

Mechanical determinants of superior horizontal deceleration performance in multidirectional sportspersons

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Abstract

This study aimed to (a) examine the mechanical determinants of superior horizontal deceleration, and (b) compare ground reaction force (GRF) characteristics of the first and second braking foot contacts during horizontal deceleration between higher and lower deceleration performers. Forty-two trained males from multidirectional team sports performed three maximal deceleration trials following a 15 m sprint, with GRF data over the first two braking steps collected using force plates. Horizontal velocity was collected using a radar gun and $p < 0.05$ was considered statistically significant. Greater mean and peak deceleration were statistically significantly correlated with greater mean horizontal GRF ratio at both braking foot contacts ($\rho = 0.31-0.49$, $p < 0.05$). Comparing lower mean and peak deceleration performers, greater performers displayed statistically significantly greater mean horizontal GRF ratios at both braking steps ($ES = 3.53-5.00$, $p < 0.05$), and lower approach momentum ($ES = 0.62-0.66$). Compared to lower approach momentum performers, greater performers displayed statistically significantly greater mean and peak deceleration scores ($ES = 0.62-0.70$, $p < 0.05$). Practitioners should aim to maximize horizontal GRF production and orientate force more horizontally for more effective deceleration. However, faster approach velocities, especially when accompanied with greater body mass (and thus momentum), will likely see a reduction in deceleration performance on account of higher braking demands. This is likely an unavoidable paradox and thus deceleration performance must always be presented considering approach velocity and momentum.

Keywords: kinetics; braking; momentum; velocity

Introduction

The capacity to quickly decelerate in a high-speed sprint is one of the most crucial physical qualities for successful performance in multi-directional team sports (e.g., football and rugby), allowing athletes to suddenly evade opponents and create favorable conditions (37). In elite male football matches, the total number of decelerations is similar to that of performing accelerations (37), whereas more high-intensity decelerations ($\leq -3 \text{ m/s}^2$) were performed than high-intensity accelerations ($\geq 3 \text{ m/s}^2$) (5). Furthermore, deceleration performance has been identified as a crucial component of change of direction (COD) maneuvers (11), with the rate of reduction of approach momentum (indicating deceleration performance) directly influencing the re-acceleration and directional change performance. In addition to their importance for performance, deceleration actions are also non-contact anterior cruciate ligament and hamstring strain injury inciting events (1,24), as well as causing muscle damage on account of high eccentric forces (15). These injuries may be attributed to high horizontal and resultant braking ground reaction forces (GRF) (10) and loading rates. Notably, greater mechanical and metabolic stresses are observed following regular horizontal decelerations (36), which contributed to 5-7% of the total player load for all player positions during an elite soccer match (4). Thus, the risk of ACL injury would likely increase due to neuromuscular fatigue induced by repetitive deceleration tasks. Therefore, given the dual significance of horizontal deceleration maneuvers in team sports for performance and potential injury, understanding the mechanical determinants of superior horizontal deceleration is imperative.

While the mechanical determinants and characteristics of the last three-foot contacts during COD tasks are well understood, limited studies have investigated the biomechanical determinants of maximal horizontal deceleration. Previous studies showed that greater horizontal braking GRF contributed to reducing COM velocity and approach momentum, thus faster COD completion time (9,10). Additionally, compared to slower COD performers, significantly greater horizontal braking GRF was observed in faster COD performers (7). Therefore, although the mechanical determinants of COD performance are angle-dependent (8), greater horizontal force has been considered a major contributor of superior 180° COD performance (9,10). Notably, there are obvious differences between maximal horizontal deceleration and COD tasks. For example, there is no propulsive phase during a maximal horizontal deceleration maneuver, thus findings from COD braking steps may just provide superficial insights into maximal horizontal deceleration performance. To the best of the authors' knowledge, there are only three studies that examined the biomechanical determinants of horizontal deceleration tasks (2,3,22), reporting that increased horizontal deceleration demands required increased posterior positioning of the center of mass (COM). For example, as the percentage of maximum effort increased during horizontal decelerations, the distance from the foot to the COM also increased (effort: 50% vs 75% vs 100%, distance: 0.39 m vs 0.40 m vs 0.44 m, respectively) (22). A

more posterior positioning of the COM and thus a greater distance from the foot to the COM is central for horizontal braking force production and orientating the force posteriorly for more effective deceleration. Notably, the magnitude of horizontal braking GRF is not only determined by the magnitude of peak resultant braking GRF, but also by the angle of the horizontal force vector relative to vertical force (known as horizontal GRF ratio). As of yet, the GRF determinants of maximum horizontal deceleration are still unknown, thus insights into this will likely facilitate improvements in horizontal deceleration performance.

