Journal of Sports Sciences

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rjsp20

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To cite this article: James J Wild, Ian N. Bezodis, Jamie S. North & Neil E. Bezodis (2021): Characterising initial sprint acceleration strategies using a whole-body kinematics approach, Journal of Sports Sciences, DOI: 10.1080/02640414.2021.1985759

To link to this article: https://doi.org/10.1080/02640414.2021.1985759

Published online: 06 Oct 2021.

JOURNAL OF SPORTS SCIENCES
https://doi.org/10.1080/02640414.2021.1985759

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SPORTS MEDICINE AND BIOMECHANICS

Characterising initial sprint acceleration strategies using a whole-body kinematics approach

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ABSTRACT
Sprint acceleration is an important motor skill in team sports, thus consideration of techniques adopted during the initial steps of acceleration is of interest. Different technique strategies can be adopted due to multiple interacting components, but the reasons for, and performance implications of, these differences are unclear. 29 professional rugby union backs completed three maximal 30 m sprints, from which spatiotemporal variables and linear and angular kinematics during the first four steps were obtained. Leg strength qualities were also obtained from a series of strength tests for 25 participants, and 13 participants completed the sprint protocol on four separate occasions to assess the reliability of the observed technique strategies. Using hierarchical agglomerative cluster analysis, four clear participant groups were identified according to their normalised spatiotemporal variables. Whilst significant differences in several lower limb sprint kinematic and strength qualities existed between groups, there were no significant between-group differences in acceleration performance, suggesting inter-athlete technique degeneracy in the context of performance. As the intra-individual whole-body kinematic strategies were stable (mean CV = 1.9% to 6.7%), the novel approach developed and applied in this study provides an effective solution for monitoring changes in acceleration technique strategies in response to technical or physical interventions.

ARTICLE HISTORY
Accepted 22 September 2021

KEYWORDS
Degeneracy; ecological dynamics; performance; rugby union; sprinting; technique

Introduction

Sprinting is an important motor skill in team sports where it is carried out frequently over short distances during both training and competition (Harper et al., 2019; Nicholson et al., 2020). From an ecological dynamics perspective, humans are complex adaptive systems with multiple interacting components (Davids et al., 2014) which is thought to result in different patterns of emergent behaviours. In this regard, athletes have an array of different strategies available to them, when sprinting, to achieve the same outcome – a concept known as degeneracy (Tononi et al., 1999). The process through which the system self-organises and behaviour emerges is considered spontaneous and is explained by dynamical systems theory which describes the arrangement of dynamical patterns as a function of the interaction of the performer (athlete), task and environmental constraints (Newell, 1986). Therefore, variation in the technique strategies adopted during initial sprint acceleration is likely, given the different interacting constraints at any one point.

Due to the multi-articular nature of sprinting, portraying an acceleration strategy is complex owing to the multiple degrees of freedom that coordinate to achieve the task goal (Bernstein, 1967). Consequently, the data required to provide a full description of an athlete's movement coordination during sprinting is highly challenging to assimilate, and would lead to a vast amount of information which is of limited value to coaches pursuing an actionable basis for their technical interventions. Determining an individual's acceleration strategy through higher-level spatiotemporal characteristics may therefore be a more viable "whole-body" approach. Such an approach is consistent with ecological dynamics where information on system behaviour at a holistic level is deemed richer than information on individual constituent parts (Button et al., 2020). From an applied perspective, this is beneficial as spatiotemporal measures can be obtained promptly. Measures such as step length, step rate, contact time and flight time are the outcome of a complex interaction between linear and angular kinematic and kinetic factors underpinning this motor skill, and they provide rich holistic-level information regarding system behaviour during acceleration.

If acceleration strategies can be identified using a whole-body approach, it is important to establish whether a discrete number, or a widespread continuum, of strategies exists, even within a relatively homogeneous cohort of individuals from the same sport who are typically subjected to similar task and environmental constraints. If a given cluster of individuals, defined by a discrete strategy, is shown to achieve better acceleration performance than other clusters, then a training approach targeting the more successful strategy may be warranted across the entire group. If clusters cannot be identified, but performance is associated with a given strategy on a continuum, then this may also signify that all individuals might benefit from interventions aimed at facilitating a shift towards that strategy. Alternatively, if there is no clear

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indication that the strategy of a given cluster, or on a continuum if clear clusters do not exist, is superior in performance terms, then each individual's needs ought to be considered with regards to the enhancement of acceleration performance.

To provide more granular information to inform the training practices of coaches where a shift in sprinting strategy is deemed necessary, an understanding of the linear and angular kinematic technical features and strength qualities that underpin the different strategies adopted is necessary. An additional factor which needs to be considered is the consistency of a given individual's strategy, since high levels of variability (i.e., a less stable strategy) would undermine training interventions if a representative strategy for an individual cannot be identified. Therefore, determining levels of intra-individual variability is important so that meaningful changes in strategies can be identified with confidence.

The primary aim of this study was to investigate whether sub-groups of different strategies could be classified during initial sprint acceleration according to the combination of normalised spatiotemporal variables, using professional rugby backs as an exemplar group of athletes from within a single sport. Secondary aims were to determine how technical features and strength-based qualities differed between these strategies, and how stable these whole-body kinematic strategies were at the intra-individual level.

Methods

Twenty-nine male professional rugby union backs (mean ± SD: age 25 ± 3 years; stature 1.81 ± 0.06 m; leg length 1.00 ± 0.05 m; body mass 93.7 ± 9.1 kg) competing in the English Premiership were analysed in this study. Since these data were pre-existing from the testing conducted during the players' usual training schedule, and were anonymised, informed consent was not required (Haugen et al., 2019; Winter & Maughan, 2009). Study protocols were approved by the University Ethics Committee of the lead author. At the time of testing, participants were injury free and frequently completed maximal sprint accelerations within their usual weekly training regime.

Procedures

Following 48 hours of abstinence from running, sprinting and lower body strength training, participants completed a 20-min standardised warm-up, then three maximal effort 30 m sprints from a 2-point start, on an outdoor 3 G artificial grass pitch, wearing a t-shirt, shorts and moulded stud boots. Rest periods between each sprint were 4–5 minutes. All testing conditions took place under similar weather conditions at the same time of day. Testing was only ever undertaken when the surface was dry and on days when no head or tail winds were deemed to be noticeable by the coaching staff.

Two smart phone high-speed video cameras (iPhone8, Apple Inc, Cupertino, Ca) were used to capture sagittal plane video images (1920 × 1080 pixels) of the first four steps at 240 Hz. The cameras were positioned perpendicular to, and 12 m from, the running lane to capture sagittal plane images from both sides of the body within a 7.5 m wide field of view. A 5.00 m horizontal video calibration was recorded. Spatiotemporal variables (step length, step rate, contact time and flight time) and linear kinematics (touchdown distance, toe-off distance, contact length and flight length) were attained using the procedures outlined in Wild et al. (2018). From the spatiotemporal variables, two additional variables – step length/step rate and contact time/flight time ratios (hereafter referred to as length/rate and contact/flight ratios) – were calculated as a measure of each participant's whole-body kinematic strategy. These ratios provide more sufficient information than step length and step rate alone, and have recently been used to categorise distinctive running styles to guide future measurement and interpretation (Van Oeveren et al., 2021), although whether this approach can be applied to initial acceleration is not known.

The vertex of the head, halfway between the suprasternal notch and the 7th cervical vertebra, shoulder, elbow, and wrist joint centres, head of third metacarpal, hip, knee, and ankle joint centres, posterior heel, and toe tip were digitised (×6 zoom in Kinovea, v.0.8.27) to create a 14-segment rigid body model. Scaled coordinates were exported to Excel (Microsoft 2013) to calculate angular orientations (°) of the stance foot, shank, and thigh, and trunk, segments (with respect to the horizontal) and of the stance ankle, knee and hip joints.

To minimise the potentially confounding influence of inter-individual differences, spatiotemporal, linear kinematic and angular velocity variables were normalised according to the equations of Hof (1996). Normalised average horizontal external power (NAHEP) was calculated as a measure of initial sprint acceleration performance from the instant of the first touchdown to the end of the fourth contact phase (N. Bezodis et al., 2010; Wild et al., 2018).

To address the second aim regarding the stability of whole-body kinematic strategies, 13 participants completed the above testing protocol on three additional occasions. At all three sessions, NAHEP and normalised spatiotemporal variables were obtained, resulting in data being collected for 12 sprints for 13 participants (i.e., three sprints on four separate occasions) over the course of six to eight weeks during the middle and late pre-season.

