

TITLE

Enhancing the Initial Acceleration Performance of Elite Rugby Backs. Part I: Determining Individual Technical Needs

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VERSIONS

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1 **ENHANCING THE INITIAL ACCELERATION PERFORMANCE OF ELITE**
2 **RUGBY BACKS. PART I: DETERMINING INDIVIDUAL TECHNICAL NEEDS**
3

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

24
25 **Keywords/phrases:** sprinting, constraints, training, motor control, biomechanics

43 INTRODUCTION

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

51 The relationships between initial acceleration performance (approximately the first 4 steps⁵)
52 and aspects of technique, including spatiotemporal variables like step length, step rate and
53 contact and flight times, have been widely investigated in team sports and track and field
54 sprinters.⁶⁻¹⁰ However, due to inconsistent relationships reported at the whole group level,
55 conflicting perspectives remain on which, if any, of these spatiotemporal variables are
56 associated with better initial acceleration performance.

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

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

82 Wild et al.¹¹ developed a framework for practitioners to measure individual *whole-body*
83 *kinematic strategies*, depicted by the spatial location of cartesian coordinates based on SL/SR
84 and CT/FT ratios. This analysis extended the work of Salo et al.¹² by providing a more
85 detailed understanding of how a given sprint performance is achieved. Monitoring an
86 individual's *whole-body kinematic strategy* using this combination of variables can facilitate
87 a deeper understanding of how spatiotemporal variables collectively, and individually,
88 change in relation to changes in initial acceleration performance. If meaningful within-

89 individual relationships are found, it is possible that focusing speed training interventions on
90 the spatiotemporal variables most closely related to initial acceleration performance may be
91 more likely to enhance a rugby back's sprinting ability during the initial steps.

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

102 The primary aim of this study was to quantify the within-individual relationships between
103 sprint spatiotemporal variables (SL/SR and CT/FT ratios and normalized spatiotemporal
104 variables) and initial acceleration performance in elite rugby backs, and to use these to
105 identify the direction of the relationship between their *whole-body kinematic strategy* and
106 performance. The second aim was to establish a normative data set of relevant strength-based
107 measures from which strength capacity deficits for individual backs. Collectively, this
108 information could be used to inform future interventions (see part II¹³). Finally, although
109 normalized average horizontal external power (NAHEP) is commonly used as an initial
110 acceleration performance measure,¹⁶ it typically requires considerable data processing time to
111 determine whole body center of mass location at touchdown and toe-off. Therefore, the third
112 aim was to determine whether an alternative, less time-consuming, initial acceleration
113 performance measure could be used to enhance the likelihood of practitioner application.

114

115 **METHODS**

116 *Participants*

117 Data from 35 elite¹⁷ male rugby union backs (mean \pm SD: age 25 ± 3 years; stature $1.81 \pm$
118 0.06 m; leg length 1.00 ± 0.05 m; body mass 93.0 ± 8.5 kg) competing in the English
119 Premiership were analyzed. At the time of testing, participants were free from injury and
120 frequently completed maximal sprint accelerations within their weekly training regime.
121

122 *Procedures*

123 The research was conducted in two stages (Table 1), primarily following a multiple-single-
124 subject design. In Stage 1 normalized spatiotemporal variables and NAHEP were obtained
125 from all 35 participants over the first four steps of three sprints on a single occasion, using the
126 video-based protocols of Wild et al.¹¹ A second initial acceleration performance measure (5
127 m time) was also determined for all participants to enable the third aim to be addressed. This
128 was determined in Kinovea (v.0.8.27) from when the back foot had visibly lifted off the
129 ground until the mid-hips passed 5 m.¹⁸ The 5 m distance was selected because it is the
130 closest distance to that covered during the first four steps which is used in applied settings to
131 measure initial acceleration performance.^{19,20}
132

133 For 25 of the Stage 1 participants, selected angular and linear kinematics were also collected
134 during the sprint testing (Figure 1). The same 25 participants then undertook three strength-

135 based assessments. From a repeated unilateral in-place jump test (repeated jumps), jump
136 heights (m), contact times (s) and the reactive strength index (RSI; ratio of jump height to
137 contact time)^{21,22} were obtained for each side using a modified approach from Comyns et al.²³
138 Based on adapted protocols from Samozino et al.²⁴ and Goodwin and Bull²⁵, maximal
139 mechanical power output during squat jump profiling (P_{\max} [W/kg]) and peak unilateral
140 isometric torque (Nm/kg) of the hip extensors (hip torque) were obtained, respectively. The
141 hip torque / repeated jump contact time ratio (hip torque / repeated CT) was also determined
142 for each participant. Full protocols for these strength-based assessments and the reliability of
143 measures obtained (CV 4.2 to 5.4%) are reported in Wild et al.¹¹

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145
146 ***FIGURE 1 NEAR HERE***
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149 In Stage 2, the same sprint testing as in Stage 1 was conducted for 19 of the 35 participants
150 on three further occasions (Table 1), which resulted in spatiotemporal variables being
151 measured for these participants for 12 sprints over six pre-season weeks (i.e., three sprint
152 trials on four separate occasions). These data were used to determine the intra-individual
153 relationships between the spatiotemporal variables (step lengths, step rates, contact and flight
154 times, SL/SR and CT/FT ratios) and initial acceleration performance.

155
156 Following a similar approach as Salo et al.,¹² participants were deemed ‘reliant’ on
157 spatiotemporal variables for improved initial acceleration performance in favor of the
158 spatiotemporal variable that demonstrated a more substantial difference in correlation
159 magnitude ($\Delta r \geq 0.1$) and when meaningful within-individual relationships were observed
160 (see Statistical Analyses). Directional changes in Cartesian plane spatial location of
161 individual backs’ *whole-body kinematic strategies* associated with higher initial acceleration
162 performance were expressed as directions on a 16-point compass. These were determined
163 according to the magnitudes of the relationships observed between each ratio (SL/SR and
164 CT/FT) and NAHEP across the 12 sprints. For example, a meaningfully positive relationship
165 (see *Statistical analyses*) between the SL/SR ratio and NAHEP for an individual would
166 denote a favorable shift northward on the Cartesian plane.