Maximal horizontal deceleration is characterized as a multi-step task; it requires several braking steps to stop. The changes in horizontal velocity are dependent on net braking impulse across all braking steps. Based on the impulse-momentum relationship, greater impulse could be obtained by longer ground contact times (GCT) and/or greater braking GRF. However, previous studies have reported that a shorter GCT was significantly correlated with faster modified 505 completion time ($R^2 = 49.1\text{--}57.3\%$) (11), faster 90° cutting completion time (10), and other CODs performance (32,33), suggesting the crucial role of minimal GCT on COD performance. Naturally, during deceleration, GCT and braking GRF are regulated by approach velocity, whereby as approach velocity increases, GRF increase and GCT reduces given the high loading demands, which, within the first three steps, are generally beyond the capacity of the athlete. This is supported by Dos'Santos et al. (9), reporting that greater braking GRF and lower GCT were observed in the antepenultimate foot contact, compared to the penultimate foot contact during 505 CODs. Consequently, the correlation between GCT and deceleration performance should be examined. Furthermore, the capacity to tolerate a greater braking impulse in the initial step, would theoretically result in less steps needed to complete the deceleration (velocity = zero), thus the athlete would decelerate over a shorter distance in a quicker time. Accordingly, a comparison of kinematic and kinetic characteristics of the first and second braking foot contact could help improve the understanding of greater deceleration performance.

To the best of our knowledge, no study has examined the GRF determinants of a linear horizontal deceleration task. Accordingly, the aim of this study was two-fold: (a) to determine the mechanical determinants of maximal horizontal deceleration performance, and (b) to compare the differences in mechanical and kinematic variables between greater and lower performers (mean deceleration, peak deceleration, peak approach velocity, and peak momentum). It was hypothesized that greater deceleration performance will be associated with greater horizontal braking GRF. Furthermore, we hypothesized that deceleration performance will be largely dependent on approach momentum.

Methods

Experimental Approach to the Problem

In answering our first research aim, a cross-sectional, correlative research design was used to examine the correlations between (peak and mean) horizontal deceleration and braking GRF variables at the first and second braking foot contacts during horizontal deceleration phases. For our second research aim, a between-subject, comparative design was conducted to investigate differences in GRF characteristics of the first and second braking foot contacts between greater (top 33%) and lower (bottom 33%) performers. Given the influence of approach velocity and approach momentum on deceleration performance, the strategy of group splitting not only involved mean deceleration and peak deceleration, but also involved peak approach velocity and peak approach momentum. When comparing groups, data was analyzed using independent *t*-tests (parametric) or Mann–Whitney *U* tests (non-parametric) and Hedges' *g* effect sizes (ES). Moreover, paired samples *t*-test was used to determine the differences between the first two-foot contacts.

Subjects

Forty-two male student-athletes from various team sports took part in the present study (age: 22.25 ± 0.15 yrs; height: 1.81 ± 0.31 m; mass: 71.61 ± 1.42 kg; relative back squat 1RM: 1.98 ± 0.48 body mass), consisting of 27 football players, 5 rugby players, and 10 basketball players. Based on the participant classification framework (26), participants in the present study were classified as trained/developmental subjects. A priori power analysis using G*Power (Version 3.1, University of Dusseldorf, Germany), showed a minimum required sample size of 40 to investigate a reported correlation value of 0.43 (horizontal braking force ratio to completion time) (11), at a power of 0.90, with a type 1 error set at 0.05. For inclusion in the present study, all participants had a minimum of 3-years experience in their respective sports and a minimum of 2-years resistance training experience before testing. In addition, all participants were free from injury 6 months before testing. Testing was conducted in the pre-season period. This study was approved by ***** University Ethics Review Board. All participants provided written informed consent to participate.

Procedures

All participants performed a 10 min standard warm-up consisting of 5 min jogging and 5 min self-selected dynamic stretches. Moreover, all participants performed 6 familiarization trials including 3 linear sprint trials and 3 horizontal decelerations trials at submaximal effort (75% of perceived maximum effort). Following 5 minutes recovery, participants performed 15 m linear sprint tests followed by maximal horizontal deceleration tests with 2-3 min of within-test intervals and 5 minutes of between-test intervals. All tests were conducted on an indoor court.

