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How early should you brake during a 180° turn? A kinetic comparison of the antepenultimate, penultimate, and final foot contacts during a 505 change of direction speed test

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ABSTRACT
The aim of the study was to compare ground reaction force (GRF) characteristics between the antepenultimate foot contact (APFC), penultimate foot contact (PFC), and final foot contact (FFC), and to examine the relationships between APFC, PFC, and FFC GRF characteristics with 505 change of direction (COD) speed performance. Twenty university male soccer players performed three COD trials, whereby GRFs were collected over the aforementioned foot contacts. Greater peak braking forces in shorter ground contact times were demonstrated over the APFC compared to the PFC and FFC ($p \leq 0.011$, $d = 0.96–7.82$), while APFC mean GRFs were greater than the PFC ($p \leq 0.001$, $d = 1.86–7.57$). Faster 505 performance was associated with greater APFC peak and mean vertical, horizontal, and resultant braking GRFs ($r^2 = 21.6–54.5\%$), greater FFC mean HGRFs ($r^2 = 38.8\%$), more horizontally orientated peak resultant APFC and PFC GRFs ($r^2 = 22.8–55.4\%$), and greater APFC, PFC, and FFC mean horizontal to vertical GRF ratios ($r^2 = 32.0–61.9\%$). Overall, the APFC plays a more pivotal role in facilitating deceleration compared to the PFC for effective 505 performance. Practitioners should develop their athletes' technical ability to express force horizontally across all foot contacts and coach braking strategies that emphasise greater magnitudes of posteriorly directed APFC GRFs to facilitate faster 505 performance.

ARTICLE HISTORY
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KEYWORDS
Braking force; ground contact time; force-vector; deceleration; impulse

Introduction

Change of direction (COD) ability is a fundamental athletic quality for athletes who participate in multidirectional sport (Bloomfield et al., 2007; Duffield & Drinkwater, 2008; Sweeting et al., 2017; Young et al., 2015). Importantly, COD ability provides the mechanical and physical basis underpinning agility (Dos'Santos, McBurnie et al., 2019; Nimphius, 2014, 2017); thus, highlighting the importance of developing athletes' physical and mechanical ability to COD in open-skilled sports (Nimphius, 2014). Specifically, the capacity to COD 180° is integral in numerous sports (Bloomfield et al., 2007; Duffield & Drinkwater, 2008; Sweeting et al., 2017); for example, soccer players perform ~100 turns of 90–180° during match play when the team is in and out of possession (Bloomfield et al., 2007), such as transitioning from defence to attack (and vice versa). Furthermore, previous research has shown soccer payers perform ~20 turns of 135–180° at moderate to high intensity (≥4 m/s) (Robinson et al., 2011). Additionally, 180° turns are also frequently performed actions in netball (Sweeting et al., 2017), while cricket batsmen can score runs by running and turning 180° between the wickets and is therefore considered a fundamental movement for successful cricket performance (Duffield & Drinkwater, 2008). In addition to match play, 180° CODs commonly feature in physical testing batteries for COD speed assessments, such as the 505, modified 505 (m505), and pro-agility, whereby these tests are frequently used for athlete monitoring and talent identification purposes in numerous sports (i.e., cricket, basketball, soccer, rugby, American football) (Nimphius et al., 2017). Specifically, Greig (2009) suggests that 180° COD assessments may better represent COD in soccer, but it is important to acknowledge that turning strategies may differ between planned and unplanned tasks (Jones et al., 2014). Nevertheless, irrespective of the scenario, and given the importance of 180° COD ability in multidirectional sports and COD speed assessments, understanding the kinetic properties which underpin faster COD performance is paramount.

A COD can be divided into four phases: 1) initial acceleration; 2) deceleration (negative acceleration); 3) COD foot plant; and 4) reacceleration (Bourgeois et al., 2017; T Dos'Santos, McBurnie et al., 2019; Graham-Smith et al., 2018), and is described as a multi-step action whereby the steps preceding and following the main COD foot plant are involved in facilitating effective deceleration, redirection, and reacceleration (Andrews et al., 1977; Dos'Santos, Thomas et al., 2018; Dos'Santos, Thomas, Comfort et al., 2019). In a recently published narrative review (Dos'Santos, Thomas et al., 2018), an "angle-velocity trade-off" concept has been discussed with respect to COD, whereby as the intended COD angle increases, deceleration requirements also increase to reduce the horizontal momentum to facilitate effective COD. This deceleration is typically accomplished via multiple foot contacts (Dos'Santos, Thomas et al., 2018; Dos'Santos, Thomas, Comfort et al., 2019), with the penultimate foot contact (PFC) (i.e., the second to last foot contact with ground prior to moving into a new intended

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direction of travel) having been shown to play a crucial role in terms of braking and facilitating faster 180° COD performance (Dos' Santos et al., 2019; Dos'Santos, Thomas, Comfort et al., 2019; Dos'Santos et al., 2017a; Graham-Smith et al., 2009; Jones et al., 2017). For example, greater PFC horizontal braking forces (HBF) have been associated with faster 180° COD performance (Dos'Santos et al., 2017a; Graham-Smith et al., 2009), which, based on the impulse-momentum relationship, results in greater change in momentum (Dos'Santos, Thomas, Comfort et al., 2019), thus velocity reduction. Additionally, faster 180° COD performance has been associated with more horizontally orientated PFC resultant braking forces (RBF) and greater horizontal to vertical mean and peak braking force ratios (Dos' Santos et al., 2019). This is advantageous because a more horizontally directed force vector should help facilitate more effective braking and net deceleration (negative acceleration) (Dos'Santos, Thomas, Comfort et al., 2019; Lu & Chang, 2012; Morin et al., 2011). Furthermore, faster m505 and 505 performers have also been reported to display greater PFC lower-limb triple flexion to help lower the centre of mass (COM) and facilitate an effective braking and push-off position (Dos' Santos et al., 2019), and is therefore considered a "preparatory step" step for sharper COD. As such, these findings have led to the recent COD coaching and technical recommendations of maximising PFC horizontally orientated braking characteristics and facilitating optimal PFC whole-body postures for faster 180° COD performance (Dos' Santos et al., 2019; Dos'Santos, Thomas, Comfort et al., 2019).

