BIOMECHANICAL DETERMINANTS OF THE MODIFIED AND TRADITIONAL 505 CHANGE OF DIRECTION SPEED TEST

ABSTRACT

The aim of this study was to investigate the whole-body biomechanical determinants of 180° change of direction (COD) performance. 61 male athletes (age: 20.7 ± 3.8 years, height: 1.77 ± 0.06 m, mass: 74.7 ± 10.0 kg) from multiple sports (soccer, rugby, and cricket) completed 6 trials of the modified and traditional 505 on their right leg, whereby 3D motion and ground reaction force data were collected during the COD. Pearson's and Spearman's correlations were used to explore the relationships between biomechanical variables and COD completion time. Independent T-tests and Hedges' *g* effect sizes were conducted between faster (top 20) and slower (bottom 20) performers to explore differences in biomechanical variables. Key kinetic and kinematic differences were demonstrated between faster and slower performers with statistically significant ($p \leq 0.05$) and meaningful differences ($g = 0.56$-2.70) observed. Faster COD performers displayed greater peak and mean horizontal propulsive forces (PF) in shorter ground contact times, more horizontally orientated peak resultant braking and PFs, greater horizontal to vertical mean and peak braking and PF ratios, greater approach velocities, and displayed greater reductions in velocity over key instances of the COD. Additionally, faster performers displayed greater penultimate foot contact (PFC) hip, knee, and ankle dorsi-flexion angles, greater medial trunk lean, and greater internal pelvic and foot rotation. These aforementioned variables were also moderately to very largely (r or $\rho = 0.317$-0.795, $p \leq 0.013$) associated with faster COD performance. Consequently, practitioners should focus not only on developing their athletes' ability to express force rapidly, but also develop their technical ability to apply force horizontally. Additionally, practitioners should consider coaching a 180° turning strategy which emphasizes high PFC triple flexion for center of mass lowering while

also encouraging whole-body rotation to effectively align the body towards the exit for faster performance.

Key words: turning; pivoting; braking force; propulsive force; force vector

INTRODUCTION

The ability to rapidly decelerate, turn 180°, and reaccelerate again is considered an important physical quality in multidirectional sports (soccer, netball, cricket, and basketball) (4, 14, 43, 50). For example, soccer players perform ~100 turns of 90-180° (4), when the team is in and out of possession, such as transitioning from defence to attack (and vice versa). Sweeting et al. (43) reported 180° turns are frequently performed movements in netball, similar to the number of 90° turns performed, and in cricket the 180° turn is a fundamental movement for batsmen, whereby approximately 40 turns are performed when scoring 100 runs during a match (14). Additionally, 180° turns feature in change of direction (COD) speed tests, such as the modified (mod505) and traditional 505 (tra505) and pro-agility (35, 37). These tests are included in the fitness testing batteries of numerous sports (7, 13, 35-37, 44, 45), and are often required by sporting national governing bodies for longitudinal monitoring purposes (7, 44). Importantly, however, these aforementioned tests are also used for talent identification, such as the National Football League combine (15), and 180° turns are performed in endurance field-based cardio respiratory tests, such as the 30-15 intermittent fitness test and bleep test. Consequently, given the importance of 180° COD ability in multidirectional sport and fitness and COD speed tasks, it is important to understand the technical and mechanical determinants of faster 180° COD performance.

Lower-limb strength and power qualities, linear speed, and technical factors such as trunk lean and posture, foot placement, and stride adjustment have been suggested as factors linked to faster COD speed performance (50). Currently, there is a paucity of studies that have investigated the biomechanical and technical determinants of 180° COD performance; however, these studies are limited to trunk kinematic (39) and ground reaction force (GRF) (9, 17, 41) determinants. Sasaki et al. (39) found mod505 performance was associated with smaller forward angular trunk displacements and shorter ground contact times (GCT) during the plant-foot contact. Other technical factors such as foot placement and pelvis rotation may be central to 180° COD performance to effectively orientate and align the body towards the intended direction of travel (10, 21). Moreover, triple flexion of hip, knee, and ankle during 180° CODs may be important to lower the center of mass (COM) to increase stability and place the athlete in an optimal position for weight acceptance and push-off (10, 23). To the best of our knowledge, no study has examined the lower-limb and trunk biomechanical determinants of 180° COD performance. This is important because coaches and practitioners are interested in coaching and technical guidelines to enhance 180° COD performance.