167
168 This process is illustrated for a single participant in Figure 2; the marker sizes in Figure 2a
169 are proportional to magnitudes of NAHEP. For this participant, the markers are typically
170 larger more northwards (i.e., higher NAHEP is achieved with a larger SL/SR ratio) and
171 eastwards (i.e., higher NAHEP achieved with a larger CT/FT ratio). If the difference between
172 the magnitude of these relationships is trivial ($r < 0.1$), then collectively the direction
173 associated with higher initial acceleration performance would be represented by an
174 intercardinal direction (northeast in this example). If both ratios are meaningfully related to
175 NAHEP, but the difference between the magnitudes of the relationships is considered at least
176 small ($r \geq 0.1$) then the cardinal direction signifying the intended shift in strategy would
177 result in a ‘half-wind’ (i.e., direction points obtained by bisecting intercardinal directions
178 yielding 16 direction categories each 22.5° from its nearest neighbors) oriented more towards
179 the relationship of a higher magnitude. For example, in Figure 2b, the within-participant
180 relationships of the SL/SR and CT/FT ratios with NAHEP were $r = 0.45$ and 0.77 ,
181 respectively, and thus the resulting direction associated with higher initial acceleration
182 performance would be E-NE for this individual. These directions were then used to inform
183 the intended technical change which would likely benefit a given individual’s initial

184 acceleration performance. Where meaningful relationships between the SL/SR and CT/FT
185 ratios and NAHEP were not found, the intended technical change was informed by the
186 relationships between normalized spatiotemporal variables in isolation and NAHEP.

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190 ***TABLE 1 NEAR HERE***

191
192 ***FIGURE 2 NEAR HERE***

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194 *Statistical analyses*

195 In Stage 1, data for normalized spatiotemporal variables, NAHEP and 5 m time were
196 averaged over four steps, and then averaged again over the three sprint trials for each of the
197 35 participants. This approach was also taken for the linear and angular kinematics obtained
198 in Stage 1. A range of descriptive statistics, including percentile ranges, were determined for
199 strength-measures collected to provide a normative dataset for strength-based performance to
200 address the second aim.

201
202 For the 19 participants who completed sprint trials on four separate occasions during Stages 1
203 and 2, each individual participant's mean \pm SD 5 m time, NAHEP, normalized
204 spatiotemporal variables and SL/SR and CT/FT ratios across the 12 sprints completed were
205 determined. All group and intra-individual descriptive data (mean \pm SD) were calculated for
206 all variables and checked for normal distribution using the Shapiro-Wilk statistic.

207
208 To assess consistency of 5 m time, group and intra-individual coefficients of variation (CV)
209 were determined. In Stage 1, the 5 m time within-participant CV for each of the 35
210 participants across their three sprint trials was calculated and the average of these across the
211 entire group was then determined to provide the group level CV. For the 19 participants who
212 completed sprint trials on four different occasions during Stages 1 and 2, the 5 m time CVs
213 for each participant across their 12 sprint efforts were also determined. The same approach
214 was taken to determine the intra-individual CVs for NAHEP, normalized spatiotemporal
215 variables and SL/SR and CT/FT ratios.

216
217 The strength of group and within-individual relationships between NAHEP and 5 m time
218 were determined using Pearson's correlation coefficient analysis (including 90% confidence
219 intervals). A group level correlation was based on the mean NAHEP and 5 m time achieved
220 by each of the 35 participants (Table 1, Stage 1) in their initial three sprint trials. The intra-
221 individual correlations were determined individually for the 19 participants across their 12
222 sprint trials.

223
224 The *whole-body kinematic strategies* and distribution of these for the 19 participants who
225 underwent the full analysis were determined using the same approaches as used in Wild et
226 al.¹¹ Participant z-scores were calculated based on the whole participant group in the current
227 study (n = 35). Pearson's or Spearman's rank order (non-parametric data) correlation
228 coefficients were used to measure the strength of intra-individual relationships (including
229 90% confidence intervals) of normalized spatiotemporal variables and the SL/SR and CT/FT
230 ratios with initial acceleration performance across their 12 sprints (see Figure 2b). All
231 relationships were deemed meaningful where the magnitude of the observed relationship was

232 greater than the smallest practically important correlation;²⁶ $r = \pm 0.43$. Relationships were
233 deemed unclear if their magnitude was within this threshold ($-0.43 < r < 0.43$). The strength
234 of relationships was defined as: (\pm) < 0.1 , trivial; 0.1 to < 0.3 , small; 0.3 to < 0.5 moderate,
235 0.5 to < 0.7 large, 0.7 to < 0.9 very large and ≥ 0.9 , practically perfect.²⁷

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237

238 RESULTS

239 Descriptive statistics for initial acceleration performance, sprint kinematic variables and
240 strength-based measures are presented in Tables 2 to 4, and supplementary material B. In
241 terms of initial acceleration performance, NAHEP ranged from 0.440 to 0.722 (mean \pm SD =
242 0.559 ± 0.074), and the 5-meter time ranged from 0.956 s to 1.106 s (mean \pm SD = $1.029 \pm$
243 0.035 s). The quartiles are presented in Tables 2 to 4 to aid in the contextualization of any
244 given rugby back, particularly for our second aim of establishing a normative data set of
245 relevant strength-based measures.

246

247 ***TABLE 2 NEAR HERE***

248 ***TABLE 3 NEAR HERE***

249 ***TABLE 4 NEAR HERE***

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

257

258 Trivial to very large within-individual relationships of NAHEP with SL/SR and CT/FT ratios
259 and each normalized spatiotemporal variable were observed for the 19 participants who
260 completed stages 1 and 2 (Figure 2; see also supplementary material A). Within-individual
261 relationships of NAHEP with SL/SR and CT/FT ratios ($|r| = 0.04$ to 0.75 and $|r| = 0.03$ to
262 0.80) were meaningful in eleven (in four, $p \leq 0.05$) and seven (in two, $p \leq 0.05$) participants,
263 respectively. Within-individual relationships between NAHEP and normalized step length ($|r|$
264 = 0.01 to 0.76) were meaningful in seven participants (in six, $p \leq 0.05$). Within-individual
265 relationships between NAHEP and normalized step rate ($|r| = 0.05$ to 0.88) were meaningful
266 in 13 participants (in seven, $p \leq 0.05$). Within-individual relationships of NAHEP with
267 normalized contact time and normalized flight time ($|r| = 0.02$ to 0.78 and $|r| = 0.22$ to 0.79)
268 were meaningful in six (in three, $p \leq 0.05$) and nine (in five, $p \leq 0.05$) participants,
269 respectively.

