Characterising coordination strategies during initial acceleration in sprinters ranging from highly trained to world class

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Abstract

Identifying the coordination strategies used by sprinters and the features that differentiate these strategies will aid in understanding different technical approaches to initial sprint acceleration. Moreover, multiple effective coordination strategies may be available to athletes of similar ability levels, which may be masked in typical group-based analyses. This study aimed to identify sub-groups of sprinters based on their thigh-thigh and shank-foot coordination during initial acceleration, and to assess sprint performance across different combinations of coordination strategies. Segment angular kinematics were obtained from 21 sprinters, and coordination was determined using modified vector coding methods, with step 1 and steps 2-4 separated for analysis. Sprint performance was assessed using metrics derived from the velocity-time profile. Using hierarchical cluster analysis, three distinct coordination strategies were identified from thigh-thigh and shank-foot coordination in step 1 and two strategies in steps 2-4. Coordination strategies primarily differed around early flight thigh-thigh coordination and early stance shank-foot coordination in step 1, while the timing of reversals in thigh rotation characterised differences in later steps. Higher performers tended to have greater lead thigh and foot dominance in step 1 and early swing thigh retraction in steps 2-4. The novel application of cluster analysis to coordination patterns provides new insights into initial acceleration technique in sprinters, with potential considerations for training and performance.

Keywords: Acceleration, kinematics, performance, sprinting, track and field

Introduction

Acceleration performance depends on positioning body segments and coordinating their rotations to effectively apply forces to the ground to propel the body forward [1–5]. In practical settings, a popular method for analysing sprint technique involves a sequence of images from key events, as demonstrated by the kinogram method [6]. These images depict ‘shapes’ [6], and whilst practitioners may visually consider the relations between segments, biomechanical investigations have typically focused on isolated joints or segments which do not facilitate easy interpretation of the relative motion of these elements, i.e. their coordination. Coordination thus describes the relative rotation of two functionally linked segments, aiding understanding of the transition from one key event (‘shape’) to another [7-9]. From a dynamical systems perspective, coordination emerges spontaneously from interacting individual, task and environmental constraints in a self-organising manner [10-13]. In acceleration, multiple technical strategies could therefore lead to the same performance outcome depending on the particular interaction between the individual, task, and environment - a feature known as degeneracy [14, 15]. Wild et al. [15] demonstrated this concept by showing that professional rugby backs could be clustered into four distinct sprint acceleration strategies based on the ratios of step length/frequency and contact time/flight time,but that no one strategy led to better acceleration performance. Such a characterisation of strategies remains unexplored from a coordination perspective, or in a trained-trained population.

The hip and ankle play important roles during the block phase and first steps of acceleration, with a relatively more minor role for the knee [16-20]. Jacobs and van Ingen Schenau [21] showed that sprinters accelerate the centre of mass through ‘rotation’ then ‘extension’ of the stance (i.e., support) limb. This aligns with the ‘shin roll’ framework proposed by Alt et al. [22], which describes shank rotation over the foot during stance in sprinting, potentially accounting, at least partly, for the ‘rotation’ component [21]. However, the foot is not a static base during stance and is an important component of ankle dorsi- and plantarflexion motions during ground contact [17, 19, 20]. Regarding the hips, bipedal gait inherently requires cyclic limb interchange [23], and Clark et al. [24] have shown the importance of large amplitudes of thigh separation and high frequencies of interchange to maximal velocity performance. Moreover, thigh action helps set up lower limb touchdown positions from which rotation occurs. Thus, characterising inter-limb thigh-thigh coordination can enhance the understanding of this interchange between limbs while intra-limb shank-foot coordination strategies can enhance the understanding of the adjacent segment rotations that comprise ankle motion.

Existing coordination and kinematic studies in acceleration have typically relied on a priori grouping based on criteria such as performance level, sprint event or task modification, when attempting to identify distinguishing kinematic parameters between groups [7, 8, 25]. However, such criteria are not always available or appropriate, especially in relatively homogeneous or continuous samples without clear divides. Moreover, a priori grouping ignores potential between-individual variation within groups, masking instances where different movement patterns can be used to produce the same performance outcome [15]. Whilst some researchers have suggested individualised profiling to address this limitation [26], such an approach overlooks the possibility that strategy sub-groups exist, owing to similarities in constraints between certain performers, as has been suggested in other running contexts [27]. Grouping sprinters based on similar coordination strategies and consequently exploring the frequency with which different strategies are adopted, and whether any strategies are typically associated with better performance outcomes, could therefore further develop knowledge regarding initial acceleration technique. While recent studies have described coordination during sprint acceleration [8, 28], none have attempted to understand acceleration technique and performance through sub-groups of coordination strategies. Given the considerable practical interest in the kinematics of effective acceleration, it is important to identify and explain the strategies adopted by sprinters, and the potential performance implications of each strategy. This will assist practitioners in assessing the technical approach of their athletes and designing individual specific interventions for training.

The purpose of this study was, firstly, to identify and characterise sub-groups of sprinters with similar coordination strategies during initial acceleration, and to assess whether different sub-groups are associated with differences in key discrete kinematic measures. Having analysed the coordination strategies of the different sub-groups, the second purpose was to compare performance between the sub-groups with a view to understanding whether certain strategies may be more beneficial for higher initial acceleration performance.

Methods

Fifteen male (age = 22.0 ± 3.6 yrs, stature = 1.77 ± 0.06 m, mass = 74.6 ± 9.7 kg, 100 m personal best = 9.89 - 11.17 s) and six female (age = 22.8 ± 6.5 yrs, stature = 1.62 ± 0.05 m, mass = 54.1 ± 2.2 kg, 100 m Personal best = 11.45 - 12.14 s) sprinters were recruited using convenience sampling and provided informed consent to take part in this study. All participants were 100 m and 200 m specialists, in the competition phase of their season, and injury free at the time of testing. According to the criteria of McKay et al. [29], fourteen sprinters (9 M, 5 F) were classified as highly trained, five as elite (4 M, 1 F) and two (2 M) as world class. For the purposes of our analysis, all were initially considered as part of a single cohort from which the sub-groups were subsequently determined using cluster analysis based on their coordination profiles. All procedures were performed in accordance with the declaration of Helsinki and the institutional research ethics committee approved the protocol (612/2020).

Participants performed three maximal effort sprint trials of at least 20 m, starting from blocks, in their own spikes. These were part of their typical sprint training and took place during regular training sessions in the competition phase of the season. Participants completed their habitual warm ups, and at least five minutes separated each trial to minimise the effects of fatigue.