Exploring the GRF determinants during the plant-foot contact of a 180° turn, Spiteri et al. (41) found faster female basketball athletes during the tra505 produced greater vertical braking (VBF) and propulsive forces (VPF) during the final foot contact (FFC) (plant-foot contact), and produced shorter braking and propulsive times, thus shorter total GCTs. Examining both vertical and horizontal GRF, Dos'Santos et al. (9) also found faster male athletes during a mod505 produced greater horizontal propulsive forces (HPF) in shorter GCTs, However, in contrast to the results of Spiteri et al. (41), faster performance was associated with lower VBF (9). Additionally, Graham-Smith et al. (17) revealed faster 180˚ COD performance was associated with greater peak FFC HBF. These findings are unsurprising because, based on the impulse-momentum relationship, greater force production will increase impulse, therefore leading to greater changes in velocity (5, 10). Moreover, the results from the aforementioned studies potentially highlight the importance of force vector specificity and the orientation of force application for effective braking and propulsion (reacceleration). Research into sprinting

GRFs has demonstrated the importance of not only the magnitude of the resultant force, but the orientation of force application for faster performance (31, 32). As force is a vector, possessing both magnitude and direction, several studies have highlighted the importance of the magnitude of single components of propulsive and braking forces (9, 17, 41) when changing direction 180°, but no study, to the best of our knowledge, has quantified the resultant braking and propulsive force and orientation of the force vector.

Because changing direction 180° requires an athlete to reduce their horizontal velocity of COM to zero (29), athletes will need to decelerate their COM by braking over a series of steps prior to changing direction (10, 29, 33). As such, changing direction is described as a multistep action (10, 26). The role of the penultimate foot contact (PFC) is an emerging area of research regarding 180˚ turning biomechanics (9, 10, 17, 29), with the results of previous research showing greater PFC HBFs associated with faster 180° COD performance (9, 17). Additionally, the PFC has also been described as a "preparatory step" which facilitates an effective body position for weight acceptance and push-off during the FFC (9, 10, 26). However, no study to date has examined the relationship between braking joint kinetic and kinematics of the PFC with 180° COD performance. Furthermore, as the mod505 and tra505 comprises of linear running prior to and following the COD (35), faster approach velocities have been identified as factors associated with faster completion times (29, 41). Jones et al. (29) reported eccentrically stronger (knee extensor) female soccer players during a 180° COD task demonstrated greater approach velocities at PFC touch-down, and demonstrated greater reductions in velocity and greater PFC braking characteristics, such as peak and mean HBF, which facilitated faster performance. As such, it appears that if greater reductions in velocity can be achieved over PFC from faster entry velocities, through greater PFC dominant braking strategies, this may facilitate faster 180° COD performance. Consequently, further research is needed that investigates the biomechanical determinants of 180° COD speed performance by considering the velocity profile over key instances of the COD (i.e. PFC and FFC) and examining the lower-limb and trunk kinetic and kinematic determinants.

The aim of this study, therefore, was to investigate the lower-limb and trunk biomechanical determinants of 180° COD performance during the mod505 and tra505 by conducting three-dimensional (3D) and GRF analysis over the PFC and FFC. Conducting such research into the technical and mechanical determinants of faster COD may assist in the development of more effective 180˚ turning coaching guidelines and strength and conditioning programmes. It was hypothesized that faster 180° COD performance would be associated with greater PFC braking forces, greater HPFs in shorter GCTs, greater approach velocities and reductions in velocity, a more horizontally orientated force vector, and greater pelvic and internal foot progression angles.

