Journal of Sports Sciences

ISSN: 0264-0414 (Print) 1466-447X (Online) Journal homepage: www.tandfonline.com/journals/rjsp20

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To cite this article: Laura Dawson, Stuart A. McErlain-Naylor, Gavin Devereux & Marco Beato (10 Sep 2025): Interunit reliability of STATSports APEX global navigation satellite system and accelerometer-derived metrics during shuttle run protocols of varied distances and change of direction frequency, Journal of Sports Sciences, DOI: 10.1080/02640414.2025.2555554

To link to this article: https://doi.org/10.1080/02640414.2025.2555554

JOURNAL OF SPORTS SCIENCES
https://doi.org/10.1080/02640414.2025.2555554

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Interunit reliability of STATSports APEX global navigation satellite system and accelerometer-derived metrics during shuttle run protocols of varied distances and change of direction frequency

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ABSTRACT

This study assessed the interunit reliability of Global Navigation Satellite System (GNSS) and accelerometer-derived metrics during high-intensity shuttle run protocols. Thirty-three female football players completed three shuttle run protocols (2 × 20 m, 4 × 10 m, and 8 × 5 m). Two STATSports Apex Pro units (18 Hz GPS and 10 Hz Augmented GNSS; 100 Hz accelerometer) recorded accelerometer-derived (fatigue index [FI] and dynamic stress load [DSL]) and GNSS-derived (total distance, acceleration and deceleration counts, maximum speed, speed intensity and total metabolic power) metrics. Interunit reliability and agreement were evaluated using intraclass correlation coefficients (ICC), and Bland-Altman analysis. GNSS metrics demonstrated *good* to *excellent* reliability (ICC: 0.845–0.999), whereas accelerometer-derived metrics, FI (ICC: 0.495) and DSL (ICC: 0.484), showed *poor* reliability. Percentage bias in accelerometer-derived metrics ranged from −1.76% (FI) to −7.72% (DSL), and in GNSS metrics ranged from −0.1% (speed intensity) to 5.83% (decelerations), limits of agreement increased in protocols with more directional changes. Overall, the interunit reliability of accelerometer-derived metrics should be considered cautiously, especially in short, high-intensity activity. ICC and Bland-Altman analysis confirmed close agreement for the GNSS metrics but highlighted variability in accelerometer-derived metrics. Practitioners are advised to avoid interchanging units between athletes and sessions to maintain reliability.

ARTICLE HISTORY
Received 14 March 2025
Accepted 25 August 2025

KEYWORDS
Global positioning system; GPS; GNSS; training load; load monitoring

Introduction

Athlete monitoring in team sports is widely recognised and typically implemented using Global Navigation Satellite System (GNSS) trunk-mounted player tracking systems (Armitage et al., 2024; Dawson, McErlain-Naylor, et al., 2024; Theodoropoulos et al., 2020). Recent studies have highlighted that practitioners believe these systems are key to informing load monitoring, training prescription, and supporting rehabilitation (Akenhead & Nassis, 2016; Dawson, McErlain-Naylor, et al., 2024; West et al., 2019). In the last two decades it has been applied in a range of sporting disciplines to allow practitioners to objectively monitor load and performance in training and competition, delivering essential data on player movements, facilitating detailed analysis and informing decision-making. Consequently, interunit reliability is essential for making accurate comparisons both within and between athletes and teams over time (Dawson, McErlain-Naylor, et al., 2024; Mejuto et al., 2024).

Previous findings have shown that the interunit reliability of GNSS units, and similar Global Positioning System (GPS) units, can be high, but also will be dependent on the model specifications (Beato & de Keijzer, 2019; Chahal et al., 2022; Dennison et al., 2025; Scott et al., 2016). For example, a review of the validity and reliability of 1, 5, 10 and 15 Hz GPS units highlighted 1 and 5 Hz had limitations when reporting distance, while 10 and 15 Hz were the most valid and reliable between units (Scott et al., 2016). The limitations in GPS systems have since led to the introduction of GNSS-enabled devices, in which the units can simultaneously track multiple-satellite systems (e.g., GPS, GLONASS, Galileo, and BeiDou) (Beato, Coratella, et al., 2018), offering increased capability compared to GPS (Jackson et al., 2018). For example, commercially available STATSports Apex Pro units have increased to 18 Hz GPS with augmented 10 Hz GNSS and a 952 Hz accelerometer. Subsequent interunit reliability studies have evaluated the 10 Hz model against the 18 Hz, in 400 m jogging,

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/02640414.2025.2555554

a 128.5 m team sport circuit, a 20 m jog, and a 20 m sprint at maximum speed, finding no meaningful difference in total distance and peak speed metrics (Beato, Coratella, et al., 2018). Jackson et al. (2018) compared 10 Hz GPS against 10 Hz GNSS in team sports movements and reported GNSS devices to have a lower horizontal dilution of precision, suggesting higher accuracy compared to GPS of the same frequency, while also finding no significant interunit differences for distance and velocity metrics in the GNSS model.