Three-dimensional (3D) kinematics were recorded using tri-axial inertial measurement units (IMUs) (200 Hz; MyoMotion, Noraxon, USA), the validity and reliability of which have been previously reported [30-33]. Nine IMUs were affixed, according to manufacturer instructions, to the upper spine (T1), lower spine (T12), sacrum, lateral aspect of both thighs, antero-medial aspect of both shanks and the dorsal surface of each foot. All were secured using double-sided tape and either self-adhesive bandages or custom velcro straps to limit movement due to impact forces [28]. A sagittal plane camera (120 Hz, Ninox-250, Noraxon, USA) recorded the first four steps of each trial. IMU and video data were captured simultaneously and synchronised in real time with the MyoSync device and MyoResearch 3.14 software (Noraxon, USA). IMUs were calibrated in an upright standing posture prior to each trial with standardised instructions to establish the 0° reference angle, according to a previously described protocol for which good reliability has been established for this IMU system [30, 34]. Touchdown and toe-off were determined from video, with touchdown defined as the first frame with visible ground contact and toe-off the first frame where the foot was no longer visibly contacting the ground. Steps were defined from toe-off until the subsequent toe-off of the contralateral foot, starting from front foot block exit (TO_0). Flight time was determined as the time from toe-off until touchdown of the contralateral foot and contact time as the time from touchdown until toe-off. Limbs were designated as leading or trailing based on their relative position at the beginning of the step (i.e. toe-off) [8, 24]. Due to the cyclic nature of sprinting, whether the right or left leg was leading or trailing alternated at each toe-off. Angles of the trunk, lead and trail thigh, and lead limb shank and foot were extracted and defined according to the 0° reference angle of the standing calibration posture [28, 30]. All kinematic variables were time normalised to 101 data points for each step. Finally, average angular velocity over the entire step was determined for lead and trail thigh according to the methods of Clark et al. [24].

For each trial, a radar gun recorded instantaneous horizontal velocity (47 Hz; Stalker Pro II ATS, Stalker, USA). A simple macroscopic model was fit to velocity-time data, from which split times and force-velocity variables were extracted [35-36] using the shorts R package [37]. Theoretical maximum horizontal force (F_0), theoretical maximum velocity (V_0), maximum power (P_{Max}), maximum ratio of the horizontal force component to the resultant force (ratio of forces; RF_{Max}) and the slope of the relationship between RF and velocity (D_{RF}) were determined from the model, which have been shown to have a grand average bias of 4.7% and reliable within 2.4% for kinetic variables [36].

Inter-limb thigh-thigh and intra-limb shank-foot coordination were quantified from lead and trail thigh angles and lead limb shank and foot angles, respectively, using a modified vector coding technique [26, 28, 38]. Coupling angles (CA) were calculated as the angle of the vector between adjacent points relative to the right horizontal for each pair of consecutive points on the angle-angle plot, representing a vector between 0 and 360° describing the relative segment motion at each normalised time point (Figure 1(i)).

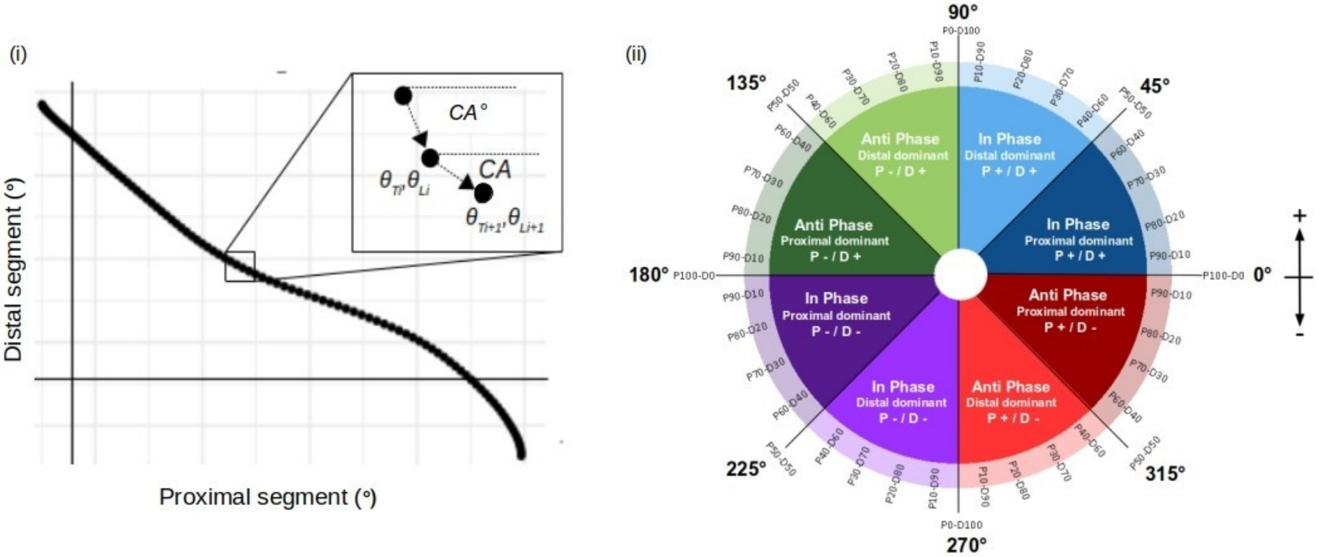


Figure 1: Example of angle-angle plot and coupling angle determination (i). Coordination bin classification system (ii), adapted from [26, 28].

Every CA was classified into a discrete bin describing the primary motion and the dominant segment according to the segment dominancy approach presented by Needham et al. [26, 28](Figure 1(ii)). Couplings were described as proximal-distal, with the trailing thigh designated as the proximal segment. Rotations were described as clockwise-anticlockwise, as viewed from the right hand side, with anticlockwise rotation designated as positive (+) [28]. Thus, coordination bins are labeled by the relative motion, the dominant segment and the direction of rotation of the dominant segment. For example, thigh-thigh coordination with an anti-phase pattern and anticlockwise leading leg segment dominance is described as anti-phase leading (+) (Figure 1) [28].

The similarity of coordination for every possible pair of participants, for each coupling, was calculated according to previously described methods [39], without the final subtraction from 1, producing a pairwise distance matrix of coupling angle distance scores (CA_{dist}). Briefly, at each time point, the angular distance between corresponding CA vectors (Figure 1(i)), θ, was calculated as follows:

$$\theta = \begin{cases} 360 - |A - B|, & \text{if } |A - B| > 180^\circ \\ |A - B|, & \text{otherwise} \end{cases} \tag{1}$$

For any pair of vectors, the maximum possible value of θ was 180◦, representing directly opposite vectors. Therefore the final CA_{dist} value was calculated as:

$$CA_{dist}(A,B) = \frac{\sum_0^t \theta(t)}{180t} \qquad (2)$$

Where *t* represents the number of normalised time points (i.e. the 100 CA vectors between the 101 time-normalised data points), yielding a value between 0 (identical vector orientations at each time point) and 1 (directly opposite vector orientations at each time point). Distance matrices were computed for all pairwise combinations of participants for thigh-thigh and shank-foot couplings. Previous studies identified step-to-step changes in kinematics during initial acceleration [3, 40] while coaching [41], kinematic [18, 19] and coordination [28] studies suggest that step 1 is different from later steps. Consequently, hierarchical agglomerative clustering analyses with complete linkage method were performed separately for step 1 and steps 2-4 coordination. The final number of clusters in each case were identified based on the agglomerative coefficient and visual inspection of the dendrograms [42-45].

Statistical Analysis

Group mean coordination profiles were determined for each cluster in step 1 and steps 2-4, and mean frequency (%) for each coordination bin was calculated. For each variable of interest, the normality assumption was assessed using a Shapiro-Wilks test. Between-cluster differences in bin frequency, linear and angular kinematic variables were assessed with Kruskal-Wallis and one-way analysis of variance (ANOVA) tests. Pairwise interactions between clusters were assessed with independent sample t-tests or Mann-Whitney U tests when two clusters were identified and Tukey or Wilcoxon signed rank tests for more than two clusters. All analyses were performed in R [46] using the *rstatix* [47] and *stats* [46] packages. Alpha level was set at 0.05.

