Citation for published version:
Colyer, SL, Nagahara, R & Salo, AIT 2018, 'Kinetic demands of sprinting shift across the acceleration phase: novel analysis of entire force waveforms', *Scandinavian Journal of Medicine and Science in Sports*, vol. 28, no. 7, pp. 1784-1792. https://doi.org/10.1111/sms.13093

DOI:
10.1111/sms.13093

Publication date:
2018

Document Version
Peer reviewed version

Link to publication

This is the peer reviewed version of the following article: Colyer, S. L., Nagahara, R., & Salo, A. I. T. (2018). Kinetic demands of sprinting shift across the acceleration phase: novel analysis of entire force waveforms. Scandinavian Journal of Medicine and Science in Sports, which has been published in final form at https://doi.org/10.1111/sms.13093. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Self-Archiving.

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Kinetic demands of sprinting shift across the acceleration phase: novel analysis of entire force waveforms

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Abstract

A novel approach of analysing complete ground reaction force waveforms rather than discrete kinetic variables can provide new insight to sprint biomechanics. This study aimed to understand how these waveforms are associated with better performance across entire sprint accelerations. Twenty-eight male track and field athletes (100-m personal best times: 10.88 to 11.96 s) volunteered to participate. Ground reaction forces produced across 24 steps were captured during repeated (two to five) maximal-effort sprints utilising a 54-force-plate system. Force data (anteroposterior, vertical, resultant and ratio of forces) across each contact were registered to 100% of stance and averaged for each athlete. Statistical parametric mapping (linear regression) revealed specific phases of stance where force was associated with average horizontal external power produced during that contact. Initially, anteroposterior force production during mid-late propulsion (e.g. 58-92% of stance for the second ground contact) was positively associated with average horizontal external power. As athletes progressed through acceleration, this positive association with performance shifted towards the earlier phases of contact (e.g. 55-80% of stance for the eighth and 17-57% for the 19th ground contact). Consequently, as athletes approached maximum velocity, better athletes were more capable of attenuating the braking forces, especially in the latter parts of the eccentric phase. These unique findings demonstrate a shift in the performance determinants of acceleration from higher concentric propulsion to lower eccentric braking forces as velocity increases. This highlights the broad kinetic requirements of sprinting and the conceivable need for athletes to target improvements in different phases separately with demand-specific exercises.

Key words: 1D analysis, regression, running velocity, SPM, track and field

Introduction

Sprint running is one of the purest athletic endeavours with the outcome entirely determined by the ability to cover a set distance in the least possible time. Strong correlations exist between 100-m sprint performance and maximal running velocity,[1-3] however, the preceding acceleration phase, which allows an athlete to attain these high velocities, is also crucial for sprinting success.[4] Consequently, many studies have analysed force production during the acceleration phase in order to better understand the kinetic determinants of sprint acceleration performance. Thus far, this has included the measurement of ground reaction forces on the track at specific distances or steps,[5,6] across reconstructed accelerations from multiple trials with varying starting block locations,[7] and across entire single sprints using force plate systems covering over 50 m,[8] as well as on an instrumented treadmill.[9]

In the acceleration phase, the generation of high propulsive anteroposterior forces, but not necessarily high vertical ground reaction forces, seems crucial to overground sprint performance.[7,8] During treadmill running, the ability of athletes to maintain a more horizontally-orientated (forward) resultant ground reaction force vector as running velocity increases appears to be a key sprint performance determinant.[9] In fact, Morin et al.[9] suggested that force application technique (directing the force vector more horizontally by producing a higher horizontal to resultant force ratio) is more important to treadmill running performance than the absolute amount of force produced. The importance of this high ratio of forces to accelerative performance has subsequently been shown during overground sprinting[7]

As the sprint progresses and higher running velocities are reached, vertical force production may become increasingly important to sprint performance as maximum speed has been associated with the average vertical force per unit body weight applied at top speed during

treadmill[9,10] and overground sprinting.[8] It has been suggested that faster runners are able to reach these higher maximum velocities through the ability to produce the effective vertical impulses (across increasingly shorter ground contact periods) required to achieve the necessary aerial times to reposition the limbs for the subsequent contact.[10]

Horizontal (forward) velocity of a sprinter's centre of mass is determined by the net anteroposterior impulses generated and air resistance, although the latter is often considered negligible in sports biomechanics research, especially across a single step. The stance phase of sprinting can be divided into an initial braking phase followed by a propulsive phase, corresponding to periods of decreasing and increasing horizontal velocity, respectively. As the overall sprint acceleration progresses, braking impulses increase and propulsive impulses decrease resulting in decreases in net anteroposterior impulse and thus, lower step-to-step acceleration.[8] When averaged over a "virtual" (i.e. reconstructed) 20-m or 40-m sprint, propulsive impulses but not braking impulses were related to mean 40-m velocity.[11] This finding has recently been confirmed by Nagahara et al.[8] across single sprints, with propulsive impulses found to be the primary contributor to acceleration between 55-95% of maximal velocity. Moreover, at the 16-m mark, propulsive impulses explained a large portion (57%) of variance in sprint velocity with only a weak tendency (7% variance) for braking impulses to differentiate performance levels.[5] When analyses were conducted across different phases of entire single sprint accelerations, however, reducing braking phase impulses in the latter parts of acceleration (75-95% maximum velocity) seemed to become an important determinant of performance.[8] This suggests that as the acceleration phase progresses, there are shifts in the kinetic determinants of sprint performance.

These studies have greatly contributed to our understanding of sprint running performance, however, they all involve the reduction of force waveforms (1-dimensional; 1D) to discrete (0-dimensional; 0D) variables. Although, for example, impulses determine change in velocity and are therefore fundamental to sprint performance, such 0D measures are unable to provide detailed information about how aspects of the entire force-time curves are associated with higher sprint performance. Waveform analysis such as statistical parametric mapping (SPM)[12] allows such insight to be gained. In the current study, rare kinetic data for the entire acceleration phase of maximum-effort sprinting were captured and analysed in a novel way using SPM. Therefore, the aim of this study was to understand the association of the entire ground reaction force waveforms for each step with performance across that ground contact period. Such analyses were used to identify the specific phases of stance where force production had the greatest influence on performance and to characterise how these vary across the acceleration phase.