Some studies have since begun to evaluate the inter-unit reliability of the GNSS-enabled systems. Chahal et al. (2022) found overall *poor* inter-unit reliability for total distance (ICC = 0.131, 95%CI = −0.024–0.556) and peak speed (ICC = 0.323, 95%CI = 0.101–0.736) in 45 m straight-line sprints using Catapult S5 OptimEye. The inter-unit reliability of STATSports Apex Pro and Catapult Vector S7 GNSS metrics have also been assessed by towing them on a sprint sled during a 40-minute team sport movement protocol, twice a week for 4-weeks (Crang et al., 2022). This study found *trivial* to *small* differences between different manufacturers' measurement of total distance; however, there were noticeable differences in velocity, moderate- and high-speed running distances, and acceleration and deceleration metrics with *small* to *very large* effect sizes. This was attributed in part to the differing processing between manufacturers. Brosnan et al. (2022) also compared GPSports EVO 10 Hz, GPSports HPU 5 Hz, and Catapult S5 10 Hz GPS units finding decreased interunit reliability in 5 Hz models, and *good* to *poor* agreement in acceleration indices (mean difference 2.21–32.74%). These studies commented that most metrics should not be compared between manufacturers, particularly regarding acceleration indices. Therefore, some current factors affecting measurement consistency include manufacturer specifications (Beato & de Keijzer, 2019; Chahal et al., 2022; Thornton et al., 2019), Global Positioning System (GPS) vs. GNSS usage, *i.e.* increased satellite availability (Jackson et al., 2018), and data collection frequency (Beato, Coratella, et al., 2018; Scott et al., 2016). This highlights the need to evaluate individual manufacturer and model specifications for GNSS player tracking systems and the accelerometer-derived metrics (Beato, Devereux, et al., 2018; Brosnan et al., 2022; Thornton et al., 2019).

While GNSS has been repeatedly evaluated across all major manufacturers (Luteberget & Gilgien, 2020), the research into accelerometer metrics is predominantly limited to Catapult devices and the PlayerLoad^{TM} metric (Dawson, Beato, et al., 2024). Accelerometer-derived metrics are proposed to reflect biomechanical load independently of translational movement, unlike distance and speed metrics, which primarily measure linear movement, accelerometer-derived potentially offer a method for quantifying load during the high-magnitude accelerations, decelerations, and impacts that are integral to the physical demands of sports (Delaney et al., 2018). Rapid changes in velocity and direction can place mechanical load upon the body, and by monitoring the accumulation of such loads, coaches can better assess the true intensity of an athlete's exertion, helping to optimise training, prevent overtraining, and reduce injury risk (Colby et al., 2014; Fessi et al., 2018). Metrics derived from the accumulation of accelerations, such as Catapult's PlayerLoad^{TM} and STATSports' Dynamic Stress Load (DSL) are offered with the aim of providing a more comprehensive reflection of the intensity of whole-body loading. Previous research regarding the implementation of accelerometers for load monitoring have highlighted that the technology requires standardisation (Dawson, McErlain-Naylor, et al., 2024). Currently, standardisation across all technology manufacturers may be unrealistic due to differences in filtering, processing, and proprietary algorithms, and outputs should be applied with caution due to extraneous harness movement, noise associated with the typical trunk-mounted location of the unit, and type of activity being monitored (Dawson, Beato, et al., 2024; Edwards et al., 2019; McLean et al., 2018). However, if the accelerometer metric outputs can be evaluated and quantified, the understanding and application of these metrics could be improved. Previous evaluations of PlayerLoad^{TM} intraunit test–retest reliability range from *poor* to *good* coefficients of variation and *low to very high* correlation (Boyd et al., 2011; Clubb et al., 2022; Dawson, Beato, et al., 2024). Interunit reliability of RealTrack WIMU Pro resultant accelerations and Catapult PlayerLoad^{TM} have also reported good CV% in static, hydraulic shaker, and sport-specific tests (Boyd et al., 2011; Gómez-Carmona et al., 2020). However, a study focussed on the interunit reliability of STATSports metrics in a YoYo intermittent test and highlighted a potential issue regarding accelerometer-derived 'DSL' (Beato et al., 2023). This was the only accelerometer-derived metric assessed in this study, reporting an intraclass correlation coefficient of 0.681 (0.510–0.801) interpreted as *questionable*.