Results

Three clusters were identified in step 1, labeled A, B and C (Figure 2(iii)). Cluster B accounted for 12/21 participants, with four and five in clusters A and C, respectively. Clusters A and B produced similar thigh-thigh coordination, with no significant differences in bin frequencies and only minor temporal visible differences in mean coordination profile (Figure 2(i & iv)). In contrast, cluster C produced significantly less in-phase trailing (+)($p = 0.044$) and anti-phase trailing (+)($p = 0.032$) than B (Figure 2(iv)). Participants in cluster C almost entirely lacked anti-phase leading (+) and in-phase leading or trailing (+) in early flight (Figure 2(i)). With the lower anti-phase trailing (+) frequency, the mean anti-phase leading (-) frequency in cluster C was 16% higher than cluster A and 14% higher than cluster B, but these differences were not significant. (Figure 2(iv)). For shank-foot coordination, in-phase foot (+) frequency was significantly higher in cluster A, than both B (p = 0.022) and C (p = 0.048) while cluster B was also significantly higher than C (p = 0.007)(Figure 2 (ii & v)). In cluster A, in-phase shank (-) and anti-phase shank (-) coordination were entirely absent, significantly lower than both B (p = 0.012) and C (p = 0.045). Cluster A further had significantly less in-phase foot (-) than C (p = 0.048) (Figure 2(v)). Thus, during flight, A had prolonged in-phase anti-clockwise rotation before touchdown compared to C, which reversed to in-phase clockwise rotation in mid flight. During early stance, A showed foot dominant anti-phase rotation, compared to shank dominant rotation exhibited by the other clusters.

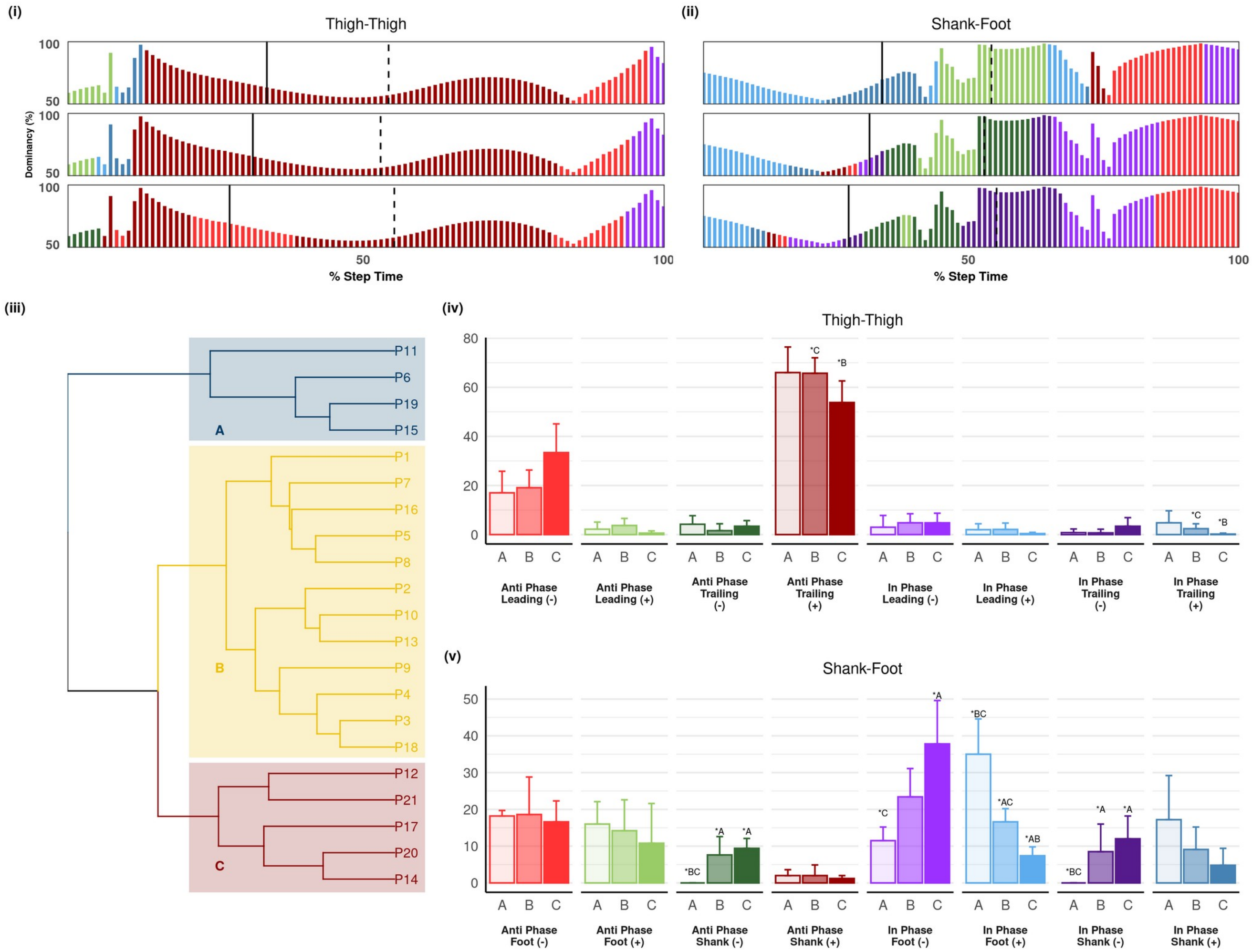


Figure 2: Step 1 mean coordination profiles for each cluster for thigh-thigh (i) and shank-foot (ii), dendrogram with clusters highlighted by colour (iii) and cluster mean coordination bin frequencies for each bin for thigh-thigh (iv) and shank-foot (v) couplings. Black vertical lines in figures (i) and (ii)indicate touchdown and dotted lines the thigh crossover in (i). The bin colours in (iv) and (v) serve as legends for (i) and (ii) respectively. *ABC annotations indicate significantly different to the respective (i.e. A, B or C) cluster, p < 0.05.

Two clusters were identified in steps 2-4, labeled X and Y (Figure 3(iii)). There were no significant differences in mean bin frequency across steps for any thigh-thigh bin (Figure 3(iv)). However, although in-phase leading (-) frequency was similar between clusters X and Y (Figure 3 (iv), participants in cluster X had in-phase coordination in late stance but those in Y had in-phase coordination during early flight (Figure 3(i)). Thus, cluster X began swing leg retraction in late stance whereas cluster Y only began at toe-off while continuing to rotate the stance leg clockwise after leaving the ground.

Cluster X had significantly less in-phase foot (+) than Y (p = 0.001), and had 5% more in-phase foot (-) coordination, but this was not significant (Figure 3(v)). Therefore, the primary difference between clusters was one of timing; participants in cluster Y spent longer in in-phase anti-clockwise rotation during flight and delayed the onset of anti-phase shank (-) and in-phase shank (-) coordination during stance (Figure 3(ii)).