METHODS

Experimental approach to the problem

This study used a mixed, cross-sectional design to determine the relationship between COD biomechanics and mod505 and tra505 performance (completion time) following as associative strategy. In addition, a between-subject, comparative design was used to explore differences in COD biomechanics between faster (top 33%, $n = 20$) and slower (bottom 33%, $n = 20$) subjects, similar to previous research (9, 41). Subjects performed six mod505 and tra505 trials from their right leg (Figure 1). 3D motion and GRF analysis was used to explore the joint kinetic, kinematic, and GRF determinants of performance. Pearson's and Spearman's correlations were used to explore the relationships between biomechanical variables and COD completion time. Independent T-tests and Hedges' *g* effect sizes were conducted between faster (top 20) and slower (bottom 20) performers to explore differences in biomechanical variables, similar to previous research (9).

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) (16). This was based upon a previously reported correlation value of 0.757 (GCT to completion time) (25), a power of 0.95, and type 1 error or alpha level 0.05. As such, 61 male athletes from multiple sports (soccer, rugby, and cricket) (mean ± SD; age: 20.7 ± 3.8 years, height: 1.77 ± 0.06 m, mass: 74.7 ± 10.0 kg) participated in this study. 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 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 approved by the institutional ethics review board, and all subjects were informed of the benefits and risks of the investigation prior to signing an institutionally approved consent and parental assent documents to participate in the study.

Procedures

Prior to maximal COD speed tasks, subjects performed a 5-minute warm up consisting of jogging, self-selected dynamic stretching, and familiarisation trials of the mod505 and tra505 (four per task performed submaximally at 75% of perceived maximum effort) (8).

Mod505 and tra505 COD assessments

Subjects performed six mod505 trials and then after 5 minutes' rest performed six tra505 trials (Figure 1). All COD trials were performed on the right leg. The mod505 and tra505 have been described previously (7, 12, 13), thus a brief overview is provided here. 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 to the turning point before changing direction 180° and exiting and reaccelerating to the finish line (Figure 1.). Each trial was interspersed with two minutes' rest. If the subject slid, turned prematurely, 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) was measured using sets of single beam Brower timing lights (Draper, UT, USA) that were set at approximate hip height for all subject, to ensure that only one body part (such as the lower torso) breaks the beam (49).

Insert Figure 1 about here

The 3D motion and GRF analysis procedures were based on previously published protocols (8, 26, 29), thus only a brief overview is provided. Prior to the COD tasks, reflective markers (14 mm spheres) were placed on bony landmarks of each subject by the lead researcher (8, 26, 29). Each subject wore a four-marker 'cluster set' (four retroreflective markers attached to a lightweight rigid plastic shell) on the right and left thigh and shin which approximated the motion of these segments during the dynamic trials. All subjects wore lycra shorts and standardised footwear (Balance W490, New Balance, Boston, MA, USA) to control for shoe–surface interface.

Data analysis

3D motions of these markers were collected during the COD trials over the PFC and FFC using 10 Qualisys Oqus 7 (Gothenburg, Sweden) infrared cameras (240 Hz). The GRFs were simultaneously collected from two 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 (Figure 1). Motion and force data were simultaneously collected and synchronised through Qualisys Track Manager software (Qualisys, version 2.16 (Build 3520), Gothenburg, Sweden) (Figure 1). Penultimate foot contact (PFC) was defined as the second last foot contact with the ground before moving into a new intended direction, and the FFC was defined as the phase during a pivot when an individual makes contact with the ground and initiates movement into a different direction (9).

From a standing trial, a 6 degrees of freedom kinematic model of the lower extremity and trunk was created for each subject (scaled for body mass and height), including pelvis, thigh, shank, and foot using Visual 3D software (C-motion, version 6.01.12, Germantown, USA). This kinematic model was used to quantify the motion at the hip, knee, and ankle joints using a Cardan angle sequence x-y-z (42). The local coordinate system was defined at the proximal joint center for each segment. A static trial position was collected for each subject which designated the subject's neutral (anatomical zero) alignment, and subsequent kinematic and kinetic measures were related back to this position. Segmental inertial characteristics were estimated for each subject (6). This model utilised a CODA pelvis orientation to define the location of the hip joint center (3). The knee and ankle joint centers were defined as the mid-point of the line between lateral and medial markers.