For applied practitioners, there is increasing reliance on GNSS and accelerometer-derived metrics when monitoring athlete load, particularly during the high-intensity, intermittent activity that often reflects both training and match play. Mara et al. (2017) found 81–84% of high-speed runs (3.4–5.3 m·s^{-1}) are performed over distances less than 10 m in female professional football, 79% of which were repeated efforts (i.e., 2 or more efforts within 20 seconds). Additionally, Dalen et al. (2021) identified a significant decrease in relative high speed (< 5.5 m·s^{-1}) running distance in small-sided games compared to match play, suggesting short shuttle distances would be reflective of small-sided games that are a commonly used training tool (Sarmento et al., 2018). These studies support the importance of assessing this technology over short-distance shuttle runs. Previous research has highlighted limitations in GNSS accuracy and between-unit agreement when measuring short-distance sprint efforts, particularly those under 15 metres (Beato & de Keijzer, 2019). However, the interunit reliability of these accelerometer-based metrics remains underexplored, especially in scenarios involving frequent changes of direction. Therefore, the current study was designed to assess the interunit reliability of both GNSS and accelerometer-derived metrics over short shuttle distances with multiple changes of direction to assess movement patterns that closely reflect some of the physical demands observed in competitive team sport environments.

Given the importance of manufacturer-specific testing for GNSS metrics, and relative lack of evidence for accelerometer-derived metrics generally, and specifically for devices other than Catapult and the PlayerLoad™ metric, this study aims to assess the interunit reliability of GNSS and accelerometer-derived metrics from STATSports Apex Pro GNSS units during shuttle run efforts over 20 m, 10 m, and 5 m distances.

Methodology

Participants

Thirty-three female football players (age 25.3 ± 4.9 years; height 1.654 ± 0.081 m; body mass 67.8 ± 7.9 kg) participated in this study. Participant inclusion required the absence of serious musculoskeletal injury in the 6 months preceding testing. The study protocol received ethical approval from the University of Suffolk Research Ethics Committee (RETH20/074). Written informed consent and physical activity readiness questionnaire were obtained from all participants prior to testing. Sample size was calculated a priori using G*Power (version 3.1.9.6). To detect a 0.52 effect size with 80% power, at a significance level of $\alpha = 0.05$, for reliability comparison between two devices, a minimum sample of 32 participants was required. This is aligned with previous research evaluating interunit reliability via ICC (Bujang & Baharum, 2017).

Experimental procedure

The GNSS (STATSports Apex Pro, v4.24) units (18 Hz GPS and 10 Hz Augmented GNSS with 100 Hz tri-axial accelerometers) provided information on GNSS and accelerometer-derived metrics. All units were turned on 10 minutes before the protocol began, to ensure all units were of working condition and to ensure connection to satellites prior to data collection (Fessi et al., 2018). Two units were placed in two separate STATSports vests and aligned horizontally on each participant's back between the scapula separate from each other (Figure 1), to allow exposure of the GNSS units for satellite connectivity as well as comfort for the participants (Beato & de Keijzer, 2019). Horizontal dilution of precision for all units was 0.4, and the mean number of connected satellites across all units was 19.7 ± 1.2.

All participants performed a standardised warm-up prior to beginning the protocol. This consisted of static and dynamic stretches and was the typical warm-up led by coaches prior to a standard training session. Distances of 20 m, 10 m and 5 m were measured via a trundle wheel and set up using cones as markers

Figure 1. STATSports Apex Pro GNSS unit alignment in harnesses on the upper-back for assessment of interunit reliability.

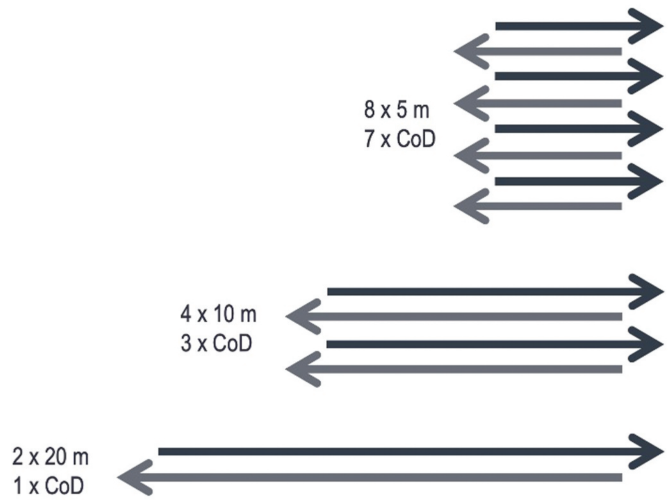

Figure 2. 2 x 20 m, 4 x 10 m and 8 x 5 m repeated sprint change of direction (CoD) protocols (matched for 40 m per set).