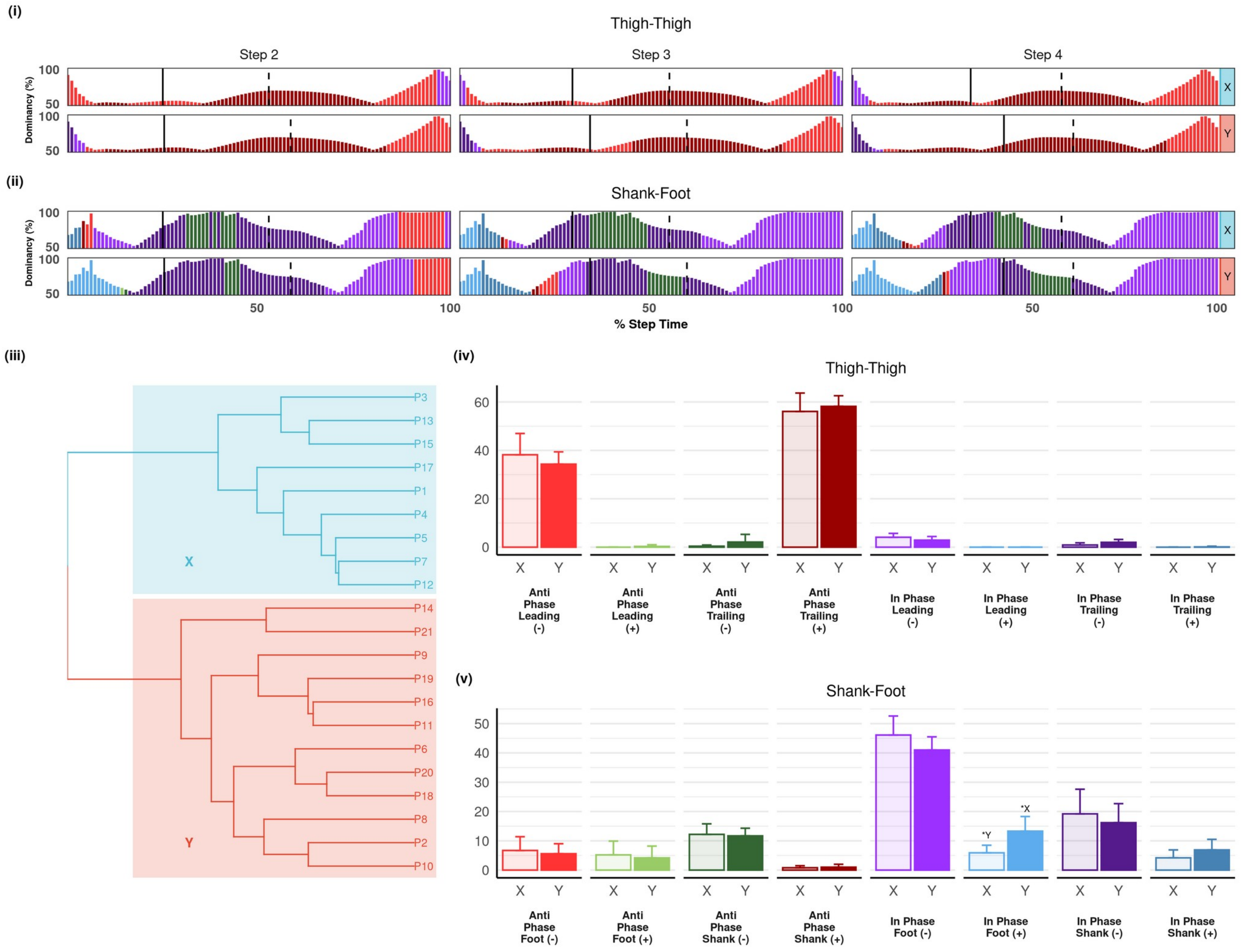


Figure 3: Step 2-4 mean coordination profiles for each cluster for thigh-thigh (i) and shank-foot (ii), dendrogram with clusters highlighted by colour (iii) and cluster mean coordination bin frequencies for each bin for thigh-thigh (iv) and shank-foot (v) couplings. Black vertical lines in figures (i) and (ii)indicate touchdown and dotted lines the

thigh crossover in (i). The bin colours in (iv) and (v) serve as legends for (i) and (ii) respectively. *XY annotations indicate significantly different to the respective (i.e. X or Y) cluster, $p < 0.05$.

At block clearance, thigh, shank and foot orientations differed between clusters (Figure 4(ii-iv)). Cluster C had significantly more vertical shank and horizontal foot orientations than both B and A, while B and A were also significantly different for both segments (Figure 4(iii-iv)). Moreover, C had a significantly more flexed lead thigh at block clearance compared to A and was 13° more flexed than B, but this was not significant (Figure 4(ii)). At touchdown, cluster A had significantly more horizontal shank orientations than both B ($p = 0.011$) and C ($p = 0.031$), as well as significantly more vertical foot orientations than C ($p = 0.037$)(Figure 4(vii-viii)). In step 1, cluster A had significantly shorter contact times (150 ± 6 ms) than C (194 ± 25 ms, $p = 0.015$), but not B (174 ± 22 ms) while there were no significant differences in flight times (A: 76 ± 9, B: 77 ± 13, C: 71 ± 13 ms) or lead (A: -272 ± 48, B: -270 ± 33, C: -291 ± 21 $°.sec^{-1}$) and trail (A: 382 ± 39, B: 360 ± 46, C: 347 ± 12 $°.sec^{-1}$) thigh angular velocities.