The trials were time normalised for each subject to 101 data points with each point representing 1% of the weight acceptance or push-off phase (i.e. 0 to 100% of weight acceptance) of the turn. Initial contact (touch-down) was defined as the instant of ground contact that the vertical GRF was higher than 20 N, and end of contact (toe-off) was defined as the point where the vertical GRF subsided past 20 N (25, 27). The weight acceptance phase was defined as the instant of initial contact to the point of maximum knee flexion (25, 27), and the push-off phase (propulsive phase) was defined as the period from maximum knee flexion to toe-off. Lower-limb joint moments were calculated using an inverse dynamics approach (47) through Visual 3D software and were defined as external moments and normalised to body mass. Using the pipeline function in Visual 3D, joint coordinate (marker) and force data were smoothed Butterworth low-pass digital filter with cut-off frequencies of 15 Hz and 25 Hz, based on *a priori* residual analysis (48), visual inspection of motion data, and recommendations by Roewer et al. (38).

Change of direction kinetic and kinematic variables

A full description of dependent variables along with definitions, abbreviations, and calculations are provided in Table 1. Briefly, joint moments were normalised relative to body mass and calculated over the PFC and FFC. Lower-limb joint and trunk angles were also calculated. GRF braking and propulsive characteristics were normalised relative to body weight, with vertical, anterior-posterior, and medio-lateral corresponding to Fz, Fx, and Fy, respectively. GRF variables were calculated as the peak and mean. Horizontal COM velocity profiles over key instances of the COD were calculated as described previously (29).

Insert Table 1 about here

A subset of the sample (n = 10) performed the tra505 on two separate occasions separated by 7 days to establish between-session reliability. The reliability measures for COD biomechanics data is presented in Table 1 of supplemental digital content 1, but all joint angle (Intraclass correlation coefficient [ICC] = 0.858-0.953, coefficient of variation [CV] = 2.9-5.3%), joint moment (ICC = 0.743-0.888, CV = 6.9-14.9%), and GRF (ICC = 0.717-0.966, CV = 3.6-7.3%) variables demonstrated high and acceptable reliability (i.e. ICC ≥ 0.70, CV ≤ 15%) (2, 19). Completion times also demonstrated high reliability (ICC = 0.935, CV% = 1.4). A minimum of four trials was used for the analysis for each subject based on visual inspect of motion files (26) and the average of individual trial peaks for each variable were calculated as recommended by previous research for discrete point analysis (8).

Statistical Analyses

All statistical analyses were performed in SPSS v 25 (SPSS Inc., Chicago, IL, USA) and Microsoft Excel (version 2016, Microsoft Corp., Redmond, WA, USA). Normality was inspected for all variables using a Shapiro-Wilk's test. To explore the biomechanical determinants of completion time, Pearson's (for parametric data) or Spearman's (for non-parametric data) correlations were used. 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) (24). Moreover, comparisons in COD biomechanics between the faster and slower (top third vs. bottom third completion times), were also performed using independent sample t-tests (parametric) or Mann-Whitney U tests (non-parametric), similar to previous research (9, 41). To explore the magnitude of differences between groups, Hedges' *g* ESs with 95% confidence intervals were calculated as described previously (22), and interpreted as trivial (< 0.19), small (0.20 – 0.59), moderate (0.60 – 1.19), large (1.20 – 1.99), very large (2.0 – 4.0), and extremely large (>4.0) (24). Statistical significance was defined $p \leq 0.05$ for all tests, with p values Bonferroni corrected to control for type 1 error.

RESULTS

Descriptive statistics for mod505 and tra505 COD biomechanics variables are presented in Table 2 of supplemental digital content 2. Completion times for the mod505 and tra505 were 2.728 ± 0.160 s and 2.472 ± 0.146 s, respectively.