Methods

Experimental procedures

Twenty-eight male track and field athletes (mean ± SD age, mass and height were 20 ± 1 yr, 66.5 ± 3.6 kg and 1.73 ± 0.04 m, respectively) volunteered to participate in this study. All participants were sprint, jump or decathlon specialists with 100-m personal best times ranging from 10.88 to 11.96 s. A research ethics committee provided ethical approval for this research to be conducted and all athletes provided written consent prior to participating. Athletes performed between two and five maximal-effort 60-m sprints from their normal crouched block start position on an indoor running track. All participants wore their own spikes and a rest period of at least 15 minutes was provided between efforts. Fifty-four force platforms (1000 Hz; TF-90100, TF-3055, TF-32120; Tec Gihan, Uji, Japan) connected to a single computer

measured ground reaction forces during sprinting through 52 m from 1.5 m behind the starting line to the 50.5-m mark.

Data processing

Force data were firstly filtered using a fourth-order low-pass Butterworth filter with a 70-Hz cut-off frequency derived through residual analysis. Resultant force was computed using the anteroposterior and vertical forces, and ratio of forces was calculated as the ratio of anteroposterior to resultant force.[9] The thresholds to detect touchdown and take-off were set at 20 N of vertical force. Horizontal velocity was calculated using the impulse-momentum relationship. In order to account for the influence of air resistance on calculated horizontal velocity, which would accumulate considerable errors across the sprint, aerodynamic drag of each athlete was estimated using the approach of Samozino, Rabita, Dorel, et al.[13]. Such methods incorporate the athlete's height and mass, along with each athlete's aerodynamic friction coefficient, which was estimated from temperature and barometric pressure using methods proposed by Arsac and Locatelli.[14] As detailed environmental data were not available in the current study, temperature and barometric pressure were assumed to be 20 °C (30 °C when athletes were tested in the summer months, n = 2) and 760 mmHg, respectively. Sensitivity analyses revealed that realistic variation (±4° and ±20 mmHg) in these two variables made very small differences to the velocities calculated (average step velocity differences calculated across all steps were < 0.01 m/s). Horizontal velocities at touchdown and take-off (calculated using anteroposterior ground reaction force impulses and estimated aerodynamic drag) were combined with contact duration to provide average horizontal external power, which was used as a key performance criteria for each ground contact period based on Bezodis, Salo and Trewartha.[15] This power was expressed relative to body mass.

To verify the accuracy of these aerodynamic drag estimations, average step horizontal velocity from take-off of one step to take-off of the following step was computed from the force data and compared against the horizontal step velocity calculated using respective spatiotemporal data. The position of the stance foot during ground contact was defined as the position of the centre of pressure mid-stance, and step length was calculated as the difference between the foot positions of two consecutive ground contact periods in the running direction. Step frequency was computed as the inverse of duration of step time. Subsequently, average step velocity was calculated as the product of step length and frequency. Comparisons between the step-averaged horizontal velocities calculated using the force data and spatiotemporal data revealed close agreement between methods (root mean square difference < 0.23 m/s; Figure 1). Maximum horizontal velocity (mean ± SD) was 9.43 ± 0.31 and 9.42 ± 0.31 m/s, when calculated using the ground reaction force data (adjusted for aerodynamic drag) and spatiotemporal data, respectively, with a root mean square difference of <0.14 m/s.

Figure 1 near here

Statistical analysis

The entire force waveforms were analysed using SPM 1D, which maintains the dimensionality of the raw data. Open-source SPM 1D software[16] was used to assess the relationship between the force waveforms (1D data) and the average horizontal external power (0D data) produced for all 28 athletes across each ground contact. The lowest number of steps taken by any athlete was 24, and thus this analysis was only performed across the first 24 ground contact periods. Firstly, force data (anteroposterior, vertical, resultant and ratio of forces) for each ground contact were registered to 101 nodes (0-100% of stance). Data were then averaged across all trials conducted for each individual athlete. Using random field theory, which describes

probabilistic behaviour of random curves and accounts for the smoothness of the data, a critical threshold ($\alpha = 0.05$) was set (above which only 5% of random curves with the same smoothness would exceed) for each ground contact and each force variable. Subsequently, SPM 1D linear regression models were applied to each of the 101 nodes resulting in a SPM{t} curve. If the SPM{t} curve exceeded the critical threshold, the force at these specific nodes was deemed to be significantly related to average horizontal external power. Finally, the probability that the observed supra-threshold regions of the SPM{t} curve with the same geometry could have resulted from repeated samplings of equally smooth random curves was computed.

Results

Horizontal step-averaged velocities appeared to plateau within 24 steps (Figure 1). Anteroposterior force was significantly and positively related to average horizontal external power for 22 out of the 24 steps (Figure 2). In the early steps of the acceleration, these relationships were found primarily during propulsion in the second half of the stance phase (for example, between 58 and 92% of stance for the second ground contact; Figure 3a). However, as the acceleration progressed, the relationships were found earlier in the ground contact (Figure 3b) and were generally found to occur during the braking phase in the latter parts of the sprint, when athletes were running at higher velocities (for example, during ground contact 19, between 19-25%, 28-35%, 38-64% of stance; Figure 3c).

Figure 2 near here

Figure 3 near here

Table 1 provides the range of stance where greater anteroposterior forces where associated with higher horizontal external power (first and last supra-threshold cluster). These are provided in

both relative (% of stance) and absolute (in seconds from touchdown) terms. The latter, alongside mean contact times, provide more complete temporal context for each ground contact. Relationships between ratio of forces and average horizontal external power seemed to follow a similar pattern to anteroposterior forces, however, the supra-threshold clusters were less pronounced and occurred across fewer steps (Figure 4). Vertical forces were related to average horizontal external power only during the fourth ground contact, and resultant forces were related to performance across the first, second, fourth, sixth and 12th ground contact (see figures in supporting information).