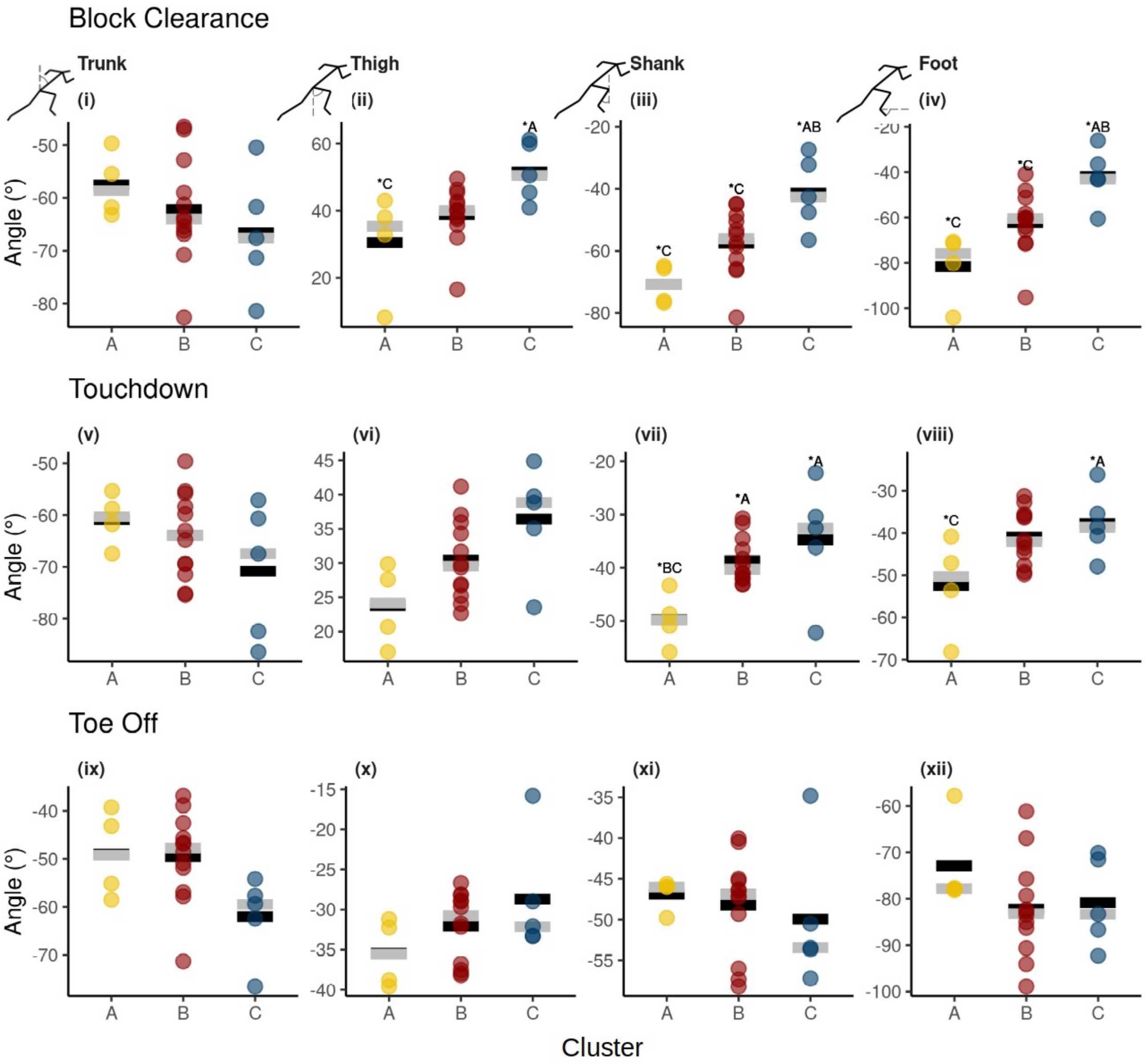


Figure 4: Discrete trunk, thigh, shank and foot segment angles at block clearance (i-iv), touchdown (v-viii) and toe-off (iv-xii) in step 1 for coordination clusters A, B and C. All angles are lead limb (designated at block clearance). Black horizontal bar represents the mean and the grey bar represents the median. *ABC annotations indicate significantly different to the respective (i.e. A,B or C) cluster, $p < 0.05$.

In steps 2-4, there were no statistically significant differences in mean touchdown and toe-off angular kinematics (Figure 5), nor did clusters differ significantly in contact times (X: 149 ± 17, Y: 141 ± 13 ms) or flight times (X: 60 ± 13, Y: 71 ± 14 ms). However, cluster X had significantly higher average lead thigh angular velocity (-399 ± 32 $°.s^{-1}$) compared to cluster Y (-372 ± 26 $°.s^{-1}$).

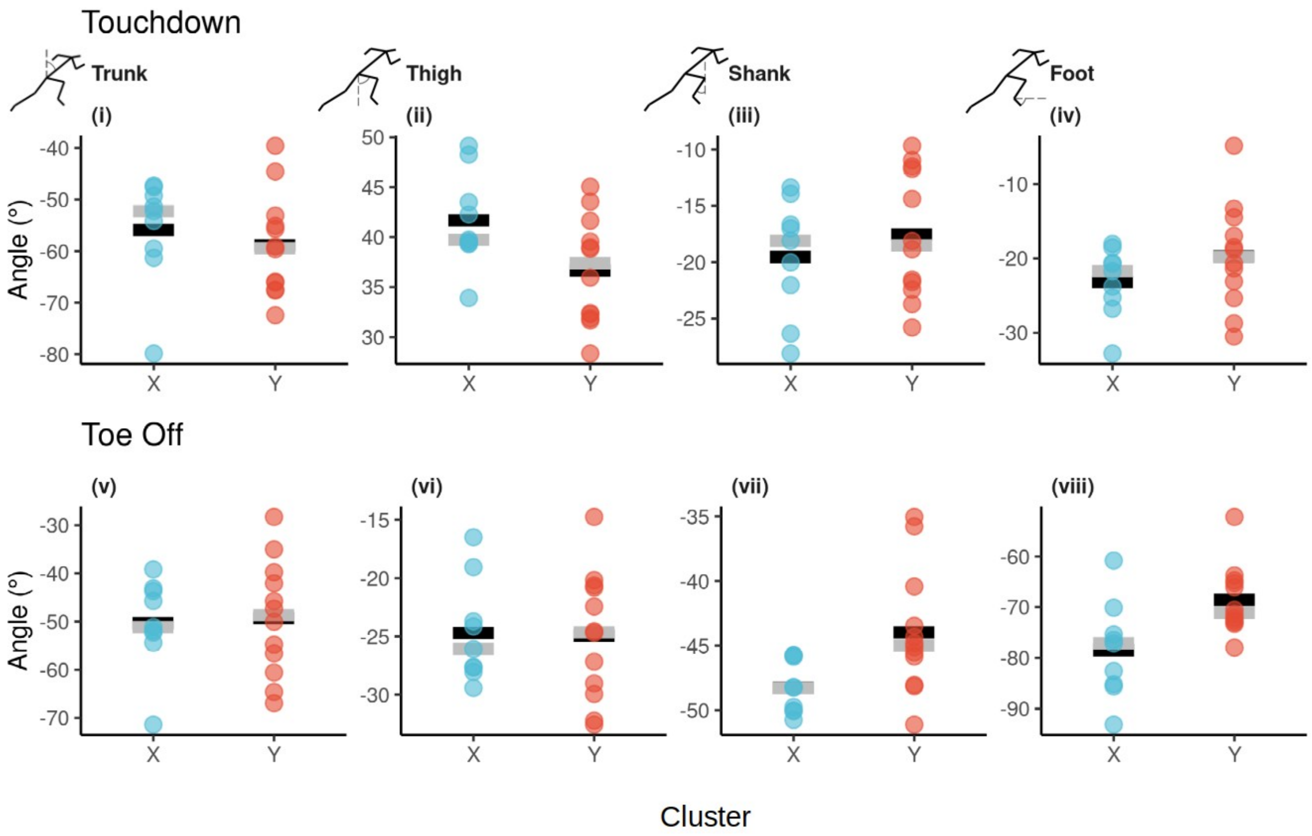
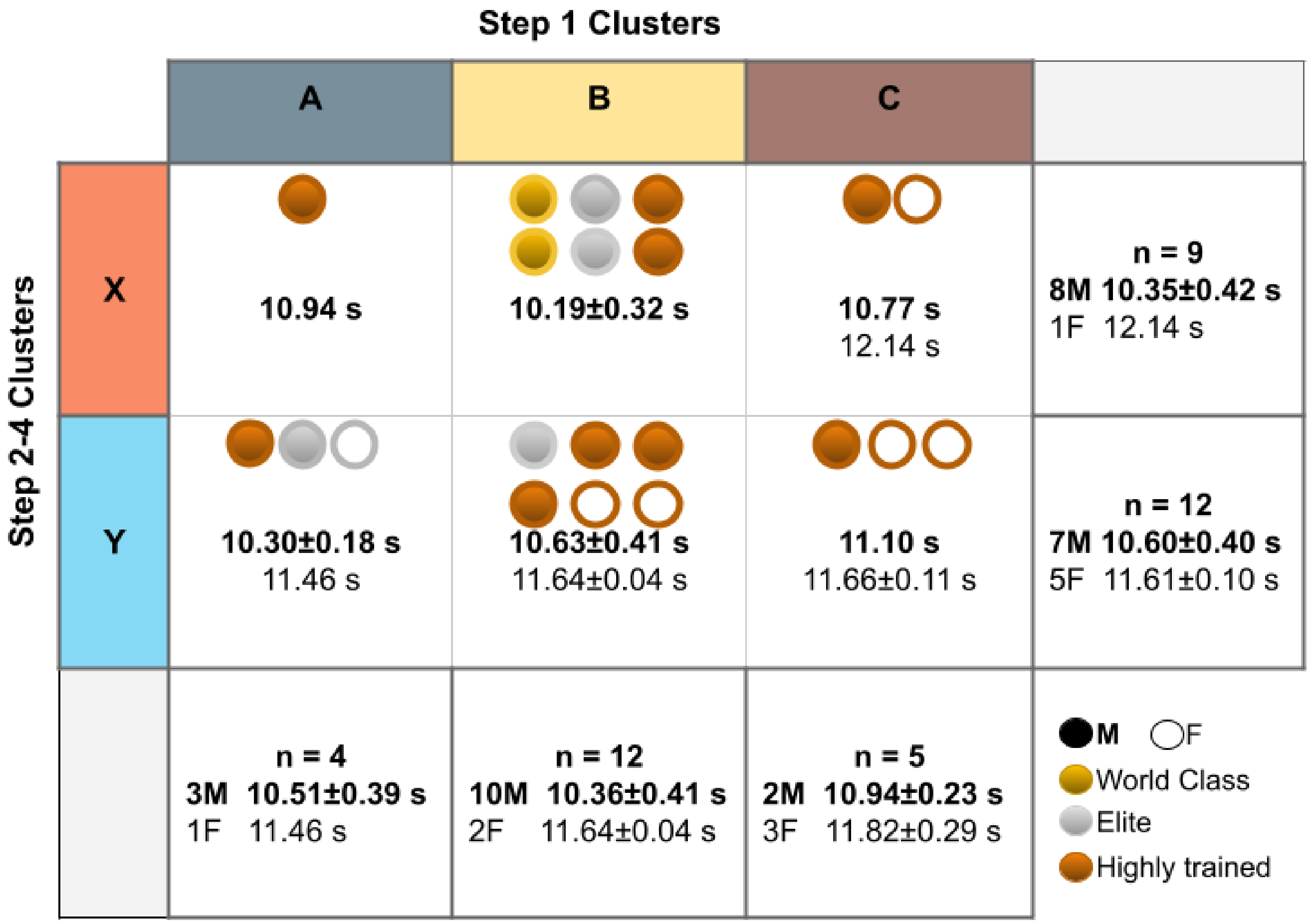


