the step of interest.

Practical Applications

Two main practical implications emerged from this study. Firstly, while GRF magnitudes are responsible for changes in acceleration, time of force application needs consideration to fully understand sprint acceleration performance. Faster running velocities have previously been associated with shorter contact times.[30] It could, therefore, be theorised that faster running velocity could also be associated with shorter braking times, however, the current analysis found that step velocity only explained a small amount of the variance in braking time. The effect of touchdown kinematics could further explain differences in braking time across participants and practitioners should account for the "front-side mechanics"[35] of sprinters as they progress through a sprint. Kinematic variables such as foot velocity and leg angle at touchdown have previously been associated with larger braking impulses,[6] however, the mechanism linking technical variables at touchdown and braking impulses are still unclear. In addition, this analysis showed that smaller average CM angles (Figure 3) during the initial acceleration and transition phases were associated with a larger NAHEP. Therefore, sprinters with better acceleration performances exhibited more forward lean which could allow them to direct forces more horizontally.[36] Such a measure can be assessed in the field to monitor key determinants of acceleration in cases where force platforms are not always readily available. Secondly, during maximal velocity sprinting, contact time shared most of the variance with vertical ground reaction force (i.e. they explain the same variance in performance). This suggests that contact times can be used as a field based alternative to estimating forces to understand how sprinters are achieving their sprint performance. Furthermore, the identification of peak propulsive force as a key variable in maximal velocity sprinting provides a novel insight into performance. Although generating a sufficiently larger vertical force is key as running velocities increase,[9] sprinters also need to be able to generate a sufficiently large propulsive impulse to match increases in braking impulses. During the maximal velocity phase, a larger peak propulsive force would maintain a sufficiently large propulsive force magnitude and attenuate the decreases in propulsive impulses due to a shorter propulsive duration (Table 1). This would ensure that sprinters continue to accelerate further and therefore reach their peak running velocity later in a sprint. Maximal velocity sprinting is therefore not only dependent on sprinters' ability to generate appropriate vertical forces after touchdown,[37] but also on their ability to generate a sufficiently large peak propulsive force as they approach toe-off. Future work could consider how running technique and external ground reaction forces are linked.

Conclusions

The findings of this study show that propulsive force plays a key role in determining sprint acceleration performance during the initial acceleration and transition phases, while braking time is an important determinant in sprint acceleration performance during the transition phase. During the maximal velocity phase, contact time, vertical force and peak propulsive force were key determinants of performance (step velocity). However, peak propulsive force provided the largest unique contribution to the regression model for step velocity. These results clarified the role of force and time variables in sprinting performance.

References

1. Mero A. Force-time characteristics and running velocity of male sprinters during the acceleration phase of sprinting. *Res Q Exerc Sport*. 1988;59(2):94-98.

2. Morin JB, Edouard P, Samozino P. Technical Ability of Force Application as a Determinant Factor of Sprint Performance. *Med Sci Sport Exerc*. 2011;43(9):1680-1688. doi:doi: 10.1249/MSS.0b013e318216ea37

3. Rabita G, Dorel S, Slawinski J, et al. Sprint mechanics in world-class athletes: A new insight into the limits of human locomotion. *Scand J Med Sci Sport*. 2015;25(5):583-594. doi:10.1111/sms.12389

4. Nagahara R, Mizutani M, Matsuo A, Kanehisa H, Fukunaga T. Association of sprint performance with ground reaction forces during acceleration and maximal speed phases in a single sprint. *J Appl Biomech*. 2017:1-20. doi:10.1123/jab.2016-0356

5. Colyer SL, Nagahara R, Salo AIT. Kinetic demands of sprinting shift across the acceleration phase: novel analysis of entire force waveforms. *Scand J Med Sci Sports*. 2018;44(0). doi:10.1111/sms.13093

6. Hunter J, Marshall R, McNair P. Relationship between ground reaction force impulse and kinematics of sprint-running acceleration. *J Appl Biomech*. 2005;21:31-43. doi:10.1123/jab.21.1.31

7. Colyer SL, Nagahara R, Takai Y, Salo AIT. How sprinters accelerate beyond the velocity plateau of soccer players : Waveform analysis of ground reaction forces. *Scand J Med Sci Sports*. 2018;28(12):2527-2535. doi:10.1111/sms.13302

8. Nagahara R, Kanehisa H, Matsuo A, Fukunaga T. Are peak ground reaction forces related to better sprint acceleration performance ? *Sport Biomech*. 2019;00(00):1-10. doi:10.1080/14763141.2018.1560494