(Figure 2). Participants were required to run 2 × 20 m, 4 × 10 m and 8 × 5 m from a standing still position to the required cone marker. Participants completed 5 sets of each shuttle run protocol (covering a total 200 m per protocol), with 30 s rest between sets and 2 min rest between protocols. The protocols were completed in a randomised order for each participant. Each shuttle distance was demonstrated to familiarise participants with the protocols and number of turns. Participants were instructed to ensure their whole body passed the cone before changing direction so that the GNSS unit was covering the required distance, and to remain still after completing a set, to limit any additional distance covered. All data were collected outdoors on a grass football pitch in an open area and in good meteoritical conditions, to reduce the risk of satellite disruption (Beato & de Keijzer, 2019).

Data analysis

STATSports metrics were processed using manufacturer proprietary software Sonra (Version 2.0, STATSports, Northern Ireland), the protocols for each participant were cropped into 'drills' using satellite time recorded at the start and end of each set, then nine performance metrics were exported from each drill. GNSS-derived metrics were total distance (m), acceleration and deceleration counts (number of events that exceed ±3 $m{\cdot}s^{-2}$), maximum speed ($m{\cdot}s^{-1}$; peak speed recorded), speed intensity (AU; manufacturer propriety value based on convexly weighted sum of instantaneous speed multiplied by the time between successive speed values *i.e.* 0.1 s), and total metabolic power (W; estimated metabolic power based on the equation of diPrampero et al. (2005); 'estimated energy cost per metre multiplied by speed'). Accelerometer-derived metrics were DSL (AU; the weighted sum of acceleration events ≥2 g; Beato & Drust, 2021; Dawson, Beato, et al., 2024) and Fatigue Index (FI) (AU; $FI_i = DSL_i/Speed_i^k$, where '*k*' is a weighting factor; Beato & Drust, 2021). A summary of the means and standard deviations for these variables in each protocol is presented in Table 3 (supplementary).

Statistical analysis

Interunit reliability for each metric was assessed using intraclass correlation coefficient $^{(1,1)}$ (ICC) for each individual protocol and for all protocols combined, interpreted as 1 > 0.9 = *excellent*; 0.9 > 0.75 = *good;* 0.75 > 0.5 = *moderate;* 0.5 ≥ *poor* (Koo & Li, 2016). One-way ANOVAs with post-hoc Bonferroni comparison were used to assess the effect of shuttle run protocol on the metrics reported. Bland-Altman analysis was conducted to assess the agreement between the devices for each metric. For each metric, the bias, standard deviation (SD) of the differences, and 95% confidence intervals (CI) for both the bias and LoA were calculated and the plots were constructed to visually inspect the bias (mean difference) and the 95% limits of agreement (LoA). The analysis was conducted separately for three repeated shuttle run protocols (2 × 20 m, 4 × 10 m, and 8 × 5 m) to assess the device agreement under different testing conditions. The bias and LoA values have also been reported as a percentage of the mean for each metric, providing context where values are higher for some metrics than others (Giavarina, 2015). When compared between protocols, metrics that resulted in a minimal bias (< 5% of mean) and narrow LoA (< 10% of mean) were considered to show good agreement, while metrics with greater bias or wider LoA were interpreted as less consistent between devices. Data were analysed using SPSS Statistics, (version 29, IBM Corp., NY, USA), and the significance was set at $p < 0.05$.

Results

Across all protocols, the GNSS metrics demonstrated *good* to *excellent* interunit reliability (ICC between 0.845 and 0.999) (Table 1). Accelerometer-derived metrics Fatigue Index (ICC: 0.495) and DSL (ICC: 0.484) showed *poor* interunit reliability overall and in each protocol, with the 95% CI ranging from *poor* to *moderate* (Table 1).