270

271 Differences in magnitude between the within-individual relationships of 5 m time and
272 NAHEP with SL/SR and CT/FT ratios and each normalized spatiotemporal variable were
273 trivial to small (mean \pm SD difference: SL/SR ratio, $\Delta r = 0.08 \pm 0.06$; CT/FT ratio, $\Delta r = 0.10$
274 ± 0.07 ; normalized step length, $\Delta r = 0.08 \pm 0.06$; normalized step rate, $\Delta r = 0.09 \pm 0.06$;
275 normalized contact time, $\Delta r = 0.12 \pm 0.07$; normalized flight time, $\Delta r = 0.10 \pm 0.06$; Figure 2
276 and supplementary material A). Of the number of meaningful within-individual relationships
277 ($n = 54$) across participants between NAHEP and spatiotemporal variables, 82% ($n = 44$) of

278 the same relationships were also found to be meaningful when NAHEP was replaced by 5 m
279 time (Figure 2 and supplementary material A and C). Six further meaningful relationships of
280 spatiotemporal variables observed with 5 m time were not observed with NAHEP
281 (differences in relationship magnitudes ranged between 0.01 and 0.16). Of the number of
282 statistically significant within-individual relationships ($n = 26$) across participants between
283 NAHEP and spatiotemporal variables, 88% ($n = 23$) of the same relationships were also
284 found to be significant when NAHEP was replaced by 5 m time. Five further significant
285 relationships of spatiotemporal variables observed with 5 m time were not observed with
286 NAHEP (supplementary material C).

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289

290 **DISCUSSION**

291

292 This study's primary aim was to determine how spatiotemporal variables (normalized
293 spatiotemporal variables and SL/SR and CT/FT ratios) of elite rugby backs related
294 individually to initial acceleration performance. Meaningful within-individual relationships
295 were found between spatiotemporal variables and NAHEP (Figure 2 and supplementary
296 material A) in all but two (P1 and P5) of 19 participants. This outcome highlights the specific
297 variables that were associated with greater initial acceleration performance in individual
298 participants, and builds on previous research¹² in which elite track sprinters were found to
299 individually 'rely' on either greater average step length or step rate (or neither variable) for
300 better sprinting performance in 100 m races. Of the 11 sprinters studied by Salo et al.,¹² three
301 'relied' on step length and one on step rate for better sprint performance. Consequently, based
302 on those analyses alone, practitioners would be left without a technical training direction for
303 the majority of sprinters from that cohort. To overcome similar challenges when analyzing
304 just the initial acceleration phase, the current study sought to understand how performance
305 was not only related individually to step length and step rate, but also to contact and flight
306 times and the SL/SR and CT/FT ratios which form the *whole-body kinematic strategies* of
307 participants. This approach provides a more detailed understanding of the spatiotemporal
308 variables which athletes may 'rely' on for better sprint performance.

309

310 Eleven of the 19 participants (Figure 2 and supplementary material A) were found to
311 individually 'rely' on step length ($n = 6$) or step rate ($n = 5$) based on a meaningful r value of
312 ≥ 0.43 being evident with NAHEP, and the difference in correlation magnitude between the
313 relationships of step length and step rate with NAHEP for each of these participants also
314 being ≥ 0.10 . However, when also considering SL/SR and CT/FT ratios and contact and
315 flight times in addition to just step length and step rate, 17 of the 19 participants were
316 observed to individually 'rely' on at least one spatiotemporal variable for better initial
317 acceleration performance (Figure 2 and supplementary material A). Therefore, assessing a
318 more holistic *whole-body kinematic strategy* when determining within-individual
319 relationships between sprint-technique variables and initial acceleration performance is more
320 likely to provide valuable direction for practitioners to inform the individualization of their
321 technical interventions. The set of normative strength-based data (Table 4) which addressed
322 the second aim of this study also provides a means to inform the modification of performer
323 constraints which could ultimately be used to facilitate the intended technical changes (see
324 part II¹⁵).

325

326 The method used to obtain NAHEP provides a reliable (CV = 5.5%, supplementary material
327 B) and objective²⁹ measure of initial acceleration performance). However, it requires
328 digitization of 22 segment endpoints to determine whole-body CM location, which must be
329 done twice (at the beginning of first contact and at the end of fourth contact). In applied
330 settings, a simpler way to measure initial acceleration performance is valuable so that
331 actionable information can be communicated quickly. A less time-intensive initial
332 acceleration performance measure (5 m) was concurrently used to address the third aim of
333 this study by determining how closely the within-individual relationships with SL/SR and
334 CT/FT ratios and normalized spatiotemporal variables compared with those assessed against
335 NAHEP. 5 m time was more reliable (CV = 2.1%, supplementary material B) than NAHEP,
336 and differences in the correlation magnitudes between NAHEP and 5 m time with
337 spatiotemporal variables were only trivial to small (range in mean r difference = 0.08 to
338 0.12). For all meaningful relationships, when correlation coefficients were inverted for 5 m
339 time, the direction of relationships with spatiotemporal variables were the same as NAHEP.
340 In cases where the direction was different ($n = 6$), the relationships were all trivial (absolute
341 magnitudes were $r < \pm 0.16$). Given these findings and the similarity in statistically
342 significant and/or meaningful within-individual relationships of spatiotemporal variables with
343 both NAHEP and 5 m time (supplementary material C), 5 m time is an appropriate measure
344 to identify variables which are associated with higher initial acceleration performance. This
345 offers a more practical alternative to NAHEP when assessing large cohorts of athletes in a
346 high-performance environment where time is often limited as it requires timestamping just
347 two occurrences. The approach can also be used when quick feedback for monitoring
348 progress during longer-term interventions (e.g., Part II¹⁵) is required.

349

350

351 PRACTICAL APPLICATIONS

352

353 This study demonstrates the importance of considering individual needs for understanding
354 elite rugby backs' initial acceleration performance, and presents a novel, robust method
355 which will enable practitioners to effectively identify them in applied environments.
356 Determining the within-individual relationships between spatiotemporal variables, SL/SR and
357 CT/FT ratios, and initial acceleration performance, along with potential deficits in the context
358 of the set of strength-related normative data presented in this study, can easily be established
359 during a baseline period, such as the pre-season. This information may then inform
360 individually targeted training interventions, specifically focused on improving initial
361 acceleration performance. The findings of this study can also be applied to other sports that
362 require rapid initial acceleration, making it a valuable resource for coaches and athletes
363 across a range of sports. Future research on individual-specific case study interventions (see
364 Part II¹⁵) is required to substantiate whether this approach is effective in enhancing the initial
365 acceleration performance of athletes.