Following the sprint trials, participants undertook three different strength-based assessments which they were familiar with from prior training experience. Firstly, participants completed repeated unilateral in-place jumps testing (hereafter referred to as repeated jumps). This involved performing two series of 10 continuous jumps with hands on hips aiming to achieve maximum height whilst spending the smallest possible time in contact with the ground. The hip and knee of the non-test side were flexed to approximately 90° throughout the jumps. Participants performed two warm-up efforts separated by 2-min rest. Following a further 2-min rest, participants completed the first series of 10 repeated jumps (left side, followed by right side) and rested for 3 min before completing a second series. Jump heights (m; determined from flight times) and contact times (s) were collected for each jump, using an infrared timing system (Optojump, Microgate), from which the reactive strength index (RSI) was determined by the ratio of jump height to contact time (Flanagan & Comyns, 2008; Flanagan et al., 2008). Using a modified approach from Comyns et al.

(2019), the average of the best three RSI scores within the series of 10 jumps was used to establish an overall RSI value for that series. Contact times and jump heights for each of the three jumps which produced the highest overall RSI within the 10 jumps on the left side were averaged and retained for analysis, as were the equivalent values on the right side. The left and right-side jump heights, contact times and RSI were then averaged and used within the statistical analyses.

Secondly, participants completed squat jumps under different loaded conditions based on procedures modified from Samozino et al. (2013). Participants performed two maximal effort squat jumps under five different loading conditions (0, 20, 40, 60 and 80 kg) as a variety of loads have been shown to produce valid and reliable F_0, V_0 and P_{max} results (García-Ramos et al., 2021). The maximum load equated to, on average, 85% of participants' body mass (range 75% to 100%). Squat depth was self-selected by participants according to the depth they felt would achieve the highest jump height based on their experience of performing squat jumps across a number of loads, which has also been shown to be valid and reliable (Janicijevic et al., 2020). Three measures were determined from the loaded squat jumps (Samozino et al., 2013): 1) theoretical maximal force production of the lower limbs (F_0 [N/kg]); 2) theoretical maximal extension velocity of the lower limbs (V_0 [m/s]); 3) maximal mechanical power output (P_{max} [W/kg]).

Thirdly, the peak isometric torque (Nm/kg) of the hip extensors (hereafter referred to as hip torque) was assessed using adapted protocols from Goodwin and Bull (2021) and Czasche et al. (2018). Participants were supine with hips (just below ASIS) positioned beneath an immoveable bar where hard, dense matting was placed between the hips and the bar to prevent gapping and provide comfort. The foot of the testing side was strapped to a wooden wedge attached to a linear bearing rail permitting vertical movement only (Figure 1), while the heel of each participant was positioned in the centre of a force plate (PASCO, PS-2141; 1000 Hz), with the foot of the non-testing side lifted off the ground. Using a hand-held goniometer, the hip angle of the testing side was set at ~120° and the knee angle was set to ~75° (quantitative analysis of sagittal plane videos captured during the testing confirmed that hip and knee angles ranged between 119–122° and 73–77°, respectively). The moment arm was measured (m) as the distance from the centre of the right greater trochanter to the point where the heel was in contact with the force plate (m). After establishing a baseline vertical force for approximately 5 seconds, participants were instructed to "push their heel down into the force plate as fast and as hard as they can, as if pressing the bar with their hips up towards the ceiling" until the vertical force had visibly plateaued (≤5 s). After three minutes rest, participants completed a second trial. This sequence took place three times on both left and right sides, with the peak force achieved averaged across all trials for each side after removal of the baseline force. These forces were then multiplied by the respective moment arm and normalised to body mass before being averaged across both sides to determine an overall peak hip torque for each participant.

One additional variable was also calculated which combined measures from across two of the above tests: hip torque/repeated jump contact time. This was selected based on stance kinetics during acceleration where hip extensor power generation and leg stiffness qualities are observed as the ankle absorbs energy and are thought to act synergistically to facilitate horizontal CM acceleration (e.g., Schache et al., 2019; Veloso et al., 2015). Due to changes in their weekly training schedule, four participants were unable to undertake strength testing, and it was not possible to obtain their linear and angular kinematics during speed testing due to camera availability. Therefore, normalised spatiotemporal variables were collected for all participants (n = 29), whereas the linear and angular kinematics, and strength data of 25 participants were obtained.

Statistical analyses

Mean data for kinematic variables were obtained over four steps and averaged across the three sprint trials for each participant. Group descriptive data (mean ± SD) were calculated for all variables and checked for normal distribution using the Shapiro–Wilk statistic. The within individual coefficient of variation (CV) was calculated for each individual and the average of these across the entire group was then determined as a measure of relative

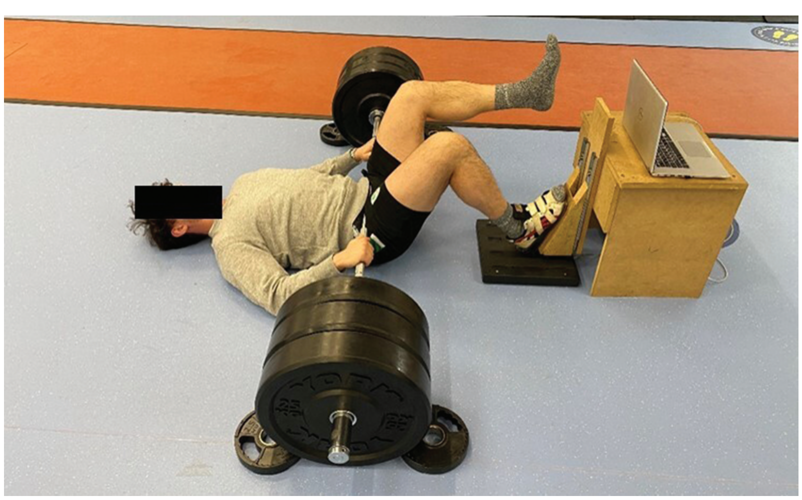

Figure 1. Set up for the isometric hip extensor torque assessment.

reliability representing the typical error as a percentage of the mean for each measurement (Atkinson & Nevill, 1998). To examine the relationships of normalised spatiotemporal variables and strength qualities with NAHEP, semi-partial correlation coefficients controlling the independent variables for body mass or bivariate correlations were used. Therefore, the direct effects of inter-individual differences in both body mass and leg length on the results of this analysis were minimised. Confidence intervals (90%) of relationships were calculated to determine the smallest clinically important correlation (Hopkins, 2007), equating to a value of r = ± 0.24. Relationships were deemed unclear if their magnitude was within this threshold. The strength of relationships were 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 (Hopkins, 2002).

The length/rate and contact/flight ratios were standardised as z-scores across the group. Cartesian plane quadrants were formed with these standardised length/rate and contact/flight ratios on the vertical and horizontal axes, respectively, to provide a novel single visual representation of each individual's whole-body kinematic strategy. A hierarchical agglomerative cluster analysis (Everitt et al., 2011) was then conducted to determine homogenous participant groups according to the combination of their normalised spatiotemporal variables. The complete linkage approach (Gordon, 1999; Lance & Williams, 1967) was used and the final number of clusters was determined by visual inspection of the scree plot (Hair et al., 2019; Jauhiainen et al., 2020), with the dendrogram also visually inspected to confirm the number of clusters identified (Phinyomark et al., 2015; Watari et al., 2018).

To identify any differences in normalised spatiotemporal variables, linear and angular kinematics and strength qualities between clusters, a one-way ANOVA was conducted and, where significant main effects were observed, post hoc testing (Tukey's HSD) was run. The Kruskal–Wallis test was used where data were not normally distributed. All analyses were performed using SPSS (v26.0) with alpha set at $p < 0.05$.

For the 13 participants who undertook testing on four separate occasions, coefficients of variation and intraclass correlation coefficients (ICC) were calculated to determine the reliability of measured variables across their 12 sprint efforts. To determine the within-session consistency on each of the four testing occasions, the CV over three sprint efforts was calculated for each individual. The CVs obtained from each testing occasion were then averaged for each individual. These values were averaged across the group to establish the group mean CV. An acceptance threshold of <10% for CV was used (Atkinson & Nevill, 1998) to indicate whether these strategies were reliable. To determine the consistency of participants' sprinting strategies between testing sessions, for all variables, the mean value for each individual participant from each testing occasion were entered into WG Hopkins (2015) spreadsheet to calculate ICC and their 90% confidence intervals based on a single-rater, absolute agreement, 2-way mixed-effects model (Koo & Li, 2016). Intraclass correlation coefficient values were defined as poor (ICC = < 0.50), moderate (ICC = 0.50 to <0.75), good (ICC = 0.75 to <0.90) and excellent (ICC = ≥ 0.90) reliability (Koo & Li, 2016).