The correlation values with 95% confidence intervals between COD biomechanical variables and mod505 and tra505 completion times are presented in Table 2. Faster mod505 completion times were very largely associated with a greater horizontally orientated RPF vector (Figure 2a), and greater horizontal to vertical peak and mean propulsive force ratios.

Additionally, greater PFC horizontal to vertical peak and mean braking force ratios, greater PFC peak hip flexion angles, greater PFC peak knee flexion angles (Figure 2b), and more horizontally directed PFC peak RBF vectors were largely associated with faster mod505 performance. Faster mod505 completion times were also moderately associated with greater FFC peak and mean HPFs, shorter FFC GCTs, greater PFC peak ankle dorsi-flexion angles, greater PFC and FFC forward trunk inclination angle at IC, greater PFC trunk displacement, and medial trunk flexion at IC.

A very large association was observed between tra505 completion times and PFC horizontal to vertical mean braking force ratio**.** Faster tra505 completion times were largely associated with a greater horizontally orientated RPF vector (Figure 2c), greater horizontal to vertical peak and mean propulsive ratios, and greater PFC horizontal to vertical peak braking force ratios. Faster tra505 completion times were largely associated with greater peak and mean HPFs, greater horizontally orientated PFC and FFC RBF vectors, and shorter approach times. Faster tra505 performance was also moderately associated with shorter FFC GCTs, greater PFC peak hip flexion angles, greater PFC peak knee flexion angles (Figure 2d), greater PFC peak ankle dorsi-flexion angles, greater PFC trunk inclination angles at IC, greater medial trunk lean at IC, greater FFC mean HBFs, greater mean RPFs, greater approach velocities and velocity at FFC touch-down, and greater reductions in velocity over the FFC.

Insert Figure 2 about here

Insert Table 2 about here

Fast versus slow comparisons in mod505 COD biomechanics are presented in Table 3 which contain descriptives, *p* values, and ESs with 95% CIs. Significant and extremely large differences were observed for mod505 completion times. Faster athletes demonstrated a significantly more horizontally orientated RPF vector, and greater peak and mean horizontal to vertical propulsive force ratios, and PFC peak and mean horizontal to braking force ratios compared to slower, with large to very large effect sizes. Faster athletes demonstrated significantly greater PFC peak hip flexion angles, greater PFC peak knee flexion angles, and greater PFC peak ankle dorsi-flexion angles compared to slower athletes, with moderate to large effect sizes. Faster athletes produced significantly greater peak and mean HPFs in shorter FFC GCTs, with moderate effect sizes, while also demonstrating more horizontally directed PFC and FFC RBF vectors with large and moderate effect sizes, respectively. Faster athletes displayed significantly greater PFC and FFC forward trunk inclinations angles at IC and PFC trunk displacement compared to slower; all of which were classed as moderate differences. Although not significantly different, faster athletes demonstrated greater pelvic rotation and IFPAs compared to slower, with moderate effect sizes. No significant differences were observed for sagittal plane joint moments and velocity profiles at key instances, with differences classed as trivial to small.

Fast versus slow comparisons in tra505 COD biomechanics are presented in Table 4 which contain descriptives, *p* values, and ESs with 95% CIs. Significant and extremely large differences were observed for tra505 completion times between faster and slower performers. Faster athletes demonstrated a greater horizontally directed RPF vector, and greater peak and mean horizontal to vertical propulsive ratios, and PFC peak and mean horizontal to braking force ratios compared to slower, with moderate to very large effect sizes. Faster athletes compared to slower athletes demonstrated significantly greater PFC peak hip, knee, and ankle dorsi-flexion angles with moderate to large effect sizes. Faster athletes produced significantly greater peak and mean HPFs in shorter GCTs, displayed greater FFC mean HBFs, and a more horizontally orientated PFC and FFC RBF vector, with moderate to large effect sizes. Faster athletes compared to slower demonstrated significantly faster approach times, greater approach velocities and FFC touch-down velocities, and greater reductions in velocity over key instances of the PFC and FFC, which were classed as moderate to large differences. No significant differences were observed between faster and slower athletes for sagittal plane joint moments and pelvic and IFPA, with small effect sizes.