366

367

368 CONCLUSION

369

370 This study has developed a process to quantify individual rugby backs' technical 'reliance'
371 for achieving higher levels of initial acceleration performance. A theoretical desired change
372 in the Cartesian plane spatial location of each participant's *whole-body kinematic strategy*
373 was determined for all but two of the 19 participants studied. This information, combined
374 with the normative data based on strength qualities associated with different initial

375 acceleration strategies, provides objective, evidence-based direction which can be applied to
376 individual-specific interventions. Furthermore, we demonstrated that a simple performance
377 measure (5 m time) which can be determined quickly in applied environments, can be used.
378 This approach will now be used in Part II¹⁵ to inform individual-specific interventions for
379 elite rugby backs, and its effectiveness will be assessed through detailed measurement of
380 technical features during initial acceleration and performance at numerous instants
381 throughout an 18-week in-season intervention.

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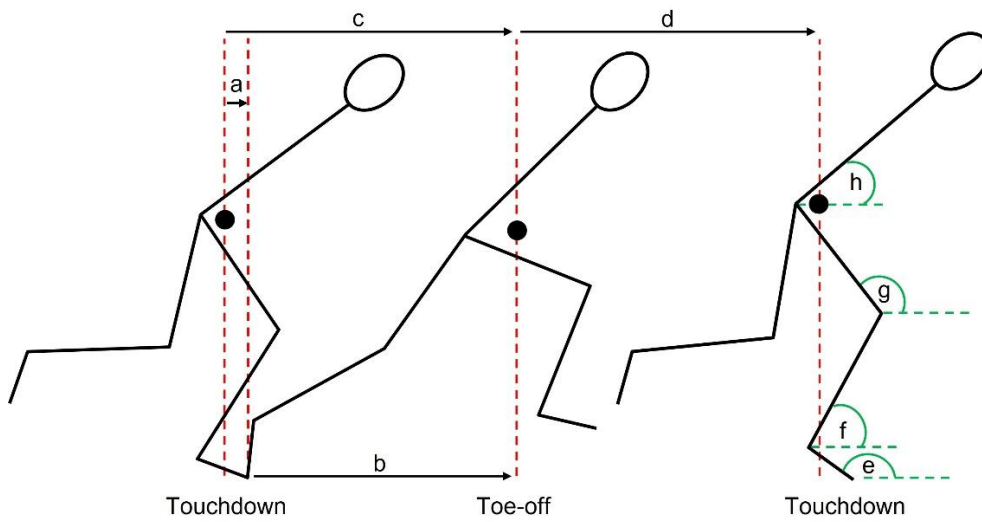
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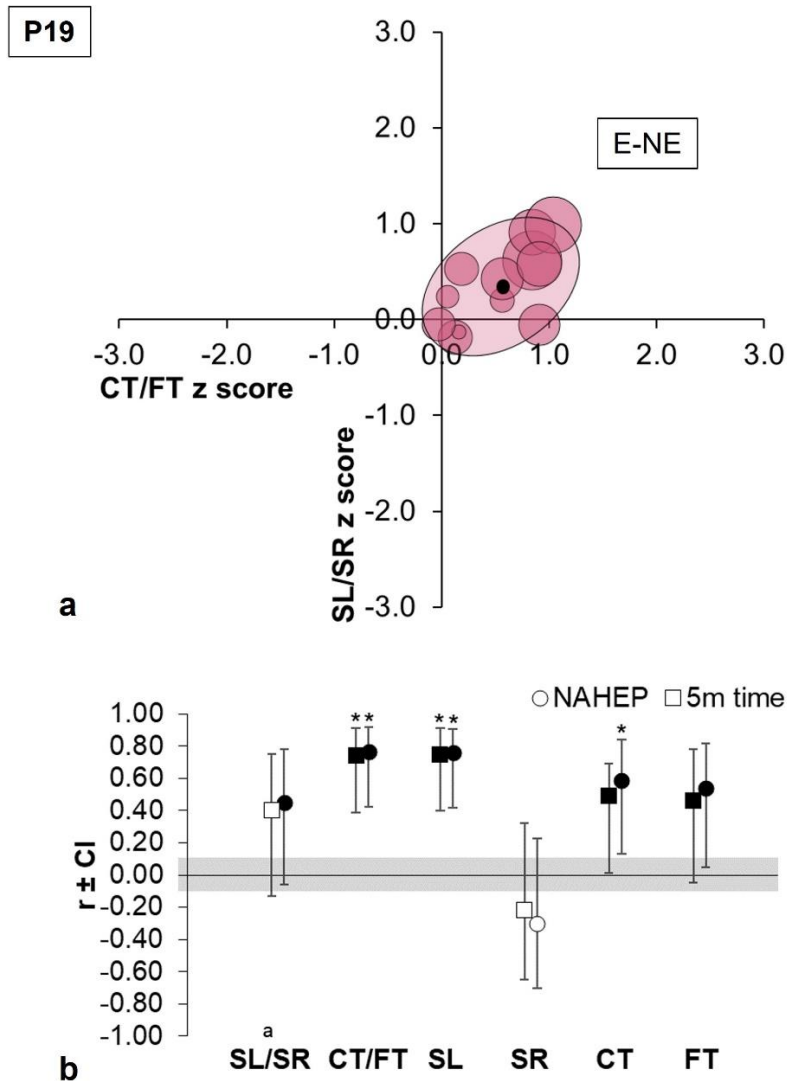
542 **FIGURES**
543



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

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

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562 **Figure 2.** An example of a *whole-body kinematic strategy* (a) for an example participant
 563 (P19). Each marker depicts a single sprint, with marker sizes scaled to reflect initial
 564 acceleration performance (a larger marker size equates to greater NAHEP). Where sprinting
 565 kinematics are meaningfully related to NAHEP, the theoretical favorable Cartesian plane
 566 spatial location change in strategy for better sprint performance is included as a compass
 567 bearing (see *Procedures* section for full details). Relationships (with 90% confidence
 568 intervals) of SL/SR and CT/FT ratios and normalized spatiotemporal variables with NAHEP
 569 and 5 m time are shown in (b). For clarity, to aid comparisons between relationships of
 570 NAHEP and 5 m time with variables, the direction of relationships between 5 m time and
 571 variables has been inverted. Black filled makers depict meaningful relationships where the
 572 magnitude of relationships were greater than the smallest practically important correlation²⁶
 573 ($r = \pm 0.43$) and asterisks indicate that relationships are statistically significant ($p < 0.05$).