During 180° CODs athletes are required to reduce their horizontal velocity of COM to zero (Dos' Santos et al., 2019; Jones et al., 2017), thus athletes will need to reduce their momentum over a series of foot contacts before changing direction (Dos'Santos, Thomas et al., 2018; Dos'Santos, Thomas, Comfort et al., 2019). For example, deceleration stopping distances of ~3-6 metres have been observed during 10–20 metre sprints (Ashton & Jones, 2019; Greig & Naylor, 2017; Harper et al., 2018), highlighting the multi-step nature of deceleration. In the context of the 505, athletes are required to sprint, decelerate, and COD 180° at turning point 15 metres away from the start. Graham-Smith et al. (2018) reported deceleration stopping distances of 6.61 ± 0.40 metres during a sprint task that required athletes to stop at pre-determined point 15-m away, thus closely resembling the task demands of the 505. As such, ~44% of the 15-m distance covered can be classified as deceleration, which indicates that the steps preceding the PFC are undoubtedly involved in facilitating deceleration. As such, due to the distance required to stop, the antepenultimate foot contact (APFC) (i.e., third to last foot contact with the ground prior to moving in a new intended direction of travel) may have a more substantial role in terms of facilitating braking and deceleration for sharper CODs compared to the PFC and thus, warrants investigation. The APFC could be advantageous for braking because this foot contact is most likely performed in the sagittal plane which is a more optimal position to generate posterior braking force (Dos'Santos, Thomas, Comfort et al., 2019; Graham-Smith et al., 2018), whereas some athletes have been documented to pre-rotate during the PFC to reduce the directional demands but potentially comprising the ability to display greater magnitudes of PFC braking characteristics (Dos' Santos et al., 2019; Dos'Santos, Thomas, Comfort et al., 2019). However, surprisingly, no study to date has compared GRF braking characteristics between the APFC, PFC, and final foot contact (FFC) during 180° COD, nor has any study quantified the APFCs role in facilitating faster 180° COD performance. To the best of our knowledge, Nedergaard et al. (2014) is the only study to examine the role of the APFC during 135° CODs, reporting greater average trunk decelerations during this foot contact compared to the FFC. However, the authors did not examine the GRF characteristics of the APFC; thus, further insight into the kinetic properties of the APFC is required to improve our understanding of effective braking strategies for faster 180° COD performance.

The aim of the study, therefore, was two-fold: 1) to compare GRF characteristics between the APFC, PFC and FFC; and 2) to examine the relationships between APFC, PFC, and FFC GRF characteristics with 180° COD performance as measured via a 505 test. It was hypothesised that greater peak and mean GRFs would be demonstrated during the APFC compared to the PFC and FFC. Additionally, it was hypothesised that greater horizontal and resultant GRF characteristics and more horizontally orientated force vectors across all foot contacts would be associated with faster 180° COD performance. Conducting this research will provide greater insight into GRF determinants of faster COD which may assist in the development of more effective 180° turning coaching guidelines and strength and conditioning programmes.

Methods

Experimental approach to the problem

This study used a mixed, cross-sectional design to determine the relationship between APFC, PFC, and FFC GRF characteristics and 505 performance (completion time) following an associative strategy. Additionally, a within-subjects, comparative design was used to compare GRF characteristics between COD foot contacts. Subjects performed three trials of a 505 from their right limb, whereby tri-axial GRFs were collected during the APFC, PFC, and FFC (Figure 1).

Subjects

A minimum sample size of 16 subjects was determined from an *a priori* power analysis using G*Power (Version 3.1, University of Dusseldorf, Germany) (Faul et al., 2009). This was based upon a previously reported correlation value of 0.680 (mean horizontal to vertical GRF ratio to completion time) (Dos' Santos et al., 2019), a power of 0.95, and type 1 error or alpha level 0.05. As such, 20 university-level male soccer players (mean ± SD; age: 23.8 ± 3.8 years, height: 1.79 ± 0.05 m, mass: 80.5 ± 10.9 kg) participated in this study (18 subjects stated right preferred kicking and turning limb). For inclusion in the study, all subjects had played their respective sport for a minimum of 5 years and regularly performed 1 game and 2 structured skill-based sessions per week. All subjects were free from injury and none of the subjects had suffered a prior severe knee injury such as a knee ligament injury. At the time of testing, subjects were currently in-season (competition phase). The investigation was

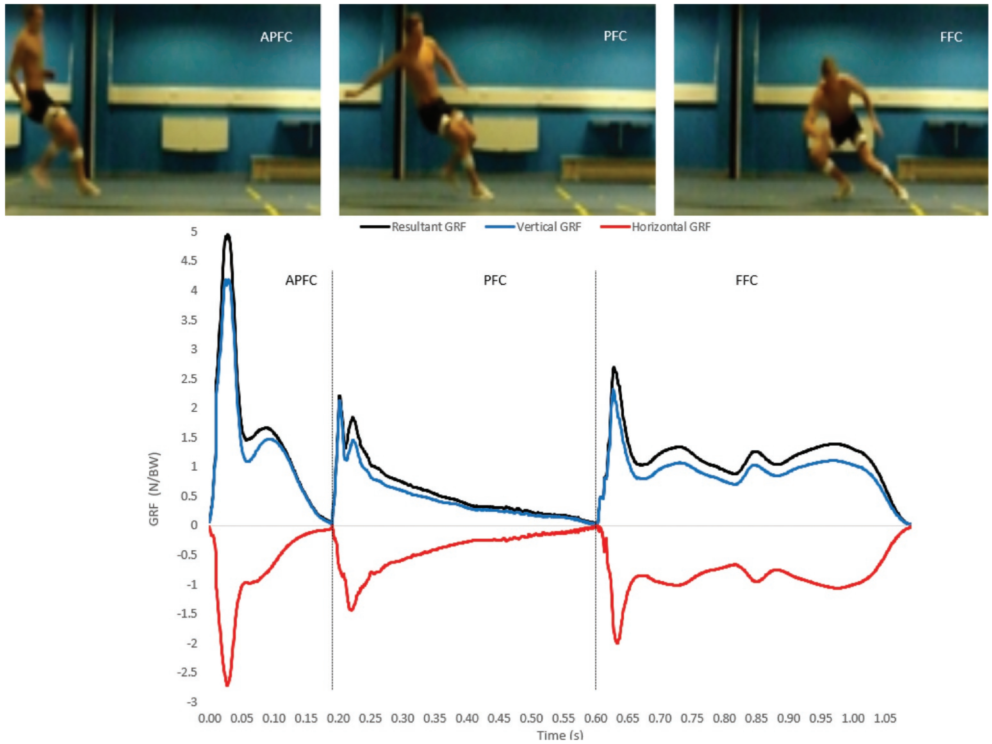

Figure 1. Photo-sequence and GRF characteristics of the APFC, PFC, and FFC during the traditional 505.

approved by the institutional ethics review board, and all subjects were informed of the benefits and risks of the investigation prior to signing institutionally approved consent documents to participate in the study.

Procedures

Anthropometric assessments (height [m] and mass [kg]) were completed before performing a standardised warm-up. Prior to maximal COD speed tasks, subjects performed a 5-min warm up consisting of jogging, self-selected dynamic stretching, and four familiarisation trials of the 505 performed at 75% of perceived maximum effort (Dos'Santos, Comfort et al., 2018).