Linear Sprint Testing

All participants performed three 15 m sprint trials at maximal effort, with 2-3 min

recovery intervals between trials, using 2 pairs of timing gates (Smartspeed, Fusion Sport, Queensland, Australia) positioned at 0 and 15 m. The height of timing gates was set at 0.8 m based on previous research (29). To prevent a false trigger, participants started in a crouching position (staggered stance) 0.5 m behind the start line. The best completion time of three trials was used as a “criterion” time to determine whether a trial of horizontal deceleration was performed with a sufficient approach velocity.

Maximal Horizontal Deceleration

Due to the limited lab size, a modified acceleration-deceleration-ability (ADA) test was performed in the present study (Fig 1). Participants performed a maximal horizontal deceleration following 15 m sprint at maximal effort. The completion time of 15 m sprint was collected by timing gates, which were positioned and set similarly to 15 m linear sprint testing. A radar device (Stalker ATS II, Applied Concepts, Inc., Dallas, TX, USA) sampling at 47 Hz was positioned 5 m behind the start line to collect the instantaneous horizontal velocity (17). During the deceleration phase, participants were required to stop as quickly as possible, and then backpedal to the start line. Any trial where the 15 m linear speed time during the modified ADA testing was 5% greater than the best 15 m linear sprint performance was discarded (17), and an extra trial was performed following a 3 min rest interval.

*** Insert Fig 1 about here ***

Data Collection and Analysis

Tri-axial GRF data of the first- and second-foot contacts during the deceleration phase were collected using two adjacent 40cm × 60cm Kistler force platforms (Switzerland, Kistler 9281CA) sampling at 1200 Hz. Any trials where participants did not make foot contact with force platforms or touched the border of the force platforms were considered as unsuccessful trials. The initial contact of the braking phase was defined as the frame where the vertical component of braking GRF was greater than 20 N, and the toe-off was defined as the frame where the vertical GRF was lower than 20 N (20). The braking GRF data were low-pass filtered at 25 Hz (38). The mean and peak horizontal deceleration data were processed and calculated based on previous studies (17,31). The calculations for GRF variables and angle of peak resultant GRF are presented in Table 1, based on previous studies (6,21,23,27). Kinematic variables, including GCT and mean and peak deceleration, were analyzed in the present study, similar to previous research (17).

*** Insert Table 1 about here ***

Statistical Analyses

Descriptive data were presented as mean ± SD. All statistical procedures were

performed with SPSS software (SPSS 22, Chicago, IL, USA). The Shapiro-Wilk test was used to evaluate the normality of all data. Within-session reliability was examined using intraclass correlation coefficients (ICC) and values of 0.1, 0.3, 0.5, 0.7, 0.9 and 1.0 were presented as low, moderate, high, very high, nearly perfect, and perfect, respectively (19). Coefficient of variation (CV) was determined from the typical error and was interpreted as following criteria: < 5 excellent, 5-10 good, 10-15 moderate, >15 poor (30). The correlations between horizontal deceleration performance and GRF variables were examined using Pearson's (parametric data) or Spearman's (non-parametric data) correlations. The correlation coefficients of 0.1, 0.3, 0.5, 0.7, 0.9, and 1 were indicated as trivial, small, moderate, large, very large, nearly perfect, and perfect (18). Only correlation coefficients ≥ 0.30 were reported in this study. Within-subject differences in braking GRF variables and ground contact time between the first- and second-braking steps were examined using a paired sample *t*-test and between-subject (top vs bottom 33%) differences in mechanical variables were determined using independent samples *t*-test (parametric) or Mann-Whitney *U* tests (non-parametric). Effect sizes (Hedges' *g*) were conducted to assess the magnitude of differences, and were interpreted as trivial (< 0.19), small (0.20 - 0.59), moderate (0.60 - 1.19), large (1.20 - 1.99), and very large (2.0 - 4.0). $p \leq 0.05$ was considered statistically significant.

Results

All variables showed acceptable reliability (ICC = 0.49-0.91, CV = 1.4-12.2%) (Table 2). There were moderate to large differences in most mechanical variables between the first and second braking foot contact during horizontal deceleration (ES = -1.77 to 8.00, $p < 0.05$), excluding peak horizontal braking GRF ratio and angle of peak horizontal resultant GRF (ES = 0.15-2.00, $p > 0.05$) (Table 2).

