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Spatio-Temporal Signatures and Acceleration Performance in Para-Athletes Across Classification Groups: A Comparison With Olympic Athletes

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Background: Acceleration over the first 20 m is a determining factor in 100 m sprint performance. Elite olympic athletes appear to use individual combinations of spatio-temporal parameters to enhance acceleration performance, but whether this holds for para-athletes and what role different impairments play remains unknown. The aim was to compare performance and spatio-temporal parameters between para- and olympic athletes during the acceleration phase and examine the role of classification group within para-athletes.

Methods: 23 para-athletes (10 female; seven classification groups) and 20 olympic athletes (10 female), highly-trained to world-class, performed maximal 20 m sprints from blocks. Velocity was measured by laser and touchdown events by optical measurement units. Step length to step frequency and contact time to flight time ratios were normalised to biological or artificial leg length, averaged over the steps to 20 m and expressed as z-scores relative to sex-specific olympic athlete values, defining the spatio-temporal signature. Velocity was analysed with a linear mixed model and signatures with permutational multivariate analysis of variance and a nested variance decomposition (athletes within classification groups).

Results: Para-athletes accelerated more slowly, with a velocity deficit that increased from 0.60 $m \cdot s^{-1}$ at 5 m to 1.17 $m \cdot s^{-1}$ at 20 m (cohort × distance, $p < 0.001$; all $|g| \geq 1.83$). Both cohorts displayed a variety of spatio-temporal signatures, and cohort centroids, pooled across sexes, did not differ significantly ($p = 0.379$). However, a cohort × sex interaction emerged ($p = 0.002$), and para-athletes adopted a ground-based, step-length-dominant style not observed in Olympic athletes. Classification group explained 44.4% of signature variance

among para-athletes ($p = 0.042$), yet the nested decomposition showed that variance between para-athletes within the same group exceeded between-group variance 3.4-fold (step length to step frequency) and 1.4-fold (contact time to flight time).

Conclusion: Para-athletes showed a progressive velocity deficit but no distinct para-specific spatio-temporal signature. Classification group appeared to constrain spatio-temporal signatures, yet individual variation dominated, suggesting that athletes combine spatio-temporal parameters individually within classification-specific bandwidths. This study outlines a practical tool for profiling spatio-temporal signatures and may support training approaches referenced to an athlete's own profile rather than group-based norms.

Keywords: paralympic; classification; biomechanics; track and field; sprint running

Key Points

- This is the first study to compare the acceleration phase across seven International Paralympic Committee (IPC) classification groups with olympic sprinters. Para-athletes were slower throughout the first 20 m but used similar spatio-temporal signatures on average.
- Para-athletes showed a wider range of spatio-temporal signatures than olympic athletes, including a ground-based, step-length-dominant style that no olympic athlete used.
- Athletes in the same classification group differed more from each other than the groups differed from one another. Acceleration training in para-athletics should therefore be based on each athlete's own spatio-temporal signature rather than on classification-based norms.

Introduction

At the start of any sprint event, athletes commence from a static position in the starting blocks and must produce considerable acceleration to propel the body forward. Empirical data from world-class olympic athletes (OLY) suggest that they reach approximately 84% of their maximum sprinting velocity when passing the 20 m mark, underlining the significance of the acceleration phase in facilitating overall 100 m race performance[1,2]. The acceleration phase is often referred to as the initial twelve to fourteen steps (~20 m) and is distinguished from later phases by step-to-step kinematic changes[3,4]. The acceleration phase is, thus, crucial not only for the time to reach 20 m but also for how it sets up the remainder of the race[5]. While sprint performances of para-athletes (PARA) and OLY are constrained by the same fundamental physical principles, practical complexities arise in how athletes navigate the mechanical challenges during accelerated sprinting[6]. The classification system of the International Paralympic Committee (IPC) is based on level of amputation and/or similar levels of activity limitations due to impairments[7,8]. Athletes are grouped into sport classes based on eligible impairments, which include but are not limited to: loss of limb or limb deficiency, impaired vision, functional impairments like impaired muscle power, passive range of movement in the lower limbs, or co-ordination impairments and cognitive impairments[9]. Previous studies have shown that differences between PARA and OLY are particularly pronounced during the acceleration phase. Lower-limb amputee sprinters, for example, may take up to 40% longer to reach the 20 m mark[10]. Spatio-temporal metrics can provide a practical first-layer insight into how such differences emerge. The analysis of normative data of OLY indicates some general mechanisms related to the combination of spatiotemporal variables that produce world-class sprint performance. For example, step length (SL) typically increases rapidly in a hyperbolic manner during the whole acceleration phase,

while step frequency (SF) often exceeds 90% of the frequencies achieved at upright sprinting (maximum velocity phase) by the first step[11,12]. Ground contact times (CT) decrease with increasing running velocity, whereas flight times (FT) tend to increase during the acceleration phase[13]. While these general trends are well established in the literature, studies with elite OLY suggest that within these broader guidelines they may adopt specific individual "spatio-temporal acceleration strategies" to optimize acceleration performance[14]. To quantify these "acceleration strategies" and contribute to solving inconsistencies regarding the link between isolated spatio-temporal parameters and sprint performance, it was proposed to combine these parameters into ratios such as step length to step frequency ratio (SL to SF ratio) and contact time to flight time ratio (CT to FT ratio), which makes it possible to describe different "styles" along a dual-axis graph[15]. Various terms have been used for this position in the dual-axis graph, including "spatio-temporal acceleration strategy," "whole-body kinematic strategy" and "individual motor preferences". Following conventions in gait analysis, we use spatio-temporal signature[16] for the position in the Cartesian plane, and sprinting style for the broader categorization given by which of the four quadrants an athlete occupies. We favor *signature* and *style* over strategy, as the present design does not establish deliberate selection of a movement solution and the four styles should not be read as discrete athlete types: the underlying ratios are continuous, and the quadrants are an interpretable overlay on that continuum rather than a natural clustering. As spatio-temporal signatures may be influenced by individual organismic constraints such as anthropometrics, strength and mobility[17], it can be assumed that individual impairments of PARA are likely to influence spatio-temporal signature, potentially producing IPC group-specific adaptations[18,19,20]. However, research on the acceleration phase in PARA remains limited, and no synthesis spanning multiple IPC groups is currently available, leaving it unclear whether IPC group

can explain spatio-temporal signature or whether individual variation within the same IPC group predominates.