Subjects performed three 505 trials as fast as possible, with all trials performed with a turn from their right leg. The 505 has been described previously (Dos'Santos et al., 2017b, 2019; Draper & Lancaster, 1985); thus, a brief overview is provided. Testing took place in the human performance laboratory on an indoor track (Mondo, SportsFlex, 10 mm; Mondo America Inc., Mondo, Summit, NJ, USA). For all tasks, subjects adopted a two-point stance 0.5-m behind the start line, to prevent early triggering of the timing gates, and sprinted as fast as possible in a straight line towards the turning point (making sure the foot made contact with the turning point) before changing direction 180° and exiting and reaccelerating towards the finish line. Each trial was interspersed with 2 minutes' rest. If the subject slid, did not contact the turning point, or missed the force platform(s), the trial was discarded and subsequently another trial was performed after 2 minutes' rest. Completion time (recorded to the nearest 0.001 second) and approach time was measured using sets of single beam Brower timing lights (Draper, UT, USA) that were set at approximate hip height for all subjects, to ensure that only one body part (such as the lower torso) breaks the beam (Yeadon et al., 1999). All subjects wore previously used standardised footwear (Balance W490, New Balance, Boston, MA, USA) to control for shoe–surface interface.

The GRF analysis procedures were based on previously published protocols (Dos' Santos et al., 2019; Dos'Santos et al., 2017a), thus a brief overview is provided here. Tri-axial GRFs were collected from three 600 mm × 900 mm AMTI (Advanced Mechanical Technology, Inc, Watertown, MA, USA) force platforms (Model number: 600900) embedded into the running track sampling at 1200 Hz using Qualisys Track Manager software (Qualisys, version 2.16 (Build 3520), Gothenburg, Sweden), with vertical, anterior-posterior, and medio-lateral force corresponding to Fz, Fx, and Fy, respectively. Ground reaction force data were exported and smoothed using a Butterworth low-pass digital filter with a 25 Hz cut-off frequency in a customised Microsoft Excel analysis spreadsheet (version 2016, Microsoft Corp., Redmond, WA, USA), and the Fz, Fx, and Fy force components were also analysed in a separate customised Microsoft Excel analysis spreadsheet. The following dependent variables derived from the force–time curves with Table 1 outlining the definitions and calculations: peak vertical braking force (VBF), peak HBF, and peak RBF; mean vertical, mean horizontal, and mean resultant GRFs; angle of peak RBF, peak and mean horizontal to vertical GRF ratios, and GCTs for all foot contacts. Initial contact (touch-down) was defined as the instant of ground contact that the vertical GRF (VGRF) was higher than 20 N, and end of contact (toe-off) was defined as the point where the VGRF subsided past 20 N (Dos' Santos et al., 2019; Dos'Santos et al., 2017a). All GRF and impulse variables were normalised to body weight (BW), and the average of three trials was used for further analysis.

Table 1. Definitions and calculations for GRF characteristics.

Variable	Foot contact	Abbreviation	Definition or calculation
Peak vertical braking force (Fz)	APFC, PFC and FFC	VBF	Peak normalised VGRF (Fz) value during ground contact
Mean vertical GRF (Fz)	APFC, PFC and FFC	Mean VGRF	Average normalised VGRF (Fz) during ground contact
Total vertical impulse (N·s/BW)		-	Area under VGRF curve (force × time)
Peak horizontal braking force	APFC, PFC and FFC	HBF	Calculated using Pythagoras theorem (horizontal force = √ (medio-lateral GRF^2 + anterior-posterior GRF^2)). Peak normalised HGRF value during ground contact.
Mean horizontal GRF	APFC, PFC and FFC	Mean HGRF	Average normalised HGRF during ground contact
Total horizontal impulse (N·s/BW)		-	Area under HGRF curve (force × time)
Resultant braking force	APFC, PFC and FFC	RBF	Calculated using Pythagoras theorem (resultant force = √ (Vertical force^2 + Horizontal force^2)) during ground contact. Peak normalised RGRF value during ground contact
Mean resultant GRF	APFC, PFC and FFC	Mean RGRF	Average normalised RGRF during ground contact
Total resultant impulse (N·s/BW)		-	Area under RGRF curve (force × time)
Angle of peak resultant braking	APFC, PFC and FFC	-	Calculated using trigonometry (angle of resultant force = tan^{-1}(vertical force/horizontal force) (smaller angle = more horizontally orientated)
Horizontal to vertical GRF ratio	APFC, PFC and FFC	-	Horizontal force/Vertical force (greater value = greater horizontal force contribution). Peak and mean forces.
Ground contact time	APFC, PFC and FFC	GCT	Duration from IC to toe-off

Key: APFC: Antepenultimate foot contact; PFC: Penultimate foot contact; FFC: Final foot contact; IC: Initial contact; GRF: Ground reaction force; VGRF: Vertical GRF; HGRF: Horizontal GRF; MLGRF: Medio-lateral GRF; RGRF: Resultant GRF.

Statistical analyses

All statistical analysis was performed in SPSS v 25 (SPSS Inc., Chicago, IL, USA) and Microsoft Excel. Normality was inspected for all variables using a Shapiro-Wilk's test. Within-session reliability for all variables were assessed using Intraclass correlation coefficients (ICC) (two-way mixed effects, average measures, absolute agreement) and coefficient of variation (CV%). ICCs were interpreted based on the following scale (Koo & Li, 2016): poor (≤ 0.49), moderate (0.50–0.74), good (0.75–0.89), and excellent (≥ 0.90). The CV% was calculated as SD/mean × 100 for each participant and then averaged across all participants, with values <15% considered acceptable (Haff et al., 2015).

GRF characteristics were compared across the three foot contacts using a repeated-measures analysis of variance (RMANOVA), with Bonferroni post-hoc pairwise comparisons in cases of significant differences for parametric variables. Partial eta squared effect sizes and observed powers were calculated for all RMANOVAs, with the values of 0.010–0.059, 0.060–0.149, and ≥ 0.150 considered as small, medium, and large, respectively, according to Cohen (1988). For non-parametric variables, a Friedman's test was used, and in cases of significant differences, individual Wilcoxon-sign-ranked tests were used to explore differences. Cohen's *d* effect sizes (Flanagan, 2013) were calculated for all pairwise comparisons between foot contacts, and interpreted as trivial (≤ 0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), very large (2.00–3.99), and extremely large (≥ 4.00) (Hopkins, 2002). Additionally, relationships between GRF characteristics and completion time were examined using Pearson's (for parametric data) and Spearman's (for non-parametric data) correlations. Coefficient of determinations ($r^{2\%}$) were also calculated. Correlations were evaluated as follows: trivial (0.00–0.09), small (0.10–0.29), moderate (0.30–0.49), large (0.50–0.69), very large (0.70–0.89), nearly perfect (0.90–0.99), and perfect (1.00) (Hopkins, 2002). A correlation cut-off value of ≥ 0.40 was considered relevant (Welch et al., 2019). 95% confidence intervals (CI) were calculated for ICCs, CV%, effect sizes, and correlations. Statistical significance was defined $p \leq 0.05$ for all tests.