574 SL/SR = step length/step rate ratio; CT/FT = contact time/flight time ratio; SL = step length;
 575 SR = step rate; CT = contact time; FT = flight time. ^aIndicates where data were non-
 576 parametric and that Spearman's rank order correlation coefficients were used to determine
 577 relationships rather than Pearson's correlation coefficients which were used for parametric
 578 data.

579 TABLES
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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	<p>Sprint testing for all 35 participants on a single testing occasion (3 sprints)</p> <p>Strength-based testing on a single testing session for 25 of the 35 participants</p>	<p>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)</p>
Data obtained	<p>Normalized spatiotemporal variables, <i>whole-body kinematic strategies</i>, SL/SR and CT/FT ratios and initial acceleration performance measures (NAHEP and 5 m time) for all 35 participants</p> <p>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</p>	<p>Normalized spatiotemporal variables, <i>whole-body kinematic strategies</i>, SL/SR and CT/FT ratios and initial acceleration performance measures (NAHEP and 5 m time) for all 19 participants</p>

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

^aVariables have been normalized according to the equations of Hof²⁸ 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).

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

^aValues normalized to leg length

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

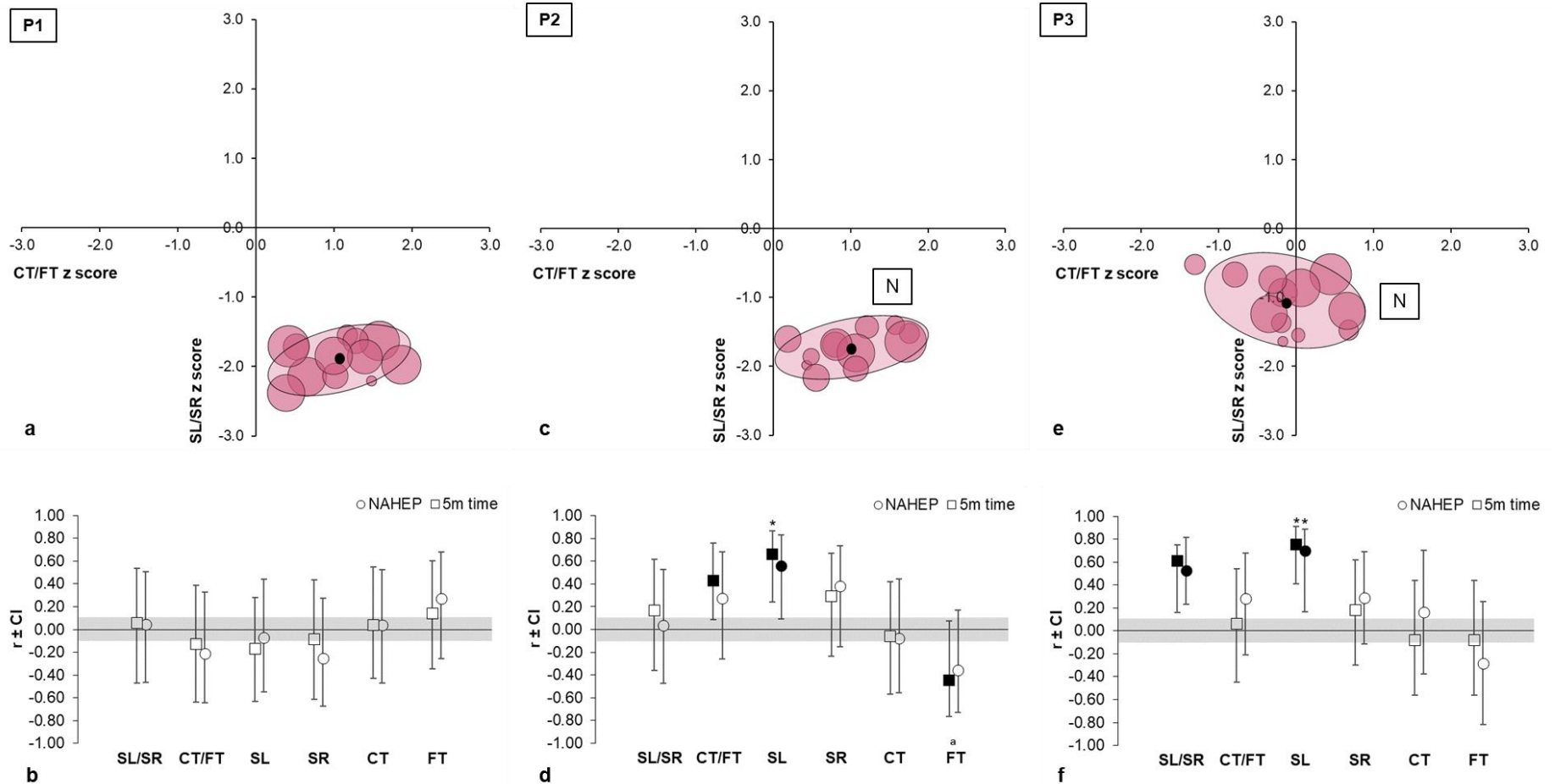
Variables	Mean \pm SD	Min.	25th%	Median	75th%	Max.
P_{\max} (W/kg)	28.94 \pm 4.74	18.00	26.91	29.48	32.37	38.67
Hip torque (Nm/kg)	5.81 \pm 0.79	4.46	5.27	5.87	6.06	7.77
Repeated contact time (s)	0.276 \pm 0.025	0.316	0.295	0.274	0.258	0.240
Repeated jump height (m)	0.176 \pm 0.021	0.133	0.165	0.174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

