ENHANCING THE INITIAL ACCELERATION PERFORMANCE OF ELITE RUGBY BACKS. PART I: DETERMINING INDIVIDUAL TECHNICAL NEEDS

Purpose: This study sought to quantify the within-individual relationships between spatiotemporal variables and initial acceleration sprint performance in elite rugby backs, and to establish a normative data set of relevant strength-based measures. **Methods:** First, the spatiotemporal variables, step length / step rate and contact time / flight time ratios and initial acceleration performance were obtained from 35 elite male rugby backs (mean ± SD: age 25 ± 3 years) over the first four steps of three sprints. Angular and linear kinematic aspects of technique and strength-based qualities were collected from 25 of these participants. Secondly, the same spatiotemporal variables were collected from 19 of the participants on three further occasions (12 trials in total) to determine the within-individual associations of these variables and initial acceleration performance. **Results:** Moderate to very large meaningful within-individual relationships ($|r|$ = 0.43 to 0.88) were found between spatiotemporal variables and initial acceleration performance in 17 of the 19 participants. From these relationships, a theoretically 'desirable' change in *whole-body kinematic strategy* was individually determined for each participant, and normative strength-based measures to contextualize these were established. **Conclusions:** Meaningful within-individual relationships are evident between sprint spatiotemporal variables and initial acceleration performance in elite rugby backs. Individualized approaches are therefore necessary to understand how aspects of technique relate to initial acceleration performance. This study provides an objective, evidence-based approach for applied practitioners to identify the initial acceleration technical needs of individual rugby backs.

Keywords/phrases: sprinting, constraints, training, motor control, biomechanics

INTRODUCTION

Sprint acceleration capacities of professional rugby backs are related to key performance indicators during matches and discriminate between playing standards.[1-3] This is logical since an increase in sprint acceleration capacity may increase the opportunities available for rugby backs to positively impact match outcomes. Therefore, understanding how features of the movement patterns used to perform the sprint acceleration action ('technique'[4]) contribute to acceleration performance of rugby backs during the initial steps of sprinting is important to ensure effective evidence-based sprint-training practices.

The relationships between initial acceleration performance (approximately the first 4 steps[5]) and aspects of technique, including spatiotemporal variables like step length, step rate and contact and flight times, have been widely investigated in team sports and track and field sprinters.[6-10] However, due to inconsistent relationships reported at the whole group level, conflicting perspectives remain on which, if any, of these spatiotemporal variables are associated with better initial acceleration performance.

One explanation for inconsistent results is that a single optimal combination of spatiotemporal characteristics does not exist for all athletes during initial acceleration. For example, in 29 elite rugby backs, Wild et al.[11] found that different *whole-body kinematic strategies* (based on the combination of step length/step rate (SL/SR) and contact time/flight time (CT/FT) ratios) were adopted by individuals when achieving equivalent levels of initial acceleration performance. Therefore, previously reported relationships between technique-based characteristics and initial acceleration performance based on groups may not apply to any given individual. This scenario suggests that individualized approaches to understanding how technical features relate to initial acceleration performance are necessary.

Salo et al.[12] highlighted the importance of examining how step length and step rate are individually related to 100 m sprint performance in elite track sprinters. The researchers determined whether sprinters were individually 'reliant' on producing longer step length or higher step rate for better sprinting performance by calculating the within-individual correlations between the spatiotemporal variables and 100 m time across multiple races. Where practically important differences between correlations were found within an individual participant, they were declared either step length or step rate 'reliant' when the correlation differences favored either step length or step rate respectively. They suggested focusing on enhancing, or at least avoiding negative effects on, the spatiotemporal variables that individuals 'rely' on for better sprinting performance. However, this concept has not been explored further, including in team sport athletes such as rugby backs, or specifically during the initial acceleration phase. Furthermore, focusing on step length and step rate alone may not provide a sufficiently detailed understanding of an individual's initial acceleration strategy. This may explain why only four of the 11 sprinters investigated by Salo et al.[12] could be categorized as being 'reliant' on either step length or rate for better 100 m sprinting performance.

Wild et al.[11] developed a framework for practitioners to measure individual *whole-body kinematic strategies*, depicted by the spatial location of cartesian coordinates based on SL/SR and CT/FT ratios. This analysis extended the work of Salo et al.[12] by providing a more detailed understanding of how a given sprint performance is achieved. Monitoring an individual's *whole-body kinematic strategy* using this combination of variables can facilitate a deeper understanding of how spatiotemporal variables collectively, and individually, change in relation to changes in initial acceleration performance. If meaningful within-individual relationships are found, it is possible that focusing speed training interventions on the spatiotemporal variables most closely related to initial acceleration performance may be more likely to enhance a rugby back's sprinting ability during the initial steps.

The different initial acceleration *whole-body kinematic strategies* identified in elite rugby backs by Wild et al.[11] were also, in part, underpinned by strength-related qualities. On the premise that movement preferences will be influenced by an individual's physical capabilities,[13,14] it is feasible that a strength-based intervention could also be used to achieve the intended manipulation of rugby backs' technical features during initial acceleration. Therefore, in addition to determining the technical features that backs may be 'reliant' on for better initial acceleration performance, it is valuable to determine potential strength-related deficits to support strength-based interventions when looking to address individual technical needs. However, experimental research is required to confirm the efficacy of these proposed technical and strength-based approaches within an applied setting.

The primary aim of this study was to quantify the within-individual relationships between sprint spatiotemporal variables (SL/SR and CT/FT ratios and normalized spatiotemporal variables) and initial acceleration performance in elite rugby backs, and to use these to identify the direction of the relationship between their *whole-body kinematic strategy* and performance. The second aim was to establish a normative data set of relevant strength-based measures from which strength capacity deficits for individual backs. Collectively, this information could be used to inform future interventions (see part II[13]). Finally, although normalized average horizontal external power (NAHEP) is commonly used as an initial acceleration performance measure,[16] it typically requires considerable data processing time to determine whole body center of mass location at touchdown and toe-off. Therefore, the third aim was to determine whether an alternative, less time-consuming, initial acceleration performance measure could be used to enhance the likelihood of practitioner application.

METHODS

Participants

Data from 35 elite[17] male rugby union backs (mean ± SD: age 25 ± 3 years; stature 1.81 ± 0.06 m; leg length 1.00 ± 0.05 m; body mass 93.0 ± 8.5 kg) competing in the English Premiership were analyzed. At the time of testing, participants were free from injury and frequently completed maximal sprint accelerations within their weekly training regime.

Procedures

The research was conducted in two stages (Table 1), primarily following a multiple-single-subject design. In Stage 1 normalized spatiotemporal variables and NAHEP were obtained from all 35 participants over the first four steps of three sprints on a single occasion, using the video-based protocols of Wild et al.[11] A second initial acceleration performance measure (5 m time) was also determined for all participants to enable the third aim to be addressed. This was determined in Kinovea (v.0.8.27) from when the back foot had visibly lifted off the ground until the mid-hips passed 5 m.[18] The 5 m distance was selected because it is the closest distance to that covered during the first four steps which is used in applied settings to measure initial acceleration performance.[19,20]

For 25 of the Stage 1 participants, selected angular and linear kinematics were also collected during the sprint testing (Figure 1). The same 25 participants then undertook three strength-based assessments. From a repeated unilateral in-place jump test (repeated jumps), jump heights (m), contact times (s) and the reactive strength index (RSI; ratio of jump height to contact time)[21,22] were obtained for each side using a modified approach from Comyns et al.[23] Based on adapted protocols from Samozino et al.[24] and Goodwin and Bull[25], maximal mechanical power output during squat jump profiling (P_{max} [W/kg]) and peak unilateral isometric torque (Nm/kg) of the hip extensors (hip torque) were obtained, respectively. The hip torque / repeated jump contact time ratio (hip torque / repeated CT) was also determined for each participant. Full protocols for these strength-based assessments and the reliability of measures obtained (CV 4.2 to 5.4%) are reported in Wild et al.[11]

FIGURE 1 NEAR HERE

In Stage 2, the same sprint testing as in Stage 1 was conducted for 19 of the 35 participants on three further occasions (Table 1), which resulted in spatiotemporal variables being measured for these participants for 12 sprints over six pre-season weeks (i.e., three sprint trials on four separate occasions). These data were used to determine the intra-individual relationships between the spatiotemporal variables (step lengths, step rates, contact and flight times, SL/SR and CT/FT ratios) and initial acceleration performance.