9. Weyand PG, Sternlight DB, Bellizzi MJ, Wright S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol*. 2000;89(5):1991-1999. doi:10.1152/jappl.2000.89.5.1991

10. Morin JB, Slawinski J, Dorel S, et al. Acceleration capability in elite sprinters and ground impulse: Push more, brake less? *J Biomech*. 2015;48(12):3149-3154. doi:10.1016/j.jbiomech.2015.07.009

11. Kawamori N, Nosaka K NR. Relationships between ground reaction impulse and sprint acceleration performance in team sport athletes. *J Strength Cond Res*. 2013;27(3):568-573.

12. von Lieres und Wilkau HC, Irwin G, Bezodis NE, Simpson S, Bezodis IN. Phase analysis in maximal sprinting: an investigation of step-to-step technical changes between the initial acceleration, transition and maximal velocity phases. *Sport Biomech*. 2018;3141:1-16. doi:10.1080/14763141.2018.1473479

13. Seagrave L. Introduction to sprinting. *New Stud Athl*. 1996;11(2):93-113.

14. Nagahara R, Matsubayashi T, Matsuo A, Zushi K. Kinematics of transition during human accelerated sprinting. *Biol Open*. 2014;3(8):689-699. doi:10.1242/bio.20148284

15. Nagahara R, Kanehisa H, Fukunaga T. Ground reaction force across the transition during sprint acceleration. *Scand J Med Sci Sports*. November 2019:sms.13596. doi:10.1111/sms.13596

16. Hedrick TL. Software techniques for two- and three-dimensional kinematic measurements of biological and biomimetic systems. *Bioinspiration and Biomimetics*. 2008;3(3). doi:10.1088/1748-3182/3/3/034001

17. Meershoek L. Matlab routines for 2-D camera calibration and point reconstruction using the DLT for 2-D analysis with non-perpendicular camera angle. http://isbweb.org/software/movanal.html. Accessed February 10, 2014.

18. Walton J. Close-range cine-photogrammetry: A generalised technique for quantifying gross human motion. 1981.

19. Challis JH. A procedure for the automatic determination of filter cutoff frequency for the processing of biomechanical data. *J Appl Biomech*. 1999;15(3):303-317.

20. Winter DA. *Biomechanics and Motor Control of Human Movement*. 4th ed. John Wiley & Sons, Inc.; 2009. doi:10.1002/9780470549148

21. de Leva P. Adjustments to Zatsiorsky–Seluyanov's segment inertia parameters. *J Biomech*. 1996;29(9):1223-1230. doi:https://doi.org/10.1016/0021-9290(95)00178-6

22. Bezodis NE, Salo AIT, Trewartha G. Lower limb joint kinetics during the first stance phase in athletics sprinting: Three elite athlete case studies. *J Sports Sci*. 2014;32(8):738-746. doi:10.1080/02640414.2013.849000

23. Bezodis NE, Salo AIT, Trewartha G. Choice of sprint start performance measure affects the performance-based ranking within a group of sprinters: Which is the most appropriate measure? *Sport Biomech*. 2010;9(4):258-269. doi:10.1080/14763141.2010.538713

24. Hopkins WG. Spreadsheets for analysis of validity and reliability. *Sportscience*. 2015;19(19):36-44. doi:sportsci.org/2017/wghxls.htm

25. Portney, L.G. and Watkins MP. *Foundations of Clinical Research: Applications to Practice*. 3rd ed. Pearson Higher Education & Professional Group; 2013.

26. Batterham AM, Hopkins WG. Making meaningful inferences about magnitudes. *Int J Sports Physiol Perform*. 2006;1(1):50-57. doi:10.1123/ijspp.1.1.50

27. Nimon K. Regression Commonality Analysis: Demonstration of an SPSS Solution. *Mult Linear Regres Viewpoints*. 2010;36(1):10-17.