*** Insert Table 2 about here ***

Greater mean and peak deceleration were moderately correlated with mean horizontal GRF ratio at the first foot contact ($\rho = 0.31$ and 0.32 , $p < 0.01$), and with greater mean horizontal GRF, mean horizontal GRF ratio, and peak horizontal GRF ratio ($\rho = 0.39$ to 0.49 , $p < 0.01$) at the second foot contact. Peak approach momentum was correlated with mean ($\rho = -3.07$, $p = 0.004$) and peak deceleration ($\rho = -2.82$, $p = 0.009$) (Table 3).

*** Insert Table 3 about here ***

Comparisons of greater vs. lower mean and peak deceleration performers demonstrated that greater performers demonstrated higher mean horizontal GRF ratio at the first braking foot contact, and higher mean horizontal GRF ratio, peak horizontal GRF ratio and mean horizontal GRF at the second braking foot contact (ES

= 2.97 to 5.00, very large, $p < 0.05$). The greater peak deceleration group also demonstrated higher mean horizontal GRF and peak horizontal GRF at the first and second braking foot contact, respectively (ES = 2.08 to 2.43, very large, $p < 0.05$) (Table 4). Moreover, comparisons showed that a statistically significantly greater approach momentum (ES = 0.62 and 0.66, respectively, moderate, $p < 0.05$) was observed in lower mean and peak deceleration performers, with statistically significantly greater approach velocity observed in lower mean deceleration performers (ES = 0.56, small, $p < 0.05$) (Table 4).

Comparisons of greater vs lower peak approach velocity performers demonstrated that greater performers show lower mean deceleration and peak deceleration (ES = 0.55 to 0.57, moderate, $p < 0.05$), and shorter GCT, and higher peak vertical GRF and peak resultant GRF (ES = 0.50 to 1.33, small to moderate, $p < 0.05$) at both braking foot contacts (Table 4). Comparisons showed that statistically significantly greater mean and peak deceleration (ES = 0.62 and 0.62, respectively, moderate, $p < 0.05$), but lower approach momentum (ES = 0.63, moderate, $p < 0.05$) were observed in lower approach velocity performers.

*** Insert Table 4 about here ***

Comparisons of greater vs lower peak momentum performers demonstrated that greater performers show higher mean loading rate at the second foot contact (ES = 0.58, small, $p < 0.05$), and a tendency for lower mean and peak deceleration (ES = 0.50, small, $p < 0.05$ –0.053) (Table 4). Moreover, comparisons showed that statistically significantly higher mean and peak deceleration (ES = 0.70 and 0.66, respectively, moderate, $p < 0.05$) and lower body mass (ES = 4.08, very large, $p < 0.05$) were observed in lower approach momentum performers (Table 4).

Discussion

This study aimed to investigate the mechanical determinants of maximal horizontal deceleration and to compare the differences in mechanical and kinematic variables between greater and lower performers (mean deceleration, peak deceleration, peak approach velocity and peak momentum). The primary findings of this study provided evidence that greater mean and peak deceleration were statistically significantly correlated with greater mean horizontal GRF ratio at the first and second braking foot contacts. Compared to lower peak approach velocity/momentum performers, greater performers showed statistically significantly lower mean and peak deceleration. Therefore, practitioners should aim to maximize horizontal GRF production and thus orientate force more horizontally for more effective deceleration. However, faster approach velocities, especially when accompanied with greater body mass (and thus momentum), will likely see a reduction in deceleration performance on account of higher braking demands. This is likely an unavoidable paradox and thus deceleration

performance must always be presented considering approach velocity and momentum.

We found that the magnitude of horizontal GRF and the horizontal GRF ratio were the primary mechanical determinants of superior horizontal deceleration. These findings were expected as according to Newton's 2nd law, increased horizontal braking GRF could facilitate for greater changes in acceleration, thus horizontal velocity. Also, based on the impulse-momentum relationship, greater increases in impulse due to increased force results in greater changes in momentum, thus greater deceleration. This finding is pivotal as for the same magnitude of resultant braking GRF, a greater proportion of horizontal braking GRF could facilitate greater changes in horizontal velocity, thus superior deceleration performance. Notably, previous research has identified that the horizontal GRF ratio was strongly attributed to technical ability (27). Therefore, to achieve greater or more effective braking force and orientation, the center of mass should be lower and positioned further posterior to the center of pressure (i.e., supported leg) during the braking steps, which may be achievable through technical work and coaching drills, as well as increasing the strength of eccentric muscle actions.