Following a similar approach as Salo et al.,[12] participants were deemed ‘reliant’ on spatiotemporal variables for improved initial acceleration performance in favor of the spatiotemporal variable that demonstrated a more substantial difference in correlation magnitude ($\Delta r \geq 0.1$) *and* when meaningful within-individual relationships were observed (see Statistical Analyses). Directional changes in Cartesian plane spatial location of individual backs’ *whole-body kinematic strategies* associated with higher initial acceleration performance were expressed as directions on a 16-point compass. These were determined according to the magnitudes of the relationships observed between each ratio (SL/SR and CT/FT) and NAHEP across the 12 sprints. For example, a meaningfully positive relationship (see *Statistical analyses*) between the SL/SR ratio and NAHEP for an individual would denote a favorable shift northward on the Cartesian plane.

This process is illustrated for a single participant in Figure 2; the marker sizes in Figure 2a are proportional to magnitudes of NAHEP. For this participant, the markers are typically larger more northwards (i.e., higher NAHEP is achieved with a larger SL/SR ratio) and eastwards (i.e., higher NAHEP achieved with a larger CT/FT ratio). If the difference between the magnitude of these relationships is trivial ($r < 0.1$), then collectively the direction associated with higher initial acceleration performance would be represented by an intercardinal direction (northeast in this example). If both ratios are meaningfully related to NAHEP, but the difference between the magnitudes of the relationships is considered at least small ($r \geq 0.1$) then the cardinal direction signifying the intended shift in strategy would result in a ‘half-wind’ (i.e., direction points obtained by bisecting intercardinal directions yielding 16 direction categories each 22.5° from its nearest neighbors) oriented more towards the relationship of a higher magnitude. For example, in Figure 2b, the within-participant relationships of the SL/SR and CT/FT ratios with NAHEP were r = 0.45 and 0.77, respectively, and thus the resulting direction associated with higher initial acceleration performance would be E-NE for this individual. These directions were then used to inform the intended technical change which would likely benefit a given individual’s initial acceleration performance. Where meaningful relationships between the SL/SR and CT/FT ratios and NAHEP were not found, the intended technical change was informed by the relationships between normalized spatiotemporal variables in isolation and NAHEP.

TABLE 1 NEAR HERE

FIGURE 2 NEAR HERE

Statistical analyses

In Stage 1, data for normalized spatiotemporal variables, NAHEP and 5 m time were averaged over four steps, and then averaged again over the three sprint trials for each of the 35 participants. This approach was also taken for the linear and angular kinematics obtained in Stage 1. A range of descriptive statistics, including percentile ranges, were determined for strength-measures collected to provide a normative dataset for strength-based performance to address the second aim.

For the 19 participants who completed sprint trials on four separate occasions during Stages 1 and 2, each individual participant's mean ± SD 5 m time, NAHEP, normalized spatiotemporal variables and SL/SR and CT/FT ratios across the 12 sprints completed were determined. All group and intra-individual descriptive data (mean ± SD) were calculated for all variables and checked for normal distribution using the Shapiro-Wilk statistic.

To assess consistency of 5 m time, group and intra-individual coefficients of variation (CV) were determined. In Stage 1, the 5 m time within-participant CV for each of the 35 participants across their three sprint trials was calculated and the average of these across the entire group was then determined to provide the group level CV. For the 19 participants who completed sprint trials on four different occasions during Stages 1 and 2, the 5 m time CVs for each participant across their 12 sprint efforts were also determined. The same approach was taken to determine the intra-individual CVs for NAHEP, normalized spatiotemporal variables and SL/SR and CT/FT ratios.

The strength of group and within-individual relationships between NAHEP and 5 m time were determined using Pearson's correlation coefficient analysis (including 90% confidence intervals). A group level correlation was based on the mean NAHEP and 5 m time achieved by each of the 35 participants (Table 1, Stage 1) in their initial three sprint trials. The intra-individual correlations were determined individually for the 19 participants across their 12 sprint trials.

The *whole-body kinematic strategies* and distribution of these for the 19 participants who underwent the full analysis were determined using the same approaches as used in Wild et al.[11] Participant z-scores were calculated based on the whole participant group in the current study (n = 35). Pearson's or Spearman's rank order (non-parametric data) correlation coefficients were used to measure the strength of intra-individual relationships (including 90% confidence intervals) of normalized spatiotemporal variables and the SL/SR and CT/FT ratios with initial acceleration performance across their 12 sprints (see Figure 2b). All relationships were deemed meaningful where the magnitude of the observed relationship was greater than the smallest practically important correlation;[26] r = ± 0.43. Relationships were deemed unclear if their magnitude was within this threshold (-0.43 < r < 0.43). The strength of relationships was defined as: (±) < 0.1, trivial; 0.1 to < 0.3, small; 0.3 to < 0.5 moderate, 0.5 to < 0.7 large, 0.7 to < 0.9 very large and ≥ 0.9, practically perfect.[27]

RESULTS

Descriptive statistics for initial acceleration performance, sprint kinematic variables and strength-based measures are presented in Tables 2 to 4, and supplementary material B. In terms of initial acceleration performance, NAHEP ranged from 0.440 to 0.722 (mean ± SD = 0.559 ± 0.074), and the 5-meter time ranged from 0.956 s to 1.106 s (mean ± SD = 1.029 ± 0.035 s). The quartiles are presented in Tables 2 to 4 to aid in the contextualization of any given rugby back, particularly for our second aim of establishing a normative data set of relevant strength-based measures.

TABLE 2 NEAR HERE

TABLE 3 NEAR HERE

TABLE 4 NEAR HERE

Practically perfect and statistically significant group (r [90% CI] = 0.90 [0.83 to 0.95]) and mean within-individual (r = [90% CI] -0.91 [-0.97 to -0.75]) relationships were found between NAHEP and 5 m time following Stages 1 and 2. Within-individual (supplementary material B) CV for initial acceleration performance measures, normalized spatiotemporal variables and the SL/SR and CT/FT ratios were all less than 10%, indicating acceptable relative reliability.[30]

Trivial to very large within-individual relationships of NAHEP with SL/SR and CT/FT ratios and each normalized spatiotemporal variable were observed for the 19 participants who completed stages 1 and 2 (Figure 2; see also supplementary material A). Within-individual relationships of NAHEP with SL/SR and CT/FT ratios ($|r|$ = 0.04 to 0.75 and $|r|$ = 0.03 to 0.80) were meaningful in eleven (in four, $p \leq 0.05$) and seven (in two, $p \leq 0.05$) participants, respectively. Within-individual relationships between NAHEP and normalized step length ($|r|$ = 0.01 to 0.76) were meaningful in seven participants (in six, $p \leq 0.05$). Within-individual relationships between NAHEP and normalized step rate ($|r|$ = 0.05 to 0.88) were meaningful in 13 participants (in seven, $p \leq 0.05$). Within-individual relationships of NAHEP with normalized contact time and normalized flight time ($|r|$ = 0.02 to 0.78 and $|r|$ = 0.22 to 0.79) were meaningful in six (in three, $p \leq 0.05$) and nine (in five, $p \leq 0.05$) participants, respectively.

Differences in magnitude between the within-individual relationships of 5 m time and NAHEP with SL/SR and CT/FT ratios and each normalized spatiotemporal variable were trivial to small (mean ± SD difference: SL/SR ratio, Δr = 0.08 ± 0.06; CT/FT ratio, Δr = 0.10 ± 0.07; normalized step length, Δr = 0.08 ± 0.06; normalized step rate, $\Delta\ r$ = 0.09 ± 0.06; normalized contact time, Δr = 0.12 ± 0.07; normalized flight time, Δr = 0.10 ± 0.06; Figure 2 and supplementary material A). Of the number of meaningful within-individual relationships (n = 54) across participants between NAHEP and spatiotemporal variables, 82% (n = 44) of the same relationships were also found to be meaningful when NAHEP was replaced by 5 m time (Figure 2and supplementary material A and C). Six further meaningful relationships of spatiotemporal variables observed with 5 m time were not observed with NAHEP (differences in relationship magnitudes ranged between 0.01 and 0.16). Of the number of statistically significant within-individual relationships (n = 26) across participants between NAHEP and spatiotemporal variables, 88% (n = 23) of the same relationships were also found to be significant when NAHEP was replaced by 5 m time. Five further significant relationships of spatiotemporal variables observed with 5 m time were not observed with NAHEP (supplementary material C).