The distribution of participants' whole-body kinematic sprinting strategies across their 12 sprints was represented in the form of individual confidence ellipses (90% confidence limits) calculated from the mean and covariance of their standardised length/rate and contact/flight ratios. The variability of normalised spatiotemporal variables and length/rate and contact/flight ratios was determined using the standard deviation and CV across the 12 sprints for each participant. The stability of the variables for each individual relative to the group standard deviation of the 29 participants from the single sprint was calculated as a stability index (Maselli et al., 2019) as follows, where a higher *Sj* is indicative of a more stable variable for that individual:

$$Sj = 1 - \left(\frac{intra\ individual\ SD}{inter\ individual\ SD}\right)$$

Results

Group mean CVs for NAHEP, normalised spatiotemporal variables, and length/rate and contact/flight ratios during the single testing session involving 29 participants, and strength-based variable involving 25 participants (Table 1) were all ≤6%. When controlling independent variables for body mass using semi-partial correlations, a statistically significant moderate relationship between repeated jump height and NAHEP was found (Table 1). No other significant relationships were found between NAHEP and strength variables, or between NAHEP and normalised spatiotemporal variables or length/rate and contact/flight ratios.

Table 1. Mean ± *SD* descriptive statistics for all variables, and relationships between normalised spatiotemporal variables over three sprint trials of participants and normalised average horizontal external power.

Descriptive statistics		Correlations with NAHEP	Coefficient of variation (%)
Variable	*Mean ± SD*	*r (90% CL)*	*Mean ± SD*
NAHEP	0.562 ± 0.073	-	4.0 ± 2.4
Step length	1.32 ± 0.10	−0.04 (−0.35 to 0.28)[a]	1.9 ± 1.0
Step rate	1.38 ± 0.09	0.31 (0.00 to 0.57)[a]	1.3 ± 0.8
Contact time	0.514 ± 0.041	−0.15 (−0.44 to 0.17)[a]	1.8 ± 1.0
Flight time	0.212 ± 0.032	−0.23 (−0.51 to 0.09)[a]	3.2 ± 2.3
CT/FT ratio	2.48 ± 0.46	0.18 (−0.14 to 0.47)[a]	4.1 ± 2.7
SL/SR ratio	0.96 ± 0.13	−0.18 (−0.47 to 0.18)[a]	3.0 ± 1.7
Hip torque (Nm/kg)	5.81 ± 0.79	0.39 (0.06 to 0.64)[b]	2.4 ± 1.3
P_{max} (W/kg)	28.94 ± 4.74	0.38 (0.05 to 0.64)[b]	4.2 ± 2.4
Repeated jump height (m)	0.18 ± 0.02	0.39 (0.06 to 0.64)*[a]	4.7 ± 2.5
Repeated jump CT (s)	0.276 ± 0.025	−0.06 (−0.39 to 0.28)[a]	4.4 ± 2.3
RSI (height/CT)	0.64 ± 0.09	0.36 (0.03 to 0.62)[a]	5.4 ± 3.0
Hip torque/CT ratio	21.22 ± 3.69	0.35 (0.01 to 0.61)[b]	5.2 ± 2.2

[a]Semi-partial correlations controlling the independent variables for body mass
[b]Bivariate correlations
*Statistically significant (p= < 0.05)
Spatiotemporal variables are in their dimensionless form (Hof, 1996)

Four homogenous clusters were established based on the combination of participants' length/rate and contact/flight ratios (Figures 2(a,b)). No significant differences in NAHEP were evident between these clusters (Figure 2(c)). The initial sprint acceleration strategies were achieved through significant differences in a range of linear and angular kinematics between clusters, whilst several strength-based characteristics also differed significantly between clusters (Figures 3–7).

Step lengths were successively greater across clusters A to D, with significant differences between cluster A participants and all other clusters and between clusters B and D (Figure 3(a)). Differences in step length were accounted for primarily through touchdown distance and contact length which were both significantly smaller in clusters A and B compared with clusters C and D (Figure 4(a,c)). Step rates were successively less across clusters A to D, with significant differences evident between cluster A participants and all other clusters and between clusters B and D (Figure 3(b)). These differences in step rate between clusters were accounted for through differences in contact time, flight time, or both (Figure 3(c,d)).

Regarding angular kinematics, significantly smaller foot and thigh segment touchdown angles (i.e., both segments were more vertical) were observed in clusters A and B, compared with clusters C and D (Figure 5(a,c) and Figure 8). At toe-off, trunk angles of cluster D participants were significantly greater (more vertical; Figure 5(d)) and they also achieved significantly greater hip extension at toe-off compared with clusters A and B (Figure 6(f)). Of the strength characteristics assessed, higher hip torque/contact time ratios were achieved by clusters A and B compared with clusters C and D (Figure 9(f)).

For the 13 participants who undertook three sprint efforts on four separate occasions, ICCs and CVs (Table 2) across mean NAHEP, normalised spatiotemporal variables and length/rate and contact/flight ratios from each of the four testing sessions indicated excellent reliability (ICC > 0.90; mean CL 0.86–0.99, CVs 1.1–4.4%).

A representative sample of individual acceleration strategies were observed in the 13 participants studied over four sessions in the context of the z-scores of all 29 participants studied on one occasion (Figure 9). Greater intra-individual variability in contact/flight ratios than length/rate ratios was evident (Figure 9), with a mean CV of 4.3% to 9.9% and SD of 0.117 to 0.244 in the contact/flight ratio across individuals compared with 2.7% to 5.4% and an SD of ≤0.052 in the length-rate ratios (Table 3). Even with greater intra-individual variability for the contact/flight ratio, only two participants (participants 2 and 3) exhibited SDs considered greater than the smallest worthwhile differences ($d \leq 0.20$; Hopkins, 2002; Winter, Abt & Nevill, 2014).

The length/rate and contact/flight ratios were stable at the intra-individual level with the stability index of participants ranging between 75% and 85% (Table 3), where 0% would represent the same variation in intra-individual SD across the 12 sprints for the 13 participants as that observed at the inter-individual level for the group of 29 participants during the single testing session. On average, the normalised spatiotemporal variables were 8% "more stable" compared with the length/rate and contact/flight ratios, where the stability index for participants ranged between 82% and 91% (Table 3). This was also reflected in less intra-individual variability of the normalised spatiotemporal variables where the CV ranged between 0.0 and 8.9%, and SD between 0.006 and 0.061 across individuals. The mean CV for normalised spatiotemporal variables, in order of magnitude, were 1.9%, 2.2%, 2.7% and 5.5% for step rate, contact time, step length, and flight time, respectively.

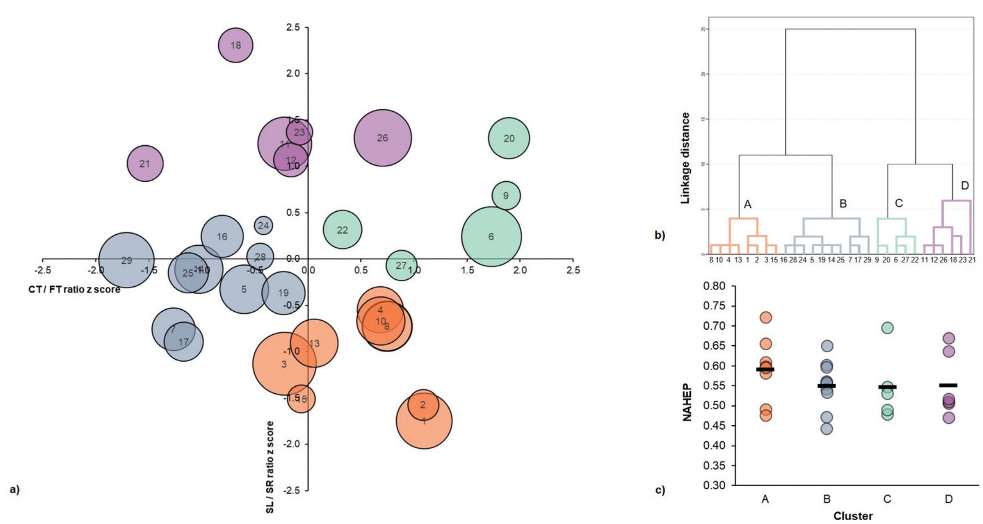

Figure 2. Cluster analysis used to establish homogenous groups of rugby backs according to their initial sprint acceleration strategy: a) a quadrant depicting the dispersion of participants according to their contact/flight and normalised length/rate ratios (standardised as z scores). Each marker and their centred number represent an individual. Participants have been grouped according to the four clusters identified during the hierarchical analysis (see Figure b) and the size of each marker is reflective of initial sprint acceleration performance, with a larger marker equating to a greater magnitude of normalised average horizontal external power (NAHEP); b) a dendrogram for the hierarchical cluster analysis of participants' spatiotemporal step characteristics during the first four steps of a sprint. Individuals are represented by numbers on the x-axis. Four clusters are identified by colour and letters (A-D); c) NAHEP of each participant (circles) and the mean (black filled rectangles) for each cluster. No significant were evident between the mean NAHEP of clusters.