Results

Completion times (2.409 ± 0.106 s, ICC = 0.903, 95% CI = 0.795–0.959, CV% = 2.0, 95% CI = 1.4–2.5) and approach times (1.963 ± 0.104 s, ICC = 0.947, 95% CI = 0.890–0.977; CV % = 1.8, 95% CI = 1.2–2.3) displayed high and acceptable reliability and variance. All GRF variables demonstrated very good to excellent reliability, excluding FFC peak and mean Horizontal to Vertical braking and GRF ratios and PFC GCT which displayed moderate reliability (Table 2). All variable displayed acceptable variability (Table 2).

Comparisons

RMANOVA and Friedman's test revealed significant differences in GCTs, peak braking forces, mean GRFs, total impulse, angle of peak RBF, and horizontal to vertical braking ratios between foot contacts (Table 3). Pairwise comparisons revealed that significantly greater peak VBFs, peak HBFs, peak RBFs, and mean VGRFs, in shorter GCTs were displayed during the APFC in comparison to PFC and FFC (Table 3, Figure 2)), with moderate to extremely large effect sizes. APFC mean HGRFs, VGRFs, and RGRFs were also significantly greater than the PFC with large to extremely large effect sizes (Table 3, Figure 2)); however, significantly greater vertical, horizontal, and resultant total impulses were displayed during the PFC compared to the APFC, with moderate to large effect sizes (Table 3). The greatest mean HGRFs and mean RGRFs were demonstrated during the FFC in comparison to the other foot contacts, with moderate to extremely large effect sizes (Table 3, Figure 2). Additionally,

Table 2. Reliability measures for GRF characteristics.

	APFC						PFC						FFC					
Variable	ICC	LB	UB	CV%	LB	UB	ICC	LB	UB	CV%	LB	UB	ICC	LB	UB	CV%	LB	UB
GCT	0.866	0.718	0.943	5.9	4.1	7.6	0.697	0.381	0.869	7.7	5.5	9.9	0.796	0.571	0.913	8.4	5.6	11.1
Peak VBF	0.964	0.925	0.985	7.6	5.8	9.4	0.918	0.828	0.965	8.4	5.9	10.8	0.844	0.675	0.933	10.2	7.5	12.9
Mean VGRF	0.968	0.934	0.986	4.2	3.1	5.3	0.898	0.786	0.956	8.1	5.7	10.5	0.950	0.890	0.979	4.0	3.0	5.1
Vertical Total impulse	0.968	0.932	0.986	5.8	4.6	7.1	0.869	0.727	0.944	8.8	5.8	11.7	0.877	0.745	0.947	9.4	6.7	12.2
Peak HBF	0.980	0.958	0.992	9.2	6.8	11.5	0.882	0.755	0.950	10.3	6.7	13.9	0.803	0.591	0.915	10.4	7.7	13.1
Mean HGRF	0.982	0.961	0.992	5.7	4.5	6.9	0.883	0.757	0.950	9.0	7.1	10.9	0.915	0.823	0.963	5.3	3.8	6.7
Horizontal Total Impulse	0.984	0.967	0.993	5.0	3.6	6.4	0.918	0.827	0.965	8.3	6.1	10.5	0.914	0.820	0.963	7.4	5.4	9.4
Peak RBF	0.969	0.936	0.987	7.8	6.0	9.6	0.908	0.808	0.960	8.8	6.1	11.6	0.833	0.652	0.928	9.9	7.4	12.5
Mean RGRF	0.974	0.946	0.989	4.2	3.2	5.2	0.897	0.786	0.956	8.2	6.0	10.3	0.947	0.886	0.977	4.0	2.9	5.2
Resultant Total Impulse	0.973	0.943	0.988	5.4	4.3	6.6	0.888	0.764	0.952	8.1	5.3	10.9	0.893	0.776	0.954	8.6	6.2	11.0
Angle of Peak RBF	0.978	0.955	0.991	1.3	0.9	1.7	0.770	0.511	0.902	2.2	1.6	2.9	0.761	0.490	0.899	3.2	2.4	4.0
Peak H to VBF Ratio	0.979	0.956	0.991	3.6	2.4	4.7	0.767	0.507	0.901	4.6	3.2	6.0	0.749	0.464	0.894	5.6	4.3	7.0
Mean H to VGRF Ratio	0.964	0.924	0.985	5.0	3.7	6.3	0.853	0.692	0.937	4.9	3.8	6.0	0.726	0.420	0.883	3.6	2.2	5.0

Key: ICC: Intraclass correlation coefficient; CV%: Coefficient of variation; LB: 95% confidence interval lower bound; UB: 95% confidence interval upper bound; APFC: Antepenultimate foot contact; PFC: Penultimate foot contact; FFC: Final foot contact; GRF: Ground reaction force; VGRF: Vertical GRF; HGRF: Horizontal GRF; RGRF: Resultant GRF; GCT: Ground contact time; VBF: Vertical braking force; HBF: Horizontal braking force; RBF: Resultant braking force; H: Horizontal.

significantly greater vertical, horizontal, and resultant impulses were demonstrated during the FFC in comparison to the APFC and PFC, with extremely large effect sizes (Table 3).

Finally, more horizontally orientated peak RBF vectors and greater horizontal to vertical braking force ratios were observed during the FFC in comparison to the other foot contacts, with very large to extremely large effect sizes (Table 3), while the aforementioned variables were also statistically significantly greater for the PFC in comparison to the APFC, with very large effect sizes (Table 3). 17 (15 right/2 left limb preference) and 18 (16 right/2 left limb preference) subjects displayed greater peak HBFs and mean HGRFs in the APFC compared to the PFC (Figure 2), respectively, while 18 (16 right/2 left limb preference) and 20 (18 right/2 left limb preference) subjects displayed greater peak RBFs and mean RGRFs in the APFC compared to the PFC (Figure 2), respectively. Interestingly, the two subjects who stated left limb preference demonstrated greater peak HBFs and RBFs, and mean HGRFs and RGRFs, during the APFC (right limb) compared to the PFC (left limb).

Relationships

The relationships between APFC, PFC, and FFC GRF characteristics and COD performance are presented in Table 4. Greater APFC peak VBFs, peak HBFs, peak RBFs, mean VGRFs, mean HGRFs, mean RGRFs, and horizontal total impulse were significantly and moderately to very largely associated with faster COD performance (Table 4, Figure 3), explaining 21.6–54.5% of common variance. Additionally, shorter APFC GCTs and greater FFC mean HGRFs were moderately and largely associated with faster COD performance (Table 4), respectively, explaining 20.9–38.8% of common variance. More horizontally orientated APFC RBF vectors and greater APFC horizontal to vertical braking force ratios were very largely associated with faster COD performance, explaining 54.9–61.2% of common variance (Table 4). Additionally, more horizontally orientated PFC RBF vectors and greater PFC horizontal to vertical braking force ratios were moderately to largely associated with faster COD performance, explaining 22.8–32.0% of common variance, while greater FFC

Table 3. Comparison in GRF characteristics between COD foot contacts.