Bland-Altman analyses (Figure 3a, 3b; Table 2) reported minimal bias (< 0.2%) for total distance (–0.34 m [2 × 20 m] to 0.12 m [8 × 5 m]), with LoA broadening slightly in the 8 × 5 m protocol (LoA [percentage of mean]: –5.99 m [–3.3%] to 6.24 m [3.5%]) compared to 2 × 20 m (LoA: −3.78 m [–1.8%] to 3.09 m [1.5%]). Maximum speed was also measured with high reliability across all protocols, with bias near zero (< 0.6%) and consistently narrow LoA (e.g., –0.20 [–3.7%] to 0.17 m·s^{-1} [3.1%] in 2 × 20 m). Similarly, the total metabolic power and speed intensity exhibited close agreement between units across all protocols, with LoA > 5%.

In contrast, accelerations and decelerations count bias was between 1.4% and 5.8% of the mean for all except decelerations in the 2 × 20 m protocol (–0.9%). The LoA are considerably wider than other GNSS-derived metrics, e.g.,, in the 8 × 5 m protocol (accelerations LoA: –8.80 [–66.8%] to 8.32 [63.1%], decelerations LoA: –9.48 [–67.4%] to 7.84 [55.7%]). It should also be highlighted that while overall ICCs were *good* for these metrics, the 95% CI ranged from *moderate* to *good* (Table 1).

Both accelerometer-derived metrics followed a similar pattern to each other; fatigue index bias was between −1.8% for the 2 × 20 m protocol to −6.4% for the 8 × 5 m protocol, and DSL bias was −3.1% for the 4 × 10 m protocol to −7.7% for the 8 × 5 m protocol, both also with very high LoA. Fatigue index LoA ranged from 146% to 168% away from the mean for each protocol, while similarly, the DSL LoA ranged from 157% to 180% of the mean, indicating reduced reliability for accelerometer-derived metrics during frequent directional changes compared to GNSS metrics across all protocols (Figure 3a, 3b; Table 2).

Discussion

The aim of this study was to assess the interunit reliability of GNSS and accelerometer-derived metrics from STATSports Apex Pro units across three repeated shuttle run protocols that increased in change of direction frequency (2 × 20 m, 4 × 10 m, and 8 × 5 m). Although previous research has largely focused on the validity and reliability of GNSS-based kinematic metrics such as total distance and speed in linear, continuous activity, few studies have examined how well these systems perform under shuttle run conditions of varied distances and movement patterns. Even fewer have investigated the reliability of accelerometer-derived metrics between units. ICC and Bland-Altman analysis confirmed close agreement for the GNSS metrics but highlighted variability in accelerometer-derived metrics. GNSS metrics demonstrated good to excellent reliability (ICC: 0.845–0.999 and minimal bias from – 0.1% (speed intensity) to 0.56% (maximum speed), except for accelerations and decelerations counts, which exhibited 0.93–5.83% bias. Whereas accelerometer-derived metrics showed *poor* reliability (ICC: 0.484–0.495), and percentage bias ranging from – 1.76% (FI) to – 7.72% (DSL). Overall,

Table 1. Intraclass correlation coefficients with 95% confidence intervals [95%CI] for interunit reliability of STATSports Apex metrics across 3 shuttle run protocols and all protocols combined.

	Intraclass Correlation Coefficient [95% CI]			
Metrics	All protocols	2 ×20 m	4 ×10 m	8 ×5 m
Speed intensity	0.998 [0.996–0.998]	0.997 [0.993–0.998]	0.994 [0.987–0.997]	0.994 [0.988–0.997]
Total distance	0.996 [0.994–0.997]	0.997 [0.994–0.999]	0.995 [0.990–0.997]	0.994 [0.987–0.997]
Total metabolic power	0.994 [0.991–0.996]	0.996 [0.993–0.998]	0.991 [0.982–0.996]	0.991 [0.982–0.996]
Maximum speed	0.993 [0.989–0.995]	0.978 [0.955–0.989]	0.941 [0.884–0.970]	0.971 [0.942–0.986]
Decelerations	0.917 [0.878–0.944]	0.866 [0.744–0.932]	0.861 [0.737–0.929]	0.889 [0.787–0.943]
Accelerations	0.845 [0.777–0.893]	0.692 [0.457–0.837]	0.865 [0.744–0.931]	0.789 [0.615–0.890]
Fatigue index	0.495 [0.329–0.631]	0.393 [0.057–0.649]	0.438 [0.117–0.676]	0.544 [0.251–0.745]
Dynamic stress load	0.484 [0.317–0.622]	0.445 [0.119–0.684]	0.455 [0.138–0.688]	0.539 [0.245–0.742]