To our best knowledge, this is the first study to compare differences in kinetic and kinematic characteristics between the first- and second-foot contact during maximal horizontal deceleration tasks. It must be noted that the horizontal GRF ratio is dependent on the angle of resultant GRF vector. Notably, we found a greater horizontal (mean or peak) GRF ratio or angle of resultant GRF vector in the first braking step, compared to the second braking step (Table 2 and 4). In contrast, a more horizontal GRF vector is observed in the latter foot contacts from the antepenultimate to the final foot contact during 505 CODs (9). This difference may be explained by a varied movement strategy in which athletes need to reposition the body in order to propel themselves in the opposite direction. A 'side-step' strategy such as this, is characterized by large horizontal distances between the COM position and the support leg, leading to a more horizontal force vector. However, for horizontal deceleration, athletes seemingly adopt smaller 'choppy' strides with a higher frequency, due to a potentially greater horizontal velocity, and increased forces relative to body alignment (remaining 'square on').

Interestingly, we found greater peak resultant GRF at the second braking foot contact, rather than the first braking foot contact (Table 1, 3 and 4). This finding is surprising given that a greater approach velocity was observed at the first foot contact, thus a greater peak GRF would theoretically occur here. Similarly, Nedergaard et al. (28) investigated the GRF characteristics across the antepenultimate, penultimate, and final foot contacts during 135° COD and reported the greatest braking GRF at the penultimate foot contact. This unexpected finding may be due to the fact that greater approach velocities would induce greater impact forces, potentially leading to

increases in the risk of sport injury. Moreover, non-significant correlations were observed between greater (mean and peak) deceleration and longer GCT, and non-significant difference in GCT were observed between greater and lower mean and peak deceleration performers (Table 4). These findings suggest that GCT is not indicating deceleration performance, but rather, a likely byproduct of GRF relative to the athlete's physical capacity. GCT is largely influenced by the approach velocity, such that greater peak approach velocities result in shorter contact times (Table 4). GCT reflects the ability of loading toleration, which are likely best improved through strength training.

This study is seemingly also the first investigation comparing the deceleration performance between greater and lower approach velocity and momentum performers. Notably, results revealed that greater performers exhibited lower mean and peak deceleration (Table 4), suggesting the key role of approach velocity on deceleration performance. In alignment with our findings, COD studies also reported that players who had lower entry velocities exhibited greater COD performance, thus greater deceleration and directional change performance (12,13,34). This is because a greater horizontal velocity requires more foot contacts to decelerate given the limited lower limb tolerance to load (and rate of). Moreover, compared to lower approach velocity performers, greater performers showed greater peak vertical GRF and greater peak resultant GRF (Table 4). Again, this finding supports that the magnitudes of resultant GRF is regulated by the approach velocity. However, non-significant differences were observed in the magnitude of horizontal GRF and horizontal GRF ratio, suggesting a similar technique was applied (Table 4). For greater approach velocity performers, significantly greater peak resultant GRF attributed to greater vertical GRF, which was not considered "effective force" for deceleration. Therefore, deceleration performance is partially determined by the approach velocity.

We also found that greater peak approach momentum performers showed statistically significantly lower mean and peak deceleration, similar GRF variables, and peak approach velocity, but greater body mass than lower performers (Table 4). The gap in body mass was very large (62.08 kg vs. 77.83 kg, ES = 4.08), much more so than approach velocity (7.24 m/s vs. 7.36 m/s, ES = 0.41), thus represents the major contributing factor to momentum in the tested sample. Moreover, the GRF variables are normalized by body mass, leading to non-significant differences between them. Therefore, approach momentum is a crucial determinant of horizontal deceleration. In contrast, the study by Harper et al. (16) reported that a significantly greater approach velocity but a non-significantly greater approach momentum were observed in a greater mean horizontal deceleration group vs. lower group. Notably, only a small difference (ES = 0.46) was observed in approach momentum between both groups. Consequently, the differences in mean deceleration may also be small, whereas it was not reported in their study. In contrast, during COD tasks, players with greater

approach momentum exhibited a greater COD deficit (12,14), and slower 505, Zig-zag (13,25), Pro-agility (13), and L-drill performance (13), indicating that greater approach momentum led to a reduction in deceleration performance, thus lower deceleration and COD performance. These findings support ours, and thus practitioners should be aware that mean and peak deceleration is largely influenced by approach momentum. It would be unfair to assess deceleration performance in players without considering approach velocity and momentum.