										Pairwise comparisons								
	APFC		PFC		FFC					APFC vs PFC			APFC vs FFC			PFC vs FFC		
Variable	Mean	SD	Mean	SD	Mean	SD	RMANOVA	η2	Power	*p*	*d*	± CI	*p*	*d*	± CI	*p*	*d*	± CI
GCT (s)	0.199	0.022	0.458	0.041	0.478	0.070	<0.001	0.941	1.000	<0.001	7.82	1.82	<0.001	5.42	1.34	0.814	0.36	0.62
Peak VBF (N/BW)	3.38	0.62	1.79	0.35	1.76	0.28	*<0.001*			<0.001	−3.16	0.93	<0.001	−3.38	0.97	1.000	−0.11	0.62
Mean VGRF (N/BW)	1.18	0.09	0.58	0.06	1.09	0.06	<0.001	0.951	1.000	<0.001	−7.57	1.77	<0.001	−1.11	0.67	<0.001	8.41	1.94
Vertical Total impulse (N·s/BW)	0.23	0.03	0.26	0.03	0.52	0.08	<0.001	0.901	1.000	0.003	1.01	0.66	<0.001	4.90	1.24	<0.001	4.49	1.16
Peak HBF (N/BW)	1.83	0.56	1.27	0.25	1.44	0.17	0.001	0.399	0.950	0.004	−1.29	0.68	0.011	−0.96	0.65	0.027	0.76	0.64
Mean HGRF (N/BW)	0.56	0.13	0.38	0.04	0.87	0.07	<0.001	0.916	1.000	<0.001	−1.86	0.74	<0.001	3.05	0.91	<0.001	8.61	1.99
Horizontal Total Impulse (N·s/BW)	0.11	0.03	0.17	0.02	0.41	0.05	<0.001	0.953	1.000	<0.001	2.68	0.85	<0.001	7.41	1.74	<0.001	6.13	1.48
Peak RBF (N/BW)	3.85	0.79	2.20	0.43	2.27	0.32	<0.001	0.763	1.000	<0.001	−2.59	0.84	<0.001	−2.61	0.84	1.000	0.19	0.62
Mean RGRF (N/BW)	1.31	0.13	0.69	0.07	1.40	0.08	<0.001	0.943	1.000	<0.001	−5.78	1.41	0.007	0.80	0.64	<0.001	9.08	2.09
Resultant Total Impulse (N·s/BW)	0.26	0.04	0.31	0.03	0.67	0.09	<0.001	0.925	1.000	<0.001	1.65	0.72	<0.001	5.84	1.42	<0.001	5.14	1.29
Angle of Peak RBF (°)	62.09	3.82	54.70	1.81	50.53	2.16	<0.001	0.870	1.000	<0.001	−2.47	0.82	<0.001	−3.73	1.03	<0.001	−2.10	0.77
Peak H to VBF Ratio	0.53	0.08	0.71	0.05	0.83	0.06	<0.001	0.878	1.000	<0.001	2.58	0.84	<0.001	3.91	1.06	<0.001	2.08	0.77
Mean H to VGRF Ratio	0.47	0.08	0.66	0.05	0.79	0.04	<0.001	0.938	1.000	<0.001	2.93	0.89	<0.001	5.26	1.31	<0.001	2.75	0.86

Key: APFC: Antepenultimate foot contact; PFC: Penultimate foot contact; FFC: Final foot contact; GRF: Ground reaction force; VGRF: Vertical GRF; HGRF: Horizontal GRF; RGRF: Resultant GRF; GCT: Ground contact time; VBF: Vertical braking force; HBF: Horizontal braking force; RBF: Resultant braking force; H: Horizontal; RMANOVA: Repeated measures analysis of variance; CI: 95% Confidence interval. Note italic denotes non-parametric equivalent performed.

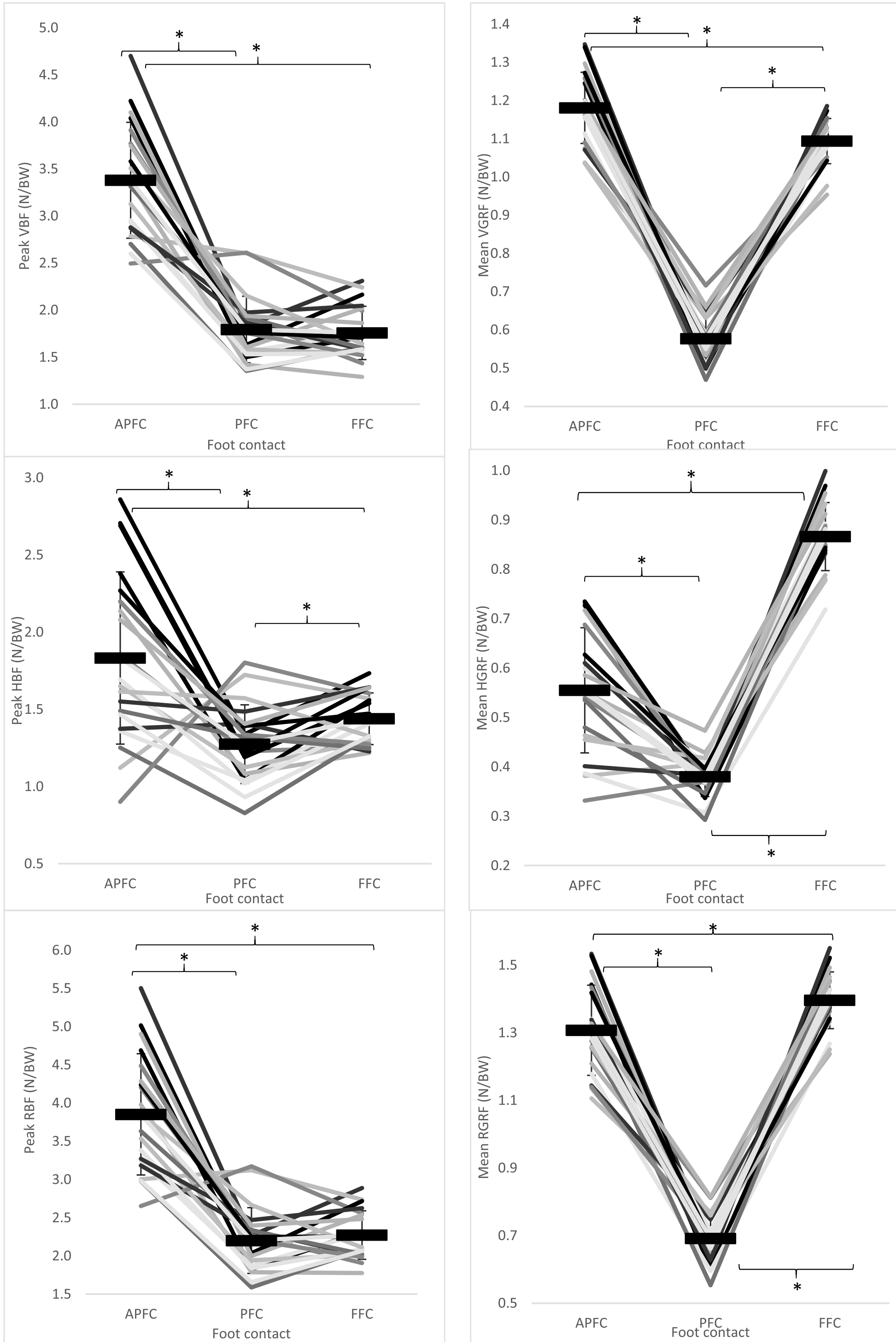

Figure 2. Comparison in vertical, horizontal, and resultant GRF characteristics between foot contacts. *: p<0.001. Note: black rectangle denotes mean

horizontal to vertical mean GRF ratios were very largely associated with faster performance (Table 4) (r^2 = 61.9%).