Insert Table 3 about here

Insert Table 4 about here

DISCUSSION

The aim of this study was to investigate the whole-body biomechanical determinants of 180° COD performance during the mod505 and tra505. To the best of our knowledge, this is the first study to examine the whole-body biomechanical determinants of the mod505 and tra505 in a large male sample while also examining the role of PFC. The primary findings were that key kinetic and kinematic differences were demonstrated between faster and slower COD performers (Tables 2-4), with faster athletes displaying greater peak and mean HPFs in shorter GCTs, more horizontally directed peak RPF and RBF vectors over the PFC and FFC, greater horizontal to vertical mean and peak braking and propulsive force ratios, greater FFC HBFs, greater approach velocities and displayed greater reductions in velocity over key instances of the COD. Additionally, faster performers displayed greater PFC hip, knee, and ankle dorsi-flexion flexion angles, greater PFC and FFC trunk inclination angles, greater medial trunk flexion and greater pelvic rotation and IFPAs (Tables 2-4). These aforementioned variables were also moderately to very largely associated with faster performance (Table 2), supporting the study hypotheses.

The majority of studies that have investigated the determinants of 180° COD performance have investigated GRF (9, 17, 41) and found faster performance was associated with greater peak HPFs and short GCTs (9, 17), while Spiteri et al. (41) found faster athletes displayed greater VBF and VPFs in short GCTs, but did not examine horizontal force. Substantiating the results of previous research (9, 17), faster performance during the mod505 and tra505 were moderately to largely associated with greater peak and mean HPFs (Table 2) in short FFC GCTs, while fast versus slow comparisons revealed moderate differences in these variables too (Tables 3-4). Conversely, VPF was not significantly associated with faster performance, and in fact greater mean and peak horizontal to vertical propulsive ratios were largely to very largely associated with faster performance (Table 2). This result is similar to Welch et al. (46) who also observed greater horizontal to vertical concentric impulse ratios were associated with faster 110° cutting performance, which highlights not only the importance of the magnitude of HPF, but the proportion of HPF relative to VPF for faster COD performance. The finding that shorter FFC GCTs is associated with faster COD is unsurprising because athletes will spend less time during the braking and propulsive phase (41), ultimately spending less time performing the COD (9, 41), and may utilise the stretch shortening cycle to a greater effect (46). Additionally, the greater propulsive forces in the horizontal direction will increase impulse, thus resulting in greater changes in momentum and subsequent exit velocity in the horizontal direction (5, 32). Stronger athletes have been shown to produce greater braking and propulsive during CODs (29, 40), and thus will partially influence an athletes ability produce high and rapid levels of braking and propulsive forces. Nevertheless, these findings support the notion that applying high and rapid levels of HPF relative to vertical force in short GCTs is necessary for maximising 180° COD performance.

To the best of our knowledge, this is the first study to calculate the RBF and RPF during a 180° COD task while also calculating the orientation of the force vector. Interestingly, mean and peak RPF demonstrated lower associations and lower effect size differences between faster and slower athletes compared to HPF (Tables 2-4). Notably, however, faster performance was largely associated with a more horizontally directed PFC and FFC RBF vector, attributed to the greater horizontal to vertical peak and mean braking force ratios observed, which were also strongly associated with faster performance and demonstrated by faster athletes (Tables 2-4). Research into sprinting GRFs has revealed faster athletes are technically more efficient at applying a more horizontally orientated force vector (31, 32). The present study confirms that 180° COD performance, too, is also dependent on the technical ability to express a more horizontally orientated braking and propulsive force vector (Tables 2-4), explaining 30 to 60% of variance of COD performance. This finding can be explained because a more horizontally directed force vector should help facilitate more effective braking and net deceleration (negative acceleration) (10) and reductions in velocity of the COM which have been associated with faster 180° COD performance (29). Additionally, trivial to small differences were observed between faster and slower performers in terms of RBF and RPF, whereas differences in HPF were statistically significant and moderate. However, it should be noted that faster athletes displayed a more horizontally orientated RPF with large to very large effect sizes observed (Tables 3-4). This finding is important because for the same RPF applied into the ground, a greater horizontal to vertical propulsive ratio (i.e. greater horizontally orientated force vector) should result in a greater net horizontal acceleration (32). Thus, these findings confirm not only the importance braking and propulsive force magnitudes, but the technical application and orientation of the force vector for maximising 180° COD performance.