28. Nathans LL, Oswald FL, Nimon K. Interpreting Multiple Linear Regression: A Guidebook of Variable Importance. *Pract Assessment, Res Eval*. 2012;17(9):1-19. doi:10.3102/00346543074004525

29. Field A. *Discovering Statistics Using IBM SPSS Statistics: (And Sex and Drugs and Rock 'n' Roll)*. 3rd Ed. London, UK: SAGE Publications Ltd; 2009. doi:10.14359/51686441

30. Hunter JP, Marshall RN, McNair PJ. Interaction of Step Length and Step Rate during Sprint Running. *Med Sci Sports Exerc*. 2004;36(2):261-271. doi:10.1249/01.MSS.0000113664.15777.53

31. di Prampero PE. Sprint running: a new energetic approach. *J Exp Biol*. 2005;208(14):2809-2816. doi:10.1242/jeb.01700

32. Bezodis NE, Trewartha G, Salo AIT. Understanding the effect of touchdown distance

and ankle joint kinematics on sprint acceleration performance through computer simulation. *Sport Biomech*. 2015;14(2):232-245. doi:10.1080/14763141.2015.1052748

33. Willwacher S, Herrmann V, Heinrich K, et al. Sprint start kinetics of amputee and non-amputee sprinters. *PLoS One*. 2016;11(11):1-18. doi:10.1371/journal.pone.0166219

34. Brazil A, Exell T, Wilson C, Willwacher S, Bezodis I, Irwin G. Lower limb joint kinetics in the starting blocks and first stance in athletic sprinting. *J Sports Sci*. 2017;35(16):1629-1635. doi:10.1080/02640414.2016.1227465

35. Mann R. *The Mechanics of Sprinting and Hurdling*. Las vegas, NV: Author; 2007.

36. Kugler F, Janshen L. Body position determines propulsive forces in accelerated running. *J Biomech*. 2010;43(2):343-348. doi:10.1016/j.jbiomech.2009.07.041

37. Clark KP, Ryan LJ, Weyand PG. A general relationship links gait mechanics and running ground reaction forces. *J Exp Biol*. 2017;220(2):247-258. doi:10.1242/jeb.138057

Table 1: Group-wide summary of the kinematic and kinetic variables from each of the three steps of interest (mean ± SD)

	Step 3	Step 9	Step 19
n	28^	20	13
Step velocity [m/s]	5.72±0.23	8.37±0.38	9.74±0.48
NAHEP	0.67±0.11	0.55±0.13	0.23±0.10
Anteroposterior Δ velocity [m/s]	0.72±0.05	0.30±0.04	0.09±0.03
Anteroposterior Δ velocity (BP) [m/s]	-0.03±0.02	-0.08±0.03	-0.18±0.03
Anteroposterior Δ velocity (PP) [m/s]	0.76±0.05	0.38±0.03	0.27±0.03
Vertical Δ velocity[m/s]	0.69±0.16	0.99±0.17	1.17±0.11
Vertical Δ velocity (BP) [m/s]	-0.03±0.02	0.23±0.15	0.67±0.13
Vertical Δ velocity (PP) [m/s]	0.72±0.15	0.76±0.19	0.50±0.14
Average anteroposterior force [BW]	0.49±0.07	0.27±0.05	0.10±0.04
Average anteroposterior force (BP) [BW]	-0.25±0.11	-0.32±0.13	-0.44±0.07
Average anteroposterior force (PP) [BW]	0.56±0.07	0.44±0.05	0.46±0.06
Average vertical force [BW]	1.47±0.13	1.88±0.18	2.18±0.17
Average vertical force (BP) [BW]	0.79±0.16	1.80±0.33	2.61±0.15
Average vertical force (PP) [BW]	1.53±0.13	1.88±0.22	1.86±0.26
Average resultant force [BW]	1.59±0.13	1.97±0.18	2.27±0.17
Peak braking force [BW]	-0.44±0.23	-0.81±0.22	-1.19±0.18
Peak vertical force [BW]	2.23±0.24	3.00±0.34	3.70±0.31
Peak propulsive force [BW]	0.89±0.09	0.83±0.09	0.80±0.10
Peak resultant force [BW]	2.33±0.24	3.01±0.34	3.71±0.31
Ratio of force [%]	31.0±3.2	13.5±2.2	4.2±1.6
Average centre of mass angle [°]	70.1±1.7	78.9±1.1	84.1±1.3
Contact time [s]	0.152±0.013	0.116±0.011	0.102±0.009
Braking time [s]	0.012±0.004	0.028±0.010	0.042±0.009
Propulsive time [s]	0.140±0.012	0.088±0.005	0.060±0.004
Flight time [s]	0.079±0.015	0.107±0.012	0.125±0.015
Step length [m]	1.32±0.09	1.86±0.14	2.21±0.20
Step frequency [Hz]	4.34±0.33	4.50±0.28	4.42±0.32

BP: Braking phase; PP: Propulsive phase; ^one participant did not produce braking forces on step 3. Therefore, for variables involving the braking phase n = 27.