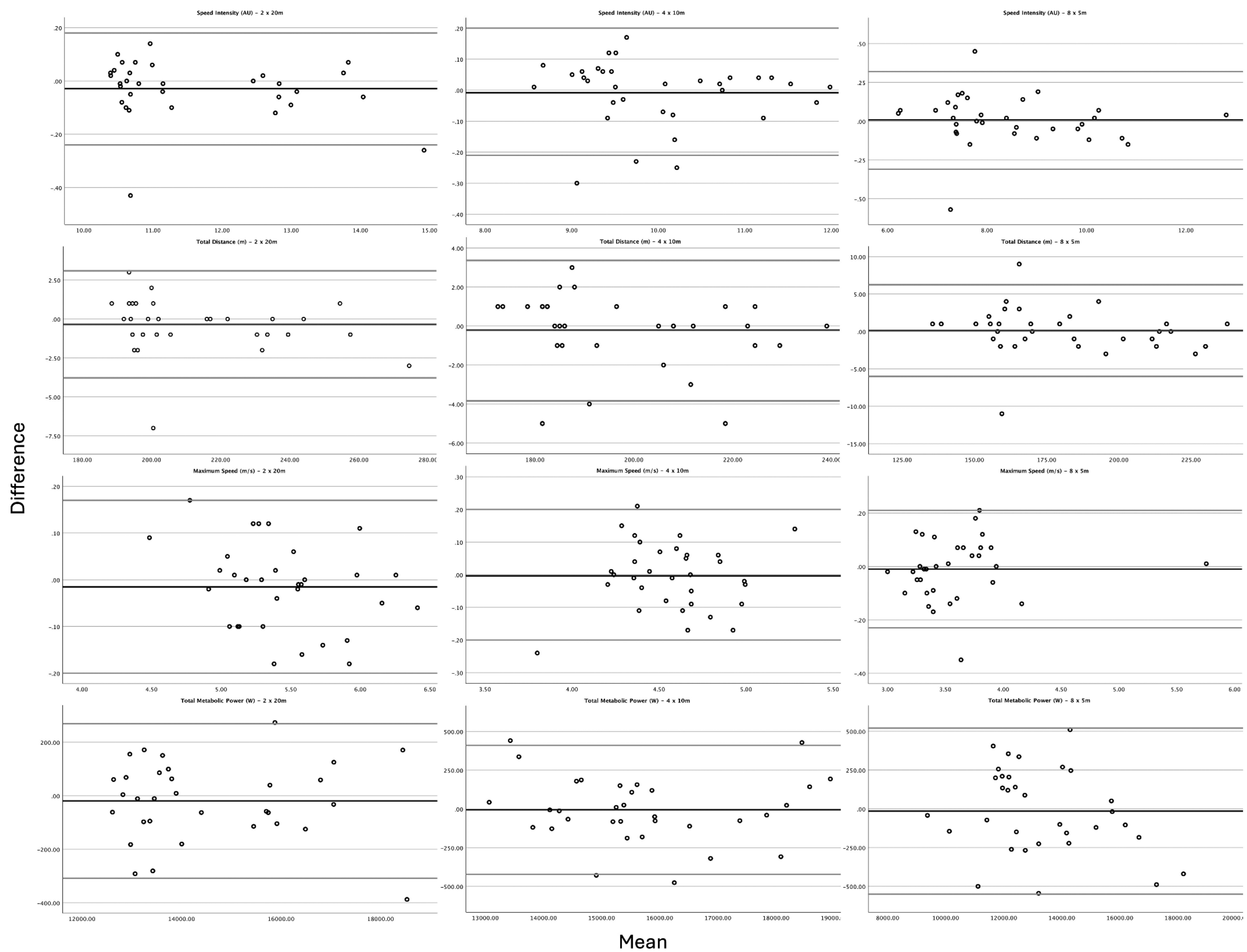

Figure 3a. Bland-Altman plots for speed intensity, total distance, total metabolic power, and maximum speed metrics in each 2x20 m, 4x10 m and 8x5 m sprint protocol. Dark grey lines represent mean (bias), light grey lines represent 95%CI upper and lower bounds.