Table 1 near here

Figure 4 near here

Discussion

For the first time ground reaction force waveforms across entire accelerations have been analysed using SPM to understand the specific phases of stance where force production is associated with sprint performance. Anteroposterior force production was positively associated with the average horizontal external power produced across 22 of the 24 ground contacts analysed in this study. Better performances were positively associated with higher anteroposterior force production in mid-late propulsion during the early parts of the sprint. These associations seemed to shift earlier in the ground contact period as the athletes progressed through the acceleration phase and primarily occurred during the braking phase when athletes were sprinting at relatively high velocities. As contact time shortens as the sprint progresses, these associations also occurred substantially earlier in absolute terms in the latter parts compared with the earlier parts of the sprints.

During the initial parts of acceleration, anteroposterior force production was positively associated with performance predominantly during the second half of stance (e.g. between 58-92% for the second step; Figures 2 and 3). Thus, performances during these early ground contacts seem to be differentiated by the amount of anteroposterior force produced during mid-late propulsion (i.e. when the athlete's centre of mass is typically ahead of the contact foot). More specifically for the first three steps, anteroposterior force production differentiated performance levels from between 0.061 and 0.136 s after touchdown (Table 1). Jacobs and van Ingen Schenau[17] have previously proposed that an effective strategy across the second step of the sprint is to prioritise the rotation of the centre of mass over the foot before powerful extension of the stance leg in the second half of ground contact. This is suggested to limit the vertical motion of the centre of mass that does not directly contribute to horizontal translation. Thus, this is a potential mechanism that could explain the finding that anteroposterior force production in the latter phases of stance differentiates performance levels of sprinters across the initial steps.

As the sprints progressed, there was a clear shift in the relationships between anteroposterior force and performance towards the earlier periods of ground contact. For example, during the eighth ground contact, anteroposterior forces were found to be significantly and positively associated with performance from 55-80% of stance, which on average equated to 0.058-0.084 s following touchdown. Although some of the stances had significant values earlier than on the eighth steps, overall these positive relationship clusters tended to appear in the propulsion phase (concentric muscle action) in the first 11 steps. Moreover, the relationships between ratio of forces and performance seemed to follow a similar pattern (Figure 4). Importantly, as acceleration continued the most performance-differentiating phases of stance were those where anteroposterior force production was lower than the peak force generated across that stance

period. Thus, if a 0D approach had been adopted whereby the peak forces generated by sprinters were analysed, these associations may have been missed, as Colyer and Salo[18] recently demonstrated in relation to the sprint start.

When athletes were approaching maximum velocity, positive relationships were observed between the anteroposterior force (and ratio of forces) and performance even closer to touchdown, predominantly during the braking phase (e.g. anteroposterior force between 19-64% of stance, or 0.017-0.057 s after touchdown, for the 19th step). Thus, the ability to limit braking forces during these latter parts of acceleration was associated with higher performance, in line with previous suggestions.[5,19] This apparent shift in the relative importance of increasing propulsion or reducing braking impulses as the sprint progresses supports recent findings within single sprints.[8]

A smaller touchdown distance and lower horizontal velocity of the foot (relative to the ground) are considered to be mechanisms to reduce braking impulse,[20,21] by creating a more "active touchdown".[5] In a previous study by Morin et al., [22] an athlete's ability to activate their hamstring muscles during late swing phase along with the capacity to produce high eccentric hamstring torques was associated with higher average anteroposterior forces during the stance phase. Moreover, energy absorption at the knee during late swing (presumably involving work done by hamstrings) was previously suggested to be responsible for continuing acceleration at near maximal velocities,[23] which could be linked to a decrease in forward horizontal foot velocity prior to touchdown and a more active touchdown. Collectively, this implicates forceful contraction of the hamstrings during the late swing phase as a sprint performance-defining factor.

In the current study, however, the associations between braking forces and performance were found to occur in the second part of the braking phase (Figure 2). Thus, the initial braking peak was not a performance-differentiating factor for these athletes. Some level of eccentric muscle stretch and elastic energy storage is a likely requisite for powerful propulsion through utilisation of a stretch shortening cycle.[24] However, this initial braking force is partly pre-determined by an athlete's momentum during the flight phase and thus athletes may not have complete active control over this phase. Indeed, Bezodis, Kerwin and Salo[25] previously found lower-limb joint moments during maximum velocity sprinting to be relatively small in the first 10% of stance and not to peak until at least 20% of stance (most notably at the hip and ankle). Thus, sprinters may not have as much opportunity to produce high joint moments very early in the stance phase (when the braking force peaks), and performance may be influenced to a greater extent by joint kinetics during second part of the braking phase.

The exact mechanism behind the commonly-accepted importance of active leg motion during late swing and minimisation of touchdown distance to reduce braking impulse is yet to be fully elucidated. Considering the findings of the current study, it is plausible that this association could be attributed to the lower limbs being configured in a more advantageous position to generate higher joint moments and attenuate eccentric force in the latter part of the braking phase, rather than immediately following touchdown. Further research combining swing phase kinematics with the ground reaction forces produced during the subsequent stance phase is required to better understand the mechanisms underlying these associations and the potential interventions to improve force production across these phases.

The observed shift in the phases of stance where anteroposterior force production was associated with average horizontal external power demonstrates the varying kinetic demands

of sprinting and reinforces its multifactorial nature. This supports previous work which has shown varying acceleration strategies across different phases of sprint running.[26,27] It is clear that athletes must be powerful across a wide spectrum of loading and contractile conditions. For example, they must be able to develop high concentric forces across longer contact periods at low velocities (e.g. during the block phase and early steps), but still be able to generate propulsive force across very short time frames when sprinting close to their limit. Moreover, this study suggests that in the latter parts of acceleration, sprinters must be able to tolerate eccentric force rapidly to attenuate the anteroposterior braking impulses and generate as high average horizontal external power as possible. This warrants careful consideration when planning training programmes to enhance performance as training responses are known to be related to the conditions (e.g. velocity and load) under which the training was conducted.[28] In fact, due to the conflicting demands across a sprint acceleration, improvements during one phase may be accompanied by reductions in performance across another. The influence of different training regimes on the different phases of sprint performance is, however, an under-studied area of biomechanics, which could potentially be addressed using forward dynamics (computer simulation) studies that permit the performance implications of different training adaptations (for example, changes to an athlete's muscle contractile characteristics) to be studied in a controlled, yet non-invasive manner.