The PFC is an emerging area of research given its role in deceleration and sharp COD performance (9, 10, 29). Previously, it has been shown that greater peak PFC HBFs were associated with mod505 performance (9, 17); however, this result was not observed in the present study. No significant association was found for any PFC peak or mean braking force variable in relation to faster performance, while fast versus slow performance comparisons also revealed non-significant trivial to small differences in the PFC braking joint moments and peak and mean braking forces (Tables 2-4). Although not significantly different, faster performers demonstrated similar mean RBFs over slightly longer PFC GCTs (small effect size) (Tables 3-4). Therefore, hypothetically, faster performers may have displayed greater braking impulse to facilitate a greater change in momentum and thus greater reductions in velocity. Importantly, however, faster performers displayed greater (moderate to large ES) hip, knee, and ankle dorsi-flexion angles, and these variables were also moderately to largely associated with faster COD performance (Table 2). Theoretically, the greater PFC triple flexion lowers the athlete's COM which increases stability and could put the athlete in a more technically effective position to produce a more horizontally orientated RBF vector, prolonging PFC GCT duration thus increasing braking impulse, while enabling a more effective body position for the FFC drive-off phase (10). Though it is worth noting that an athlete's ability to adopt favourable body postures associated with faster 180° turning will be underpinned by their physical capacity (11, 29, 34, 40). Nevertheless, a PFC braking strategy with high hip, knee, and ankle-dorsi flexion appears to be an effective strategy for faster 180°COD performance and should therefore be encouraged when coaching 180° turning technique.

A novel aspect of the present study was inspecting COM velocity over key instances of the PFC and FFC. Previously, Jones et al. (29) found a moderate relationship between PFC approach velocity and 180° COD performance, and eccentrically stronger athletes displayed greater velocity reductions over the PFC and FFC which contributed to faster COD performance. For the 505 in the present study, faster athletes displayed greater PFC approach velocities and greater velocity reduction over key instances of the COD (PFC and FFC) with moderate effect sizes observed (Tables 2-4). Although strength capacity was not examined in the current study, it could be speculated the faster athletes may have had a superior eccentric strength capacity which permits more effective braking and reductions in velocity from faster approach velocities (20, 29), and enables athletes to adopt favourable postures for faster 180° turning (11, 29, 34, 40). Further research is required that confirms whether stronger athletes display greater braking characteristics and favourable drive-off mechanics associated with faster performance. Nonetheless, these findings highlight the ability to exhibit greater changes in velocity from faster approach velocities is paramount for faster tra505 performance.