DISCUSSION

This study's primary aim was to determine how spatiotemporal variables (normalized spatiotemporal variables and SL/SR and CT/FT ratios) of elite rugby backs related individually to initial acceleration performance. Meaningful within-individual relationships were found between spatiotemporal variables and NAHEP (Figure 2 and supplementary material A) in all but two (P1 and P5) of 19 participants. This outcome highlights the specific variables that were associated with greater initial acceleration performance in individual participants, and builds on previous research[12] in which elite track sprinters were found to individually 'rely' on either greater average step length or step rate (or neither variable) for better sprinting performance in 100 m races. Of the 11 sprinters studied by Salo et al.,[12] three 'relied' on step length and one on step rate for better sprint performance. Consequently, based on those analyses alone, practitioners would be left without a technical training direction for the majority of sprinters from that cohort. To overcome similar challenges when analyzing just the initial acceleration phase, the current study sought to understand how performance was not only related individually to step length and step rate, but also to contact and flight times and the SL/SR and CT/FT ratios which form the *whole-body kinematic strategies* of participants. This approach provides a more detailed understanding of the spatiotemporal variables which athletes may 'rely' on for better sprint performance.

Eleven of the 19 participants (Figure 2and supplementary material A) were found to individually 'rely' on step length (n = 6) or step rate (n = 5) based on a meaningful *r* value of ≥ 0.43 being evident with NAHEP, and the difference in correlation magnitude between the relationships of step length and step rate with NAHEP for each of these participants also being ≥ 0.10. However, when also considering SL/SR and CT/FT ratios and contact and flight times in addition to just step length and step rate, 17 of the 19 participants were observed to individually 'rely' on at least one spatiotemporal variable for better initial acceleration performance (Figure 2 and supplementary material A). Therefore, assessing a more holistic *whole-body kinematic strategy* when determining within-individual relationships between sprint-technique variables and initial acceleration performance is more likely to provide valuable direction for practitioners to inform the individualization of their technical interventions. The set of normative strength-based data (Table 4) which addressed the second aim of this study also provides a means to inform the modification of performer constraints which could ultimately be used to facilitate the intended technical changes (see part II[15]).

The method used to obtain NAHEP provides a reliable (CV = 5.5%, supplementary material B) and objective[29] measure of initial acceleration performance). However, it requires digitization of 22 segment endpoints to determine whole-body CM location, which must be done twice (at the beginning of first contact and at the end of fourth contact). In applied settings, a simpler way to measure initial acceleration performance is valuable so that actionable information can be communicated quickly. A less time-intensive initial acceleration performance measure (5 m) was concurrently used to address the third aim of this study by determining how closely the within-individual relationships with SL/SR and CT/FT ratios and normalized spatiotemporal variables compared with those assessed against NAHEP. 5 m time was more reliable (CV = 2.1%, supplementary material B) than NAHEP, and differences in the correlation magnitudes between NAHEP and 5 m time with spatiotemporal variables were only trivial to small (range in mean r difference = 0.08 to 0.12). For all meaningful relationships, when correlation coefficients were inverted for 5 m time, the direction of relationships with spatiotemporal variables were the same as NAHEP. In cases where the direction was different (n = 6), the relationships were all trivial (absolute magnitudes were $r < \pm 0.16$). Given these findings and the similarity in statistically significant and/or meaningful within-individual relationships of spatiotemporal variables with both NAHEP and 5 m time (supplementary material C), 5 m time is an appropriate measure to identify variables which are associated with higher initial acceleration performance. This offers a more practical alternative to NAHEP when assessing large cohorts of athletes in a high-performance environment where time is often limited as it requires timestamping just two occurrences. The approach can also be used when quick feedback for monitoring progress during longer-term interventions (e.g., Part II[15]) is required.

PRACTICAL APPLICATIONS

This study demonstrates the importance of considering individual needs for understanding elite rugby backs' initial acceleration performance, and presents a novel, robust method which will enable practitioners to effectively identify them in applied environments. Determining the within-individual relationships between spatiotemporal variables, SL/SR and CT/FT ratios, and initial acceleration performance, along with potential deficits in the context of the set of strength-related normative data presented in this study, can easily be established during a baseline period, such as the pre-season. This information may then inform individually targeted training interventions, specifically focused on improving initial acceleration performance. The findings of this study can also be applied to other sports that require rapid initial acceleration, making it a valuable resource for coaches and athletes across a range of sports. Future research on individual-specific case study interventions (see Part II[15]) is required to substantiate whether this approach is effective in enhancing the initial acceleration performance of athletes.

CONCLUSION

This study has developed a process to quantify individual rugby backs' technical 'reliance' for achieving higher levels of initial acceleration performance. A theoretical desired change in the Cartesian plane spatial location of each participant's *whole-body kinematic strategy* was determined for all but two of the 19 participants studied. This information, combined with the normative data based on strength qualities associated with different initial acceleration strategies, provides objective, evidence-based direction which can be applied to individual-specific interventions. Furthermore, we demonstrated that a simple performance measure (5 m time) which can be determined quickly in applied environments, can be used. This approach will now be used in Part II[15] to inform individual-specific interventions for elite rugby backs, and its effectiveness will be assessed through detailed measurement of technical features during initial acceleration and performance at numerous instants throughout an 18-week in-season intervention.

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FIGURES

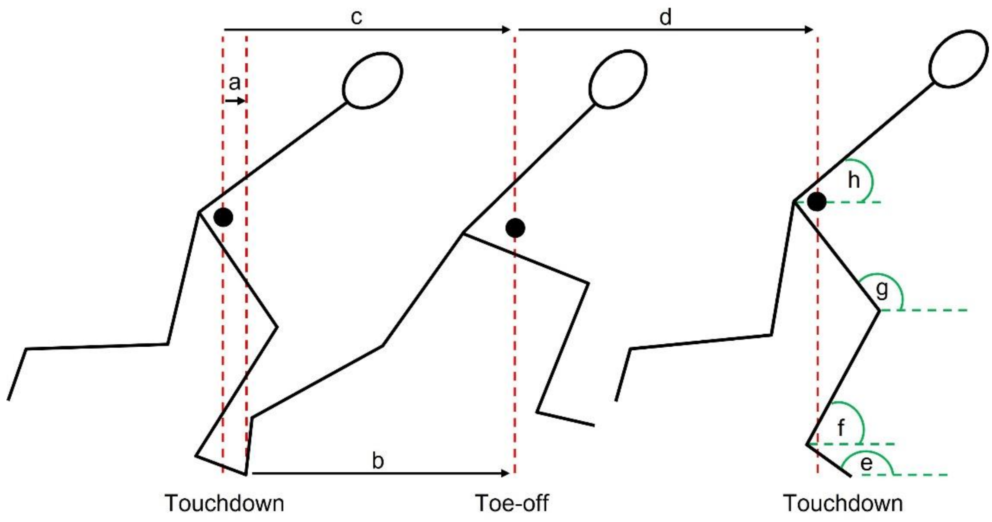


Figure 1. Selected linear and angular kinematic aspects of technique.

a, touchdown distance; b, toe-off distance; c, contact length; d, flight length; e, foot angle; f, shank angle; g, thigh angle; h, trunk angle. Note that angular measures were taken at touchdown and toe-off but to provide clarity, they are only depicted at touchdown in this figure.