Force production in the anteroposterior direction determined performance to a much greater extent than the vertical direction in this study with positive associations between vertical force and average horizontal external power produced across the fourth step only. Moreover, resultant forces were only found to be positively associated with performance across four steps (see supporting information for both vertical and resultant force associations). This provides some support to the literature which has shown the ability to generate high anteroposterior

forces (rather than resultant forces) and orientate the force vector horizontally (forward) to be associated with sprint acceleration performance during overground[7,8] and treadmill[9,29] sprinting. However, a surprising finding of the current study was the lack of association between vertical force waveforms and power produced across the final steps (at or close to maximum velocity), as associations between vertical force and maximum velocity have previously been observed.[7-10] It is unclear why this discrepancy exists, but it could be due in part to the differences in performance measures across studies (horizontal power across a single step compared with maximum running velocity) or due to the previous studies using 0D variables. Alternatively, this discrepancy could also be a result of the reduction in temporal resolution when vertical data are registered, which is a requirement and sometimes a limitation of statistical parametric mapping. For example, if faster sprinters in this study were those who generated sufficient vertical impulse across shorter ground contacts (as shown previously by Weyand et al.[10] during treadmill sprinting), this may have been somewhat masked by the temporal registration. However, to check for this possibility, the coefficients of variation of the contact times were calculated for each step in the current study and typically ranged from 5-8%. The variations for the first three steps were slightly greater (~10%). This variability was not considered to be overly problematic in the current study as the force waveforms did not appear to become markedly distorted following temporal normalisation, but this issue is certainly worthy of consideration when interpreting the outcomes of such analyses. Additionally, we acknowledge that by making these associations within a step, a biasing problem could be introduced whereby a particular step for one athlete will likely occur at a different time and distance to that of another athlete. This was a necessary compromise in order to conduct worthwhile analyses on the waveforms, as standardising the data to other variables (e.g. time or distance) would not provide any meaningful information. Nonetheless, we are,

and encourage readers to be, mindful of the aforementioned potential bias when drawing conclusions.

Perspectives

This study has shown uniquely how force production waveforms collected during entire sprint accelerations are associated with performance, and how the performance-differentiating aspects of stance change as the sprint progresses. In line with the literature,[7,9,29] anteroposterior force production explained more of the variance in sprint performance than the vertical direction. During the initial ground contacts, anteroposterior force production during mid-late propulsion was associated with higher average horizontal external power. Conversely, later in acceleration, anteroposterior ground reaction forces in the early eccentric phase of stance appeared to influence performance, as athletes who attenuated the braking forces to a greater extent also generated higher horizontal external power. These findings highlight the varying force production requirements across a sprint, and sprint coaches should consider prescribing training aligned with these demands. For example, to improve performance during the initial steps, training should perhaps include predominantly concentric exercises of the lower-limb extensor muscle groups. Conversely, in late acceleration, training to increase stiffness and an athlete's ability to quickly reverse braking forces could be more important. In fact, leg stiffness (during hopping) has been strongly related to sprint performance during the maximum velocity phase, but not the acceleration phase,[30] which supports the importance of this characteristic for high velocity sprinting.

Acknowledgement

This research was part funded by CAMERA, the RCUK Centre for the Analysis of Motion, Entertainment Research and Applications, EP/M023281/1.

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Figure Captions

Figure 1. Step average velocity profiles (mean ± SD) for 28 athletes computed from ground reaction force data (adjusted for aerodynamic drag; grey) and from spatiotemporal data (black). Dashed lines denote standard deviations.

Figure 2. Normalised mean anteroposterior force curves for 28 athletes across 24 consecutive sprint ground contacts, and the relationships with average horizontal external power produced across each contact period. Red areas indicate phases of stance across which positive relationships were observed for more than 5 nodes, as clusters of fewer nodes were considered unlikely to be meaningful.

Figure 3. Mean ± SD anteroposterior force waveforms (top panels) and SPM 1D linear regression outputs (bottom panels) for the second (A), 8th (B) and 19th (C) ground contacts. The SPM{t} curves, which are shown over the stance phase, describe the direction and strength of the linear relationships. Where the SPM{t} curve exceeds the critical threshold (dotted line), this area is shaded and a statistically significant relationship is present at those nodes with p values provided for each supra-threshold cluster.

Figure 4. Normalised mean ratio of force (horizontal to resultant) curves for 28 athletes across 24 consecutive sprint ground contacts, and the relationships with average horizontal external power produced across each contact period. Red areas indicate phases of stance across which positive relationships were observed for more than 5 nodes, as clusters of fewer nodes were considered unlikely to be meaningful.