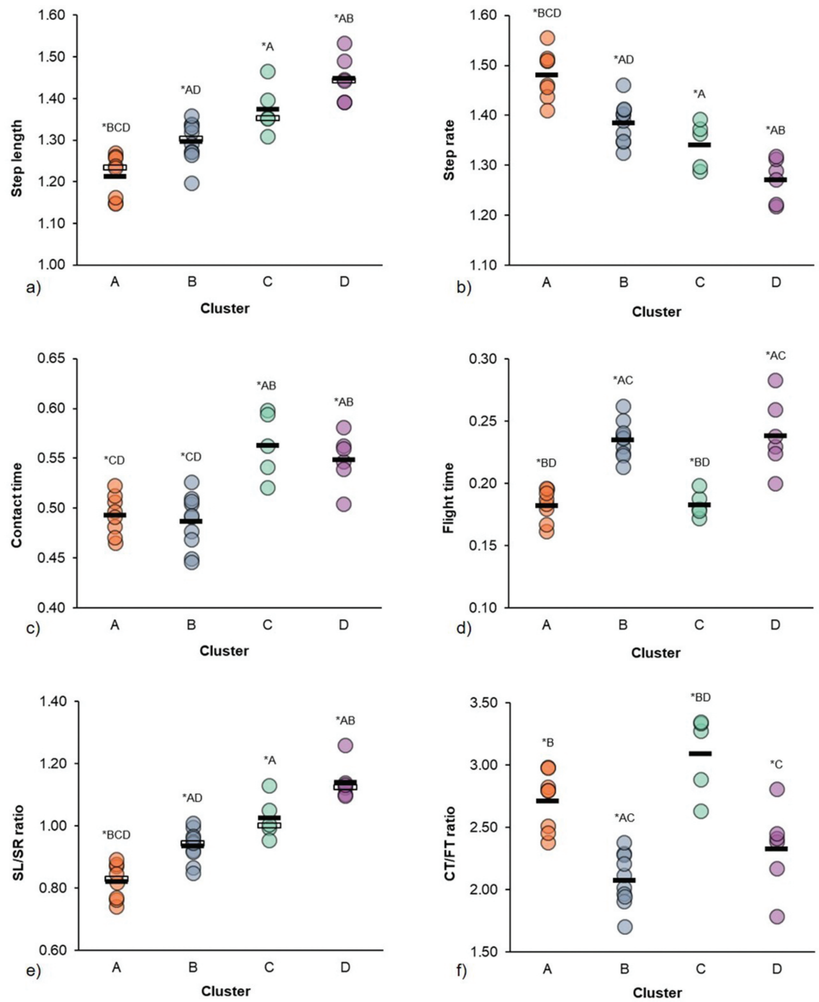

Figure 3. Normalised spatiotemporal variables, and step length/step rate and contact time/flight time ratios for clustered participants. Each marker (circle) represents an individual participant. Black filled rectangles indicate the group mean for each cluster. The Kruskal–Wallis test was used as the non-parametric alternative to the one-way ANOVA for determining differences in step length and step length/step rate ratio due to the non-normal distribution of these data for cluster "A" (step length) and cluster "D" (step length/step rate ratio). The median for each cluster in these cases is shown by the unfilled rectangles. ^{*ABCD}Data are significantly different ($p \leq 0.05$) to clusters A, B, C and D, respectively.

Discussion

The aims of the study were firstly to establish whether different acceleration strategies existed between sub-groups of professional rugby union backs based on their combined normalised spatiotemporal variables and, if so, secondly, to determine the technical features and strength qualities that underpin these strategies and how stable they are. With this novel approach, we found that participants could be grouped into four clusters which were characterised by a range of technical features and, to a lesser extent, strength qualities, although superior sprint performance was not observed in any single cluster during the first four steps. At the intra-individual level, strategies remained relatively stable across sprint efforts and can be considered specific to the individual.

If changing an individual's whole-body kinematic initial sprint acceleration strategy is deemed favourable, then information on features characterising the different clusters will help inform this process. A change in whole-body kinematic strategy does not necessarily refer to a move from one cluster to another (Figure 2(a)). Rather, it is likely indicative of a subtle change in strategy within a given cluster, depending on the stability of the individual's strategy and the proximity of their ellipse centroid (Figure 9) to other clusters.

Although noticeable differences in normalised spatiotemporal variables and linear kinematics between clusters were evident, the differences observed in the angular kinematics at touchdown and toe-off (Figure 5 to 6) were less clear. This further illustrates the levels of inter-individual degeneracy which exist during the initial sprint acceleration of rugby backs, not only in context of the different whole-body kinematic strategies used in reaching the same performance outcome but also how different arrangements in angular kinematics are observed with similar normalised spatiotemporal variables. When looking to facilitate changes in whole-body acceleration strategy, attempts to do so by explicitly coaching changes in segmental and joint angular positions to manipulate the desired normalised spatiotemporal variables associated with a given strategy must be considered with caution. There is also a risk that detailed information on limb positioning may result in coaching instructions that draw an

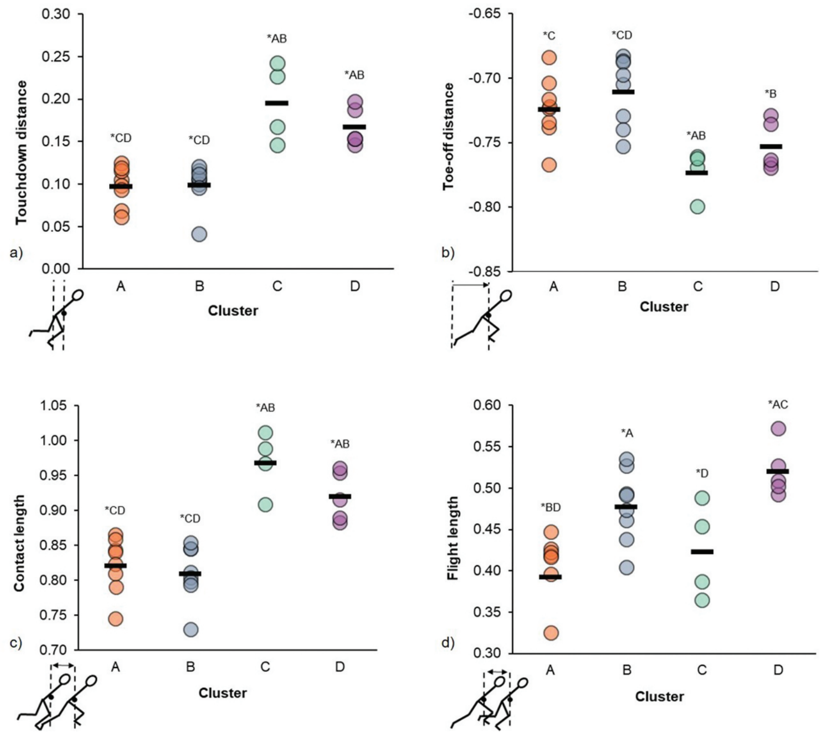

Figure 4. Normalised linear kinematics for clustered participants. Each marker (circle) represents an individual. Black filled rectangles indicate the group mean for each cluster. *ABCD Data are significantly different ($p \leq 0.05$) to clusters A, B, C and D, respectively.