We therefore hypothesised that (1) para- and olympic athletes would differ in their acceleration performance, assessed as instantaneous velocity at 20 m and in spatio-temporal signature, assessed as the combination of SL to SF and CT to FT ratios; and (2) para-athletes within the same IPC group would display similar spatio-temporal signatures during the acceleration phase.

Materials and Methods

A total of 23 para (male (m) = 13, female (f) = 10) and 20 OLY (m = 10, f = 10) athletes competing in track and field sprint events were analyzed. Under the participant classification framework[21] the sample comprised world-class (n = 10; para = 7, OLY = 3), elite (n = 23; para = 11, OLY = 12), and highly trained (n = 10; para = 5, OLY = 5). Para-athletes in this sample had won a total of 44 combined gold medals from events during Para World Championships or Paralympics and included world record holders in their respective event and IPC sport class. Written informed consent was obtained from all participants, and the experimental procedures adhered to the guidelines stated in the Declaration of Helsinki[22]. Approval was obtained from the local ethics committee (*Nr. 212/2022*). At the time of testing, all participants were free of musculo-skelettal injuries and testings were part of the regular performance diagnostics of the national high-performance program for para-athletes. All tests were carried out following a 48-hour period of abstinence from sprinting and lower body strength training. Para-athletes were grouped (hereafter referred to as “IPC group”) according to their IPC sport class: bilateral transtibial amputation (BTT, classification T62; m = 2), unilateral transtibial amputation (UTT, classification T64; m = 3, f = 1), unilateral transfemoral amputation (UTF,

146 classification T63; m = 3), unilateral transradial amputation (UTR, classification T46/47;
147 m = 1, f = 2), vision impairment (VI, classifications T12-T13; m = 1, f = 3), functional
148 impairment (FI, classifications: T35–T38; m = 3, f = 3) and cognitive impairment (CI,
149 classification T20; f = 1). Athletes with vision impairment ran independently, without a
150 guide runner.

151 ***Testing procedures***

152 Sprint testing was conducted on indoor athletics track and was embedded within typical
153 acceleration-phase training sessions during the week. Following a coach-prescribed
154 individual warm-up, artificial or biological leg length (measured as the distance from the
155 center of the trochanter major to the floor) was collected[6]. This adapted landmark
156 definition was chosen because it applies to all athletes in the sample, including those with
157 lower-limb amputation, for whom a malleolus-based measurement is not obtainable.
158 Participants then performed standardized maximal sprint efforts over a 20 m distance
159 from starting blocks, using their own equipment (e.g., spiked shoes, running-specific
160 prostheses) and preferred block settings. Rest intervals between trials were self-selected
161 according to athletes' individual needs, with a minimum of three minutes between trials.
162 During each sprint, touch down events were detected using 20 optojump beams
163 (Microgate, Bolzano, Italy), each consisting of 96 light barriers, sampling at 1000 Hz.
164 From the touch down events spatio-temporal parameters (i.e., SL, SF, CT, and FT) were
165 derived. Velocity and segment time of the athletes were simultaneously determined using
166 a laser velocity guard (LAVEG - Laser Velocity Guard, Jenoptik, Jena, Germany),
167 positioned 2.5 m behind the starting line at a height of 0.8 m to avoid angle correction
168 issues and aimed at the lower back region of each subject for the entire sprinting
169 distance[23].

Data processing

Data were exported from the recording software and processed in R (version 4.6.0; RStudio, Posit Software, PBC, Boston, MA). LAVEG displacement data were zeroed to the instant at which the athlete's lower back crossed the starting line. Velocity was obtained from the displacement signal using the "shorts" package[24] with flying-distance correction to account for hip travel from the blocks to the starting line. Instantaneous velocities ($m \cdot s^{-1}$) at the different marks (i.e., 5 m, 10 m, 15 m and 20 m) and segment times (s) (i.e. 0 – 5 m; 0 – 10 m; 0 – 15 m; 0 – 20 m) were extracted for further analysis. SL to SF and CT to FT ratios were computed from the spatio-temporal variables. To account for potential confounding effects of anthropometric differences (e.g. longer leg lengths naturally leading to greater SL) spatio-temporal data were normalized to artificial or biological leg length using Hof's equations[25]. As recommended by Wild et al.[15] normalized data were averaged across the steps taken to reach 20 m. Ratios were then standardized as z-scores, relative to the OLY data from this sample and separately by sex.

Statistical analysis

Within-athlete variation between trials was quantified as the mean absolute difference between all trial pairs for each athlete, averaged across athletes and as the within-athlete coefficient of variation (CV). 95% confidence intervals were obtained by bootstrap resampling of athletes (2000 resamples). Normality was assessed using the Shapiro-Wilk test. To evaluate the first hypothesis, only the trial with the highest instantaneous velocity at 20 m (v_{20}) was retained. Cohorts were defined as all PARA and OLY and differences were tested using Welch's t-test. Differences are reported as mean differences with 95% CI and as percentages of the OLY mean. Effect sizes are reported as Hedge`s g with 95% confidence intervals and interpreted as <0.20 (trivial), 0.20–0.59 (small), 0.60–1.19 (moderate), 1.20–1.99 (large), > 2.00 (very large)[26]. Interaction terms involving cohort,

sex and distance were tested in a linear mixed model with a random intercept per athlete. Holm's correction was applied across the eight cohort contrasts[27] Holm-adjusted p-values are reported, and α was set a priori at 0.05. To illustrate the spatio-temporal signature of each athlete (PARA and OLY), dual-axis graphs were created by plotting the marker on a Cartesian plane, with standardized SL to SF ratio z-scores on the vertical axis and CT to FT ratios on the horizontal axis (similar to the methodology of Wild et al. (2022)). V_{20} was incorporated into the visualization as the diameter of the marker. The four resultant Cartesian plane quadrants denote sprinting styles of the acceleration phase with I) ground based, step length dominant, II) flight based, step length dominant, III) flight based, step frequency dominant and IV) ground based step frequency dominant[14,15]. Differences in the position of cohort centroids were tested by permutational multivariate analysis of variance (PERMANOVA) with Euclidean distance and 9999 permutations ("vegan" package[28]), fitted pooled across sexes. The cohort × sex interaction was additionally tested on each axis by two-way analysis of variance, with simple effects computed within sex. Multivariate dispersion around cohort centroids was compared using distances to the group centroid.