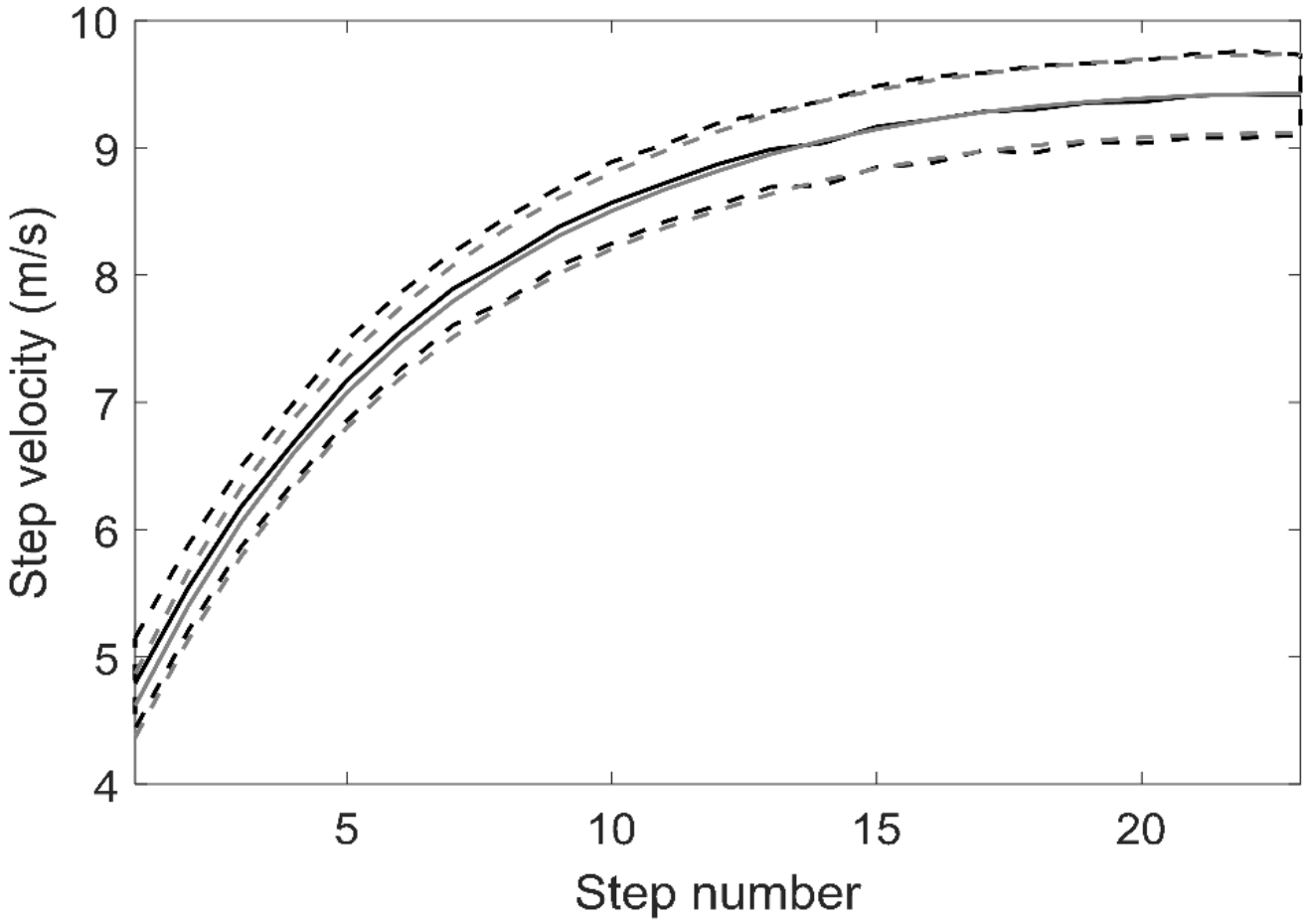
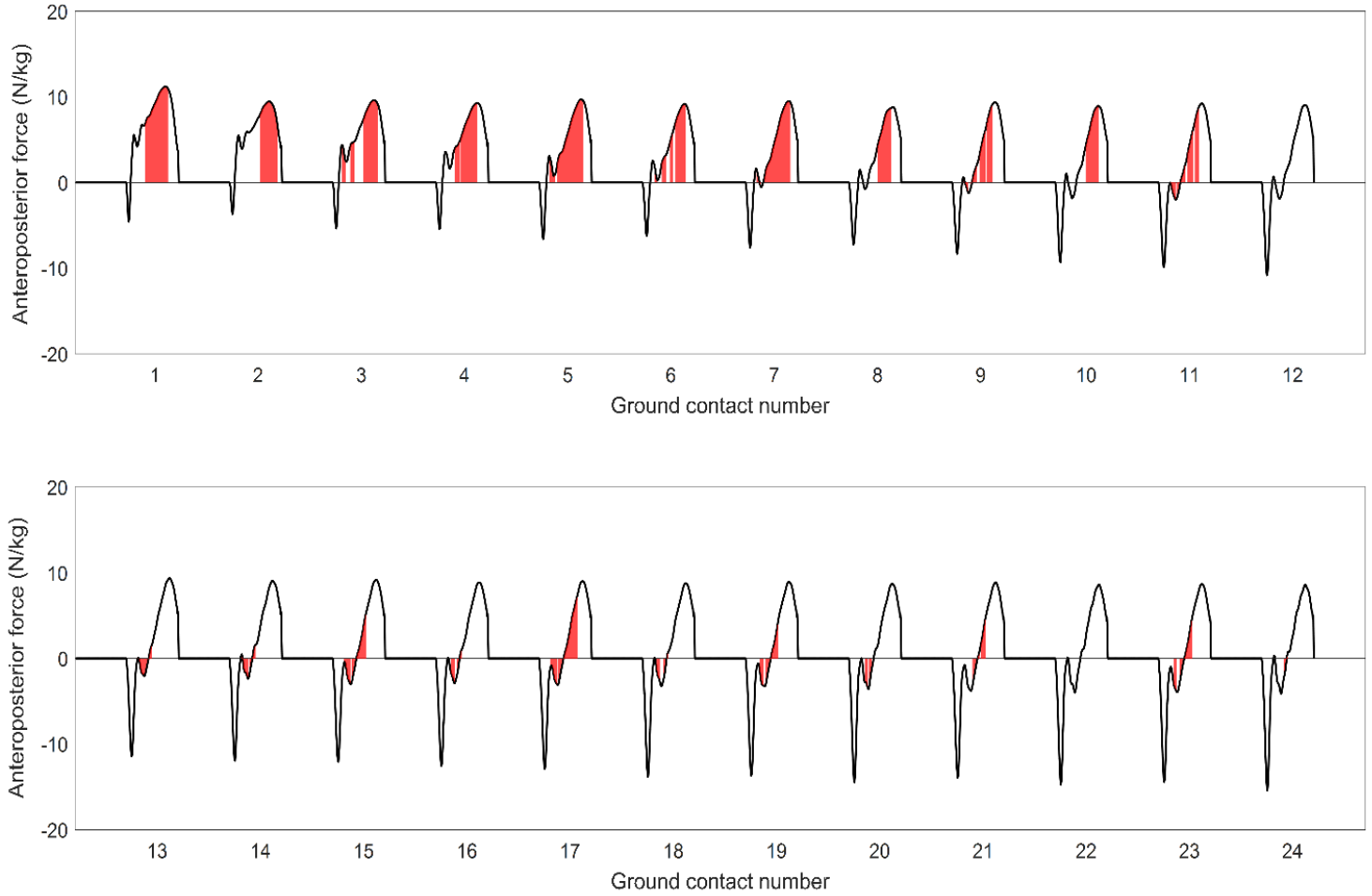