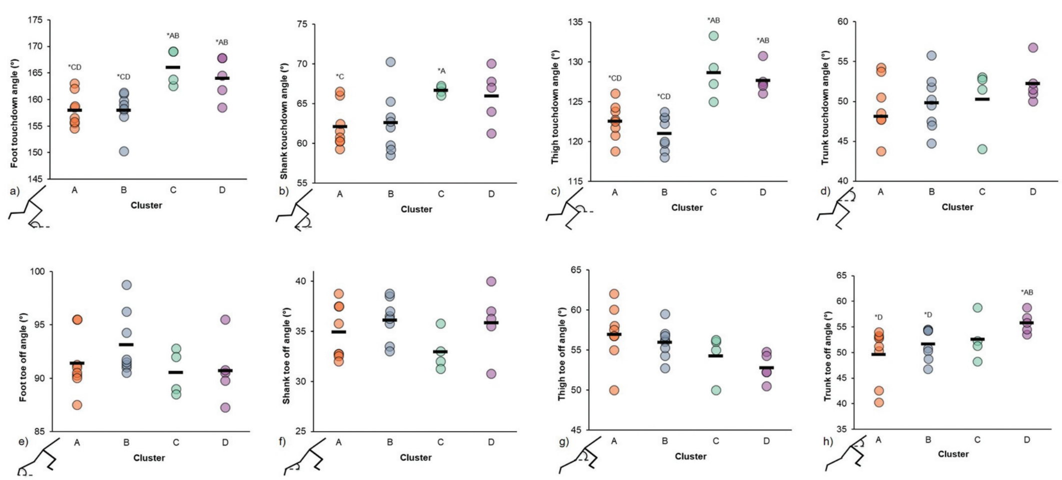

Figure 5. Segment touchdown and toe-off angular kinematics for clustered participants. Each marker (circle) represents an individual participant. Black filled rectangles indicate the group mean for each cluster. *ABCD Data are significantly different ($p \leq 0.05$) to clusters A, B, C and D, respectively.

athlete's attentional focus internally (Porter et al., 2010) and interfere with self-organisation processes, resulting in a negative performance effect (Wulf, 2013). Consequently, practitioners would be advised to consider using a more externally focussed approach with a view to facilitating changes in acceleration strategy directly or indirectly through manipulating the spatiotemporal variables or linear kinematics.

Similar to the lack of differences in the angular kinematics between clusters, strength characteristics were also generally comparable between clusters with the exception of the hip extensor torque/contact time ratio which was significantly higher in clusters A and B than C and D. This combined strength feature may have resulted in participants in clusters A and B self-organising their segment orientations at touchdown (Figure 5) and linear kinematics (Figure 4) in a favourable way to yield shorter contact times compared with clusters C and D (Figure 3(c)), without sacrificing performance. On this basis, different strength characteristics of the participants in clusters C and D interacted to produce alternative strategies (e.g., greater step length through increased contact length and/or flight length) to the participants in clusters A and B to maintain comparable levels of acceleration performance. Owing to the time-course necessary for eliciting either neuromuscular (Baroni et al., 2013; Brown et al., 2017; Moritani & deVries,

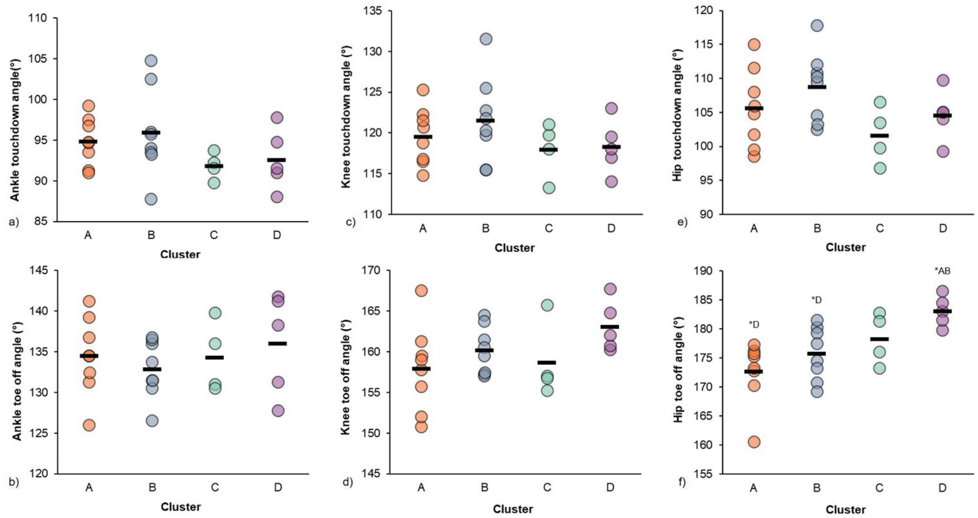

Figure 6. Ankle, knee and hip touchdown and toe-off angular kinematics for clustered participants. Each marker (circle) represents an individual participant. Black filled rectangles indicate the group mean for each cluster. *ABCD Data are significantly different (p ≤ 0.05) to clusters A, B, C and D, respectively.

1979; Rasmussen & Phillips, 2003) or technical (I. Bezodis et al., 2018) adaptations through strength-based interventions, more direct instructional methods to manipulate spatiotemporal variables will likely yield faster acute changes. However, for changes in spatiotemporal variables to emerge without conscious effort, and for the outcome to be effective, the corresponding physical changes which accompany these technical manipulations will likely be necessary so that the desired sprinting action is available to an individual (Fajen et al., 2008; Michaels, 2003).

For the participants who completed 12 sprint trials on four separate occasions, the normalised spatiotemporal variables and their ratios were highly reliable within and between testing sessions (Table 2). As a result, the strategies identified for individuals are representative of their actual strategy at the given time of testing. Although intra-individual movement variability is an inherent feature of human movement (Newell & Ranganathan, 2009; Preatoni et al., 2013), the stability indices (Table 3), covariance ellipses (Figure 9), and CVs (Table 3) demonstrate consistent individual spatiotemporal variables with respect to the inter-individual variability. Greater variability was evident in the contact/flight ratio (mean CV, 6.7%; mean SD, 0.165) than the length/rate ratio (mean CV, 3.8%; mean SD, 0.036), as illustrated by the typically greater dimensions of the covariance ellipses in the x-axis (Figure 9). The higher contact/flight ratio CV is primarily due to variability in flight time than in contact time. Further work is needed to explore the potential implications of how the variation of these measures associate with changes in acceleration performance of athletes at an individual level. These measures provide a means to determine each individual's inherent variability so that meaningful changes in acceleration strategies can be detected with certainty in response to training interventions. Given the stability of strategies evident across the four separate testing sessions, these data can be collected on separate occasions, rather than during a single session, to eliminate any potential effects of fatigue.

The novel approach used here to establish a single measure which represents an individual's whole-body kinematic initial sprint acceleration strategy (Figure 2(a)), can be performed reliably at a given point in time, as indicated by the low CVs observed for the length/rate and contact/flight ratios (Table 1). Whilst the hierarchical clustering approach was first required to determine whether discrete clustered strategies or a widespread continuum of strategies existed, the combined

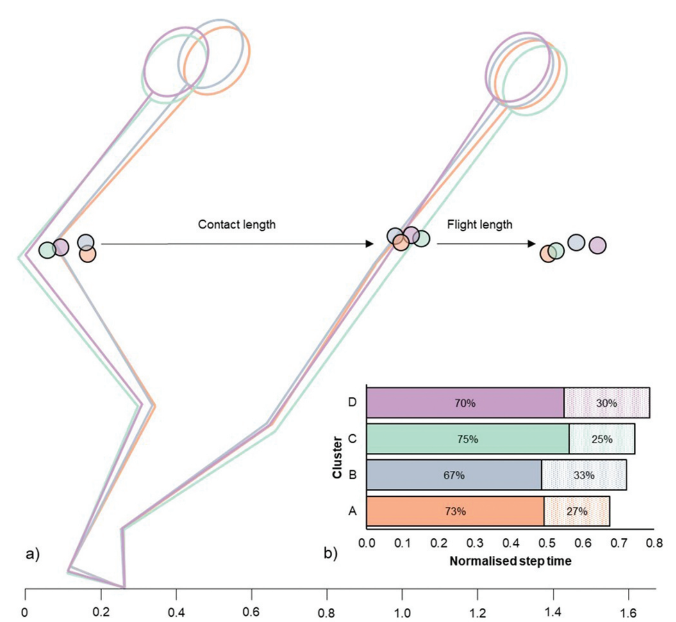

Figure 7. A) Scaled spatial model showing the average of the mean orientations of the stance leg (foot, shank, thigh), trunk and head segments across all (four) steps for each cluster at touchdown and toe-off. The mean centre of mass location at touchdown and toe-off positions for clusters across all (four) steps is depicted as markers (circles), showing normalised linear kinematic variables. Horizontal and vertical scales are the same and all normalised linear kinematic variables are referenced to position of the toe of the contact leg; b) average of the mean normalised step times for clusters, divided into contact time (filled bars) and flight time (pattern filled bars). The proportion of time spent during the contact and flight phases relative to step time are shown as percentages.