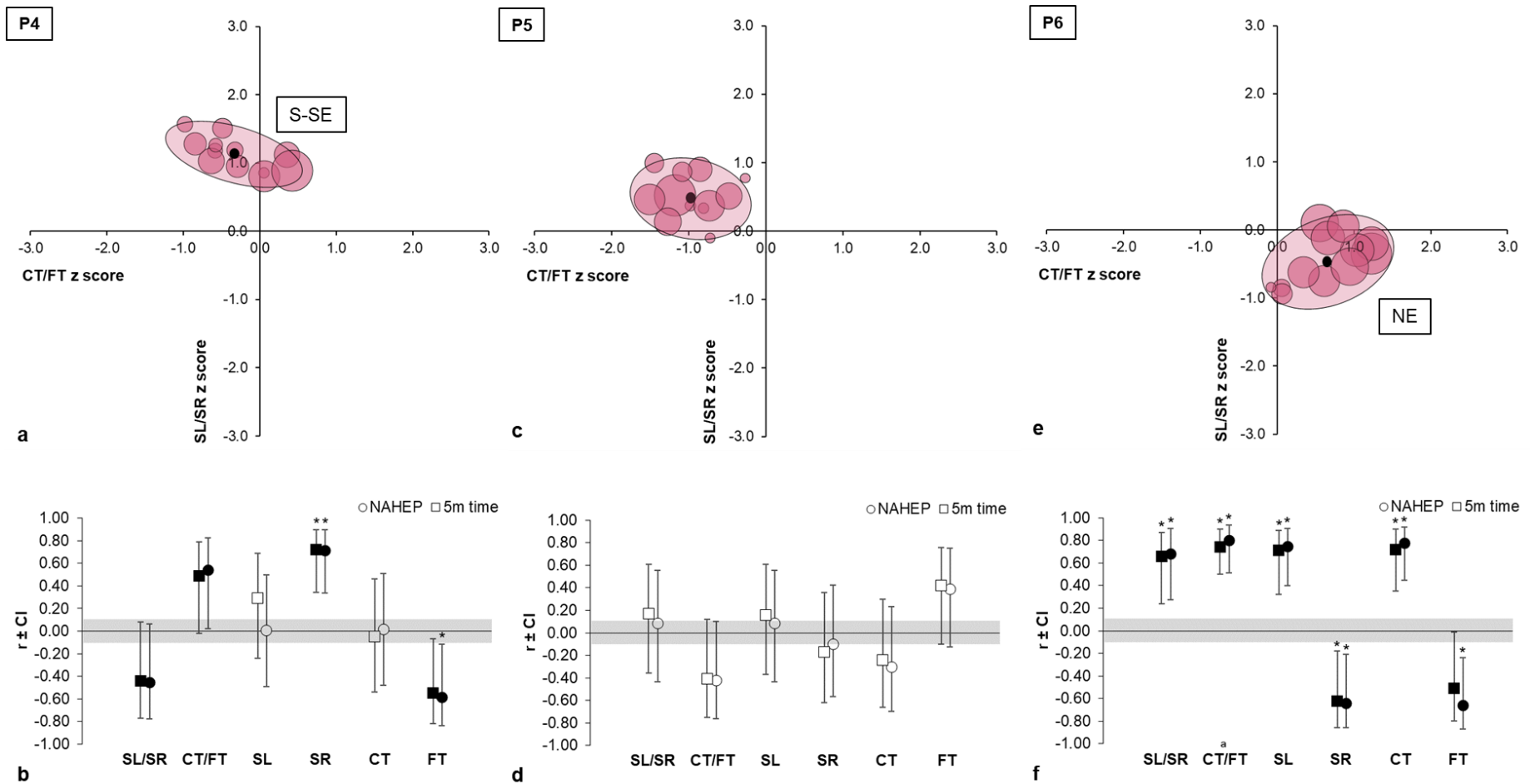
P_{\max} is the maximal mechanical power output during squat jump profiling

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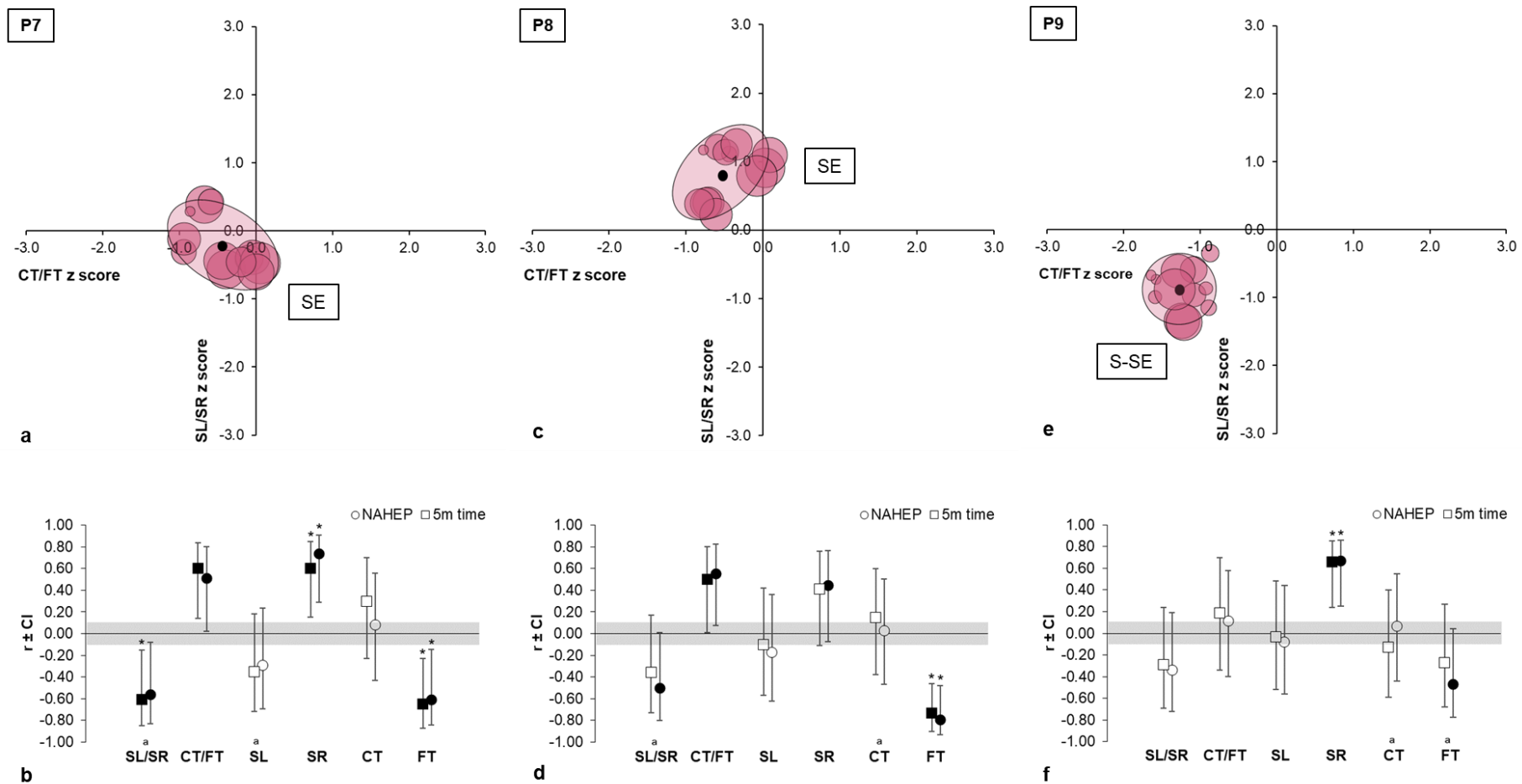
SUPPLEMENTARY MATERIAL A - ADDITIONAL FIGURES FOR THE PARTICIPANTS THAT WERE STUDIED IN PART I, BUT FOR WHOM THE FIGURES WERE NOT INCLUDED IN THE MANUSCRIPT