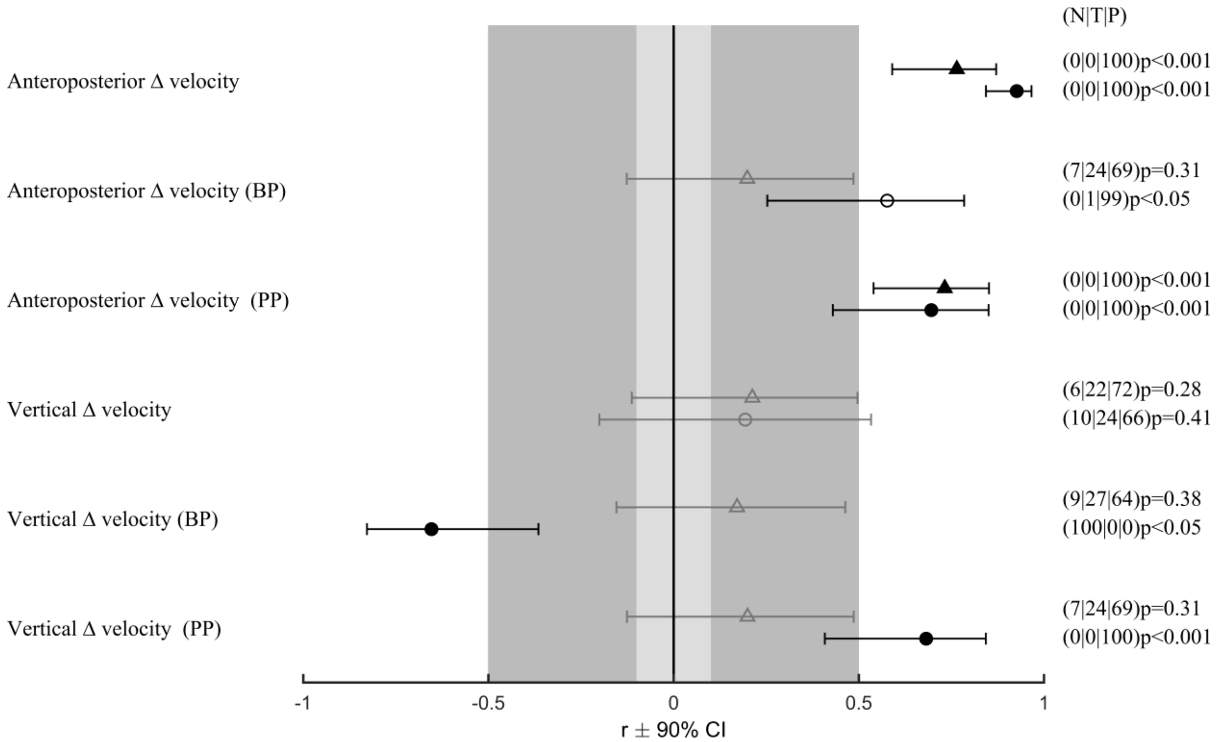

Figure 1: Pearson correlation coefficients (± 90% CI) between NAHEP and impulse variables for steps 3 (triangles) and 9 (circles). Central light grey region (r = −0.1 to 0.1) indicates a trivial relationship. Dark grey region (r= -0.1 to -0.5 & 0.1 to 0.5) indicates small to moderate relationships. Percentages represent the likelihoods that the relationship is truly Negative | Trivial | Positive. Marker colour indicates unclear (grey outline), likely (grey filled), very likely (black outline), and almost certain (black fill) relationships. The P-value for each correlation coefficient is also presented.