The present study sheds light into the mechanical determinants of maximal horizontal deceleration tasks from a performance perspective, with several limitations that should be acknowledged to improve our understanding of achieving faster performance. Firstly, there are approximately 4-6 braking steps during the deceleration phase following 15 m sprint acceleration, but only the first two steps were analyzed in this study. Due to the changes in approach momentum, the GRF characteristics will be varied across the early to later foot contacts. Comparing GRF characteristics across all foot contacts will provide greater insight into mechanical determinants of faster horizontal deceleration performance. Therefore, further studies should be conducted to elucidate the multi-step nature of horizontal deceleration. Secondly, the technical characteristics of horizontal deceleration and differences in technique characteristics across all foot contacts during the deceleration phase should be analyzed, such as lower limb joint angle (hip, knee, and ankle) at initial contact, along with maximal flexion angle and range of motion. Additionally, the findings of the present study may only be applicable to the population we examined, and further investigations are required to carefully extrapolate this to other population, sports, and genders.

Practical applications

Practitioners should aim to maximize horizontal ground reaction force production and orientate force more horizontally for more effective deceleration. This can be achieved by coaching an athlete's technique such that they learn to adopt a position in which their center of mass is positioned low and posterior to the center of pressure (i.e., supported leg). Finally, faster approach velocities, especially when accompanied with greater body mass (and thus momentum), will likely see a reduction in deceleration performance, on account of higher braking demands. This is likely an unavoidable paradox and thus deceleration performance must always be presented considering approach velocity and momentum.

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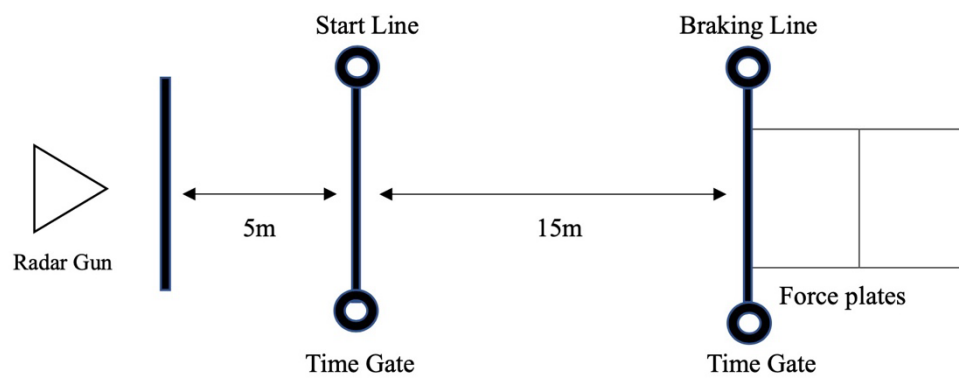


Figure 1

Table 1. Definitions and calculations for GRF variables, loading rate and deceleration ratio

Variable	Definition or calculation
horizontal GRF	$\sqrt{\text{anterior} - \text{posterior } GRF^2 + \text{medio} - \text{lateral } GRF^2}$
resultant GRF	$\sqrt{\text{horizontal } GRF^2 + \text{vertical } GRF^2}$
horizontal GRF ratio	horizontal GRF / vertical GRF
Angle of peak resultant GRF	$\tan^{-1}$ (vertical GRF/horizontal GRF)

Anterior-posterior x, Vertical z, Medio-lateral y, F force, T time

Table 2. Descriptive data and comparisons between first and second braking foot contact