Figure 1.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Ground contact number
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Anteroposterior force (N/kg)
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Ground contact number

Figure 2

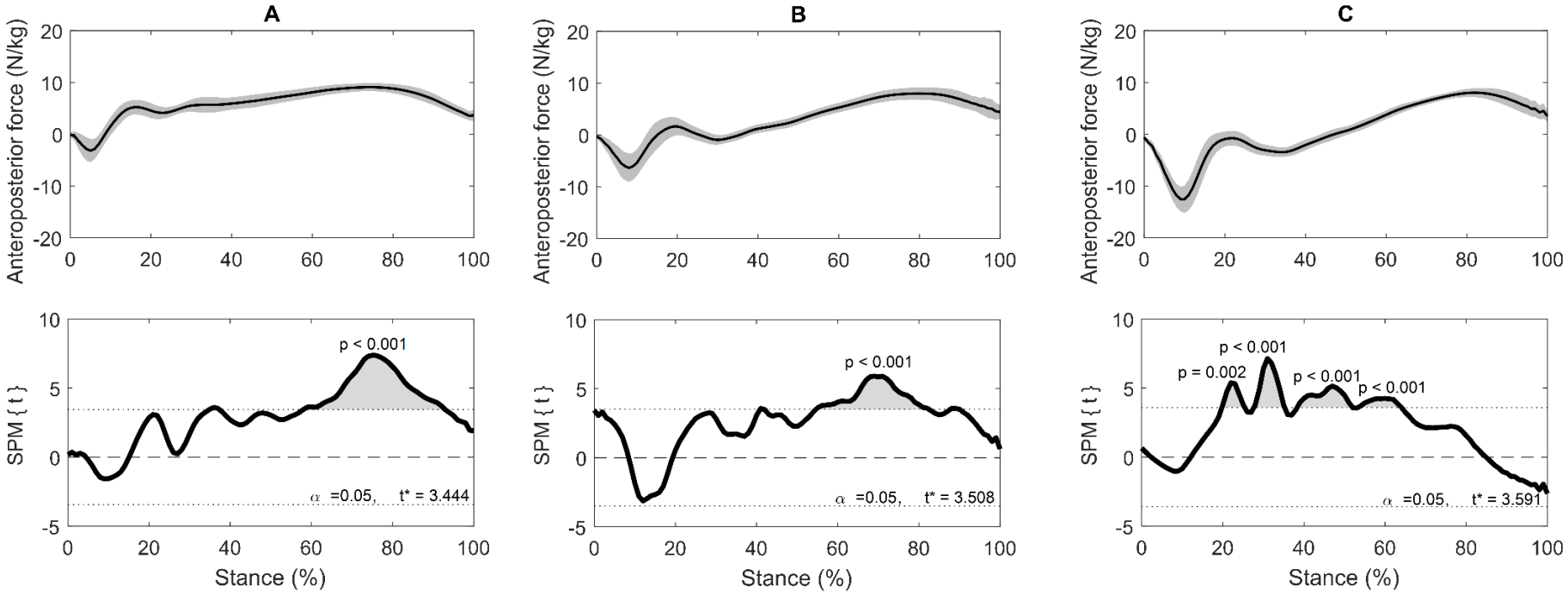

A
B
C
Anteroposterior force (N/kg)
SPM { t }
p < 0.001
p = 0.002
α =0.05, t* = 3.444
α =0.05, t* = 3.508
α =0.05, t* = 3.591
Stance (%)