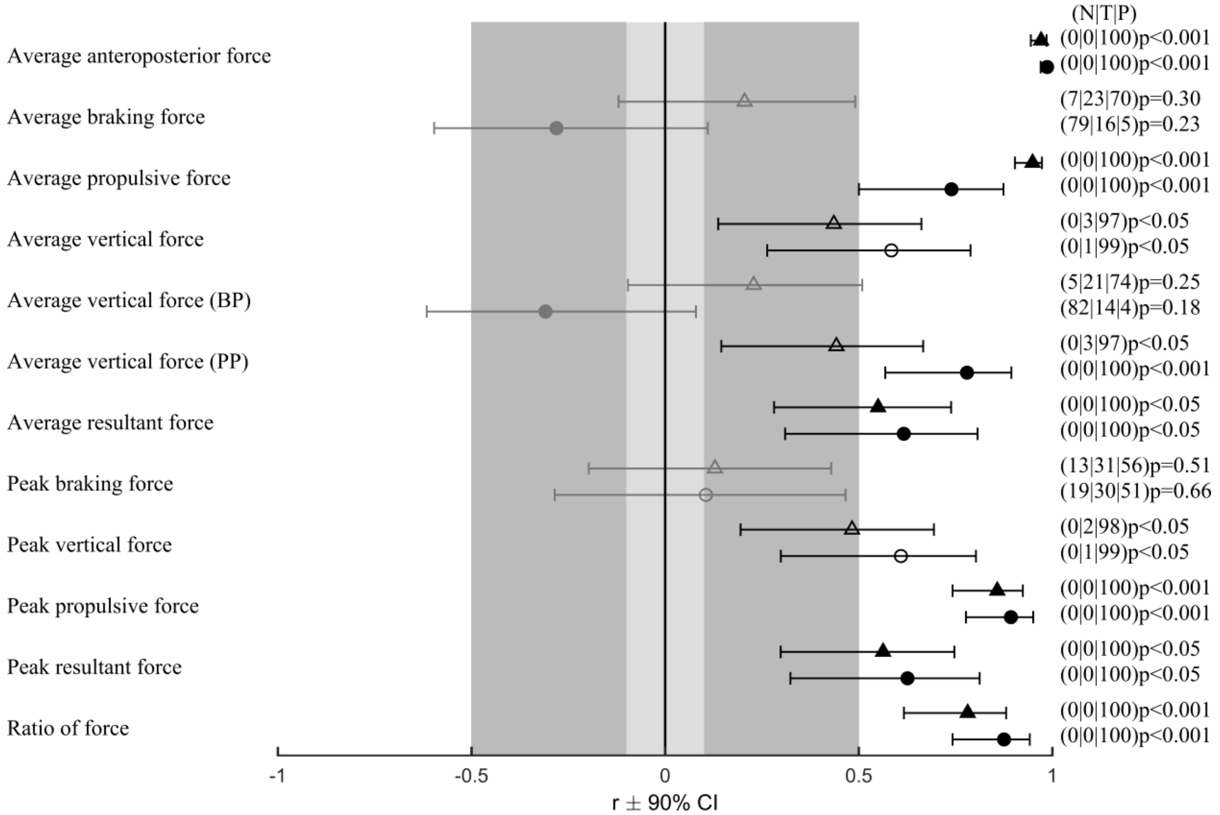

Figure 2: Pearson correlation coefficients (± 90% CI) between NAHEP and force variables for steps 3 (triangles) and 9 (circles). Central light grey region (r = −0.1 to 0.1) indicates a trivial relationship. Dark grey region (r= -0.1 to -0.5 & 0.1 to 0.5) indicates small to moderate relationships. Percentages represent the likelihoods that the relationship is truly Negative | Trivial | Positive. Marker colour indicates unclear (grey outline), likely (grey filled), very likely (black outline), and almost certain (black fill) relationships. The P-value for each correlation coefficient is also presented.