Figure 5: Discrete trunk, thigh, shank and foot segment angles averaged across steps 2-4 at touchdown (i-iv) and toe-off (v-viii) for coordination clusters X and Y. All angles are lead limb (designated at toe-off). Black horizontal bar represents the mean and the grey bar represents the median.

Before to comparing performance between clusters, male and female participants were compared to ensure that sex distribution across clusters did not influence comparisons. Performance levels in female participants were significantly lower across all performance variables ($p < 0.001$), except D_{RF}, compared to males. Given these between-sex differences in performance and the small number of female participants in the sample, females were excluded from between-cluster statistical comparisons of performance and only male athletes were compared. In males, no significant differences existed between step 1 or steps 2-4 clusters for any performance variable.

Six combinations were possible across the two sets of clusters (Figure 6). The two most common combinations resulted from the twelve cluster B participants in step 1 dividing equally into X and Y in steps 2-4. Both world-class and two out of four elite male participants were in B-X, while B-Y and A-Y had one and two elite participants respectively. Given the participant distribution, statistical comparisons between combinations was restricted to the two most common: B-X and B-Y. Participants in B-X were significantly faster over 20 m (2.97 ± 0.04 s) than those in B-Y (3.18 ± 0.15 s, $p = 0.02$)(Figure 7(i)). Participants in B-X also produced higher F_0 (9.13 ± 0.68 $N.kg^{-1}$), P_{max} (23.8 ± 1.8 $W.kg^{-1}$) and RF_{max} (58 ± 2%) than those in B-Y (F_0 : 8.25 ± 0.90 $N.kg^{-1}$; P_{max} (20.0 ± 2.8 $W.kg^{-1}$; RF_{max} (54 ± 3%), but these differences were not significant.



	A	B	C	
X	● 10.94 s	● ● ● ● ● ● 10.19±0.32 s	● ○ 10.77 s 12.14 s	n = 9 8M 10.35±0.42 s 1F 12.14 s
Y	● ● ○ 10.30±0.18 s 11.46 s	● ● ● ● ○ ○ 10.63±0.41 s 11.64±0.04 s	● ○ ○ 11.10 s 11.66±0.11 s	n = 12 7M 10.60±0.40 s 5F 11.61±0.10 s
	n = 4 3M 10.51±0.39 s 1F 11.46 s	n = 12 10M 10.36±0.41 s 2F 11.64±0.04 s	n = 5 2M 10.94±0.23 s 3F 11.82±0.29 s	

Figure 6: Matrix demonstrating step 1 and steps 2-4 cluster combinations with sex, performance level and 100 m personal bests. Gold, silver and bronze colours denote performance level classification according to criteria of McKay et al. [29].