To evaluate the second hypothesis, four trials for each PARA were plotted in the dual-axis graph and convex hulls were computed. Two PARA were excluded from this analysis: the single athlete in the CI group, for whom no within-group comparison was possible, and one athlete for whom only three distinct trials were available; 21 para-athletes were therefore retained. Convex hulls were used to visually assess whether athletes of the same IPC group differed in their spatio-temporal signature. Statistical differences were tested by PERMANOVA on athlete centroids. The variance in each axis attributable to IPC group, to athletes within IPC group, and to trials within athlete was estimated by restricted maximum likelihood in a nested random-effects model. As a

descriptive complement, mean pairwise centroid distances and the proportion of athlete pairs occupying the same quadrant were computed within and between IPC groups. All analyses were conducted in R (version 4.6.0), with statistical significance accepted at $p < 0.05$.

Results

Trial-to-trial variation

Within-session variation was small and comparable between cohorts. The mean absolute within-athlete difference in v_{20} was 0.099 $m \cdot s^{-1}$ (95% CI [0.070, 0.133]) in PARA and 0.125 $m \cdot s^{-1}$ ([0.087, 0.172]) in OLY; for 0-20 m segment time the corresponding values were 0.035 s ([0.027, 0.045]) and 0.018 s ([0.013, 0.023]). For the spatio-temporal parameters in PARA, mean absolute within-athlete differences were 3.51 cm (CV 2.21 %) for SL, 0.102 Hz (CV 2.16 %) for SF, 0.005 s (CV 3.07 %) for CT and 0.004 s (CV 3.46 %) for FT; equivalent values in OLY were 2.46 cm (CV 1.22 %), 0.051 Hz (CV 0.92 %), 0.004 s (CV 2.19 %) and 0.004 s (CV 3.54 %). On the standardized axes, used for the Cartesian plane representation, the mean absolute within-athlete difference was 0.33 z ([0.27, 0.41]) for the SL to SF ratio and 0.50 z ([0.38, 0.62]) for the CT to FT ratio.

Acceleration performance

Instantaneous velocities at selected marks and segment times for cohort and IPC groups are presented in Table 1.

*** Table 1 near here ***

PARA were slower than OLY at every mark, and the deficit widened with distance (cohort × distance, $F(3,123) = 26.9$, $p < 0.001$). In female athletes the difference increased from Δ 0.44 $m \cdot s^{-1}$ at 5 m (95 % CI [0.22, 0.66]; −7.2 %; $g = -1.83$ [−2.84, −0.81]; $p = 0.001$) to Δ 1.07 $m \cdot s^{-1}$ at 20 m ([0.68, 1.47]; −12.4 %; $g = -2.46$ [−3.69, −1.32]; $p <$

0.001). In male athletes it increased from Δ 0.80 $m \cdot s^{-1}$ at 5 m ([0.51, 1.09]; −11.9 %; g = −2.15 [−3.16, −1.13]) to Δ 1.35 $m \cdot s^{-1}$ at 20 m ([0.91, 1.77]; −14.1 %; g = −2.39 [−3.45, −1.34]). All eight contrasts remained significant after Holm correction (all $p \leq 0.015$, all $|g| \geq 1.83$). The rate at which the velocity deficit accumulated from 5 to 20 m did not differ between female and male PARA (cohort × sex × distance, $F(3,117) = 0.39$, $p = 0.760$), nor did the overall magnitude of the deficit (cohort × sex, $F(1,39) = 2.05$, $p = 0.154$). The sex difference in v20 within PARA was 0.69 $m \cdot s^{-1}$. Sex-adjusted hierarchy of v_{20} in PARA was UTR > UTT > BTT > VI > CI > FI > UTF. Descriptive data for v_{20} and velocity traces for each IPC group are presented in Figure 1B and C.

*** Figure 1 near here ***

Spatio-temporal signatures

Absolute spatio-temporal data for cohort and IPC groups are reported in Table 2.

*** Table 2 near here ***

For visual representation and comparison of the individual spatio-temporal signatures, Figure 2 displays the dual-axis graph with four quadrants for the entire sample (PARA and OLY combined). Both cohorts used a variety of different sprinting styles and were distributed across the four quadrants (I: n = 9; II: n = 13; III: n = 8; IV: n = 13). PARA occupied all four quadrants (I: n = 9; II: n = 4; III: n = 4; IV: n = 6), whereas OLY occupied three, with no OLY athlete located in quadrant I (I: n = 0; II: n = 9; III: n = 4; IV: n = 7).

Pooled across sexes, the cohort explained 2.3 % (pseudo-F = 0.96; p = 0.379) of the variance in the spatio-temporal signature with a significant interaction effect (cohort × sex; pseudo-F =8.02; p = 0.002). On the SL to SF axis there was a strong cohort × sex interaction ($F(1,39) = 15.3$, $p < 0.001$) with no cohort main effect ($F(1,39) = 0.06$, $p = 0.811$): relative to olympic athletes of the same sex, female para-athletes were displaced

towards step-length dominance (+1.38 z, 95% CI [0.53, 2.22]; g = +1.46; p = 0.003) and male para-athletes towards step-frequency dominance (−1.08 z, [−2.06, −0.09]; g = −0.93; p = 0.035). Multivariate dispersion around the cohort centroid did not differ between PARA and OLY (mean distance to centroid 1.61 vs 1.32 z; pseudo-F = 2.10; p = 0.155), nor did the mean distance of individual athletes from the origin (1.66 ± 0.71 vs 1.33 ± 0.61 z; mean difference 0.33 z, 95 % CI [−0.07, 0.74]; p = 0.106). Differences in v_{20} between quadrants did not meet the criteria of statistical significance when cohort and sex were accounted for ($F(3,37) = 2.82$, p = 0.052) (Fig. 2B).