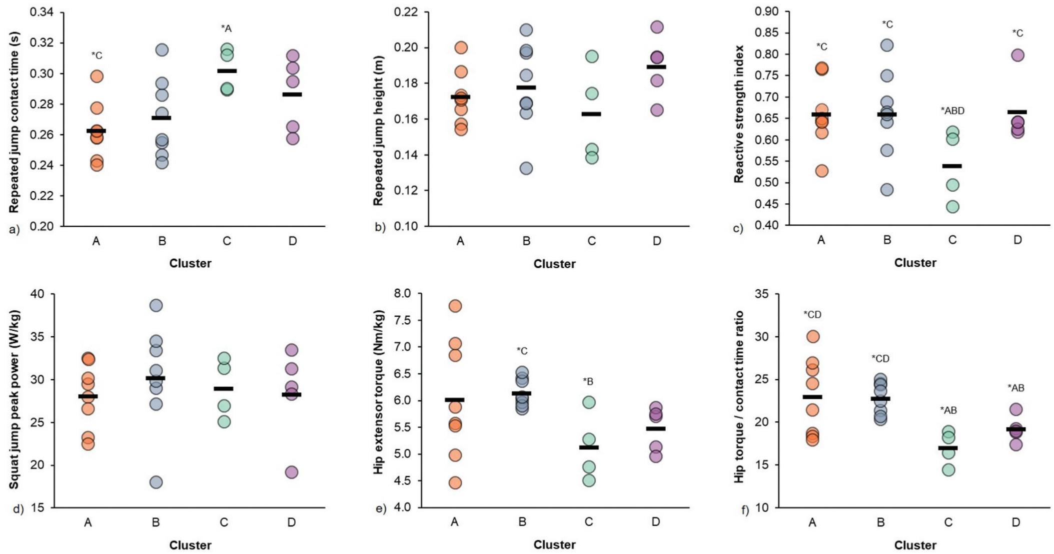

Figure 8. Strength qualities for clustered participants. Each marker (circle) represents an individual. Black filled rectangles indicate the group mean for each cluster. *ABCD Data are significantly different ($p \leq 0.05$) to clusters A, B, C and D, respectively.

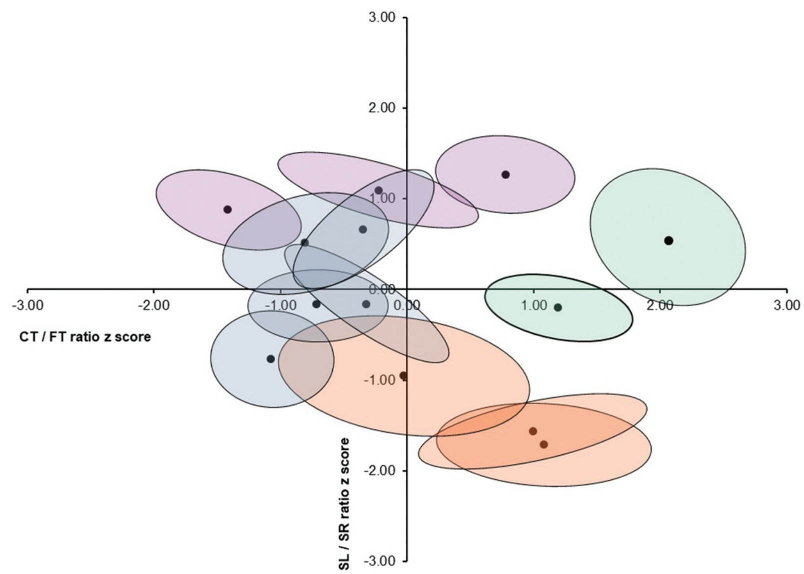

Figure 9. Covariance ellipses (90% confidence level) for the 13 participants who completed testing on four separate occasions, depicting the within- and between-participant distribution of their individual sprinting strategies. The centre of each ellipse (black markers) represents the mean of a given individuals' contact/flight and length/rate ratios. Each ellipse is colour coded according to the clusters of sprinting strategies identified. Z-scores are taken from the original data (Figure 6.2a) based on all 29 participants within this study.

length/rate and contact/flight ratios as a whole-body kinematic measure, represented by a single data point on a quadrant, provides a way for practitioners to assess changes in acceleration whole-body kinematic strategies over time. However, deciding on what changes could be used to enhance acceleration performance is not straightforward, as no significant relationships were found between NAHEP and any normalised spatiotemporal variables or their ratios (Table 1) and there were no significant differences in NAHEP between clusters of participants (Figure 2). These findings suggest that different technical strategies can be adopted to achieve similar performance outcomes during the initial steps, which may explain the inconsistent findings of previous research investigating the relative importance of isolated spatiotemporal variables to acceleration performance in team sport athletes (Lockie et al., 2011, 2013; Murata et al., 2018; Murphy et al., 2003; Nagahara et al., 2018; Standing & Maulder, 2017; Wild et al., 2018).

The findings reported in this study suggest that a single optimum technique does not exist during initial sprint acceleration in rugby backs and so efficacy of technique strategies ought to be considered at the individual level to inform sprint training practices. This would require selected variables to be measured over multiple trials for each individual and considered with the performance outcome measure across each trial (Glazier & Mehdizadeh, 2018). Consequently, practitioners

Table 2. Reliability of normalised average horizontal external power and normalised spatiotemporal variables of rugby backs during initial sprint acceleration over four testing sessions.

	Coefficient of variation (%)	Intraclass correlation coefficients
Variable	*Mean ± SD*	*Mean (90% CL)*
NAHEP	3.9 ± 2.1	0.94 (0.87 to 0.97)
Step length	2.1 ± 1.5	0.93 (0.86 to 0.97)
Step rate	1.1 ± 0.7	0.97 (0.93 to 0.99)
Contact time	1.4 ± 0.9	0.95 (0.91 to 0.98)
Flight time	3.6 ± 1.5	0.95 (0.90 to 0.98)
CT/FT ratio	4.4 ± 1.6	0.95 (0.89 to 0.98)
SL/SR ratio	2.8 ± 1.6	0.97 (0.94 to 0.99)

change in relation to changes in acceleration performance. Interventions can then be implemented to enhance the variables associated with an individual's reliance to increase their acceleration performance or, at least, to ensure they are able to consistently produce a high performance in this phase relative to their individual capabilities.

Collectively, the findings from this study have demonstrated that the normalised spatiotemporal variables and the length/rate and contact/flight ratios can be used to reliably portray acceleration strategies. Using this novel approach, four clusters of professional rugby backs were identified according to the similarity of their normalised spatiotemporal variables, but acceleration performance did not differ significantly between clusters. This implies that a single optimal strategy does not exist during initial sprint acceleration and therefore the efficacy of technique strategies used ought to be considered at the individual level to inform sprint training practices. At the intra-individual level, the variables which portray the individual strategies of participants remained consistent relative to the inter-individual variability observed. The approach employed in this study provides a new solution for longitudinally monitoring changes in an individual's whole-body acceleration strategy to accurately detect any changes in response to influencing factors (e.g., training interventions, fatigue, training load and rehabilitation from injury).

Table 3. Stability of the individual strategy of backs over the initial four steps of maximal sprinting across 12 sprint trials (3 sprints conducted on 4 separate testing occasions).