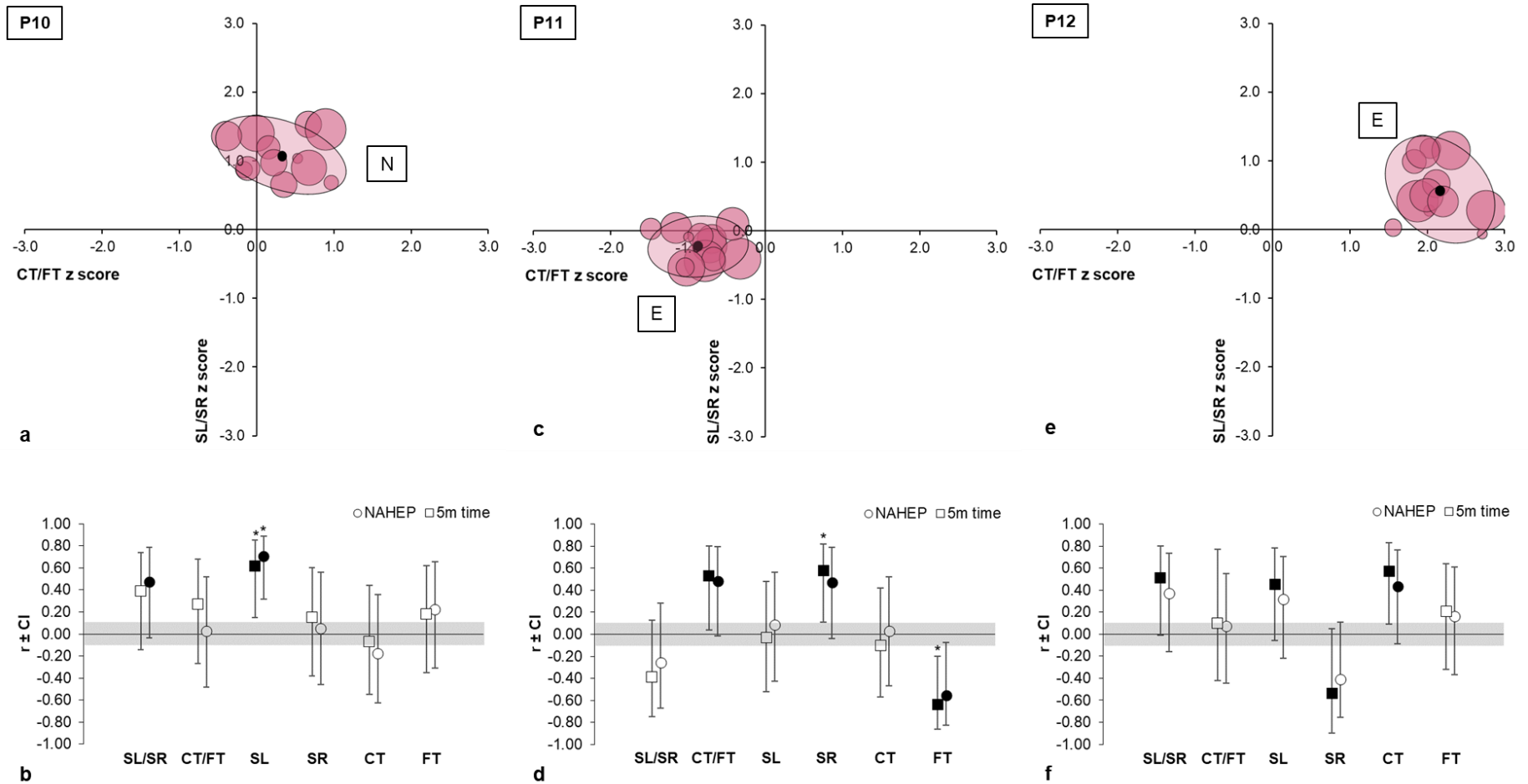
A1. Whole-body kinematic strategy (a,c and e), and relationships (with 90% confidence intervals) of SL/SR and CT/FT ratios and normalised spatiotemporal variables with NAHEP and 5 m time (b, d and f) of participants 1 to 3. See Figure 2 caption in the published journal article for full explanation.