Discussion

The aim of the study was two-fold: 1) to compare GRF characteristics between the APFC, PFC and FFC; and 2) to examine the relationships between APFC, PFC, and FFC GRF characteristics with 180° COD performance as measured via a 505 test. The key findings were that greater peak braking forces in substantially shorter GCTs were demonstrated over the APFC compared to the PFC and FFC (Table 3, Figure 2), while APFC mean GRFs were also greater than the PFC (Table 3, Figure 2), supporting the study hypotheses. Additionally, faster 180° COD performance was associated with greater APFC peak and mean vertical, horizontal, and resultant braking GRFs explaining 21.6–54.5% of common variance, while greater FFC mean HGRFs were also associated with faster performance

Table 4. Relationship between foot contact GRF characteristics and completion time.

	APFC association with completion time			PFC association with completion time			FFC association with completion time			
Variable	r	± CI	r^2 (%)	r or ρ	± CI	r^2 (%)	r	± CI	r^2 (%)	Inference
GCT	0.457*	± 0.365	20.9	−0.081	± 0.440	0.7	0.350	± 0.398	12.2	Smaller GCT = faster performance
Peak VBF	−0.465*	± 0.362	21.6	*0.144*	± *0.435*	2.1	0.173	± 0.432	3.0	Greater force = faster performance
Mean VGRF	−0.555*	± 0.326	30.8	0.094	± 0.439	0.9	−0.136	± 0.436	1.9	Greater force = faster performance
Vertical Total impulse	0.040	± 0.442	0.2	0.043	± 0.442	0.2	0.274	± 0.415	7.5	
Peak HBF	−0.626*	± 0.291	39.2	0.208	± 0.427	4.3	0.008	± 0.442	0.0	Greater force = faster performance
Mean HGRF	−0.738**	± 0.226	54.5	−0.297	± 0.411	8.8	−0.623**	± 0.293	38.8	Greater force = faster performance
Horizontal Total Impulse	−0.527*	± 0.338	27.8	−0.341	± 0.400	11.6	−0.050	± 0.442	0.3	Greater impulse = faster performance
Peak RBF	−0.524*	± 0.339	27.5	0.325	± 0.397	10.6	0.123	± 0.437	1.5	Greater force = faster performance
Mean RGRF	−0.636**	± 0.286	40.4	−0.026	± 0.442	0.1	−0.387	± 0.388	15.0	Greater force = faster performance
Resultant Total Impulse	−0.126	± 0.437	1.6	−0.092	± 0.440	0.9	0.168	± 0.432	2.8	
Angle of Peak RBF	0.744**	± 0.222	55.4	0.477*	± 0.358	22.8	0.359	± 0.395	12.9	Smaller angle = faster performance (more horizontally orientated GRF vector)
Peak H to VBF Ratio	−0.741**	± 0.224	54.9	−0.485*	± 0.355	23.5	−0.350	± 0.398	12.3	Greater ratio = faster performance (greater horizontal contribution)
Mean H to VGRF Ratio	−0.782**	± 0.195	61.2	−0.566**	± 0.321	32.0	−0.787**	± 0.192	61.9	Greater ratio = faster performance (greater horizontal contribution)

Key: APFC: Antepenultimate foot contact; PFC: Penultimate foot contact; FFC: Final foot contact; GRF: Ground reaction force; VGRF: Vertical GRF; HGRF: Horizontal GRF; RGRF: Resultant GRF; GCT: Ground contact time; VBF: Vertical braking force; HBF: Horizontal braking force; RBF: Resultant braking force; CI: 95% Confidence interval; H: Horizontal. Note italic denotes non-parametric equivalent performed. **: $p < 0.001$; *: $p < 0.05$

(r^2 = 38.8%) (Table 4, Figure 3). Conversely, no significant or meaningful relationships were observed for PFC peak or mean GRFs ($r^2 \leq 10.6\%$) with COD performance (Table 4). These findings indicate that the APFC plays a more pivotal role in facilitating braking and deceleration for effective 180° COD within a 505 test, in line with the study hypotheses. Finally, in terms of force-vector specificity, faster 180° COD performance was associated with more horizontally orientated peak RBFs over the APFC and PFC (r^2 = 22.8–55.4%), while greater mean horizontal to vertical GRF ratios for all foot contacts was also associated with faster performance (r^2 = 32.0–61.9%). Overall, these results highlight not only the importance of peak and mean GRFs, particularly during the APFC, but highlight the importance of the technical application and orientation of the GRF vector across the three foot contacts for maximizing 180° COD performance within a 505 test; supporting the study hypotheses.

Changing direction 180°, particularly with longer approach distances, requires substantial deceleration to reduce the horizontal velocity of the COM to zero to facilitate effective redirection (Dos' Santos et al., 2019; Dos'Santos, Thomas et al., 2018; Graham-Smith et al., 2018; Jones et al., 2017). As such, the ability for athletes to display effective braking strategies is considered highly important for effective 180° COD performance (Dos' Santos et al., 2019; Dos'Santos, Thomas et al., 2018; Dos'Santos, Thomas, Comfort et al., 2019; Dos'Santos et al., 2017a). To the best of our knowledge, this is the first study to examine the GRF characteristics of the APFC and quantify its role during 180° COD. Importantly, greater APFC