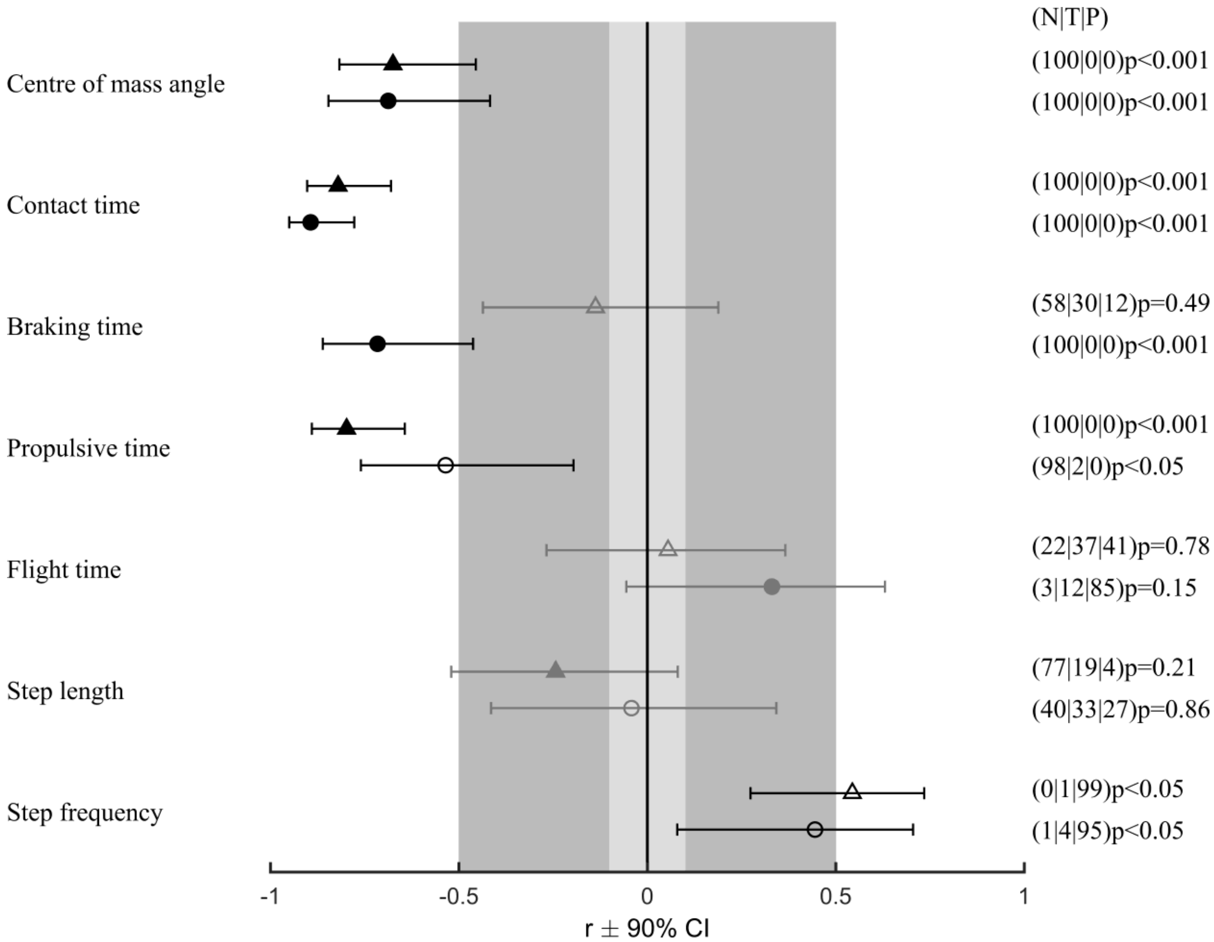

Figure 3: Pearson correlation coefficients (± 90% CI) between NAHEP and spatiotemporal variables for steps 3 (triangles) and 9 (circles). Central area (r = −0.1 to 0.1) indicates a trivial relationship. Dark grey region (r= -0.1 to -0.5 & 0.1 to 0.5) indicates small to moderate relationships. Percentages represent the likelihoods that the relationship is truly Negative | Trivial | Positive. Marker colour indicates unclear (grey outline), likely (grey filled), very likely (black outline), and almost certain (black fill) relationships. The P-value for each correlation coefficient is also presented.