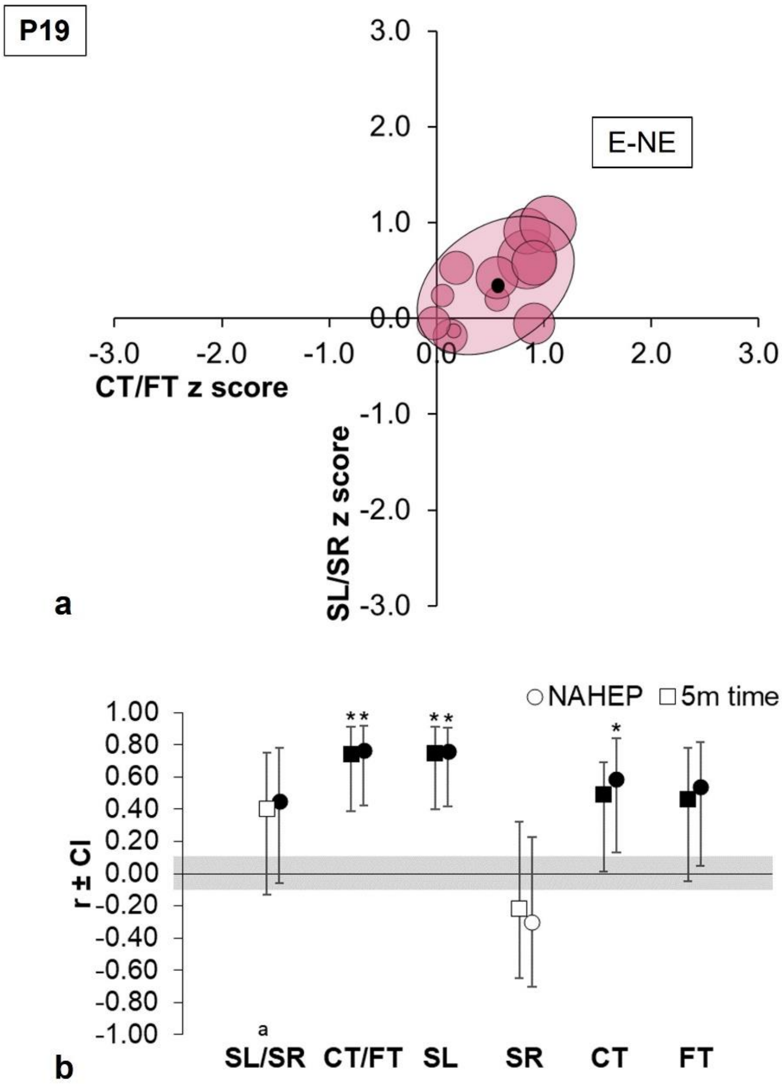


Figure 2. An example of a *whole-body kinematic strategy* (a) for an example participant (P19). Each marker depicts a single sprint, with marker sizes scaled to reflect initial acceleration performance (a larger marker size equates to greater NAHEP). Where sprinting kinematics are meaningfully related to NAHEP, the theoretical favorable Cartesian plane spatial location change in strategy for better sprint performance is included as a compass bearing (see *Procedures* section for full details). Relationships (with 90% confidence intervals) of SL/SR and CT/FT ratios and normalized spatiotemporal variables with NAHEP and 5 m time are shown in (b). For clarity, to aid comparisons between relationships of NAHEP and 5 m time with variables, the direction of relationships between 5 m time and variables has been inverted. Black filled makers depict meaningful relationships where the magnitude of relationships were greater than the smallest practically important correlation[26] ($r = \pm 0.43$) and asterisks indicate that relationships are statistically significant ($p < 0.05$).

SL/SR = step length/step rate ratio; CT/FT = contact time/flight time ratio; SL = step length; SR = step rate; CT = contact time; FT = flight time. [a]Indicates where data were non-parametric and that Spearman's rank order correlation coefficients were used to determine relationships rather than Pearson's correlation coefficients which were used for parametric data.

TABLES

Table 1. An outline of the different stages in the study, including number of participants included, type of testing undertaken, and the nature of data obtained within each phase.

Duration	← **6 weeks** →		
Stage	**1**	→	**2**
No. participants	35		19
Testing undertaken	Sprint testing for all 35 participants on a single testing occasion (3 sprints) Strength-based testing on a single testing session for 25 of the 35 participants		Sprint testing for all 19 participants on 3 further occasions (3 sprints on 3 separate occasions. The number of days between testing occasions ranged between 5 and 7)
Data obtained	Normalized spatiotemporal variables, *whole-body kinematic strategies*, SL/SR and CT/FT ratios and initial acceleration performance measures (NAHEP and 5 m time) for all 35 participants Linear kinematic variables, touchdown and toe-off angular kinematics and strength-based variables (from the repeated jump, hip torque and squat jump profiling assessments) for 25 of the 35 participants		Normalized spatiotemporal variables, *whole-body kinematic strategies*, SL/SR and CT/FT ratios and initial acceleration performance measures (NAHEP and 5 m time) for all 19 participants

Table 2. Initial acceleration performance of 35 elite rugby union backs and their spatiotemporal variables averaged over the first four steps from three sprint trials during a single testing session in Stage 1.

Variable	Mean ± SD	Min.	25^{th}%	Median	75^{th}%	Max.
NAHEP[a]	0.559 ± 0.074	0.440	0.502	0.550	0.603	0.722
5 m time (s)	1.029 ± 0.035	1.103	1.055	1.029	1.006	0.956
Step length (m)	1.32 ± 0.13 (1.31 ± 0.10[a])	1.08	1.23	1.33	1.41	1.56
Step rate (Hz)	4.28 ± 0.31 (1.38 ± 0.09[a])	3.62	4.15	4.29	4.52	5.03
Contact time (s)	0.164 ± 0.014 (0.514 ± 0.041[a])	0.139	0.157	0.162	0.171	0.196
Flight time (s)	0.068 ± 0.011 (0.212 ± 0.032[a])	0.050	0.058	0.068	0.075	0.091
CT/FT ratio	2.48 ± 0.46 (2.48 ± 0.46[a])	1.70	2.23	2.45	2.79	3.34
SL/SR ratio	0.31 ± 0.05 (0.96 ± 0.13[a])	0.22	0.27	0.31	0.34	0.43

[a]Variables have been normalized according to the equations of Hof [28] with a modification to the calculation of NAHEP as used by Bezodis et al.[29]

To help with clarity, 5 m time values have been inverted so that worse to better performance can be observed for initial acceleration performance measures from left to right, respectively (i.e., a shorter 5 m time is better in performance terms).

Table 3. Linear and angular kinematic variables of 25 elite rugby union backs averaged over the first four steps from three sprint trials during a single testing session in the Stage 1.

Variables	**Mean ± SD**	**Min.**	**25th%**	**Median**	**75th%**	**Max.**
Touchdown distance (m)	0.12 ± 0.05 (0.13 ± 0.05[a])	0.03	0.09	0.11	0.15	0.23
Toe-off distance (m)	-0.74 ± 0.03 (-0.73 ± 0.03[a])	-0.83	-0.77	-0.74	-0.72	-0.67
Contact length (m)	0.85 ± 0.07 (0.86 ± 0.07[a])	0.70	0.81	0.84	0.91	1.01
Flight length (m)	0.44 ± 0.07 (0.45 ± 0.07[a])	0.26	0.41	0.43	0.49	0.56
Foot angle at touchdown(°)	161 ± 5	150	158	160	163	169
Shank angle at touchdown (°)	64 ± 3	59	61	63	67	70
Thigh angle at touchdown (°)	124 ± 4	118	122	124	127	133
Trunk angle at touchdown (°)	50 ± 4	39	48	51	53	57
Foot angle at toe-off (°)	92 ± 3	87	90	91	93	99
Shank angle at toe-off (°)	35 ± 3	31	33	36	37	40
Thigh angle at toe-off (°)	55 ± 3	50	54	56	57	62
Trunk angle at toe-off (°)	52 ± 4	40	50	53	55	59