Trunk stability has also been suggested to be a factor linked to faster COD performance (30, 39, 46). Sasaki et al. (39) found faster athletes during the mod505 demonstrated smaller forward trunk angular displacements ($r = 0.61, p < 0.05$), and also suggested a potential optimal lateral trunk inclination may exist. Conversely, in the present study, faster performance was associated with greater PFC and FFC trunk forward inclination angles and displacements (Tables 2-4). It is unknown why an opposing finding was found to Sasaki et al. (39) but it is speculated that a greater forward trunk inclination could be used to lower the COM and be a by-product of faster approach velocities. Interestingly, and most likely more important for faster 180° COD performance, was faster athletes displayed greater (small to moderate ES) medial trunk flexion (i.e. leaning towards the intended direction of travel) and demonstrated greater pelvic rotation and internal foot progression angles (i.e. pelvis and foot rotated towards intended direction of travel) (Table 2-4), as illustrated in Figure 3. By emphasizing greater whole-body pre-rotation and medial trunk lean during the FFC, the athlete is more effectively aligning their COM towards the intended direction of travel and minimizing their COM displacement relative to their base of support, and the COM will not have to travel as much distance relative to the turning line, thus positively contributing to faster performance (10, 21). Consequently, coaching greater whole-body rotation (i.e. trunk, pelvis, lower-limb) and medial trunk lean could be an effective strategy to improve 180° COD performance (Figure 3A). However, practitioners should acknowledge that greater internal foot progression angles are associated with increased knee abduction moments (10, 27), and thus be aware of the performance-injury trade-off when coaching this technique.

Insert Figure 3 about here

While this study improves our understanding of the biomechanical determinants of the mod505 and tra505, the study does have a several limitations which should be noted. The present study only examined male athletes from soccer, cricket, and rugby, thus caution is advised generalizing the findings to different sexes and athletic postulations. Further research is needed that investigates the biomechanical determinants of 505 performance in female athletes and athletes from different athletic populations. The biomechanics of FFC and PFC were inspected; however, COD is a multistep action and deceleration is most likely going to occur over a series of steps, especially for the traditional 505 where greater approach velocities are attained (10, 18). Future research should therefore consider inspecting the role of pre-penultimate foot contact and examining its role in facilitating deceleration during the tra505.

It should be noted that the present study focused on the determinants of mod505 and tra505 performance which is pre-planned. Although investigating pre-planned COD was the aim of this study, coaches and practitioners should be cautious applying the present study's findings and technical and coaching recommendations for unplanned (agility) 180° CODs. For example, researchers have shown differences in braking strategies between pre-planned and unplanned 180° COD (28), and it is argued that the postures and associated mechanics adopted for faster pre-planned 505 are performed to "pass the test". The mechanics adopted during preplanned 505 tasks are most likely going to differ to unanticipated 180° CODs that are performed in multidirectional sports, such as turning in response to a ball or opponent. However, further research is needed to confirm this contention. Nevertheless, although the mod505 and tra505 differ in terms of approach distance and subsequent approach velocities, technical and mechanical determinants were similar between tasks (Table 2). Faster athletes adopt similar turning strategies between tasks (Tables 2-4); thus, practitioners can consider using similar technical guidelines presented in this study for 180° turning from low- and high-entry velocities.

PRACTICAL APPLICATIONS

In light of these factors associated with faster performance, coaches and practitioners should consider developing their athletes' ability to express force rapidly using resistance training and horizontally orientated lower-limb plyometrics (i.e. broad jumps, bounds, horizontal hopping) (1, 5, 11), and encourage 180° turning strategies which maximise and emphasize a more horizontally orientated braking and propulsive force vector. Additionally, faster approach velocities and velocity reductions over the PFC and FFC were also linked to faster performance. Previous research has shown that eccentrically stronger athletes can approach faster and display greater reductions in velocity over the PFC and FFC during 180° turns (29), and it is central that athletes have the physical capacity in order to adopt the favourable body postures associated with faster COD performance. Therefore, developing athletes' strength capacity, particularly eccentric strength, is a recommended training strategy. Finally, faster athletes demonstrated greater PFC hip, knee, and ankle dorsi-flexion angles, which mostly likely contributed to increased COM lowering and facilitating a more horizontally orientated RBF vector, while faster athletes also displayed greater whole-body rotation and medial trunk lean over the 8FFC. Consequently, coaches and practitioners are recommended to coach a 180° turning strategy which emphasizes high PFC triple flexion to lower the COM, facilitate an effective braking position, increase braking impulse, and emphasize a horizontally directed force-vector; while also encouraging whole-body (i.e. trunk, pelvis, lower-limb) rotation towards the intended direction of travel to minimise COM displacement and effectively align the COM.

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