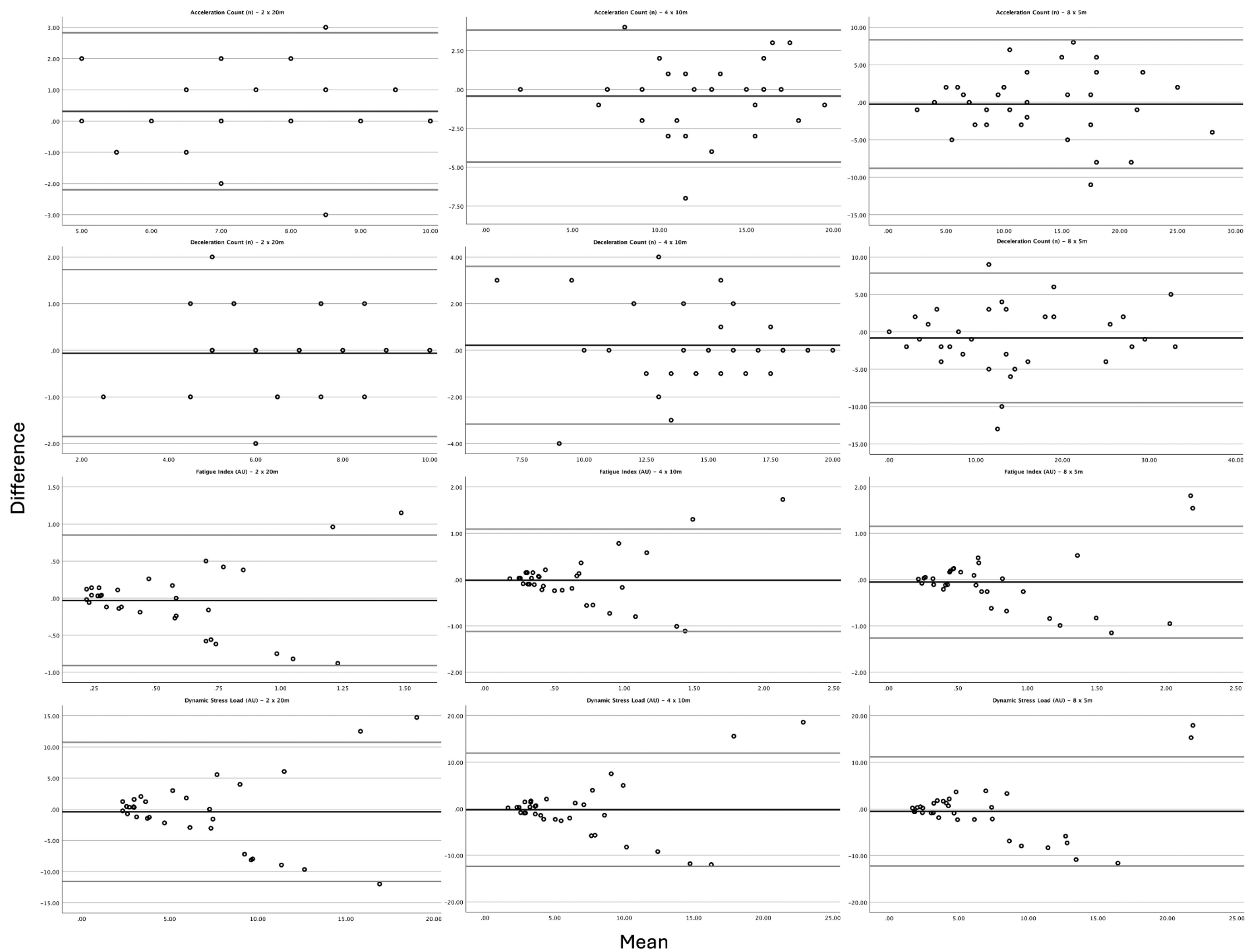

Figure 3b. Bland-Altman plots for acceleration count, deceleration count, fatigue index, and dynamic stress load metrics in each 2x20 m, 4x10 m and 8x5 m sprint protocol. Dark grey lines represent mean (bias), light grey lines represent 95%CI upper and lower bounds.

Table 2. *Bland-Altman analysis results for STATSports apex Pro metrics across three shuttle run protocols (2 ×20 m*, 4 × 10 m, and 8 × 5 m). Bias with 95% confidence intervals (CI), limits of agreement (LoA) with 95% CI, and the percentage of mean for each value are reported for each metric.