[a]Values normalized to leg length

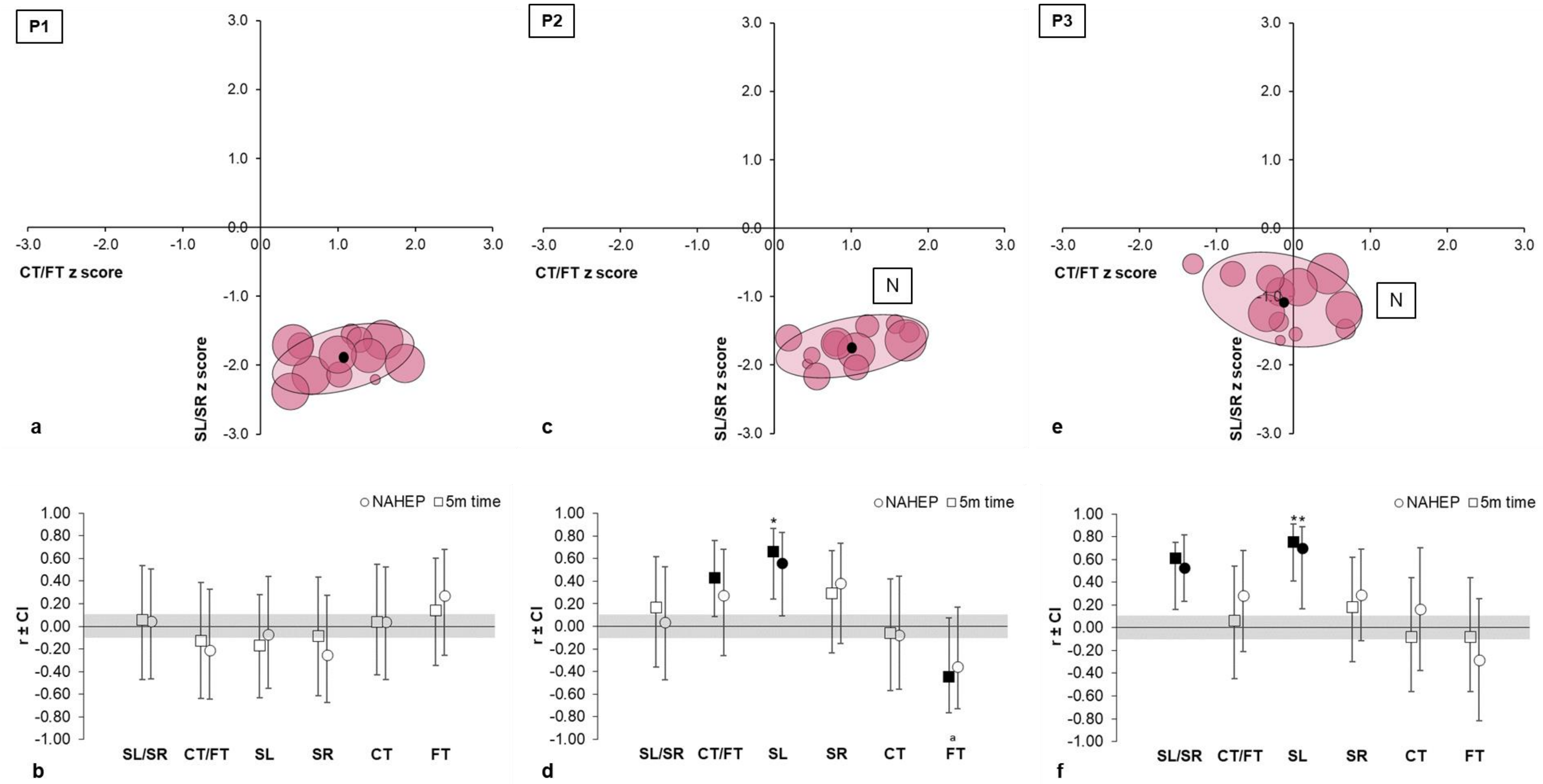
Table 4. Strength-based variables of 25 elite rugby union backs obtained during Stage 1.

Variables	Mean ± SD	Min.	25th%	Median	75th%	Max.
P_{max} (W/kg)	28.94 ± 4.74	18.00	26.91	29.48	32.37	38.67
Hip torque (Nm/kg)	5.81 ± 0.79	4.46	5.27	5.87	6.06	7.77
Repeated contact time (s)	0.276 ± 0.025	0.316	0.295	0.274	0.258	0.240
Repeated jump height (m)	0.176 ± 0.021	0.133	0.165	0.174	0.195	0.212
Repeated RSI (height / CT)	0.64 ± 0.09	0.44	0.62	0.64	0.67	0.82
Hip torque / repeated CT ratio	21.22 ± 3.69	14.46	18.70	20.69	24.42	30.06

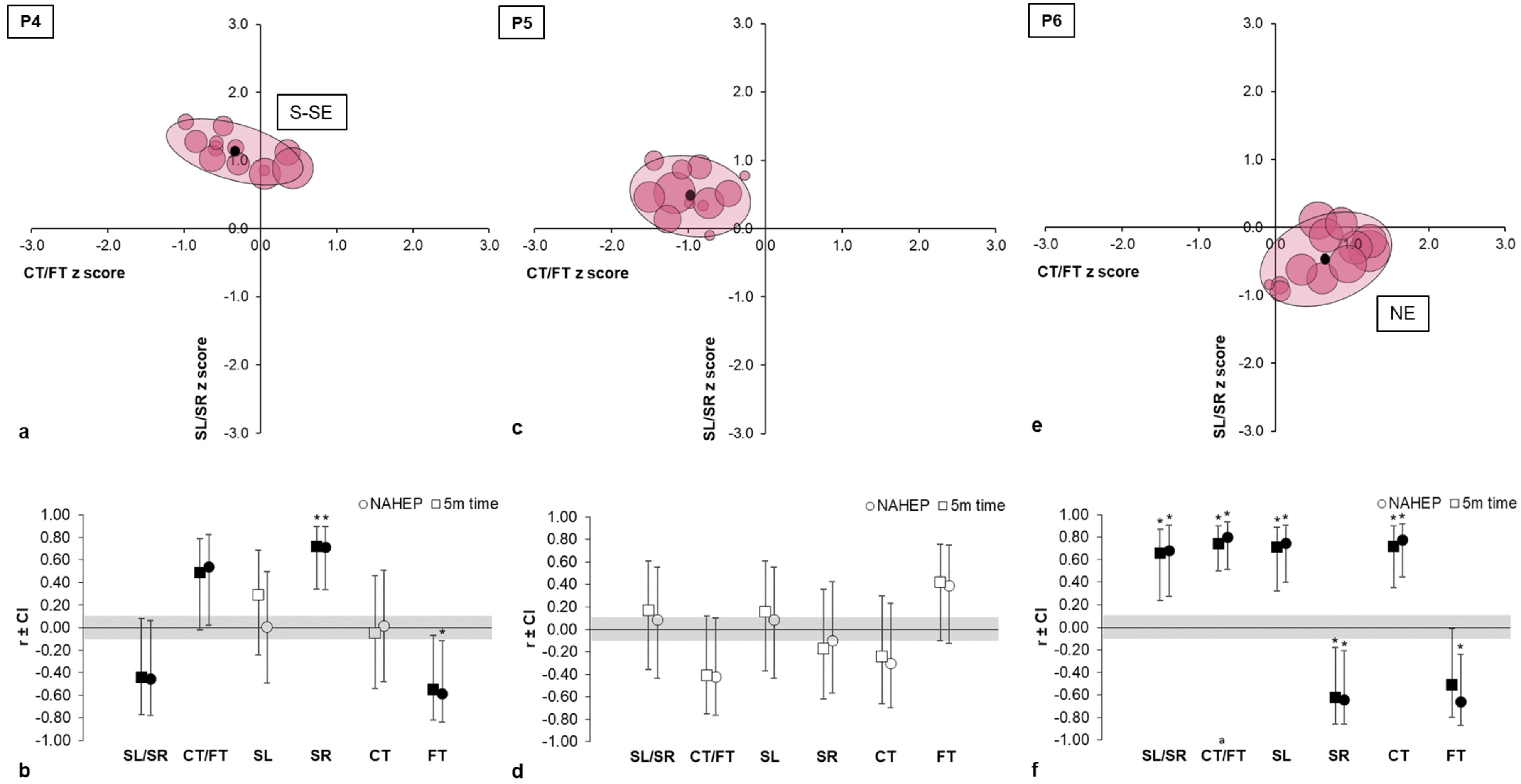
To help with clarity, repeated CT values have been inverted so that worse to better performance can be observed for all variables from left to right, respectively (i.e., a lower repeated contact time is better in performance terms)