*** Figure 2 near here ***

Comparing the centroids of the four trials of each PARA (n = 21 athletes), IPC group explained 44.4 % of the variance in position in the dual-axis graph (pseudo-F = 2.40; p = 0.042). Examined per axis, IPC group accounted for 41.2% of the variance in SL to SF ratio z-scores and 52.1% in CT to FT ratio z-scores. The nested variance decomposition showed that this group-level association was smaller than the variation between athletes sharing an IPC group. For the SL to SF axis, IPC group accounted for 22.0% of total variance, athletes within IPC group for 74.4% and trials within athlete for 3.6%; for the CT to FT axis the corresponding shares were 33.0%, 45.9% and 21.1%. Between-athlete variance within IPC groups therefore exceeded between-group variance by 3.39-fold on the SL to SF axis and 1.39-fold on the CT to FT axis. Descriptively, centroids of PARA within the same IPC group were only marginally closer to one another than those of PARA from different IPC groups (mean pairwise distance 1.89 vs 2.32 z). 29 % of within-IPC-group athlete pairs occupied the same quadrant of the dual-axis graph, compared with 24 % of between-group pairs (Figure 3).

*** Figure 3 near here ***

Discussion

The goal of this study was to investigate sprint performance and spatio-temporal parameters during the acceleration phase in PARA and OLY. Specifically, this study aimed to compare similarities and differences between PARA and OLY cohorts as well as between IPC groups and identify individual spatio-temporal signatures. To our knowledge, a synthesis of spatio-temporal and performance parameters of PARA from seven IPC groups for the entire 0 to 20 m acceleration phase has not been previously published.

Our data demonstrated that PARA were statistically significantly slower at the end of the acceleration phase, with a velocity deficit that accumulated progressively from 5 to 20 m. However, on a cohort-level average, spatio-temporal signature did not differ in PARA and OLY, yet sex affected the sprinting style in PARA and PARA also adopted sprinting styles (I: ground based, step length dominant) that were not evident in OLY cohort. Within PARA, the IPC group accounted for 44.4% of variance, yet athletes within the same IPC group demonstrated greater between-athlete variance than variance between IPC groups. Taken together, these results indicate that even though PARA and IPC group-specific factors seem to influence spatio-temporal signature, individual characteristics are still dominant and may be more important when analyzing the acceleration phase.

Acceleration performance

As expected, PARA showed lower velocities and longer segment times at all four marks (Table 1), with large effects in males and females and no evidence of sex-specific differences in the magnitude or accumulation of the deficit. The increase of the velocity deficit with distance aligns with reports that PARA might require an extended

317 acceleration phase before reaching maximal velocity[10]. Ranked by v_{20} and adjusted by
318 sex effect the hierarchy was: OLY > UTR > UTT - BTT > VI > CI > FI > UTF. This
319 hierarchy offers novel insight through synthesis of various IPC groups and thereby
320 extends previous findings from single IPC group studies. UTR athletes performed best
321 after accounting for sex, which is consistent with studies in OLY where arm movement
322 restrictions during accelerated sprinting only led to a 1.6% performance decrement in 0
323 to 30 m sprint time[29]. Greater differences in our study may be partly related to the
324 additional challenges emerging from the block starts. Both transtibial groups followed
325 and were indistinguishable from one another once sex was accounted for. That bilateral
326 amputation did not entail a further decrement relative to unilateral amputation at the same
327 level is consistent with experimental work showing that running-specific prostheses
328 reduce force generation but also remove the inter-limb asymmetry that a unilateral
329 configuration imposes[10,30]; the two effects appear to offset one another over the first 20
330 m in the present sample. In vision impaired athletes, alterations in sprint performance and
331 spatio-temporal parameters are probably related to postural stability and sensory deficits
332 rather than pronounced differences in strength and power capacities compared to
333 OLY[31,32]. On the other hand, athletes with functional impairments are typically associated
334 with increased passive muscle stiffness and impaired rapid force application, which
335 plausibly accounts for the longest relative CT observed in this group. Consistent with
336 previous work, more proximal amputations (i.e., UTF vs UTT) were associated with
337 lower v_{20}[33]. Taken together, this hierarchy should be read as a descriptive synthesis;
338 however, the ordering principle still holds interesting information: impairments directly
339 associated with force production capacities showed the largest deficits in acceleration
340 performance, whereas those influencing sensory mechanisms and those not affecting
341 muscles contributing to propulsive impulses seemed to be related to performance deficits

342 to a lesser extent.

343 ***Spatio-temporal parameters***

344 Supporting the first hypothesis, cohorts differed in absolute spatio-temporal parameters
345 (Table 2). Cohort differences were primarily due to lower SF as a result of longer CT
346 (Table 2). In normalized step length to step frequency ratio z-scores and contact time to
347 flight time ratio z-scores, pooled across sex, cohorts only explained 2.3% of the variance
348 in spatio-temporal signature. This may be at least partly caused by sex-specific clustering
349 in PARA; female PARA were displaced towards step-length dominance and male PARA
350 towards step-frequency dominance (Figure 1). Whether the divergence reflects
351 differences in the IPC group mix within each sex in this sample, or a genuine sex-specific
352 response to comparable constraints, cannot be resolved with the present group sizes.
353 PARA were spread across all four quadrants, indicating more variation in sprinting style
354 and greater interindividual differentiation in how they achieved their spatio-temporal
355 signature. The absence of any OLY in quadrant I (ground based, step length dominant)
356 indicates that PARA reach configuration of contact and step characteristics that OLY in
357 this sample did not. Relatively longer CT in PARA may reflect a reduced capacity to
358 generate high mass-specific forces, such that the duration over which force is applied
359 needs to be extended to achieve sufficient propulsive impulse. Studies of OLY, by
360 contrast, have associated prolonged CT as a necessity of "shin-roll motion"[34], and a more
361 horizontal orientation of the resultant ground reaction force[35.] Both a compensatory and
362 an advantageous mechanism might lead to similar ratio values, offering one possible
363 explanation for why athletes with similar sprinting styles recorded both high and low v_{20}
364 (Figure 2B). Across the full sample, sprinting style was not associated with v_{20} once sex
365 and cohort were accounted for ($p = 0.052$), aligning with previous suggestions that

366 relatively similar performances in the acceleration phase can be achieved through a
367 variety of spatio-temporal solutions[15].
368 Taken together, these findings suggest that on a cohort-level PARA seem to make use of
369 similar spatio-temporal signatures, while at the same time thresholds of OLY in CT, for
370 example, seem to be shifted. While in OLY recent studies suggested that in elite athletes
371 there might be general mechanisms related to the combination of spatio-temporal
372 parameters that produce fast sprint times[14,15] athletes nevertheless seem to operate within
373 certain "bandwidths" based on their individual organismic constraints when combining
374 spatio-temporal parameters to optimize performance. In PARA, IPC-group-specific
375 impairments present another layer of individual organismic constraints which could
376 influence the expression of spatio-temporal signatures and shift the sprinting style of a
377 certain IPC group[18,19,20,36].