	Deceleration performance								
	M ± SD	ICC (95% CL)	CV(%)	M ± SD	ICC (95% CL)	CV(%)	T	P	ES
P-A-Vel (m/s)	7.23 ± 0.32	0.64(0.45, 0.80)	9.8						
P-A-Mom (kg·m/s)	510.90 ± 57.86	0.63(0.43, 0.79)	5.6						
M-Dec (m/s ²)	4.21 ± 1.80	0.87(0.74,0.94)	1.5						
P-Dec (m/s ²)	5.38 ± 2.41	0.88(0.75, 0.95)	1.6						
Time to stop (s)	1.92 ± 0.36	0.64 (0.44, 0.79)	6.4						
Distance to stop (m)	6.99 ± 2.40	0.50 (0.28, 0.70)	12.3						
	The first braking foot contact			The second braking foot contact					
P-VGRF (N/kg)	40.85 ± 11.40	0.67(0.36, 0.88)	12.2	45.51 ± 9.20	0.59(0.21,0.86)	9.7	3.94	<0.001	4.48
P-HGRF(N/kg)	18.08 ± 5.11	0.63(0.31,0.86)	4.1	19.42 ± 5.63	0.66(0.47, 0.81)	5.8	-2.49	0.01	-1.78
P-RGRF (N/kg)	44.83 ± 11.82	0.70(0.40, 0.89)	7.4	49.60 ± 11.54	0.54(0.30, 0.74)	12.1	-4.40	<0.001	-4.28
P-HGRF-R	0.42 ± 0.07	0.91(0.52,0.97)	3.1	0.40 ± 0.08	0.52(0.23, 0.77)	6.3	0.516	0.607	2.00
M-VGRF (N/kg)	13.48 ± 2.75	0.73(0.36, 0.88)	1.5	11.69 ± 1.52	0.52(0.29, 0.71)	1.5	-7.46	<0.001	-5.86
M-HGRF (N/kg)	5.90 ± 1.31	0.61(0.19,0.87)	4.8	4.30 ± 1.37	0.80(0.67, 0.90)	1.4	8.67	<0.001	8.00
M-RGRF (N/kg)	15.03 ± 2.98	0.90(0.69, 0.96)	1.4	12.52 ± 1.60	0.54(0.33, 0.73)	1.6	8.48	<0.001	6.88
M-HGRF-R	0.38 ± 0.07	0.56(0.20, 0.84)	2.3	0.34 ± 0.10	0.82(0.70, 0.91)	5.1	2.882	0.005	4.00
Ang-P-RGRF(°)	65.93 ± 4.82	0.82(0.71, 0.90)	5.3	66.69 ± 5.13	0.84(0.75,0.92)	9.3	-0.62	0.540	0.15
Contact time (s)	0.12 ± 0.02	0.53(0.28, 0.75)	8.1	0.15 ± 0.04	0.79(0.65, 0.89)	6.1	-9.97	<0.001	-1.77

P Peak, *VGRF* Vertical ground reaction force, *HGRF* Horizontal ground reaction force, *RGRF* Resultant ground reaction force, *R* ratio, *M* mean, *LR* loading rate, *SD* Standard deviation, *ES* Effect size, *Ang* Angle, *A* approach, *Vel* velocity, *Mom* momentum

Table 3 Correlations between deceleration performance and mechanical variables

	<i>r</i> or <i>ρ</i>	<i>p</i>	<i>r</i> or <i>ρ</i>	<i>p</i>
	The first braking foot contact		The second braking foot contact	
M-Dec				
M-HGR-R	0.31	0.02	0.43	0.005
M-HGRF			0.42	0.006
P-HGRF-R			0.39	0.01
Peak Dec				
M-HGRF-R	0.32	0.04	0.49	0.001
M-HGRF			0.47	0.002
P-HGRF-R			0.44	0.003

Dec Deceleration, *M* Mean, *HGRF* Horizontal ground reaction force, *H* horizontal, *R* ratio