P_{max} is the maximal mechanical power output during squat jump profiling

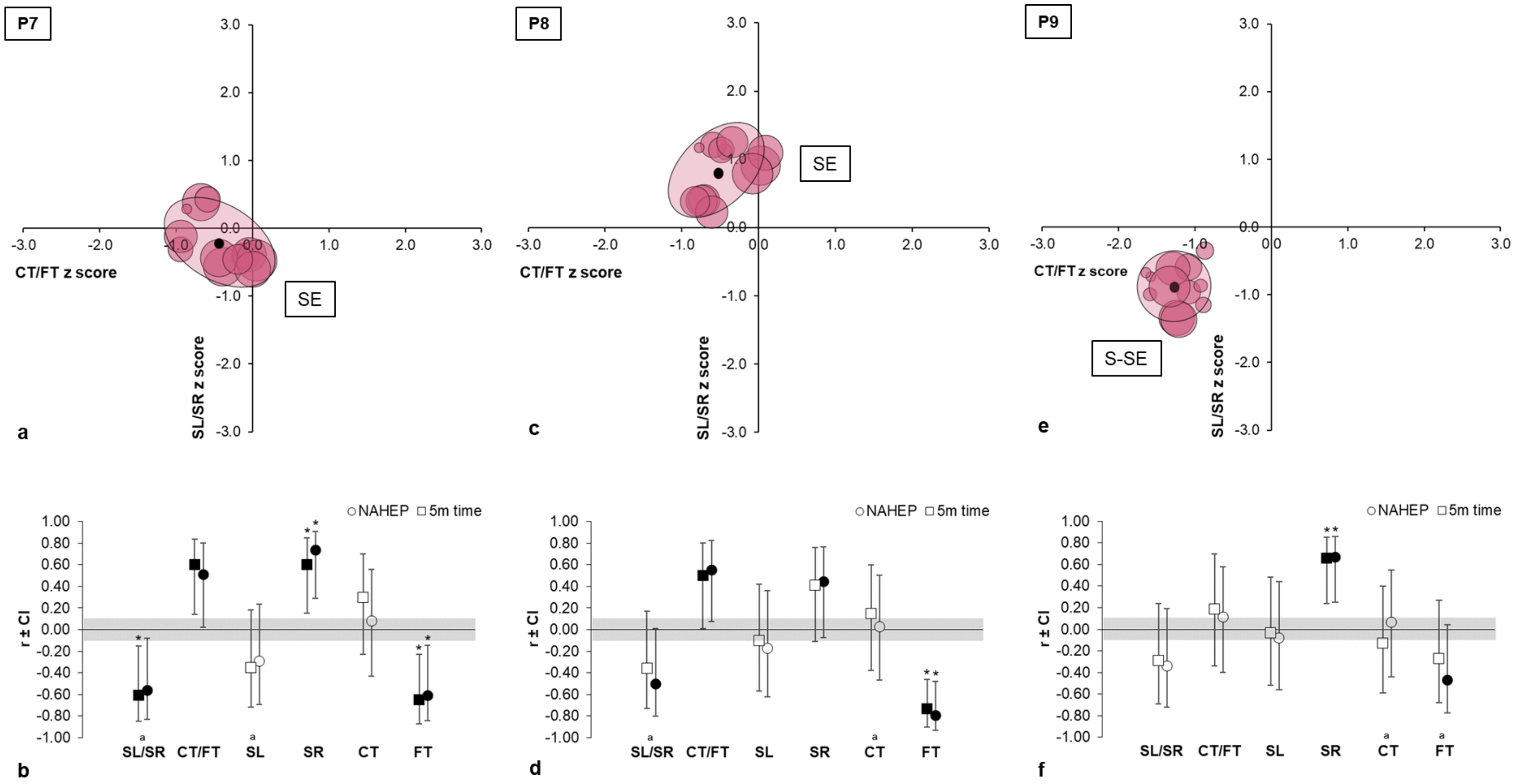
SUPPLEMENTARY MATERIAL A - ADDITIONAL FIGURES FOR THE PARTICIPANTS THAT WERE STUDIED IN PART I, BUT FOR WHOM THE FIGURES WERE NOT INCLUDED IN THE MANUSCRIPT



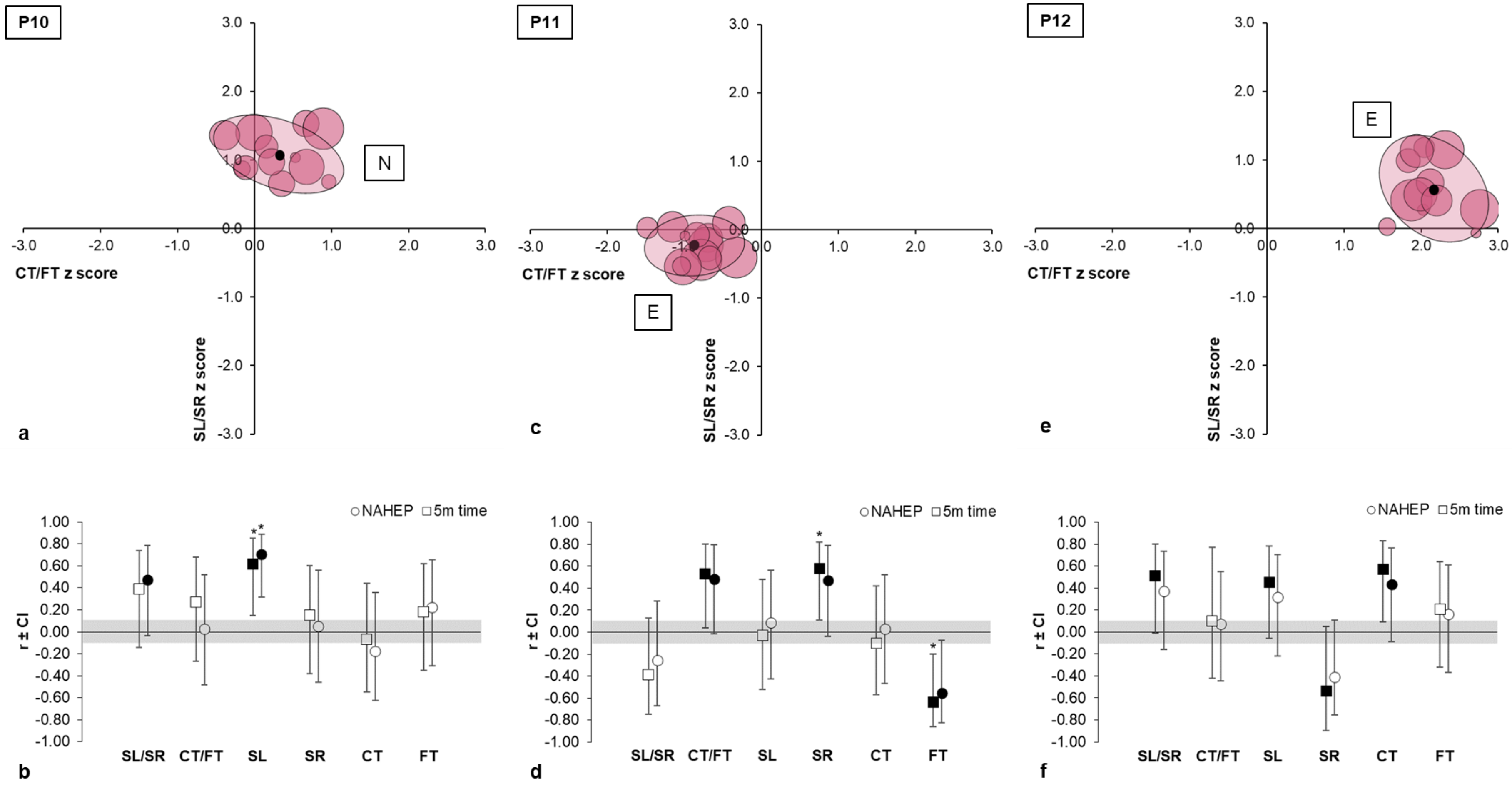
A1. Whole-body kinematic strategy (a,c and e), and relationships (with 90% confidence intervals) of SL/SR and CT/FT ratios and normalised spatiotemporal variables with NAHEP and 5 m time (b, d and f) of participants 1 to 3. See Figure 2 caption in the published journal article for full explanation.