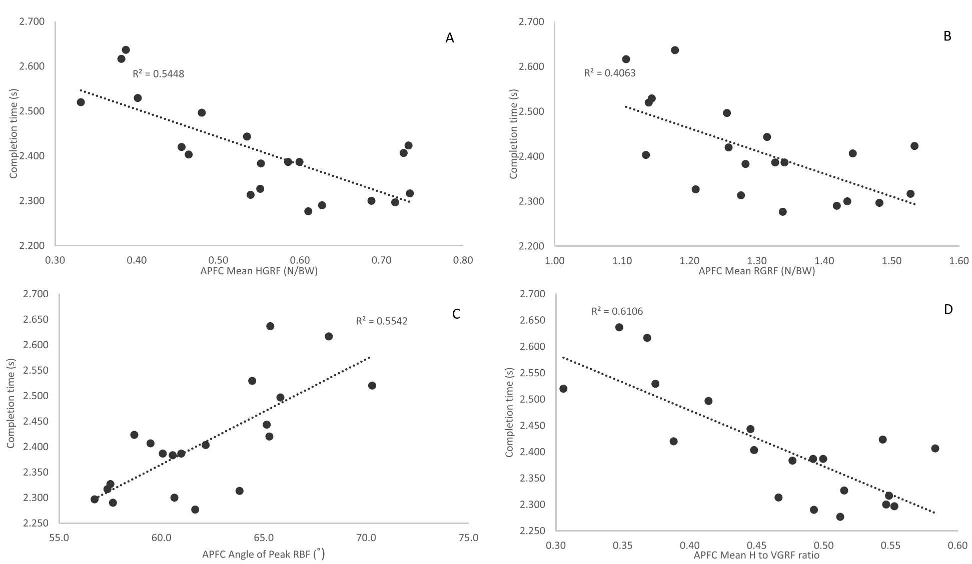

Figure 3. Scatter plots between foot contact GRF characteristics and tra505 completion times. A: APFC Mean HGRF; B: APFC Mean RGRF; C: APFC Angle of Peak RBF; D: APFC Mean H to VGRF ratio.

GRFs, particularly horizontal GRF and horizontal total impulse, in a more horizontally orientated direction were largely to very largely associated with faster COD performance in the present study (Table 4, Figure 3). Based on Newton's 2nd law, increases in force are proportionate to change in acceleration (i.e., negative acceleration), while greater forces also increase impulse which, based on the impulse–momentum relationship, leads to greater changes in momentum, thus reductions in horizontal velocity. While maximising force production is indeed important, the ability to orientate force in an optimal direction is also advantageous for faster COD performance (Dos' Santos et al., 2019; Dos'Santos, Thomas, Comfort et al., 2019). Interestingly, greater mean horizontal to vertical GRF ratios across all three foot contacts, and more horizontally orientated peak APFC and PFC RBFs were moderately to very largely related to faster 180° COD performance (Table 4, Figure 3), substantiating previous research that highlighted the importance of orientation of GRF vector during COD (Dos' Santos et al., 2019; Welch et al., 2019). This finding is important because for the same resultant GRF applied into the ground, a greater horizontal to vertical propulsive ratio (i.e., greater horizontally orientated force vector) should facilitate greater net horizontal acceleration (Morin et al., 2011). As such, based on these findings, braking strategies which emphasise greater GRF characteristics during the APFC appear to be advantageous for faster 180° COD performance, while the technical ability to apply force horizontally across the APFC, PFC, and FFC is also beneficial.

Substantiating the results of previous research (Dos' Santos et al., 2019; Dos'Santos et al., 2017a; Graham-Smith et al., 2009; Jones et al., 2017), greater FFC horizontal GRFs were largely associated with faster COD performance (Table 4), which should theoretically facilitate effective net acceleration in the horizontal direction (Morin et al., 2011). However, in terms of PFC peak and mean GRF characteristics, no significant or meaningful relationships with COD performance were observed (Table 4). This result contrasts with Dos'Santos et al. (2017a) and Graham-Smith et al. (2009) who found faster athletes displayed greater PFC HBFs, though this discrepancy could be attributed to differences in the 180° COD task (i.e., m505 vs. 505). For example, the abovementioned studies investigated the PFC during the m505 which consists of 5-m entry and exit. Research has shown that athletes only attain ~55% of their maximum speed during a task that required athletes to sprint and decelerate to a pre-determined point 5-m away, with stopping distances of ~3-m (Graham-Smith et al., 2018). Therefore, it is theorised that during the m505, the PFC may have a more important role in facilitating braking in contrast to the 505 whereby greater speeds are attained and subsequently longer stopping distances are required (Dos'Santos, Thomas et al., 2018; Graham-Smith et al., 2018), and thus, a greater reliance on earlier foot contacts such as the APFC. As such, deceleration and braking strategies appear specific to the approach distance and approach velocity. Although braking strategies may differ between planned and unplanned tasks (and their associated approach and braking demands) (Jones et al., 2014), most athletes will require the capacity to perform planned and unplanned turns effectively in training and competition (Dos'Santos, Thomas et al., 2018; Nimphius, 2017). Therefore, a range of braking strategies over various distances and tasks (planned and unplanned) should be coached with athletes prepared for increased movement solutions to adapt movement for different contexts where preparation time may vary (Dos'Santos, McBurnie et al., 2019; Dos'Santos, Thomas et al., 2018; Nimphius, 2014, 2017).

In context of the 505, the PFC may have a more critical role in lowering the COM and facilitating an effective posture for weight acceptance and push-off during the FFC, as shown by Dos'Santos et al. (2019) who observed faster athletes during the 505 displayed greater PFC lower-limb triple flexion angles. Notably, GCTs of ~0.5 seconds were displayed during the PFC, which were substantially longer the APFC, but similar to the FFC (Table 3, Figure 1). As such, because of the similar GCTs between the PFC and FFCs (Figure 1), athletes tend to display a dual-foot contact 180° turning strategy, with the PFC typically performed in a transverse position to reduce the redirection requirements. In the present study, ≥85% of the subjects, including the two subjects who preferred their left limb, displayed greater peak and mean GRF characteristics during the APFC compared to the PFC (Figure 2). Consequently, in relation to the 505, the APFC may have a more pivotal role in facilitating deceleration and braking compared to the PFC for effective 505 performance; however, both foot contacts are likely to serve dual roles with respect to "braking" and "positioning" the body for redirection, weight acceptance, and COM lowering (Figure 1). Finally, the FFC although containing a braking a component, its main role is propulsion and to redirect the body towards the intended direction of travel (Figure 1). As such, practitioners should be conscious of the roles of the APFC, PFC, and FFC when coaching effective braking strategies during the 505.

To the best of our knowledge, this is the first study to compare GRF characteristics between the APFC, PFC, and FFC during a 180° COD task. As stated previously, the greatest peak braking forces were observed during the APFC, whereas vertical, horizontal, and resultant total impulse, progressively increased with the latter foot contacts (PFC and FFC) (Table 3, Figure 1). This finding is unsurprising because substantially longer GCTs were observed with PFC and FFC, which contributes to the greater impulse (Table 3, Figure 1). Additionally, the orientation of the GRF towards horizontal and the HGRF contribution progressively increased across the foot contacts, with the FFC displaying the greatest horizontally orientated GRF (Table 3). Figure 4 presents the peak RBF vector across the three foot contacts, illustrating the greater magnitudes during the APFC and how the RBF vectors becomes more horizontally orientated with the latter foot contacts. This finding could be attributed to the greater COM lowering and greater changes in base of support relative to the COM to facilitate a horizontally orientated GRF vector (Dos' Santos et al., 2019; Dos'Santos, Thomas, Comfort et al., 2019), as illustrated in Figure 1.