Table 4. Comparisons between greater and lower performers

Grouping methods	Variable	Lower	Greater	T	<i>p</i>	ES
Mean Deceleration	M-Dec (m/s ²)	2.52 ± 0.58	6.40 ± 1.02		< 0.001	4.68
	P-Dec (m/s ²)	3.19 ± 0.82	8.36 ± 1.15		< 0.001	5.17
	Time to stop (s)	2.01 ± 0.35	1.94 ± 0.38		0.706	0.19
	Distance to stop (m)	6.78 ± 2.62	7.95 ± 1.63		0.344	0.54
	P-A-Vel (m/s)	7.30 ± 0.27	7.14 ± 0.30	2.114	0.039	0.56
	Body mass (kg)	71.73 ± 7.43	69.11 ± 9.38		0.128	0.31
	P-A-Mom (kg·m/s)	523.67 ± 59.04	488.43 ± 54.82	2.396	0.02	0.62
	The first braking foot contact					
	M-HGRF-R	0.37 ± 0.01	0.42 ± 0.01	-3.057	0.004	5.00
	The second braking foot contact					
	P-HGRF-R	0.36 ± 0.02	0.43 ± 0.02	-3.859	< 0.001	3.50
	M-HGRF (N/kg)	3.42 ± 0.39	4.55 ± 0.37	-4.247	< 0.001	2.97
Peak Deceleration	M-HGRF-R	0.26 ± 0.03	0.35 ± 0.02	-4.514	< 0.001	3.53
	M-Dec (m/s ²)	2.58 ± 0.63	6.34 ± 1.08		< 0.001	4.25
	P-Dec (m/s ²)	3.12 ± 0.75	8.40 ± 1.08		< 0.001	5.68
	Time to stop (s)	2.05 ± 0.33	1.92 ± 0.36		0.329	0.38
	Distance to stop (m)	7.13 ± 2.36	7.94 ± 1.63		0.478	0.40
	P-A-Vel (m/s)	7.28 ± 0.30	7.14 ± 0.30	1.726	0.09	0.47
	Body mass (kg)	72.07 ± 7.58	69.11 ± 9.38		0.08	0.35
	P-A-Mom (kg·m/s)	524.26 ± 57.91	487.29 ± 54.07	2.556	0.013	0.66
	The first braking foot contact					
	M-HGRF (N/kg)	6.45 ± 0.33	7.20 ± 0.39	-1.930	0.049	2.08

		0.35 ± 0.02	0.41 ± 0.01	-3.122	0.003	3.79
	The second braking foot contact					
	P-HGRF (N/kg)	18.85 ± 1.08	21.72 ± 1.27	-2.65	0.010	2.43
	P-HGRF-R	0.30 ± 0.02	0.43 ± 0.02	-3.43	0.001	3.00
	M-HGRF (N/kg)	1.52 ± 1.15	4.92 ± 0.28	-5.62	< 0.001	4.06
	M-HGRF-R	0.28 ± 0.03	0.37 ± 0.02	-5.91	< 0.001	3.53
Peak approach velocity	M-Dec (m/s ²)	4.76 ± 1.82	3.62 ± 1.83		0.019	0.62
	P-Dec (m/s ²)	6.03 ± 2.29	4.59 ± 2.38		0.002	0.62
	Time to stop (s)	1.94 ± 0.40	1.85 ± 0.35		0.506	0.24
	Distance to stop (m)	7.29 ± 1.75	6.42 ± 2.69		0.564	0.38
	P-A-Vel (m/s)	6.90 ± 0.16	7.57 ± 0.18	-14.745	< 0.001	3.93
	Body mass (kg)	72.77 ± 7.51	70.21 ± 8.52		0.495	0.32
	P-A-Mom (kg·m/s)	493.10 ± 53.23	529.97 ± 64.07	-2.424	0.018	0.63
	The first braking foot contact					
	GCT (s)	0.13 ± 0.02	0.11 ± 0.02	3.11	0.003	1.00
	P-VGRF (N)	37.14 ± 9.72	43.66 ± 12.85	2.09	0.041	0.57
	P-RGRF (N)	41.82 ± 10.41	47.82 ± 13.84	-1.99	0.052	0.50
	The second braking foot contact					
	P-VGRF (N)	43.43 ± 8.75	48.71 ± 9.46	2.10	0.040	0.58
	P-RGRF (N)	46.44 ± 10.15	54.58 ± 11.97	-2.91	0.005	0.73
	GCT (s)	0.17 ± 0.03	0.13 ± 0.03	4.451	< 0.001	1.33
Peak momentum	M-Dec (m/s ²)	4.72 ± 2.09	3.43 ± 1.54		0.009	0.70
	P- Dec (m/s ²)	5.95 ± 2.63	4.38 ± 2.10		0.013	0.66
	Time to stop (s)	1.86 ± 0.24	1.97 ± 0.45		0.412	0.31
	Distance to stop (m)	6.77 ± 2.18	7.23 ± 2.69		0.383	0.19

P-A-Vel (m/s)	7.24 ± 0.31	7.36 ± 0.27	-1.706	0.093	0.41
Body mass (kg)	62.08 ± 4.27	77.83 ± 3.40		< 0.001	4.08
P-A-Mom (kg·m/s)	447.19 ± 28.66	572.95 ± 29.36	-16.787	< 0.001	4.33

P peak, *GRF* ground reaction force, *VGRF* vertical ground reaction force, *HGRF* horizontal ground reaction force, *RGRF* resultant ground reaction force, *R* ratio, *M* mean, *LR* loading rate, *A* approach, *Vel* velocity, *Mom* moment