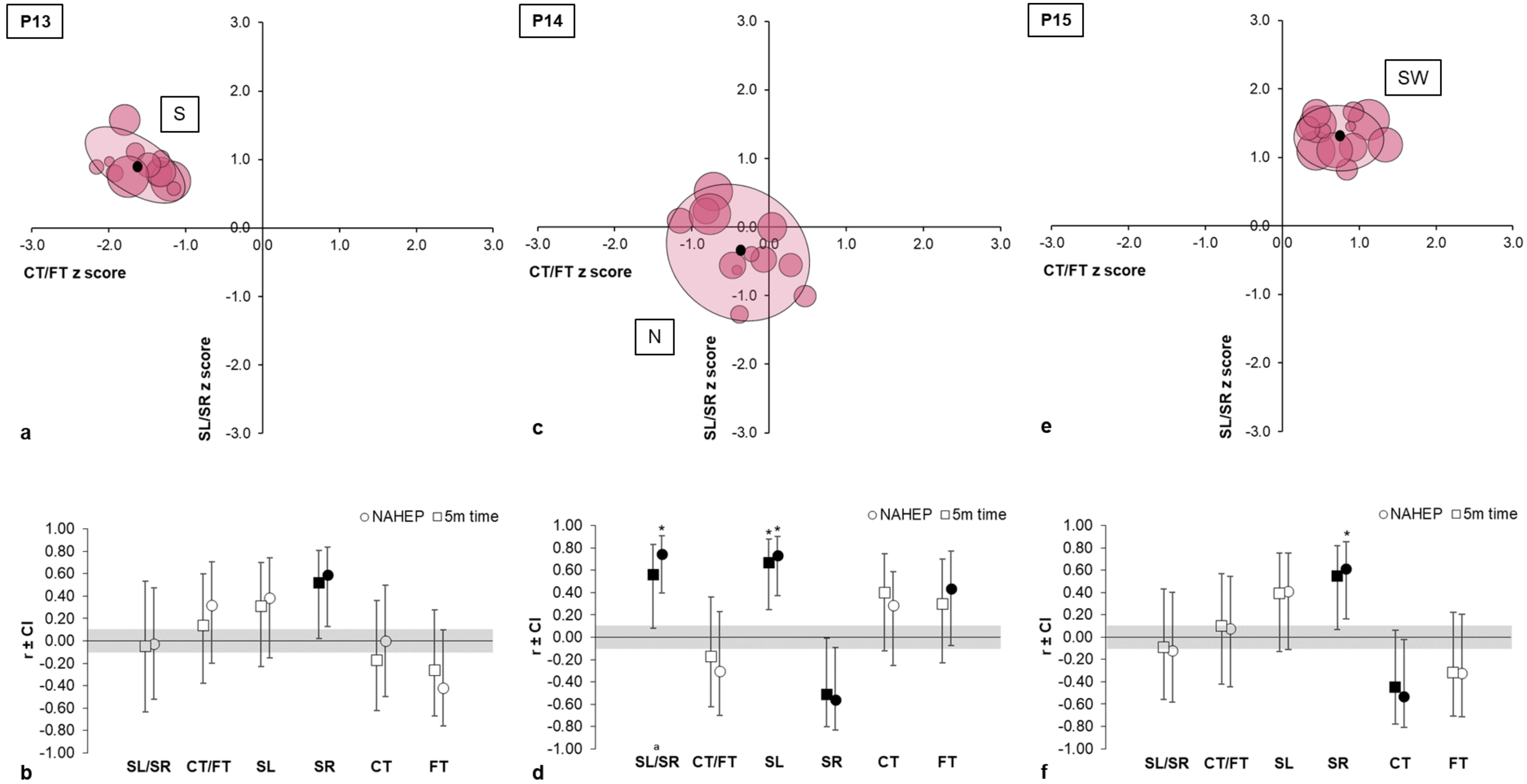
A2. Whole-body kinematic strategy (a,c and e), and relationships (with 90% confidence intervals) of SL/SR and CT/FT ratios and normalised spatiotemporal variables with NAHEP and 5 m time (b, d and f) of participants 4 to 6. See Figure 2 caption in the published journal article for full explanation.



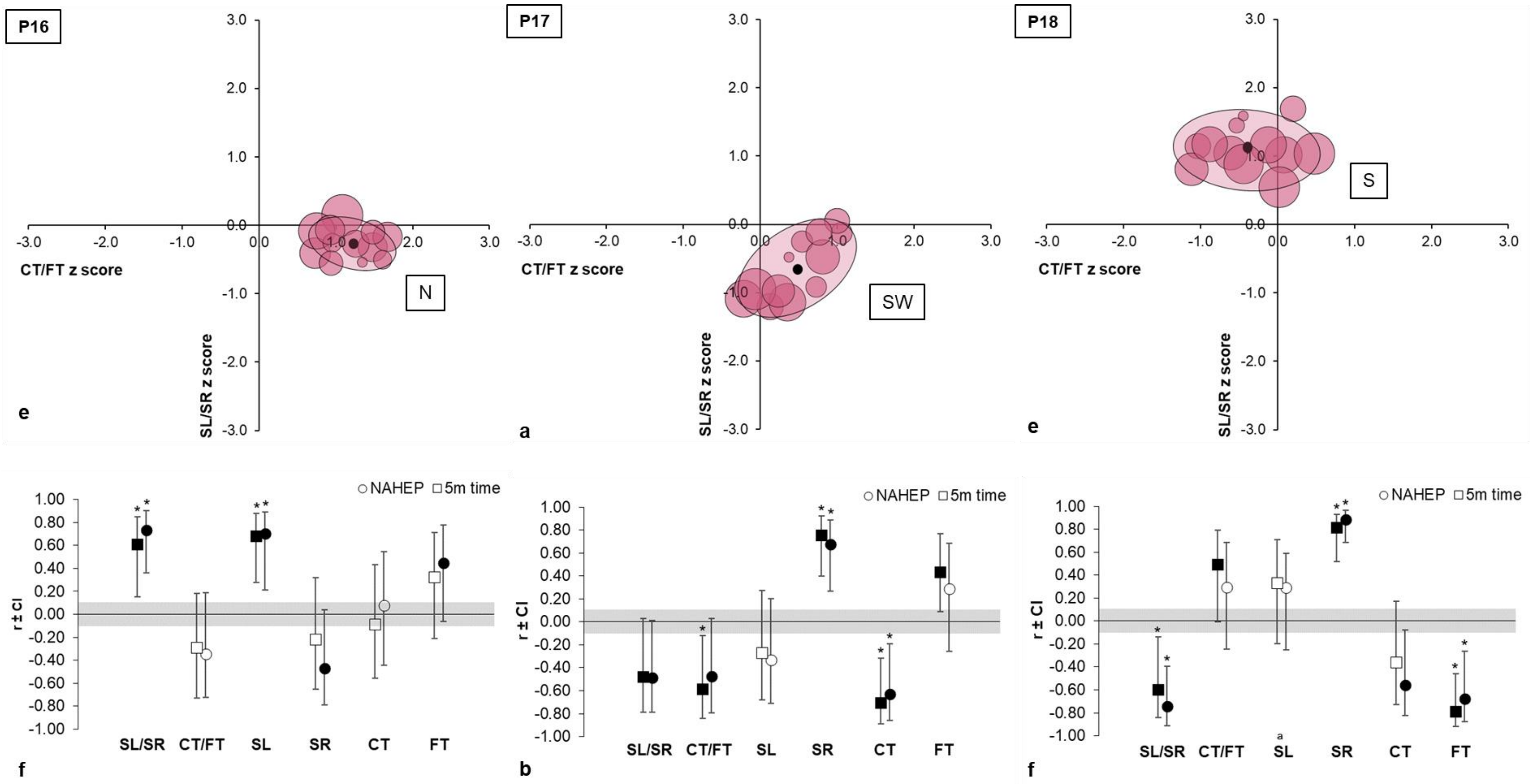
A3. Whole-body kinematic strategy (a,c and e), and relationships (with 90% confidence intervals) of SL/SR and CT/FT ratios and normalised spatiotemporal variables with NAHEP and 5 m time (b, d and f) of participants 7 to 9. See Figure 2 caption in the published journal article for full explanation.



A4. Whole-body kinematic strategy (a,c and e), and relationships (with 90% confidence intervals) of SL/SR and CT/FT ratios and normalised spatiotemporal variables with NAHEP and 5 m time (b, d and f) of participants 10 to 12. See Figure 2 caption in the published journal article for full explanation.