Figure 3

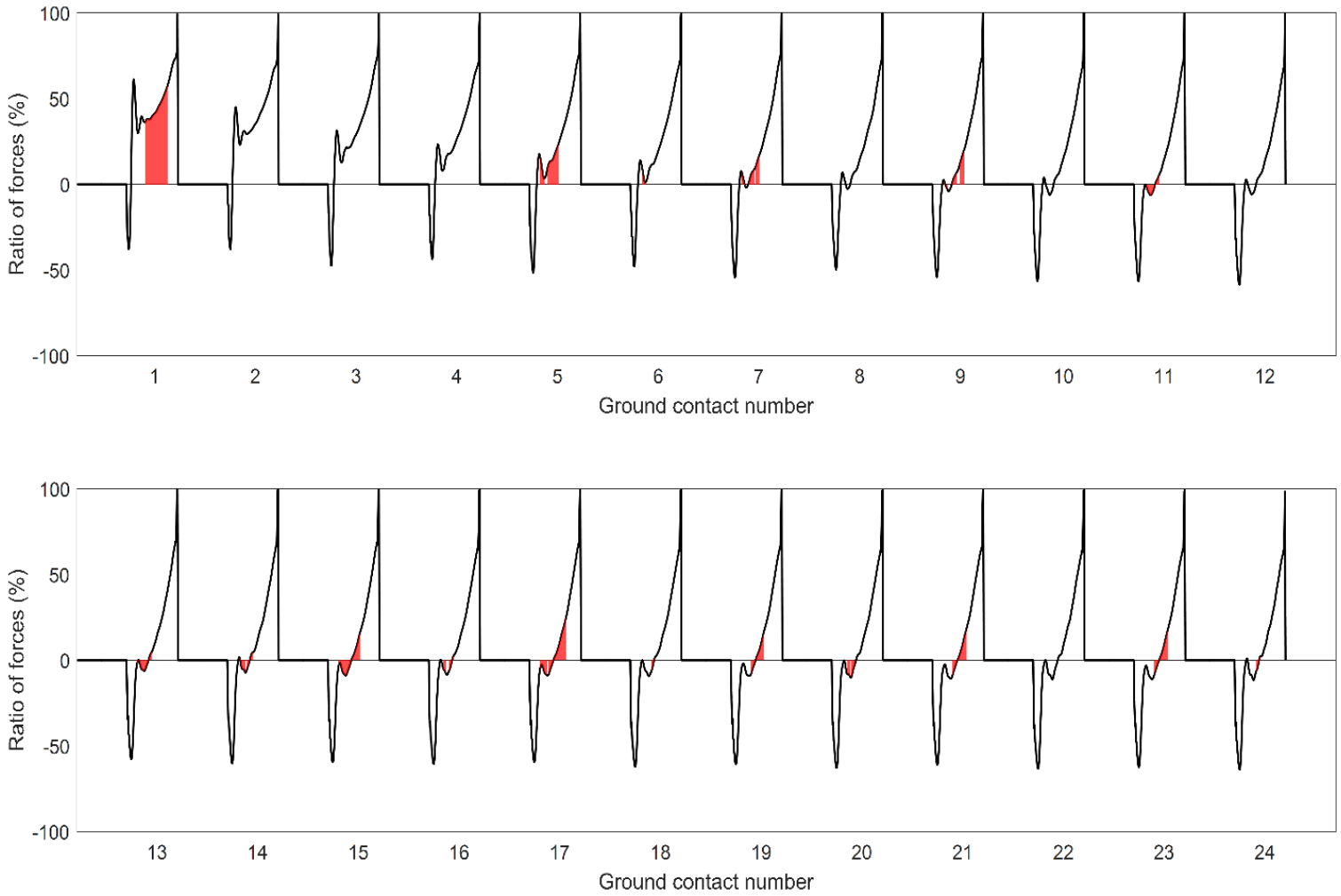
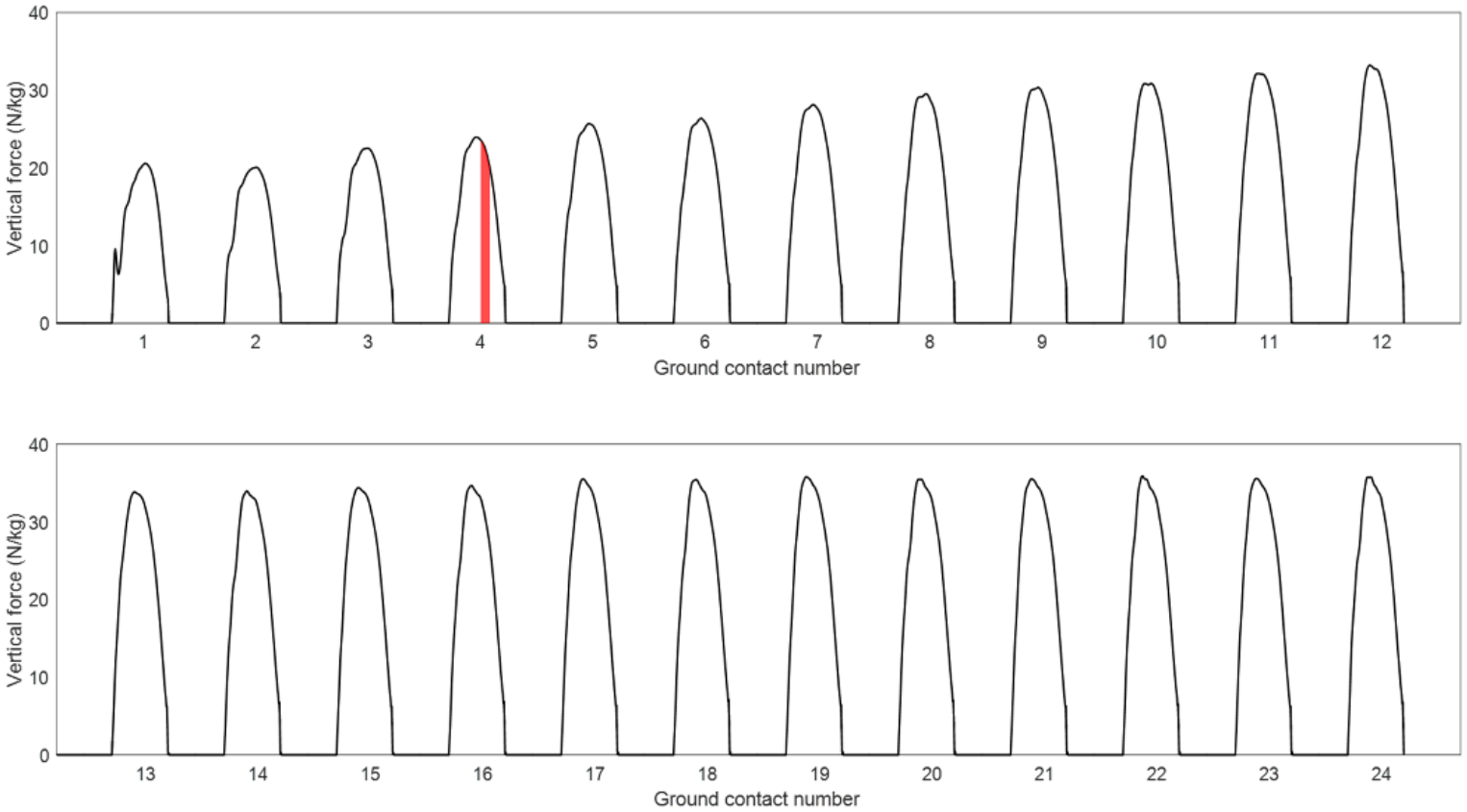
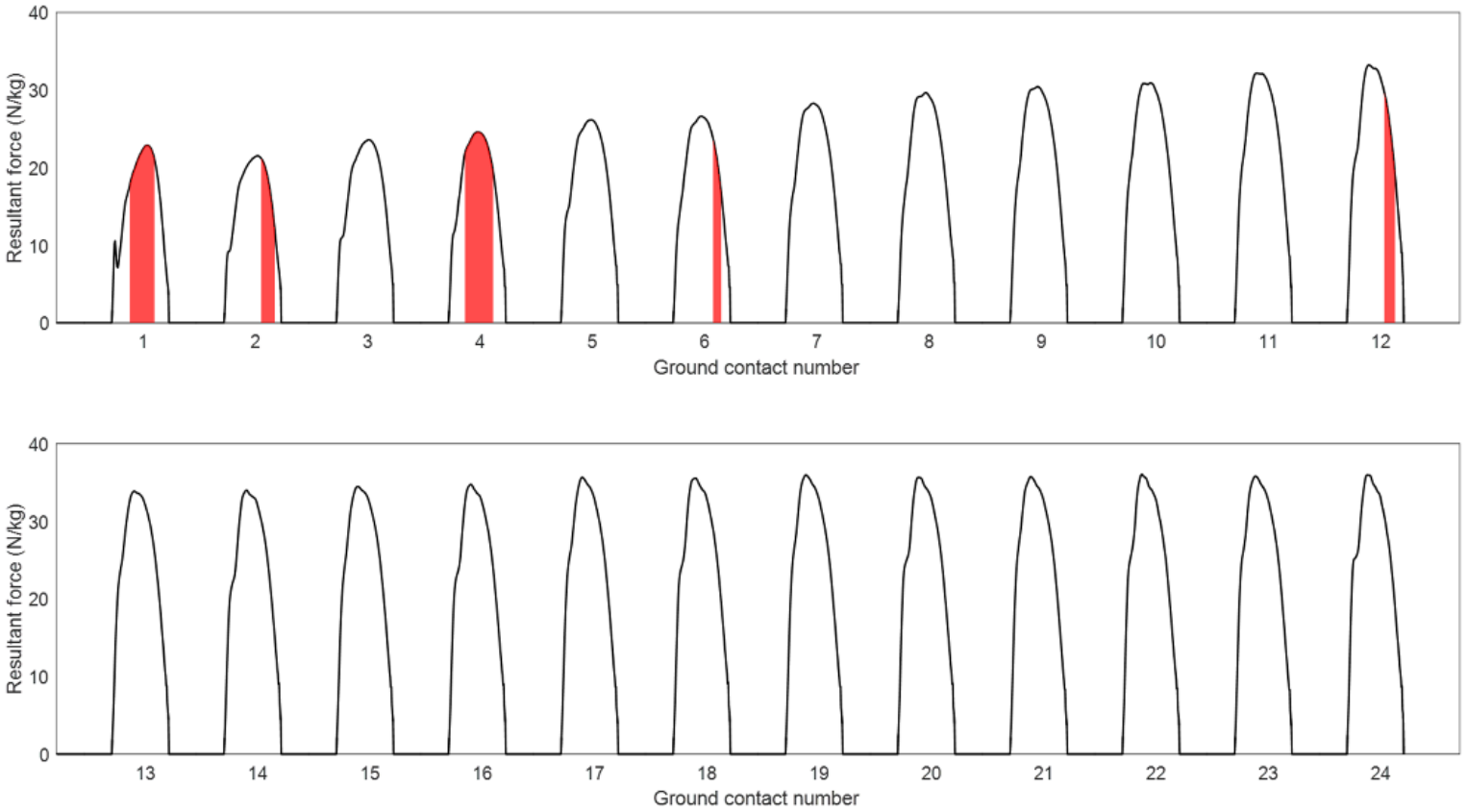