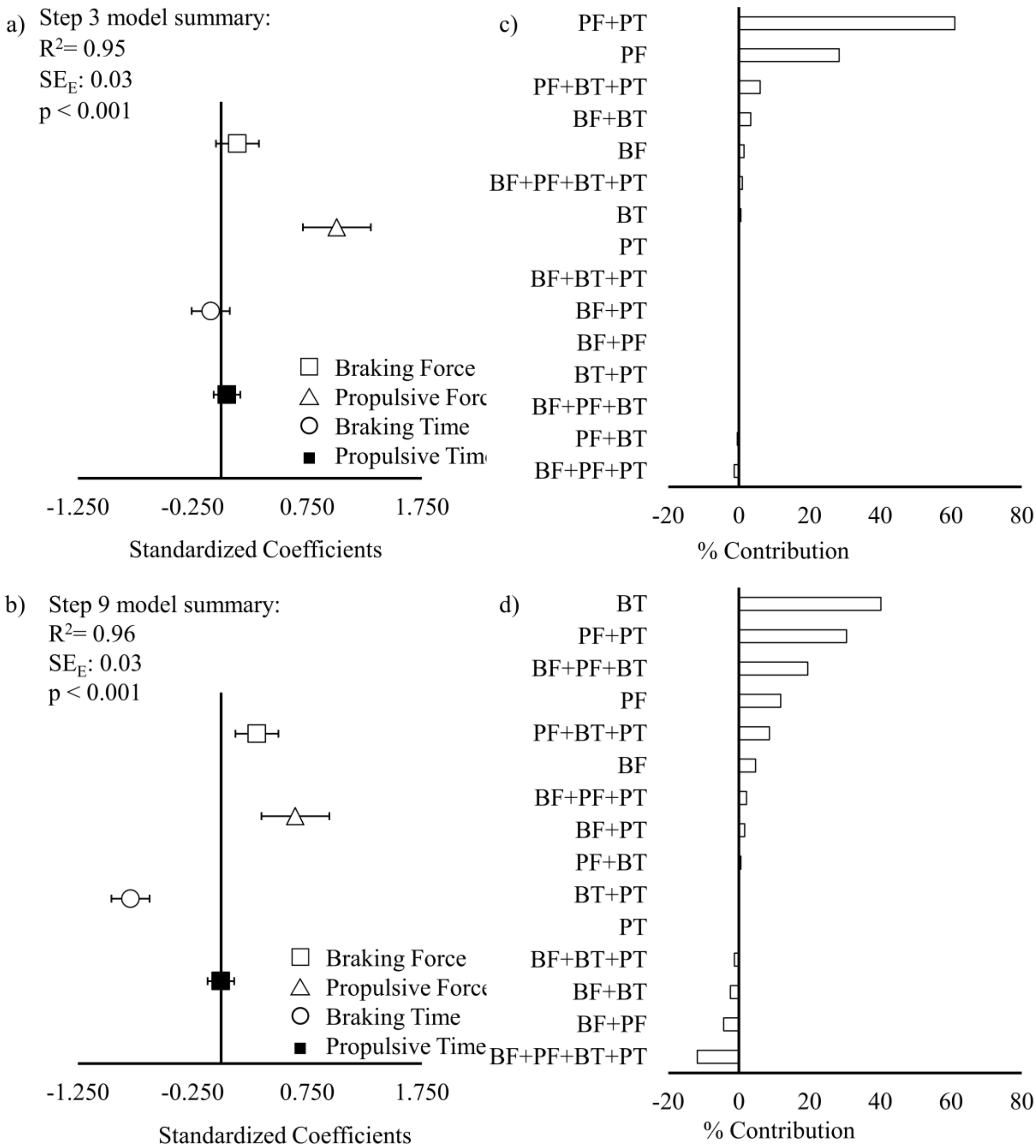

Figure 4: Standardised β coefficients ± 95% CIs of the results of the multiple-regression analysis results for NAHEP for steps 3(a) and 9 (b). Independent variables include average braking force (BF), average propulsive force (PF), braking time (BT) and propulsive time (PT). Results of the commonality regression analysis are shown in figures c (step 3) and d (step 9). Unique (identified by the labels BF, PF and BT) and common contributions are arranged highest to lowest