	Stability index (%)[a]		Variability											
			CT/FT		SL/SR		SL		SR		CT		FT	
Participants	Ratios	Spatiotemporal variables	*CV*	*SD*	*CV*	*SD*	*CV*	*SD*	*CV*	*SD*	*CV*	*SD*	*CV*	*SD*
1	75	85	7.0	0.208	4.3	0.032	4.1	0.048	1.9	0.030	1.8	0.008	6.4	0.010
2	74	89	7.6	0.222	3.7	0.028	2.4	0.027	2.5	0.038	3.8	0.019	4.8	0.008
3	71	82	9.9	0.244	5.4	0.046	4.8	0.061	1.7	0.025	2.0	0.009	8.9	0.017
14	80	86	6.8	0.160	4.7	0.044	3.7	0.049	1.3	0.018	<0.1	0.006	5.7	0.012
16	82	89	5.9	0.136	4.3	0.046	2.0	0.028	2.7	0.035	3.5	0.018	4.4	0.010
17	85	87	5.9	0.117	4.2	0.036	3.5	0.042	1.7	0.024	3.0	0.014	3.8	0.009
19	83	91	6.3	0.136	2.9	0.028	1.8	0.023	1.9	0.026	2.3	0.011	5.4	0.012
20	81	87	4.3	0.148	5.0	0.052	2.7	0.038	2.5	0.034	2.6	0.015	4.5	0.007
27	83	91	4.7	0.142	2.7	0.026	2.0	0.026	1.2	0.017	1.6	0.009	4.0	0.007
11	77	90	8.2	0.194	2.6	0.029	1.7	0.025	1.7	0.022	1.5	0.008	7.0	0.016
12	80	89	7.6	0.161	3.7	0.039	2.1	0.029	1.8	0.024	2.8	0.014	5.7	0.014
21	83	89	7.8	0.143	2.8	0.030	2.2	0.031	1.6	0.021	2.2	0.011	6.2	0.017
26	84	91	4.7	0.134	2.7	0.030	1.7	0.025	1.7	0.022	1.9	0.011	4.1	0.008
Mean	80	88	6.7	0.165	3.8	0.036	2.7	0.035	1.9	0.026	2.4	0.012	5.5	0.011

[a]Stability of the variables for each individual relative to the group standard deviation of the participants, calculated (Maselli et al., 2019) as follows, Sj = 1 − (intra-individual SD/inter − individual SD)

CV, coefficient of variation (%); SD, standard deviation for normalised spatiotemporal variables; CT/FT, contact/flight ratio; SL/SR, length/rate ratio; SL, step length; SR, step rate; CT, contact time; FT, flight time

could determine how changes in whole-body kinematic strategies, in addition to athlete's spatiotemporal variables in isolation, are associated with NAHEP to determine which variables an individual may be reliant on for better acceleration performance. For instance, for an individual who is step rate reliant (i.e., they achieve higher NAHEP when their length/rate ratio is typically lower), it would be possible to determine whether their higher step rates are achieved through a reduction in contact or flight time, or a combination of both. This information may provide a more focussed direction for a practitioner's speed training interventions when looking to target the normalised spatiotemporal variables an individual's acceleration performance is reliant on, although experimental research is required to determine the effectiveness of this approach.

Reliance on step length or step rate has been shown to be a highly individual occurrence in elite sprinters when considered across the whole 100 m sprint (Salo et al., 2011). These researchers proposed that this individual reliance should be considered in the context of an athlete's training and that the step characteristics they are reliant on for better sprinting performance ought to be prioritised (Salo et al., 2011). The added advantage of monitoring an individual's whole-body kinematic strategy, in addition to their normalised spatiotemporal variables in isolation, is that a more holistic view is provided that takes into account how the combination of all normalised spatiotemporal variables collectively

The overall outcome of this study is a novel and rigorous framework for coaches and other practitioners to assess the efficacy of their applied technical-based interventions aimed at modifying initial sprint acceleration strategies. Given that this approach can be applied to athletes across a wide range of sports, this study is likely to become a primary source of evidence for both scientists and practitioners working in the field.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The author(s) reported there is no funding associated with the work featured in this article.

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References

Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine (Auckland, N.Z.)*, *26*(4), 217–238. https://doi.org/10.2165/00007256-199826040-00002

Baroni, B., Rodrigues, R., Franke, R., Geremia, J., Rassier, D., & Vaz, M. (2013). Time course of neuromuscular adaptations to knee extensor eccentric training. *International Journal of Sports Medicine*, *34*(10), 904–911. https://doi.org/10.1055/s-0032-1333263

Bernstein, N. A. (1967). *The co-ordination and regulation of movements* (1st ed.). Pergamon Press.

Bezodis, I., Kerwin, D., Cooper, S., & Salo, A. (2018). Sprint running performance and technique changes in athletes during periodized training: An elite training group case study. *International Journal of Sports Physiology and Performance*, *13*(6), 755–762. https://doi.org/10.1123/ijspp.2017-0378

Bezodis, N., Salo, A., & Trewartha, G. (2010). Choice of sprint start performance measure affects the performance-based ranking within a group of sprinters: Which is the most appropriate measure? *Sports Biomechanics*, *9*(4), 258–269. https://doi.org/10.1080/14763141.2010.538713

Brown, N., Bubeck, D., Haeufle, D., Weickenmeier, J., Kuhl, E., Alt, W., & Schmitt, S. (2017). Weekly time course of neuro-muscular adaptation to intensive strength training. *Frontiers in Physiology*, 8, 329. https://doi.org/10.3389/fphys.2017.00329

Button, C., Seifert, L., Chow, J., Araujo, D., & Davids, K. (2020). *Dynamics of skill acquisition: An ecological dynamics approach. an ecological dynamics approach* (2nd ed.). Human Kinetics.

Comyns, T., Flanagan, E., Fleming, S., Fitzgerald, E., & Harper, D. (2019). Interday reliability and usefulness of reactive strength index derived from two maximal rebound jump tests. *International Journal of Sports Physiology and Performance*, *14*(9) 1200–1204. https://doi.org/10.1123/ijspp.2018-0829

Czasche, M., Goodwin, J., Bull, A., & Cleather, D. (2018). Effects of an 8-week strength training intervention on tibiofemoral joint loading during landing: A cohort study. *BMJ Open Sport & Exercise Medicine*, *4*(1), e000273. https://doi.org/10.1136/bmjsem-2017-000273

Davids, K., Hristovski, R., Araújo, D., Balague Serre, N., Button, C., & Passos, P. (2014). *Complex systems in sport*. Routledge. https://doi.org/10.4324/9780203134610

Everitt, B., Landau, S., Leese, M., & Stahl, D. (2011). *Cluster analysis* (5th ed.). John Wiley & Sons Ltd.

Fajen, R., Riley, M., & Turvey, M. (2008). Information, affordances, and the control of action in sport. *International Journal of Sports Psychology*, *40*(1), 79–107.

Flanagan, E., & Comyns, M. (2008). The use of contact time and the reactive strength index to optimize fast stretch-shortening cycle training. *Strength and Conditioning Journal*, *30*(5), 32–38. https://doi.org/10.1519/SSC.0b013e318187e25b

Flanagan, E., Ebben, W., & Jensen, R. (2008). Reliability of the reactive strength index and time to stabilization during depth jumps. *Journal of Strength and Conditioning Research*, *22*(5), 1677–1682. https://doi.org/10.1519/JSC.0b013e318182034b

García-Ramos, A., Pérez-Castilla, A., & Jaric, S. (2021). Optimisation of applied loads when using the two-point method for assessing the force-velocity relationship during vertical jumps. *Sports Biomechanics*, *20*(3), 274–289. https://doi.org/10.1080/14763141.2018.1545044

Glazier, P., & Mehdizadeh, S. (2018). Challenging conventional paradigms in applied sports biomechanics research. *Sports Medicine (Auckland)*, *49*(2), 171–176. https://doi.org/10.1007/s40279-018-1030-1

Goodwin, J., & Bull, A. M. (2021). Novel assessment of isometric hip extensor function: Reliability, joint angle sensitivity, and concurrent validity. *Journal of Strength and Conditioning Research*. Publish Ahead of Print. https://doi.org/10.1519/JSC.0000000000004012

Gordon, A. (1999). *Classification* (2nd ed.). London.

Hair, J. F., Black, W. C., Babin, B. J., & Anderson, R. E. (2019). *Multivariate data analysis* (Eighth ed.). Cengage Learning, EMEA.