378 ***Differences within IPC groups***
379 The IPC group did explain a statistically detectable share of the variance in centroid
380 position (R^2 = 44.4 %, pseudo-F = 2.40, p = 0.042), but the nested decomposition showed
381 between-athlete variance within groups to exceed between-group variance 3.39-fold on
382 the SL to SF axis and 1.39-fold on the CT to FT axis. In other words, this means that two
383 athletes drawn from the same IPC group were, on average, only marginally closer to one
384 another in the Cartesian plane than two athletes drawn from different IPC groups (mean
385 pairwise centroid distance 1.89 vs 2.32 z), and only 29 % of within-IPC group pairs
386 occupied the same quadrant (Figures 2 and 3). Therefore, the second hypothesis was not
387 supported.
388 This contradicts some previous work. For example, it was reported that, during the first
389 stance phase, FI-athletes generated larger horizontal braking forces and smaller
390 propulsive forces compared to OLY[18], which might be expected to yield a flight based,

391 step frequency dominant sprinting style (quadrant III). The divergence may reflect the
392 use of normalized spatiotemporal values instead of absolute values, underlining the
393 influence of anthropometric characteristics when evaluating spatial parameters.
394 As it relates to practical applications, this data and analyses indicate that the spatio-
395 temporal signature displayed is likely a combination of IPC group-specific features and
396 individual variation. The findings can be interpreted that IPC group may narrow the
397 "bandwidth" of spatio-temporal configurations available to an athlete without
398 determining a single solution within it. Individual variation within that bandwidth
399 deserves recognition rather than the imposition of one "ideal" model[37].

400 ***Strengths and limitations of the study***

401 The principal strength of this study is that it represents the first synthesis of PARA from
402 multiple IPC groups and presents a unique sample of para-sprinting research, spanning
403 highly trained to world-class athletes. While the findings of this study are highly relevant,
404 several limitations must be considered. First, individual IPC groups were still small (n =
405 1 to 6) and some contained only male or female athletes; in-depth inferential statistical
406 analysis within groups was therefore not always feasible and generalizations beyond this
407 sample are limited. Second, the use of ratios such as SL / SF and CT / FT simplifies
408 complex data into single metrics, making it more accessible for practitioners. However,
409 these ratios can be achieved through different combinations of parameters, which may
410 obscure specific underlying dynamics. As a result, it remains unclear how these ratios are
411 specifically attained and which kinematic and kinetic factors lead to the expression of
412 these spatio-temporal parameters, potentially masking critical information. Finally, this
413 study focused exclusively on the acceleration phase of the sprint, limiting the
414 generalizability of the findings to other segments of the race, where different technical
415 components and physiological demands may come into play.

Conclusion

PARA accelerated more slowly than OLY, with a velocity deficit that increased across the first 20 m. Spatio-temporal signatures, however, did not differ on average between PARA and OLY. Nonetheless, PARA covered a wider range of sprinting styles, including a ground-based, step-length-dominant style not seen in the olympic cohort and showed sex-specific shifts in sprinting style. Classification group explained part of the variance in spatio-temporal signature, but athletes within the same classification group differed more from each other than the classification groups differed from one another. These findings extend observations from elite olympic- to para-athletes. Together, these findings support the notion that no uniform spatio-temporal signature seems to exist. Instead, athletes appear to adopt individual combinations of spatio-temporal parameters within general “bandwidths” that classification group-specific impairments may narrow but not determine.

For practitioners this holds novel information, as interpreting IPC group-specific features as guidelines to design training is probably oversimplistic and it may be more valuable to identify individual spatio-temporal signatures, using biomechanical assessments and referencing training approaches to an athlete’s own profile rather than group-based norms. The dual-axis plot used in this study provides a practical tool for assessing athlete's spatio-temporal signature and could serve as a basis for guiding the design of tailored training interventions. The data and approach presented in this study can thus help researchers and coaches to identify critical inter-individual differences and represent a step towards more individualized, data-driven coaching strategies in para-athletics.

List of abbreviations

BTT	Bilateral transtibial amputation

CI	Cognitive Impairment
95% CI	95% Confidence Interval
CT	Contact time
CV	Coefficient of variation
FI	Functional impairment
FT	Flight time
IPC	International Paralympic Committee
LAVEG	Laser velocity guard
OLY	Olympic athletes
PARA	Para-athletes
PERMANOVA	Permutational multivariate analysis of variance
SF	Step frequency
SL	Step length
UTF	Unilateral transfemoral amputation
UTR	Unilateral transradial amputation
UTT	Unilateral transtibial amputation
VI	Vision impairment
v_{20}	Instantaneous velocity at 20 m

Declarations

Ethics approval

The study was approved by the ethics committee of the German Sport University Cologne (Nr. 212/2022) and was performed in accordance with the ethical standards of the Declaration of Helsinki.

Consent to participate

Written informed consent was obtained from all participants.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contribution

JK: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Software, Visualization, Writing - original draft, Writing - review & editing.

TO: Conceptualization, Methodology, Investigation, Visualization, Writing - review & editing. BB: Conceptualization, Supervision, Writing - review & editing. RR: Conceptualization, Supervision, Writing - review & editing. TA: Conceptualization, Supervision, Writing - review & editing. ThA Supervision, Writing - review & editing. MS: Conceptualization, Methodology, Supervision, Writing - review & editing.