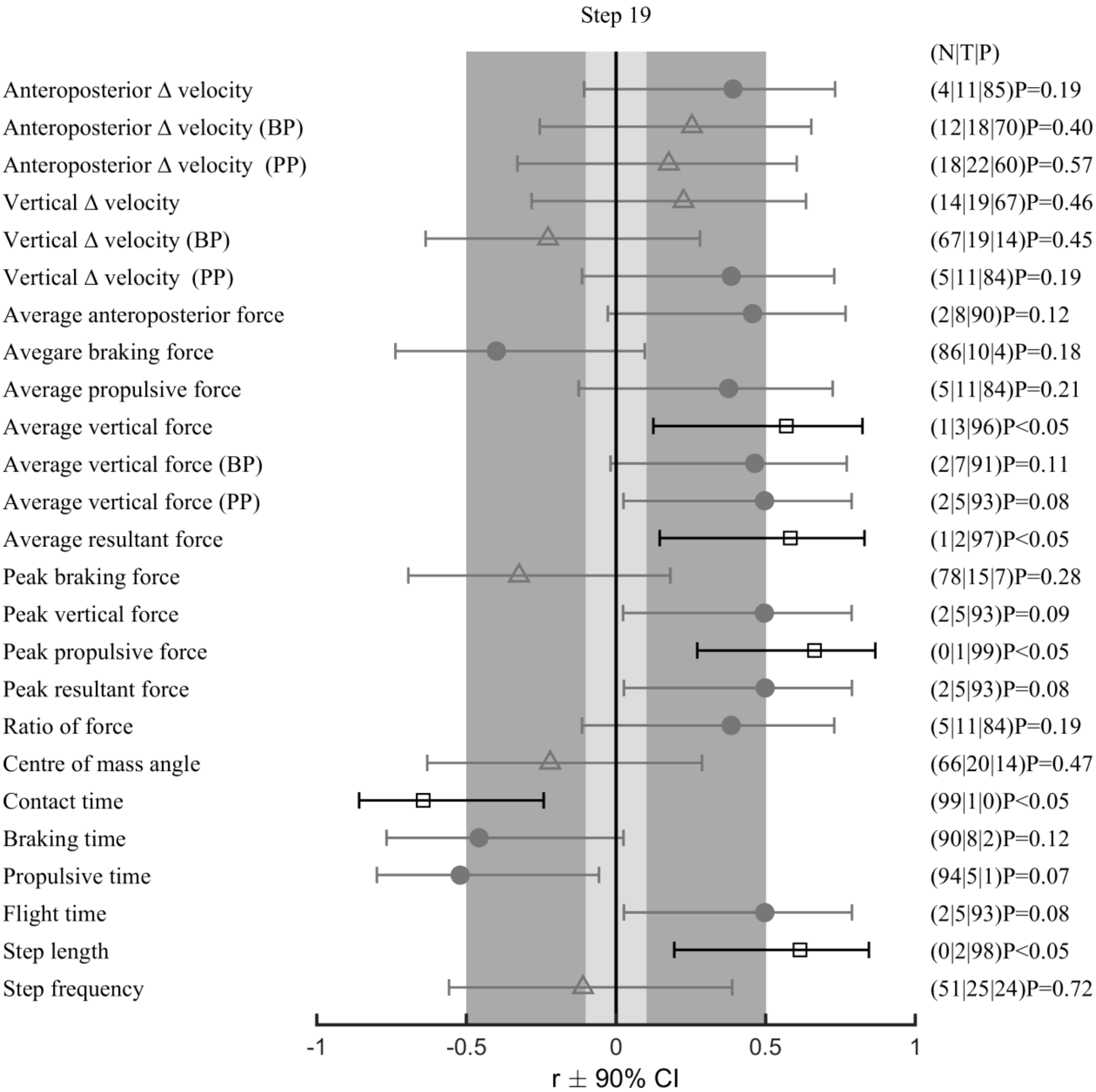

Figure 5: Pearson correlation coefficients (± 90% CI) between step velocity (step 19) and kinetic and spatiotemporal variables. Central area (r = −0.1 to 0.1) indicates a trivial relationship. Dark grey region (r= -0.1 to -0.5 & 0.1 to 0.5) indicates small to moderate relationships. Percentages represent the likelihoods that the relationship is truly Negative | Trivial | Positive. Marker colour indicates unclear (diamond, grey outline), likely (circle, grey filled), very likely (square, black outline), and almost certain (square, black fill) relationships. The P-value for each correlation coefficient is also presented.

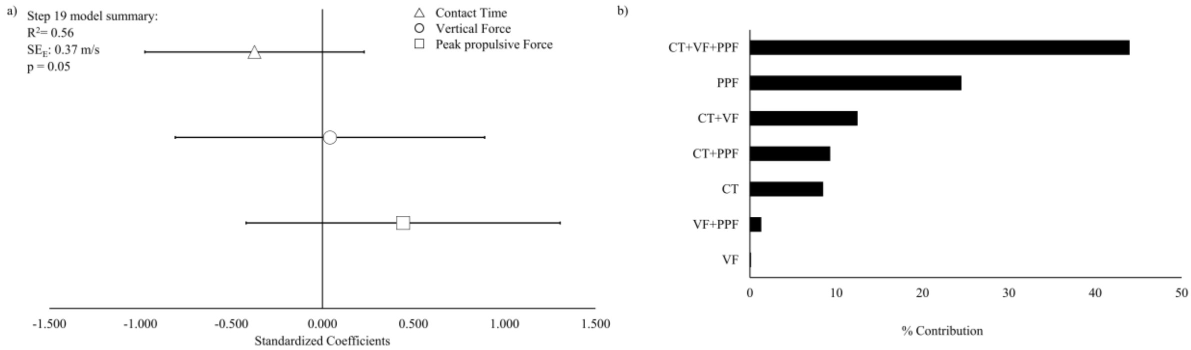

Figure 6: Standardised β coefficients ± 95% CIs of the results of the multiple-regression analysis results for step velocity. a) Standardised β coefficients ± 95% CIs for step 19 (a). b) Results of the commonality analysis. Here unique (identified by the labels CT, VF, PPF) and common contributions are shown for contact time (CT), vertical force (VF) and peak propulsive force (PPF).