Harper, D., Carling, C., & Kiely, J. (2019). High-intensity acceleration and deceleration demands in elite team sports competitive match play: A systematic review and meta-analysis of observational studies. *Sports Medicine (Auckland)*, *49*(12), 1923–1947. https://doi.org/10.1007/s40279-019-01170-1

Haugen, T., Breitschädel, F., & Seiler, S. (2019). Sprint mechanical variables in elite athletes: Are force-velocity profiles sport specific or individual? *PloS One*, *14*(7), 1–14. https://doi.org/10.1371/journal.pone.0215551

Hof, A. L. (1996). Scaling gait data to body size. *Gait & Posture*, *4*(3), 222–223. https://doi.org/10.1016/0966-6362(95)01057-2

Hopkins, W. (2002). A scale of magnitudes for effect statistics:A new view of statistics. *Sportscience* http://www.sportsci.org/resource/stats/effectmag.html

Hopkins, W. (2007). A spreadsheet for deriving a confidence interval, mechanistic inference and clinical inference from a P value. *Sportscience*, *11*, 16-20. http://sportsci.org/2007/wghinf.htm

Hopkins, W. G. (2015). Spreadsheets for analysis of validity and reliability. *Sportscience*, *19*, 36–42. http://sportsci.org/2015/ValidRely.htm

Janicijevic, D., Knezevic, O., Mirkov, D., Pérez-Castilla, A., Petrovic, M., Samozino, P., & Garcia-Ramos, A. (2020). Assessment of the force-velocity relationship during vertical jumps: Influence of the starting position, analysis procedures and number of loads. *European Journal of Sport Science*, *20*(5), 614–623. https://doi.org/10.1080/17461391.2019.1645886

Jauhiainen, S., Pohl, A. J., Äyrämö, S., Kauppi, J. P., & Ferber, R. (2020). A hierarchical cluster analysis to determine whether injured runners exhibit similar kinematic gait patterns. *Scandinavian Journal of Medicine & Science in Sports*, *30*(4), 732–740. https://doi.org/10.1111/sms.13624

Koo, T., & Li, M. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine*, *15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

Lance, G., & Williams, W. (1967). A general theory of classificatory sorting strategies: 1. hierarchical systems. *Computer Journal*, *9*(4), 373–380. https://doi.org/10.1093/comjnl/9.4.373

Lockie, R., Murphy, A., Knight, T., & Janse de Jonge, X. (2011). Factors that differentiate acceleration ability in field sport athletes. *Journal of Strength and Conditioning Research*, *25*(10), 2704–2714. https://doi.org/10.1519/JSC.0b013e31820d9f17

Lockie, R., Murphy, A., Schultz, A., Jeffriess, M., & Callaghan, S. (2013). Influence of sprint acceleration stance kinetics on velocity and step kinematics in field sport athletes. *Journal of Strength and Conditioning Research; the Journal of Strength and Conditioning Research*, *27*(9), 2494–2503. https://doi.org/10.1519/JSC.0b013e31827f5103

Maselli, A., Dhawan, A., Russo, M., Cesqui, B., Lacquaniti, F., & d'Avella, A. (2019). A whole body characterization of individual strategies, gender differences, and common styles in overarm throwing. *Journal of Neurophysiology*, *122*(6), 2486–2503. https://doi.org/10.1152/jn.00011.2019

Michaels, C. (2003). Affordances: Four points of debate. *Ecological Psychology*, *15*(2), 135–148. https://doi.org/10.1207/S15326969ECO1502_3

Moritani, T., & deVries, H. (1979). Neural factors versus hypertrophy in the time course of muscle strength gain. *American Journal of Physical Medicine*, *58*(3), 115–130. https://journals.lww.com/ajpmr/Citation/1979/06000/NEURAL_FACTORS_VERSUS_HYPERTROPHY_IN_THE_TIME.1.aspx

Murata, M., Takai, Y., Kanehisa, H., Fukunaga, T., & Nagahara, R. (2018). Spatiotemporal and kinetic determinants of sprint acceleration performance in soccer players. *Sports (Basel, Switzerland)*, *6*(4), E169. https://doi.org/10.3390/sports6040169

Murphy, A., Lockie, R., & Coutts, A. (2003). Kinematic determinants of early acceleration in field sport athletes. *Journal of Sports Science & Medicine*, *2*(4), 144–150. http://www.ncbi.nlm.nih.gov/pubmed/24688275

Nagahara, R., Takai, Y., Kanehisa, H., & Fukunaga, T. (2018). Vertical impulse as a determinant of combination of step length and frequency during sprinting. *International Journal of Sports Medicine*, 40*(39)*, 282-290. https://doi.org/10.1055/s-0043-122739

Newell, K. (1986). Constraints on the development of coordination. In M. Wade & H. Whiting (Eds.), *Motor development in children: Aspects of coordination* (pp. 341–361). Martinus Nijhoff Publishers.

Newell, K., & Ranganathan, R. (2009). *Some contemporary issues in motor learning*. Springer US. https://doi.org/10.1007/978-0-387-77064-2_20

Nicholson, B., Dinsdale, A., Jones, B., & Till, K. (2020). The training of short distance sprint performance in football code athletes: A systematic review and meta-analysis. *Sports Medicine*, *51*(6), *1179-1207*. https://doi.org/10.1007/s40279-020-01372-y

Phinyomark, A., Osis, S., Hettinga, B. A., & Ferber, R. (2015). Kinematic gait patterns in healthy runners: A hierarchical cluster analysis. *Journal of Biomechanics*, *48*(14), 3897–3904. https://doi.org/10.1016/j.jbiomech.2015.09.025

Porter, J., Wu, W., & Partridge, J. (2010). Focus of attention and verbal instructions: Strategies of elite track and field coaches and athletes. *Sport Science Review (Bucureşti)*, *19*(3–4), 77. https://doi.org/10.2478/v10237-011-0018-7

Preatoni, E., Hamill, J., Harrison, A. J., Hayes, K., Van Emmerik, R., Wilson, C., & Rodano, R. (2013). Movement variability and skills monitoring in sports. *Sports Biomechanics*, *12*(2), 69–92. https://doi.org/10.1080/14763141.2012.738700

Rasmussen, B., & Phillips, S. (2003). Contractile and nutritional regulation of human muscle growth. *Exercise and Sport Sciences Reviews*, *31*(3), 127–131. https://doi.org/10.1097/00003677-200307000-00005

Salo, A., Bezodis, I., Batterham, A., & Kerwin, D. (2011). Elite sprinting: Are athletes individually step-frequency or step-length reliant? *Medicine and Science in Sports and Exercise*, *43*(6), 1055. https://doi.org/10.1249/MSS.0b013e318201f6f8

Samozino, P., Edouard, P., Sangnier, S., Brughelli, M., Gimenez, P., & Morin, J. (2013). Force-velocity profile: Imbalance determination and effect on lower limb ballistic performance. *International Journal of Sports Medicine*, *35*(6), 505–510. https://doi.org/10.1055/s-0033-1354382

Schache, A., Lai, A., Brown, N., Crossley, K., & Pandy, M. (2019). Lower-limb joint mechanics during maximum acceleration sprinting. *Journal of Experimental Biology*, *222*(Pt 22), jeb209460, 1–12. https://doi.org/10.1242/jeb.209460

Standing, R. J., & Maulder, P. S. (2017). The biomechanics of standing start and initial acceleration: Reliability of the key determining kinematics. *Journal of Sports Science & Medicine*, *16*(1), 154–162.https:////www.ncbi.nlm.nih.gov/pmc/articles/PMC5358026/

Tononi, G., Sporns, O., & Edelman, G. M. (1999). Measures of degeneracy and redundancy in biological networks. *Proceedings of the National Academy of Sciences of the United States of America*, *96*(6), 3257–3262. https://doi.org/10.1073/pnas.96.6.3257

van Oeveren, B. T., de Ruiter, C. J., Beek, P. J., & Van Dieën, J. H. (2021). The biomechanics of running and running styles: A synthesis. *Sports Biomechanics*. https://doi.org/10.1080/14763141.2021

Veloso, A., Joao, F., Valamatos, M., Cabral, S., & Moniz-Pereira, V. (2015). Subject-specific musculoskeletal model to identify muscle contribution to the acceleration phase in elite sprinting. In F. Colloud, M. Domalain, & T. Monnet (Eds.), *Proceedings of the 33rd International Conference of Biomechanics in Sports*. (pp. 285–288). Konstanz, Germany: International Society of Biomechanics in Sports.

Watari, R., Osis, S. T., Phinyomark, A., & Ferber, R. (2018). Runners with patellofemoral pain demonstrate sub-groups of pelvic acceleration profiles using hierarchical cluster analysis: An exploratory cross-sectional study. *BMC Musculoskeletal Disorders*, *19*(1), 120–123. https://doi.org/10.1186/s12891-018-2045-3

Wild, J., Bezodis, I., North, J., & Bezodis, N. (2018). Differences in step characteristics and linear kinematics between rugby players and sprinters during initial sprint acceleration. *European Journal of Sport Science*, *18*(10), 1327–1337. https://doi.org/10.1080/17461391.2018.1490459

Winter, E., Abt, G., & Nevill, A. (2014). Metrics of meaningfulness as opposed to sleights of significance. *Journal of Sports Sciences*, *32*(10), 901–902. https://doi.org/10.1080/02640414.2014.895118

Winter, E., & Maughan, R. (2009). Requirements for ethics approvals. *Journal of Sports Sciences*, *27*(10), 985. https://doi.org/10.1080/02640410903178344

Wulf, G. (2013). Attentional focus and motor learning: A review of 15 years. *International Review of Sport and Exercise Psychology*, *6*(1), 77–104. https://doi.org/10.1080/1750984X.2012.723728