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Figures

Figure 1

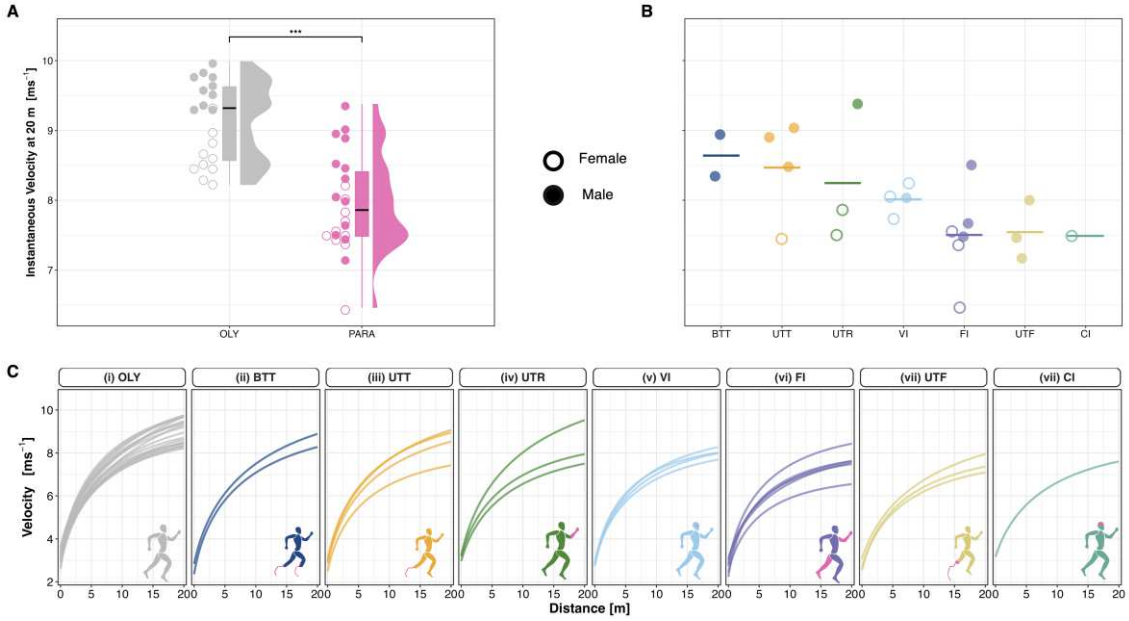
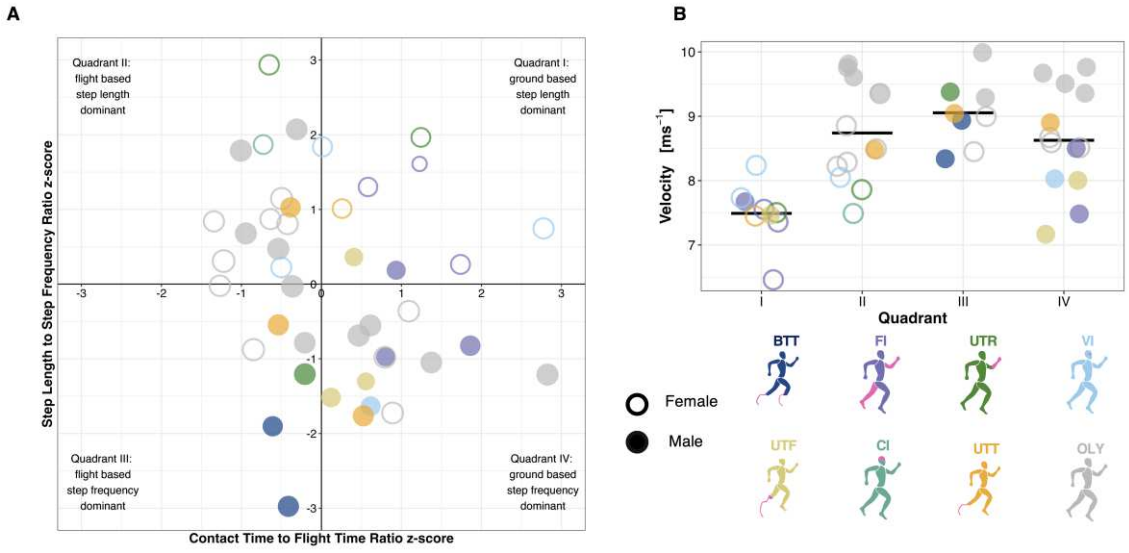
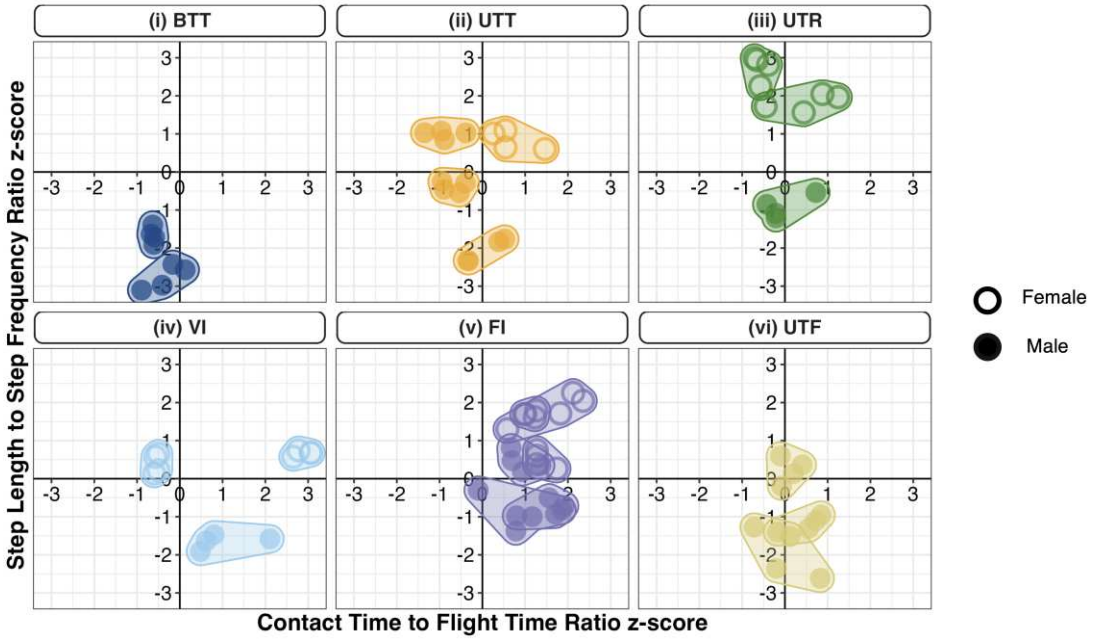