100
50
0
-50
-100
Ratio of forces (%)
1
2
3
4
5
6
7
8
9
10
11
12
Ground contact number
100
50
0
-50
-100
Ratio of forces (%)
13
14
15
16
17
18
19
20
21
22
23
24
Ground contact number

Figure 4



Supporting information figure A. Normalised mean vertical force curves for 28 athletes across 24 consecutive sprint ground contacts, and the relationships with average horizontal external power produced across each contact period. Red area indicates phases of stance across which positive relationships were observed for more than 5 nodes, as clusters of fewer nodes were considered unlikely to be meaningful.



Supporting information figure B. Normalised mean resultant force curves for 28 athletes across 24 consecutive sprint ground contacts, and the relationships with average horizontal external power produced across each contact period. Red areas indicate phases of stance across which positive relationships were observed for more than 5 nodes, as clusters of fewer nodes were considered unlikely to be meaningful.

Table 1. Ranges of stance across which positive associations (supra-threshold clusters) were observed between relative anteroposterior forces and average horizontal external power and the corresponding times for touchdown

Ground contact	First critical threshold crossing (% of stance)	Last critical threshold crossing (% of stance)	First critical threshold crossing (s from TD)	Last critical threshold crossing (s from TD)	Contact time (s; mean ± SD)
1	36	80	0.061	0.136	0.170 ± 0.018
2	58	92	0.086	0.136	0.148 ± 0.016
3	17	87	0.023	0.120	0.138 ± 0.014
4	35	80	0.044	0.101	0.125 ± 0.010
5	19	84	0.023	0.101	0.119 ± 0.009
6	22	83	0.025	0.096	0.115 ± 0.008
7	20	86	0.022	0.096	0.110 ± 0.008
8	55	80	0.058	0.084	0.105 ± 0.006
9	21	77	0.021	0.079	0.102 ± 0.007
10	58	83	0.058	0.082	0.099 ± 0.006
11	21	78	0.020	0.076	0.097 ± 0.007
12	-	-	-	-	0.094 ± 0.006
13	21	50	0.020	0.047	0.093 ± 0.007
14	24	51	0.022	0.047	0.091 ± 0.005
15	21	65	0.019	0.059	0.091 ± 0.005
16	28	51	0.025	0.046	0.089 ± 0.005
17	21	74	0.019	0.066	0.089 ± 0.005
18	28	50	0.025	0.044	0.087 ± 0.005
19	19	64	0.017	0.057	0.088 ± 0.006
20	31	34	0.027	0.030	0.087 ± 0.006
21	40	65	0.035	0.057	0.088 ± 0.006
22	-	-	-	-	0.087 ± 0.006
23	29	66	0.026	0.058	0.087 ± 0.006
24	43	51	0.038	0.045	0.086 ± 0.006

TD = touchdown. Dashes indicate no associations observed across that ground contact. Note that some steps had more than one supra-threshold cluster. For simplicity, only the first and last threshold crossing values have been presented. 75% of individual supra-threshold clusters were statistically significant to $p < 0.001$, and all clusters were significant to $p < 0.01$.