It is important to note that the FFC has two purposes: braking (weight-acceptance) and propulsion (push-off) (Dos' Santos et al., 2019), which accounts for the greater mean HGRFs observed in the present study compared to the APFC (Table 3), which is solely a braking step (Figure 1). Conversely, greater peak braking forces and mean GRFs were displayed during the APFC compared to the PFC (Table 3), while meaningful relationships were revealed only

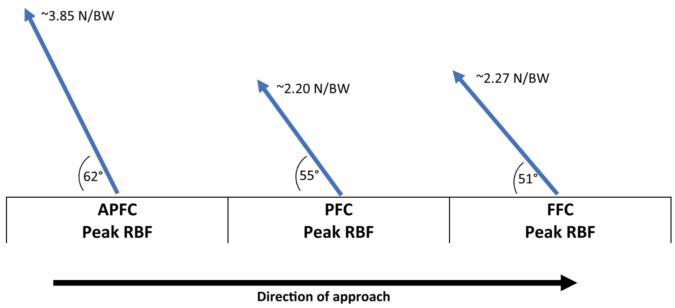

Figure 4. Comparisons in magnitude and orientation of peak resultant braking force vector between foot contacts based on average data. APFC: Antepenultimate foot contact; PFC: Penultimate foot contact; FFC: Final foot contact; RBF: Resultant braking force; BW: Body weight.

for the aforementioned GRF characteristics during the APFC (Table 4). This suggests the APFC has a more important role in facilitating effective 180° COD during the 505, and coaches are encouraged to coaching braking strategies which emphasise greater braking forces during the APFC. In contrast to previous research (Graham-Smith et al., 2009; Jones et al., 2016a, 2016b), greater peak HBFs were demonstrated during the PFC compared to the FFC, while differences in peak VBF were trivial and non-significant (Table 3). However, supporting the results of Jones et al. (2016a), greater mean GRFs and total vertical, horizontal and resultant total impulse were demonstrated during the FFC compared to the PFC (Table 3). As stated previously, the greater mean GRFs observed for the FFC can be attributed dual purposes of braking and propulsion, as illustrated by the notable differences in GRF displayed in Figure 1 between foot contact force–time curves. Nevertheless, due to the importance of the magnitudes of the braking and propulsive GRF characteristics observed in the present study for faster COD (Table 4), practitioners should consider developing their athletes' ability to rapidly produce force using resistance training (Dos'Santos, Thomas et al., 2018) and should potentially consider horizontally orientated lower-limb plyometrics due to the importance of force vector specificity observed in the present study (Dos'Santos, Thomas et al., 2018). In addition, because of the substantial deceleration requirements during the 505, and the necessity to generate high braking forces, eccentric strength may also be beneficial to facilitate more effective deceleration (Graham-Smith et al., 2018; Harper et al., 2018; Jones et al., 2017), particularly the knee extensors.

It should be noted that the present study investigated a planned 505; thus, it is emphasised that the findings from this study highlighting the importance of the APFC are applicable to high-entry velocity, planned 180° COD tasks. Thus, caution is advised regarding the generalisations of these results to CODs of different angles, approach distances, and techniques because the biomechanical demands of COD are "angle-' and 'velocity-dependent' (Dos'Santos, Thomas et al., 2018) and influenced by technique (Dos'Santos, McBurnie et al., 2019). Therefore, further research is necessary that investigates the APFC during CODs of different angles (i.e., 90° cut) and during different approach distances (i.e., m505). Because the present study investigated a planned 505, caution is advised regarding the application of the current study's findings regarding APFC dominant braking strategies for unplanned CODs in open-skill sports such as soccer. This is because of the time requirements to adopt preparatory postural adjustments to facilitate earlier, effective braking; however, future work should investigate the role of the APFC during unplanned CODs and consider its potential role during sport-specific COD actions. It should be noted that the present study only examined the GRF characteristics of the foot contacts, and did not examine the joint kinetics, kinematics, and velocity profiles over the different foot contacts and thus warrants further inspection. Additionally, future work should consider investigating the technical determinants of greater magnitudes of horizontally orientated APFC braking forces to assist in the development of coaching and technical guidelines for effective braking strategies for fast and sharp COD tasks. Finally, the present study investigated turning from the right limb only (18 subjects' preferred limb); thus, it unknown whether findings would be similar when performing turns from the left limb, which in most cases would be the current populations' non-preferred limb (18 of 20 subjects). Thus, further studies inspecting 180° turning off both limbs are required to further understand the role of APFC.

Nevertheless, in context of the present studies limitations, the results of this study regarding the importance of the APFC have widescale implications regarding the coaching of braking strategies during planned, high-entry velocity 180° CODs, particularly during the coaching of the 505 which is commonly used for athletic monitoring and talent identification in a variety of sports (Nimphius et al., 2017), and during closed COD drills which serve as the mechanical foundation before progressing to more complex unanticipated and sports-specific drills (Dos'Santos, McBurnie et al., 2019; Dos'Santos, Thomas, Comfort et al., 2019; Nimphius, 2014, 2017). In a sporting context, the 505 closely resembles the task demands of running and turning between the wickets during cricket (Foden et al., 2015), thus the findings of this study have large implications for cricket batsmen.

Practical applications

While recent braking strategy recommendations have highlighted the importance of the PFC for facilitating faster 180° COD performance (Dos' Santos et al., 2019; Dos'Santos, Thomas, Comfort et al., 2019; Dos'Santos et al., 2017a), the findings from this study indicate that the APFC plays a more pivotal role in facilitating effective deceleration for faster 180° COD performance as experienced during a 505, and should be therefore considered a key "braking step" in such tasks. As such, during 180° CODs from long approach distances, practitioners are encouraged to coach braking strategies that emphasise greater magnitudes of posteriorly directed APFCs GRFs to facilitate faster performance, while also developing their athletes' technical ability to express force horizontally across the PFC and FFC, to enable greater changes in acceleration. Substantially lower peak and mean GRFs were observed during the PFC compared to the APFC; therefore, the APFC may play a more pivotal role in facilitating deceleration and braking compared to the PFC for effective 505 performance. Nevertheless, both the APFC and PFC are likely to serve dual roles with respect to "braking" and "positioning" the body for redirection, weight acceptance, and COM lowering during sharp COD tasks (Dos'Santos, Thomas et al., 2018; Dos'Santos, Thomas, Comfort et al., 2019). Finally, in light of the GRF determinants of faster 180° COD performance, practitioners should consider developing their athletes' physical capacity to express force rapidly (Dos'Santos, Thomas et al., 2018), while ensuring they have the strength capacity, particularly knee extensor eccentric strength, to tolerate the loads and generate the high braking forces required to facilitate effective deceleration (Graham-Smith et al., 2018; Harper et al., 2018; Jones et al., 2017).

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