Figure 2



603 Figure 3



604

605 **Tables**

606 Table 1. Acceleration Performance.

		Velocity (m·s⁻¹)				Difference vs. OLY			Time (s)				Difference vs. OLY		
Cohort	n	5 m	10 m	15 m	20 m	Δ	p	g [95% CI]	5 m	10 m	15 m	20 m	Δ	p	g [95% CI]
OLY	20	6.44 ± 0.35	7.83 ± 0.43	8.53 ± 0.51	9.13 ± 0.57	–	–	–	1.00 ± 0.05	1.70 ± 0.08	2.31 ± 0.12	2.88 ± 0.15	–	–	–
Male	10	6.74 ± 0.20	8.20 ± 0.22	8.99 ± 0.21	9.61 ± 0.23	–	–	–	0.96 ± 0.02	1.63 ± 0.04	2.21 ± 0.06	2.75 ± 0.07	–	–	–
Female	10	6.15 ± 0.14	7.47 ± 0.21	8.08 ± 0.20	8.64 ± 0.34	–	–	–	1.04 ± 0.02	1.77 ± 0.03	2.41 ± 0.05	3.01 ± 0.06	–	–	–
PARA	23	5.84 ± 0.39	6.94 ± 0.51	7.59 ± 0.62	7.96 ± 0.69	12.8%	< .001	-1.79 [-2.50, -1.09]	1.12 ± 0.07	1.90 ± 0.12	2.59 ± 0.17	3.24 ± 0.23	12.3%	< .001	1.79 [1.08, 2.49]
Male	13	5.94 ± 0.44	7.10 ± 0.56	7.83 ± 0.65	8.26 ± 0.69	14.1%	< .001	-2.39 [-3.47, -1.32]	1.11 ± 0.07	1.87 ± 0.13	2.54 ± 0.18	3.17 ± 0.24	15.4%	< .001	2.22 [1.18, 3.25]
Female	10	5.71 ± 0.29	6.73 ± 0.38	7.28 ± 0.45	7.57 ± 0.48	12.4%	< .001	-2.46 [-3.62, -1.30]	1.13 ± 0.06	1.93 ± 0.11	2.65 ± 0.15	3.32 ± 0.19	10.2%	< .001	2.06 [0.98, 3.13]
Group															
BTT	2	6.00 ± 0.24	7.30 ± 0.33	8.07 ± 0.40	8.64 ± 0.42	5.3%	.013	-0.83 [-2.25, 0.59]	1.12 ± 0.06	1.88 ± 0.09	2.52 ± 0.12	3.12 ± 0.15	8.5%	.002	1.57 [0.09, 3.05]
UTT	4	6.08 ± 0.41	7.28 ± 0.57	8.04 ± 0.66	8.47 ± 0.72	7.2%	< .001	-1.07 [-2.15, 0.01]	1.08 ± 0.08	1.83 ± 0.14	2.48 ± 0.19	3.09 ± 0.25	7.3%	.002	1.21 [0.11, 2.31]
UTF	3	5.35 ± 0.24	6.44 ± 0.35	7.10 ± 0.36	7.54 ± 0.42	17.4%	< .001	-2.73 [-4.16, -1.29]	1.19 ± 0.06	2.03 ± 0.08	2.77 ± 0.12	3.46 ± 0.15	20.1%	< .001	3.71 [2.09, 5.34]
UTR	3	6.08 ± 0.53	7.23 ± 0.73	7.86 ± 0.94	8.25 ± 1.00	9.6%	.025	-1.36 [-2.60, -0.12]	1.07 ± 0.08	1.82 ± 0.15	2.49 ± 0.22	3.11 ± 0.29	8.1%	.105	1.34 [0.10, 2.57]
VI	4	5.97 ± 0.13	7.04 ± 0.21	7.67 ± 0.22	8.01 ± 0.21	12.2%	.001	-2.00 [-3.19, -0.81]	1.09 ± 0.03	1.85 ± 0.04	2.54 ± 0.07	3.17 ± 0.08	10.2%	.015	1.98 [0.79, 3.17]
FI	6	5.68 ± 0.38	6.68 ± 0.45	7.24 ± 0.60	7.50 ± 0.65	17.8%	< .001	-2.66 [-3.82, -1.50]	1.14 ± 0.07	1.95 ± 0.13	2.67 ± 0.18	3.34 ± 0.24	16.1%	< .001	2.60 [1.45, 3.75]
CI	1	5.67	6.69	7.21	7.49	17.9%	.032	–	1.11	1.93	2.64	3.32	15.3%	.123	–