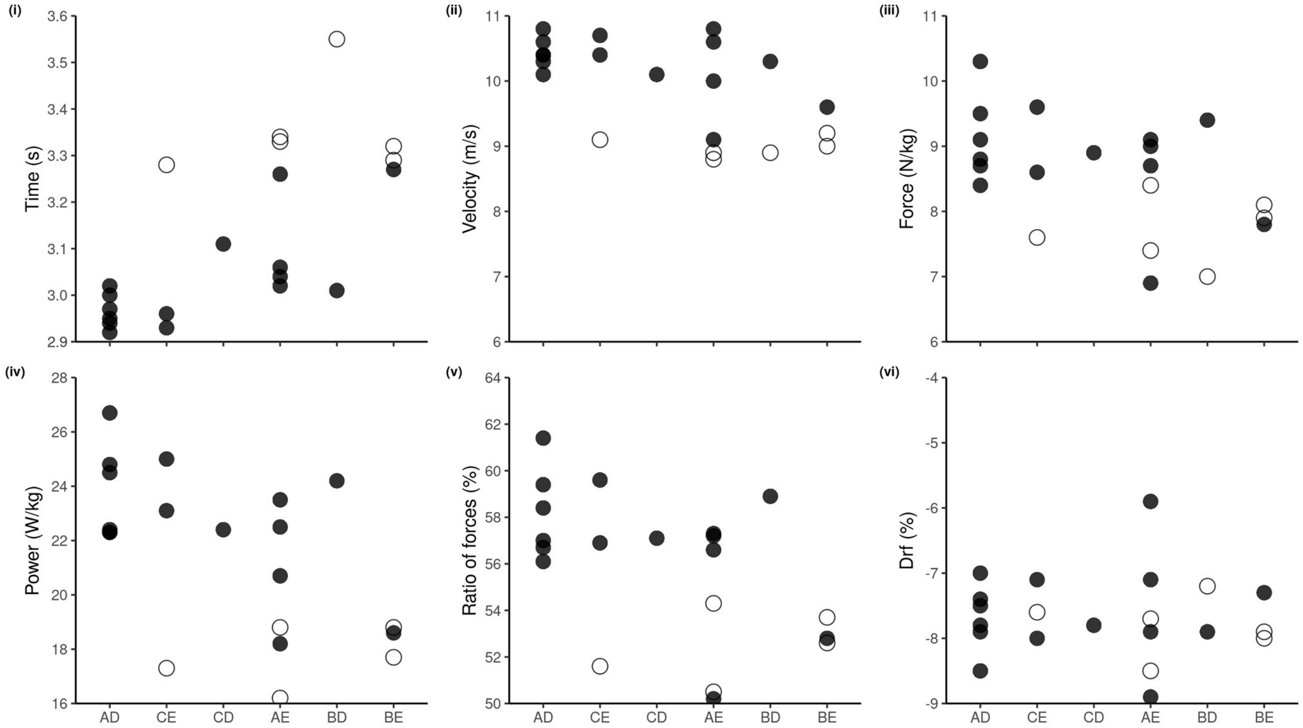


Figure 7: Performance variables for step 1 and steps 2-4 cluster combinations, 20 m time (i), theoretical maximal velocity (V_0)(ii), theoretical maximal horizontal force (F_0)(iii), maximal horizontal power (P_{Max})(iv), ratio of forces (RF_{Max})(v) and degradation of RF (D_{RF})(vi). Closed and open points reflect male and female participants respectively. Note that the y axes do not begin at 0 for any variable to enable the between- and within-group variation to be visualised.

Discussion

This study aimed to identify and characterise sub-groups of sprinters with similar coordination strategies during initial acceleration and assess whether different sub-groups are associated with differences in kinematics at key events and acceleration performance. Through a novel application of hierarchical cluster analysis to vector coding data, three distinct lower-limb sprint acceleration coordination strategies were identified in step 1 and two in steps 2-4. Clusters in step 1 were also associated with certain discrete kinematic differences at block clearance and touchdown, while steps 2-4 clusters had no discrete kinematic differences at key events. Sprint performance did not differ between clusters in either step 1 or steps 2-4, however when combined, clusters revealed a potential coordination strategy associated with higher level sprinters and better sprint times.

In step 1, clusters A and B exhibited similar thigh coordination, characterised by lead thigh dominant anti-phase coordination (increased thigh separation) immediately after block exit followed by in-phase simultaneous thigh flexion before the lead limb reversed direction and retracted and the rear limb continued to flex through. The subsequent limb interchange was trail thigh dominant. Participants in clusters A and B therefore tended to be differentiated more by shank-foot than thigh-thigh coordination. During flight, cluster A displayed only in-phase anti-clockwise shank-foot coordination while B exhibited a shorter period of in-phase rotation and had anti-phase coordination in late flight (Figure 8(i)). Thus cluster B demonstrated ‘shin block’ [22] - a reversal in shank rotation direction before touchdown - which was absent in cluster A. This difference may relate to cluster A displaying more horizontal lead limb shank orientations at block clearance compared to the other clusters (Figure 4(iii-iv)) - appearing to ‘tuck’ the shank beneath the thigh - requiring anti-clockwise rotation in flight to prepare for touchdown. Cluster A dorsiflexion had entirely foot dominant anti-phase coordination, likely reflecting the more horizontal shank orientation observed at touchdown, relying on ‘heel drop’ from a more vertical foot during dorsiflexion and less ‘shin roll’ [22] from an already horizontal shank. Cluster B, on the other hand, exhibited shank dominant coordination at the beginning and end of dorsiflexion with foot dominant coordination in-between, suggesting initial ‘shin roll’ followed by ‘heel drop’ before further ‘shin roll’ towards the end of dorsiflexion. These patterns associated with dorsiflexion were relatively longer in cluster A compared to B, implying a relatively longer portion of stance in power absorption given the resultant plantar flexor moments which are known to be present throughout the first stance phase [17].

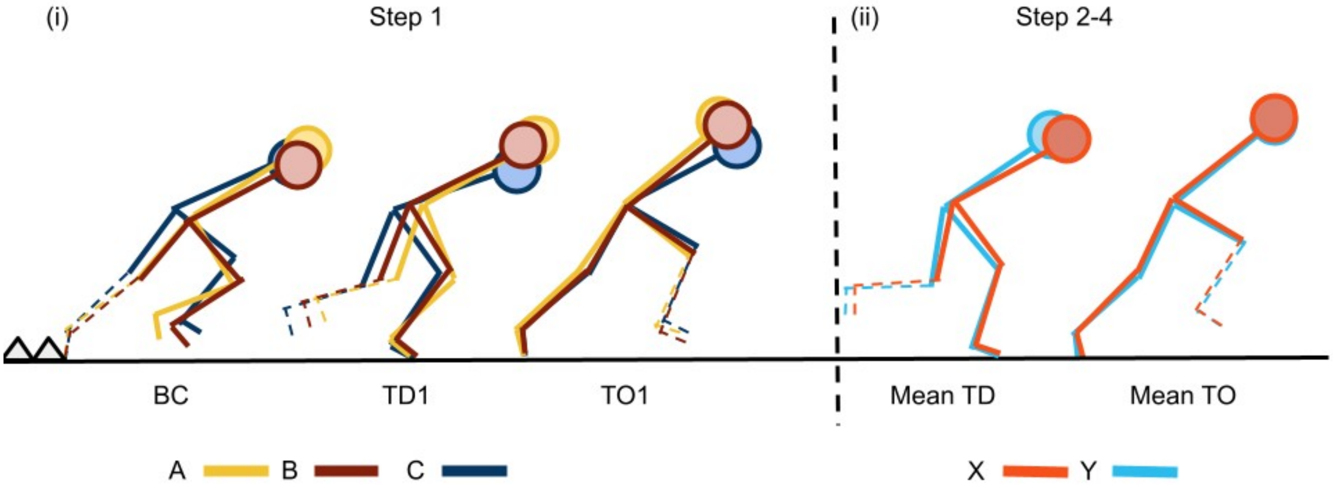


Figure 8: Typical body orientations at key events for clusters in step 1 (i) and the average segment orientations over steps 2-4 (ii). Dashed lines indicate the limb that was not analysed. BC = block clearance; TD = Touchdown; TO = Toe-off.