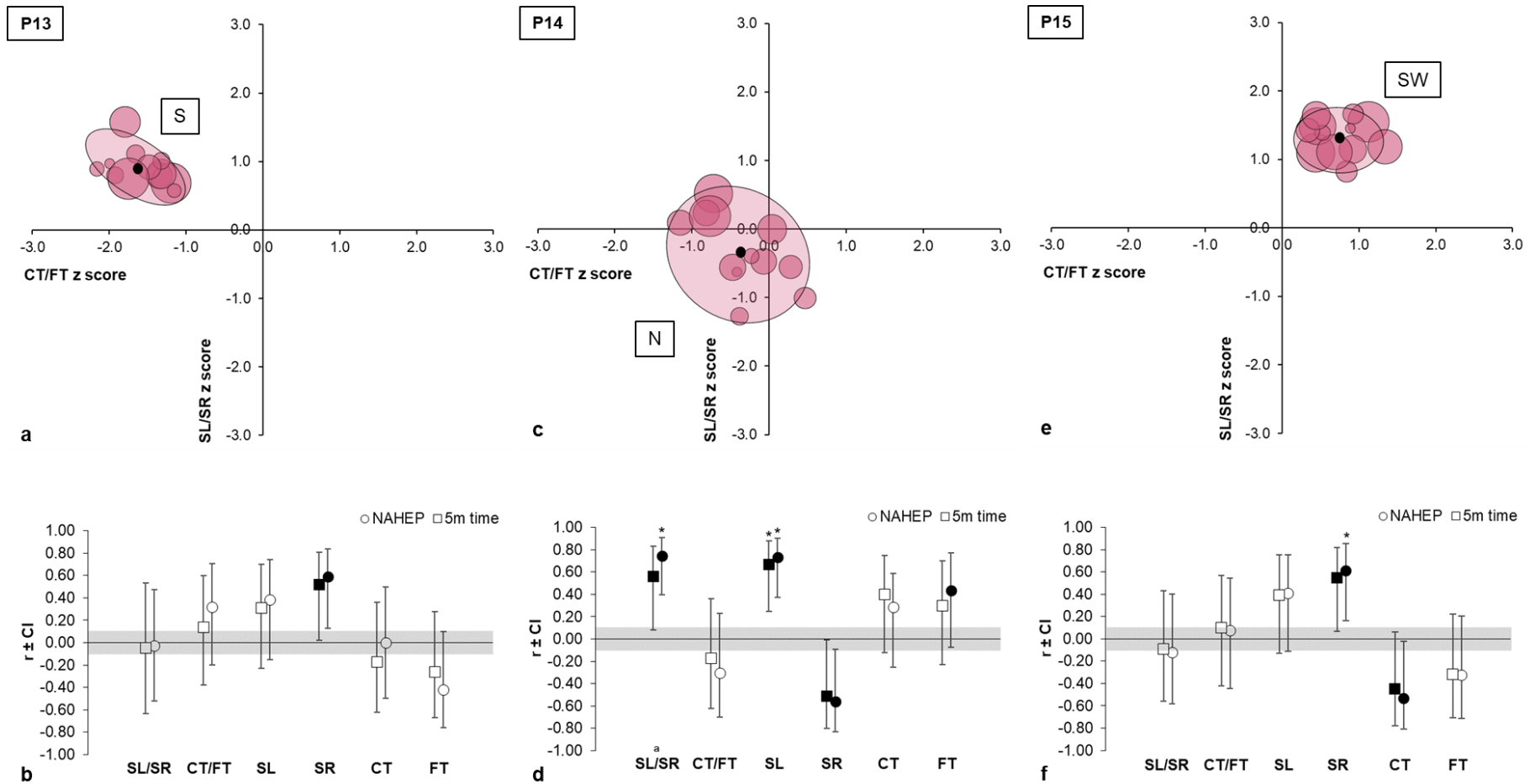
A2. Whole-body kinematic strategy (a,c and e), and relationships (with 90% confidence intervals) of SL/SR and CT/FT ratios and normalised spatiotemporal variables with NAHEP and 5 m time (b, d and f) of participants 4 to 6. See Figure 2 caption in the published journal article for full explanation.



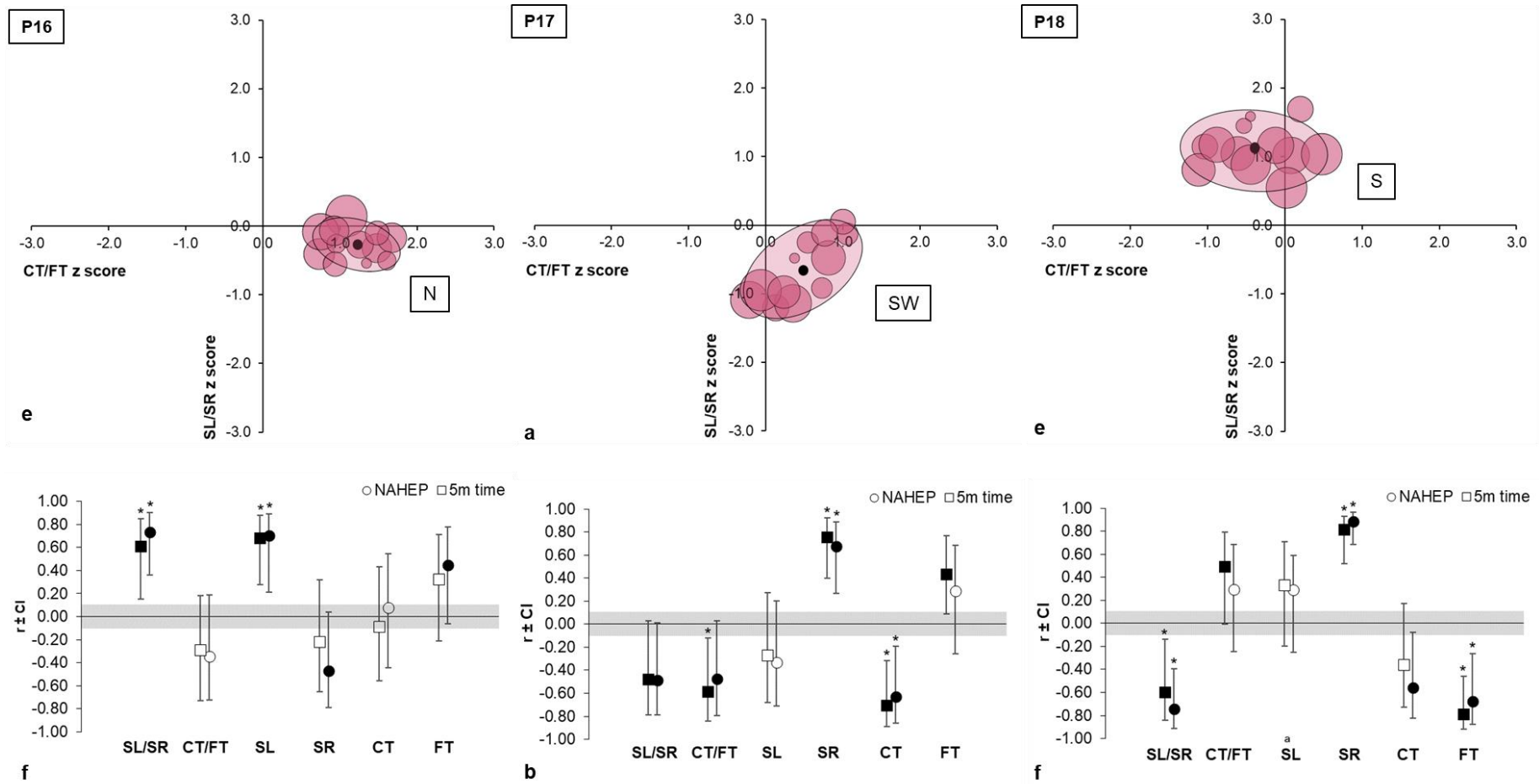
A3. Whole-body kinematic strategy (a,c and e), and relationships (with 90% confidence intervals) of SL/SR and CT/FT ratios and normalised spatiotemporal variables with NAHEP and 5 m time (b, d and f) of participants 7 to 9. See Figure 2 caption in the published journal article for full explanation.



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

Where units are not provided, variables are in their dimensionless form using the equations of Hof²⁸

SUPPLEMENTARY MATERIAL C

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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