607 Table 2. Spatio-temporal parameters of the accleration phase.

		Mean Step length (m)				Mean Step frequency (Hz)				Mean Contact time (s)				Mean Flight time (s)			
Cohort	n	M ± SD	Δ	p	g [95% CI]	M ± SD	Δ	p	g [95% CI]	M ± SD	Δ	p	g [95% CI]	M ± SD	Δ	p	g [95% CI]
OLY	20	1.57 ± 0.14	–	–	–	4.39 ± 0.16	–	–	–	0.140 ± 0.007	–	–	–	0.089 ± 0.008	–	–	–
Male	10	1.67 ± 0.11	–	–	–	4.45 ± 0.18	–	–	–	0.139 ± 0.007	–	–	–	0.087 ± 0.008	–	–	–
Female	10	1.47 ± 0.11	–	–	–	4.34 ± 0.11	–	–	–	0.141 ± 0.008	–	–	–	0.091 ± 0.007	–	–	–
PARA	23	1.49 ± 0.10	-4.9%	.025	-0.62 [-1.22, -0.02]	4.21 ± 0.29	-4.2%	.005	-0.76 [-1.38, -0.15]	0.150 ± 0.013	+7.1%	.003	0.90 [0.28, 1.52]	0.090 ± 0.008	+0.7%	.717	0.07 [-0.52, 0.66]
Male	13	1.49 ± 0.08	-10.9%	< .001	-1.89 [-2.87, -0.91]	4.33 ± 0.26	-2.8%	.215	-0.52 [-1.33, 0.29]	0.145 ± 0.013	+4.2%	.212	0.52 [-0.29, 1.33]	0.088 ± 0.006	+1.0%	.775	0.12 [-0.68, 0.91]
Female	10	1.50 ± 0.13	+1.9%	.604	0.23 [-0.62, 1.07]	4.06 ± 0.26	-6.4%	.005	-1.35 [-2.30, -0.40]	0.156 ± 0.011	+11.0%	.002	1.52 [0.54, 2.49]	0.092 ± 0.010	+0.9%	.827	0.09 [-0.75, 0.94]
Group																	
BTT	2	1.42 ± 0.05	-9.6%	.053	-1.04 [-2.47, 0.40]	4.68 ± 0.20	+6.5%	.589	1.74 [0.24, 3.24]	0.131 ± 0.004	-6.4%	.860	-1.19 [-2.64, 0.25]	0.084 ± 0.004	-5.5%	.983	-0.61 [-2.03, 0.80]
UTT	4	1.50 ± 0.06	-4.5%	.343	-0.50 [-1.55, 0.55]	4.33 ± 0.23	-1.5%	.751	-0.37 [-1.41, 0.68]	0.140 ± 0.012	+0.3%	.993	0.05 [-0.98, 1.09]	0.092 ± 0.002	+3.3%	.731	0.38 [-0.66, 1.43]
UTF	3	1.44 ± 0.06	-8.3%	.034	-0.91 [-2.11, 0.29]	4.02 ± 0.21	-8.5%	.002	-2.20 [-3.55, -0.86]	0.156 ± 0.014	+11.4%	.026	1.87 [0.57, 3.17]	0.095 ± 0.004	+7.1%	.212	0.80 [-0.39, 2.00]
UTR	3	1.65 ± 0.05	+5.0%	.477	0.55 [-0.63, 1.73]	3.99 ± 0.33	-9.3%	.014	-2.18 [-3.52, -0.84]	0.154 ± 0.014	+9.9%	.170	1.64 [0.37, 2.91]	0.099 ± 0.008	+10.8%	.210	1.18 [-0.05, 2.40]
VI	4	1.51 ± 0.10	-4.3%	.954	-0.47 [-1.52, 0.58]	4.29 ± 0.36	-2.5%	.956	-0.53 [-1.58, 0.52]	0.152 ± 0.018	+8.5%	.241	1.20 [0.10, 2.29]	0.083 ± 0.010	-6.3%	.311	-0.66 [-1.72, 0.39]
FI	6	1.45 ± 0.12	-7.5%	.104	-0.83 [-1.74, 0.09]	4.16 ± 0.14	-5.3%	.053	-1.49 [-2.46, -0.51]	0.157 ± 0.005	+11.9%	.004	2.34 [1.23, 3.44]	0.085 ± 0.005	-4.7%	.608	-0.55 [-1.45, 0.35]
CI	1	1.50	-4.6%	1.000	–	4.03	-8.3%	.557	–	0.149	+6.1%	.953	–	0.101	+13.2%	.640	–

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List of figure captions

Figure 1. A) Raincloud plot showing instantaneous velocity at 20 m for olympic- and para-athletes (male: filled marker; female: hollow marker). B) Instantaneous velocity at 20 m for each para-athlete, grouped by classification group. The mean value for each classification group is shown as black rectangle. C) Velocity traces for each athlete from 0-20 m (grouped by olympic athlete and classification groups for para-athletes). Olympic athletes and classification group is displayed by color and sex is presented as filled (male) and hollow markers (female). Note. OLY = olympic athletes; PARA = all para-athletes pooled; BTT = bilateral transtibial amputation; UTT = unilateral transtibial amputation; UTR = unilateral transradial amputation, VI = visual impairment; FI = functional impairment; UTF = unilateral transfemoral amputation; CI = cognitive impairment

Figure *2*. A) Dual-Axis graphs indicating spatio-temporal signature for each athlete (horizontal axis = ratio of contact time to flight time; vertical axis = ratio of step length to step frequency). Ratios were normalized to artificial/biological leg length and standardized as z-scores relative to the olympic athlete data from this sample and separately by sex. Instantaneous velocity at 20 m is reflected as marker size. B) Instantaneous velocity at 20 m for each athlete, grouped by quadrants of the dual-axis plot. Classification group is displayed by color and sex is presented as filled (male) and hollow markers (female).

Note. OLY = olympic sprinter; BTT = bilateral transtibial amputation; UTT = unilateral transtibial amputation; UTR = unilateral transradial amputation, VI = visual impairment; FI = functional impairment; UTF = unilateral transfemoral amputation; CI = cognitive impairment.

Figure 3. Convex hulls spanning four trials for 21 para-athletes, grouped by classification group. Classification group is displayed by color and sex is presented as filled (male) and hollow markers (female). Note. BTT = bilateral transtibial amputation; UTT = unilateral transtibial amputation; UTR = unilateral transradial amputation, VI = visual impairment; FI = functional impairment; UTF = unilateral transfemoral amputation; CI = cognitive impairment.

List of table legends

Table 1. Values are M ± SD. Δ = percentage difference from olympic athletes at 20 m. p-values and Hedges' g refer to the comparison of each row against olympic athletes at 20 m; p-values for cohort rows and classification groups are adjusted for sex, and those for the seven classification groups are additionally Dunnett-adjusted for multiple comparisons against the control group. Sex rows are compared against the same-sex olympic subgroup (unadjusted single contrasts). Hedges' g is reported with its 95% confidence interval. Dashes indicate quantities for which no comparisons were computed.
Note. OLY = olympic athletes; PARA = all para-athletes pooled; BTT = bilateral transtibial amputation; UTT = unilateral transtibial amputation; UTF = unilateral transfemoral amputation; UTR = unilateral transradial amputation; VI = vision impairment; FI = functional impairment; CI = cognitive impairment.

Table 2. Values are M ± SD, averaged across all steps of the acceleration phase (0–20 m) of each athlete's analysed trial. Δ = signed percentage difference from olympic athletes; positive values indicate a larger value than OLY. p-values for cohort rows and IPC groups are adjusted for sex, and those for the seven

658 classification groups are additionally Dunnett-adjusted for multiple comparisons
659 against the olympic athletes. Sex rows are compared against the same-sex olympic
660 subgroup (unadjusted single contrasts). Hedges' g is reported with its 95%
661 confidence interval. Dashes indicate that no comparisons were computed.
662 Note. OLY = olympic athletes; PARA = all para-athletes pooled; BTT = bilateral
663 transtibial amputation; UTT = unilateral transtibial amputation; UTF = unilateral
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666