A5. Whole-body kinematic strategy (a,c and e), and relationships (with 90% confidence intervals) of SL/SR and CT/FT ratios and normalised spatiotemporal variables with NAHEP and 5 m time (b, d and f) of participants 13 to 15. See Figure 2 caption in the published journal article for full explanation.



A6. Whole-body kinematic strategy (a,c and e), and relationships (with 90% confidence intervals) of SL/SR and CT/FT ratios and normalised spatiotemporal variables with NAHEP and 5 m time (b, d and f) of participants 13 to 15. See Figure 2 caption in the published journal article for full explanation.

SUPPLEMENTARY MATERIAL B

Mean ± SD and coefficient of variation (in brackets; %) of initial acceleration performance and normalised spatiotemporal variables of individual participants across 12 sprint trials, obtained in Stages 1 and 2.

Participant	NAHEP	5 m time (s)	CT/FT	SL/SR	SL	SR	CT	FT
1	0.628 ± 0.027 (4.2)	1.015 ± 0.018 (1.8)	2.97 ± 0.21 (7.0)	0.74 ± 0.03 (4.3)	1.17 ± 0.05 (4.1)	1.57 ± 0.03 (1.9)	0.48 ± 0.01 (1.8)	0.16 ± 0.01 (6.4)
2	0.409 ± 0.045 (9.6)	1.109 ± 0.027 (2.4)	2.94 ± 0.22 (7.6)	0.76 ± 0.03 (3.7)	1.14 ± 0.03 (2.4)	1.50 ± 0.04 (2.5)	0.50 ± 0.02 (3.8)	0.16 ± 0.07 (4.8)
3	0.644 ± 0.035 (5.4)	1.013 ± 0.035 (2.5)	2.47 ± 0.24 (9.9)	0.84 ± 0.05 (5.4)	1.26 ± 0.06 (4.8)	1.50 ± 0.03 (1.7)	0.47 ± 0.01 (2.0)	0.19 ± 0.02 (8.9)
4	0.631 ± 0.028 (4.5)	1.017 ± 0.023 (2.3)	2.38 ± 0.19 (8.2)	1.10 ± 0.03 (2.6)	1.42 ± 0.02 (1.7)	1.29 ± 0.02 (1.7)	0.55 ± 0.01 (1.5)	0.23 ± 0.02 (7.0)
5	0.505 ± 0.021 (4.2)	1.064 ± 0.013 (1.2)	2.11 ± 0.16 (7.6)	1.03 ± 0.04 (3.7)	1.37 ± 0.03 (2.1)	1.33 ± 0.02 (1.8)	0.51 ± 0.01 (2.8)	0.24 ± 0.01 (5.7)
6	0.651 ± 0.027 (4.1)	1.004 ± 0.009 (0.9)	2.79 ± 0.19 (7.0)	0.91 ± 0.04 (4.7)	1.30 ± 0.03 (2.6)	1.43 ± 0.04 (2.5)	0.51 ± 0.02 (3.9)	0.19 ± 0.01 (3.8)
7	0.626 ± 0.032 (5.1)	1.025 ± 0.027 (2.6)	2.34 ± 0.16 (6.8)	0.94 ± 0.04 (4.7)	1.32 ± 0.05 (3.7)	1.40 ± 0.02 (1.3)	0.50 ± 0.01 (1.7)	0.21 ± 0.01 (5.7)
8	0.553 ± 0.042 (7.5)	1.058 ± 0.029 (2.8)	2.32 ± 0.14 (5.9)	1.07 ± 0.05 (4.3)	1.40 ± 0.03 (2.0)	1.32 ± 0.04 (2.7)	0.53 ± 0.02 (3.5)	0.23 ± 0.01 (4.4)
9	0.610 ± 0.026 (4.2)	1.023 ± 0.014 (1.4)	1.99 ± 0.12 (5.9)	0.86 ± 0.04 (4.2)	1.21 ± 0.04 (3.5)	1.40 ± 0.02 (1.7)	0.48 ± 0.01 (3.0)	0.24 ± 0.01 (3.8)
10	0.546 ± 0.022 (4.0)	1.048 ± 0.012 (1.1)	2.65 ± 0.19 (7.1)	1.09 ± 0.04 (3.3)	1.42 ± 0.03 (2.3)	1.27 ± 0.02 (1.4)	0.56 ± 0.01 (2.2)	0.23 ± 0.01 (4.4)
11	0.539 ± 0.032 (5.9)	1.063 ± 0.019 (1.8)	2.16 ± 0.14 (6.3)	0.94 ± 0.03 (2.9)	1.29 ± 0.02 (1.8)	1.37 ± 0.03 (1.9)	0.50 ± 0.01 (2.3)	0.23 ± 0.01 (5.4)
12	0.483 ± 0.037 (7.6)	1.079 ± 0.024 (2.2)	3.42 ± 0.15 (4.3)	1.04 ± 0.05 (5.0)	1.40 ± 0.04 (2.7)	1.35 ± 0.03 (2.5)	0.57 ± 0.01 (2.6)	0.17 ± 0.01 (4.5)
13	0.517 ± 0.017 (7.8)	1.068 ± 0.008 (2.8)	1.84 ± 0.14 (2.2)	1.07 ± 0.03 (1.6)	1.40 ± 0.03 (2.2)	1.30 ± 0.02 (6.2)	0.50 ± 0.01 (3.3)	0.27 ± 0.02 (0.8)
14	0.544 ± 0.025 (4.5)	1.057 ± 0.025 (2.3)	2.37 ± 0.20 (8.6)	0.93 ± 0.06 (6.8)	1.37 ± 0.06 (4.7)	1.39 ± 0.04 (2.5)	0.51 ± 0.01 (2.1)	0.22 ± 0.02 (7.8)
15	0.635 ± 0.025 (3.9)	1.001 ± 0.015 (1.5)	2.84 ± 0.13 (4.7)	1.12 ± 0.03 (2.7)	1.47 ± 0.03 (1.7)	1.31 ± 0.02 (1.7)	0.57 ± 0.01 (1.9)	0.20 ± 0.01 (4.1)
16	0.450 ± 0.022 (5.0)	1.072 ± 0.011 (1.1)	3.03 ± 0.14 (4.7)	0.94 ± 0.03 (2.7)	1.29 ± 0.03 (2.0)	1.38 ± 0.02 (1.2)	0.54 ± 0.01 (1.6)	0.18 ± 0.01 (4.0)
17	0.535 ± 0.025 (4.6)	1.061 ± 0.022 (2.1)	2.72 ± 0.18 (6.5)	0.89 ± 0.05 (6.0)	1.28 ± 0.05 (3.9)	1.41 ± 0.03 (2.4)	0.52 ± 0.02 (4.0)	0.20 ± 0.01 (2.9)
18	0.468 ± 0.026 (5.6)	1.079 ± 0.017 (1.6)	2.36 ± 0.22 (9.2)	1.10 ± 0.04 (3.5)	1.33 ± 0.03 (1.9)	1.30 ± 0.04 (3.2)	0.54 ± 0.02 (3.5)	0.24 ± 0.02 (8.0)
19	0.627 ± 0.030 (6.1)	1.036 ± 0.022 (4.7)	2.74 ± 0.17 (3.6)	1.01 ± 0.05 (1.4)	1.34 ± 0.05 (2.3)	1.34 ± 0.02 (3.4)	0.54 ± 0.01 (4.7)	0.21 ± 0.01 (2.1)
Group mean CV ± SD (%)	5.5 ± 1.8	2.1 ± 0.9	6.5 ± 1.9	3.9 ± 1.4	2.8 ± 1.0	2.3 ± 1.1	2.7 ± 1.0	5.0 ± 2.1

Where units are not provided, variables are in their dimensionless form using the equations of Hof[28]

SUPPLEMENTARY MATERIAL C

Number of participants exhibiting meaningful or statistically significant within-individual relationships between initial acceleration performance and normalised sprint kinematic variables

Variable	SL/SR		CT/FT		SL		SR		CT		FT	
	M	S	M	S	M	S	M	S	M	S	M	S
NAHEP	11	4	8	2	7	6	12	7	6	3	10	4
5 m time	9	4	8	3	8	7	11	7	5	2	9	5

SL/SR = step length/step rate ratio, CT/FT = contact time/flight time ratio, SL = step length, SR = step rate, CT = contact time, FT = flight time, M = number of meaningful relationships, S = number of statistically significant relationships