In contrast to A and B, cluster C was trail thigh dominant after block clearance and had no in-phase coordination in early flight (Figure 2(i)). Thus, C didn’t exhibit the same pattern of dominant lead thigh flexion, rather appearing to already approach the maximum lead thigh flexion angle at block exit (Figure 4(ii); 8(i)) and subsequently increased thigh separation after block exit through clockwise trail leg rotation (hip extension). These differences in trail thigh motion may result from differences in timing of muscle actions between groups [44] or be related to differences in strength profiles between groups, such that different strength profiles may associate with different thigh-thigh coordination patterns, and further work to more directly explore this is required. Moreover, cluster C had shorter in-phase anticlockwise shank-foot rotation during flight and prolonged in-phase clockwise rotation before touchdown, indicating relatively earlier ‘shin block’ [22] compared to B. Cluster C had correspondingly more vertical shank orientations at both block clearance and touchdown. Thus, after block clearance they continued trail thigh extension before retracting the lead limb relatively earlier than other clusters, ‘planting’ the leg down into ground contact. In stance, cluster C exhibited more shank dominant anti-phase dorsiflexion, potentially indicating greater reliance on ‘shin roll’ [22] to translate the CM during that period. Such reliance on ‘shin roll’ might link to the longer contact times observed in C and could also be related to positive touchdown distance (foot ahead of CM), which has previously been associated with lower performance (e.g. [48]). The current observations suggest that lead leg segment orientations at block clearance may influence coordination during the subsequent flight and ground contact, yet these angles are rarely reported and warrant further attention in both research and practice.

The main difference in thigh-thigh coordination between step 2-4 clusters was one of timing of reversals in thigh rotation (Figure 3(i)). Cluster X exhibited an ‘early retractor’ strategy, retracting the swing thigh before toe-off, resulting in in-phase clockwise coordination in late stance. This pattern continues momentarily in early flight before the trail leg reverses to initiate anti-phase motion. Cluster Y exhibited the same general pattern, but began lead thigh retraction at toe-off and displayed longer in-phase clockwise rotation because the trail thigh continued extending after toe-off. Thus showing a delayed swing leg recovery [24] which is sometimes termed ‘overpushing’ in applied practice. Cluster X was associated with significantly higher lead thigh angular velocities compared to Y, which has been associated with faster running speeds during maximal velocity sprinting [24]. Thus, early retraction might indicate earlier initiation of accelerating the lead thigh and therefore facilitate higher angular velocities into the next step. By step 4, thigh coordination in X and Y more closely resembled each other, appearing to converge on the strategy typical of cluster Y. Clusters were also differentiated by timing differences in shank-foot coordination (Figure 3(ii)). Cluster X displayed less anti-clockwise shank and foot rotation during flight and a relatively shorter flight time, resulting in a relatively earlier ground contact than Y, likely reflecting the early lead limb retraction. As a result, X exhibited relatively earlier shank dominant anti-phase coordination during dorsiflexion, although dorsiflexion was shank dominant in both clusters. In contrast to step 1, these timing differences between clusters in both couplings were not associated with any differences in kinematics at key events (Figure 5, 8(ii)).

Of the six possible combinations of step 1 and steps 2-4 strategies, the majority of participants were either B-X (6) or B-Y (6) combinations, followed by A-Y (3) and C-Y (3), with A-X (1) and C-X (2) least common (Figure 6). Thus, early retraction (X) or delayed swing leg recovery (Y) strategies in steps 2-4 were equally likely from participants in step 1 cluster B, but other step 1 clusters were less likely to correspond with early retraction. Of the two most common strategies, B-X was associated with higher performing athletes - including both world class participants as well as two out of five elite participants whilst B-Y was almost entirely composed of highly trained participants (Figure 6). In sprint tests, comparing only male athletes, the B-X combination had the fastest 20 m times and significantly faster times than B-Y. Thus, although there were no significant differences in performance measures between isolated clusters from either step 1 or steps 2-4, the combination of clusters to define a single initial acceleration strategy implies that a B-X strategy could be associated with better performance. Further, although not significant, B-X athletes tended to perform better across force and power variables, but not V_0 or D_{RF} . Thus, initial lead thigh dominant flexion in flight and ‘shin block’ in late flight (B) in step 1 combined with early swing leg retraction (X) in later steps might be exhibited by physically stronger athletes and therefore reflect a strategy allowing them to express their physical capacities. Further work is required to investigate the relationships between coordination strategies and strength, especially in more nuanced ways than macroscopic associations with force-velocity-power profiles. The performance of the two male athletes that adopted the A-Y strategy, characterised by lead thigh flexion dominant coordination in early flight and shank tuck in step 1 combined with a delayed swing leg recovery in later steps was comparable with that of those exhibiting a B-X strategy (Figure 7). The small number of participants who displayed this approach suggest it is less common, and future work could explore what specific individual constraints might be associated with such an approach as it may be an equally effective strategy as the more common B-X. Comparable performances between B-X and A-Y combinations could potentially indicate degeneracy in these coordination strategies [15]. These strategies only differed in shank-foot coordination, such that the different shank-foot approaches (i.e., high or low foot dominancy) could be equally effective in combination with the same thigh motion and could possibly result from differences in individual anatomy or strength or coaching. It remains to be explored whether potential degeneracy in coordination could relate to degeneracy observed in linear kinematic strategies during initial acceleration [15]. However, while these observations imply the potential for degeneracy in some strategies, in totality, the performance results presented here point toward the existence of coordination strategies associated with higher performance in a sample of well-trained sprinters as well as strategies that are more commonly observed in this population.

The current study is the first to apply a clustering approach to coordination in sprinting and has provided new insights into the body organisation during initial acceleration. However, there remain several limitations. Hierarchical clustering facilitated the novel identification of initial acceleration coordination strategies, but the identified strategies are not exhaustive, and these patterns may not generalise outside the current population of experienced, high level sprinters. Whilst increasing the sample could also provide a more robust characterisation of the coordination strategies and their effectiveness, this study intentionally focused only on high level sprinters and the current sample is relatively large in comparison with other studies of such populations. Furthermore, the current study included only segment kinematics since data collection took place in an uninvasive manner during real training sessions. The future measurement of external kinetics would enable a direct assessment of the relationships between coordination and force application for each step, as well as additional consideration of joint kinetics that could enhance the understanding of coordination differences between different patterns, especially with regard to the ankle joint during dorsiflexion, given the important power absorption during this period [17, 19].

For practitioners, the approach applied in the current study highlights the potential to quantitatively profile sprinters such that their individual coordination patterns can be understood in the context of the different available strategies. These results suggest that the pattern of thigh interchange after block clearance and the balance of shank or foot dominance during ankle dorsiflexion appear to be important factors which distinguish the different coordination profiles adopted by sprinters during initial acceleration. Different coordination strategies were also associated with differences in discrete kinematics, particularly at block clearance and touchdown in step 1, suggesting coaches should be mindful of the impact on movement patterns that cues to adopt specific body positions might have.

The current study has identified distinct technical strategies from lower limb coordination patterns during acceleration. In a sample of highly-trained to world class sprinters, cluster analysis of similar coordination strategies identified three sub-groups of sprinters in the first step and two sub-groups in the subsequent three steps. The results show that, in males, coordination strategies characterised by lead thigh dominant flexion in early flight and greater foot dominant coordination during early stance dorsiflexion in step 1 combined with early swing thigh retraction in later steps was associated with faster times and higher performers. By classifying the coordination strategies used by high-level sprinters during initial acceleration, this study helps to understand the range of approaches available to sprinters and identify the key coordinative features which distinguish different strategies in this population. This aids coaches and researchers in further understanding the technical approaches used by sprinters as well as the coordination of movement between the positions adopted at key events.

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