Metrics		Bias [95% CI]	Percentage of Mean (%)	Lower LoA [95% CI]	Percentage of Mean (%)	Upper LoA [95% CI]	Percentage of Mean (%)
Speed intensity (AU)	2x20	−0.03 [−0.07,0.01]	−0.26	−0.24 [−0.30,−0.17]	−2.07	0.18 [0.12,0.24]	1.55
	4x10	−0.01 [−0.04,0.03]	−0.10	−0.21 [−0.28,−0.15]	−2.10	0.20 [0.14,0.26]	2.00
	8x5	0.01 [−0.05,0.06]	0.12	−0.31 [−0.40,−0.21]	−3.67	0.32 [0.23,0.42]	3.79
Total distance (m)	2x20	−0.34 [−0.95,0.26]	−0.16	−3.78 [−4.83,−2.73]	−1.78	3.09 [2.04,4.14]	1.46
	4x10	−0.21 [−0.84,0.41]	−0.11	−3.83 [−4.93,−2.74]	−1.97	3.41 [2.32,4.51]	1.73
	8x5	0.12 [−0.94,1.19]	0.07	−5.99 [−7.84,−4.15]	−3.33	6.24 [4.39,8.08]	3.47
Total metabolic power (W)	2x20	−19.36 [−70.42,31.69]	−0.13	−308.16 [−396.59, −219.74]	−2.12	269.43 [181.01,357.86]	1.85
	4x10	−6.34 [−78.79,66.10]	−0.04	−422.51 [−546.99, −297.03]	−2.69	409.82 [284.34,535.30]	2.61
	8x5	−15.17 [−108.38,78.04]	−0.11	−550.64 [−712.10, −389.19]	−4.14	520.30 [358.85,681.75]	3.91
Maximum speed (m·s^{-1})	2x20	−0.02 [−0.05,0.02]	−0.18	−0.20 [−0.25,−1.42]	−3.68	0.17 [0.11,0.22]	3.12
	4x10	−0.01 [−0.04,0.03]	−0.44	−0.20 [−0.26,−1.44]	−4.37	0.20 [0.14,0.26]	4.37
	8x5	−0.01 [−0.05,0.03]	−0.56	−0.23 [−0.30,−0.17]	−6.40	0.21 [0.15,0.28]	5.84
Decelerations (count)	2x20	−0.06 [−0.37,0.25]	−0.93	−1.85 [−2.40,−1.30]	−28.74	1.73 [1.18,2.27]	26.87
	4x10	0.21 [−0.38,0.80]	1.44	−3.17 [−4.20,−2.15]	−21.73	3.60 [2.58,4.62]	24.67
	8x5	0.82 [−2.33,0.69]	5.83	−9.48 [−12.09,−6.87]	−67.35	7.84 [5.23,10.45]	55.70
Accelerations (count)	2x20	0.31 [−0.13,0.76]	4.02	−2.20 [−2.97,−1.43]	−28.50	2.82 [2.05,3.59]	36.53
	4x10	−0.42 [−1.16,0.31]	−3.41	−4.67 [−5.95,−3.39]	−37.86	3.82 [2.54,5.10]	30.97
	8x5	−0.24 [−1.73,1.25]	−1.82	−8.80 [−12.09,−6.87]	−66.76	8.32 [5.74,10.90]	63.12
Fatigue index (AU)	2x20	−0.02 [−0.05,0.02]	−1.76	−0.91 [−1.18,−0.64]	−159.87	0.85 [0.58,1.12]	149.33
	4x10	−0.02 [−0.05,0.02]	−3.00	−1.12 [−1.46,−0.79]	−168.11	1.09 [0.76,1.43]	163.61
	8x5	−0.05 [−0.26,0.16]	−6.35	−1.26 [−1.63,−0.90]	−160.08	1.15 [0.79,1.52]	146.10
Dynamic stress load (AU)	2x20	−0.41 [−2.38,1.56]	−6.00	−11.57 [−14.97, −8.15]	−169.46	10.74 [7.32, 14.15]	157.30
	4x10	−0.21 [−2.32,1.91]	−3.07	−12.36 [−16.02, −8.69]	−180.58	11.94 [8.28, 15.61]	174.44
	8x5	−0.53 [−2.57,1.51]	−7.72	−12.22 [−15.76, −8.70]	−178.08	11.17 [7.64, 14.69]	162.78

suggesting interunit reliability of accelerometer-derived metrics during shuttle run activity should be considered cautiously.

Of the GNSS-derived metrics, specifically total distance (ICC: 0.994 to 0.997) and speed intensity, an arbitrary value to indicate intensity from time spent at various speeds (ICC: 0.994 to 0.998), had near-perfect interunit reliability, making them highly reliable for load monitoring and performance tracking in athletes. The Bland-Altman analysis further supports this; for example, total distance demonstrated minimal bias (–0.34 to 0.12 m, < 0.2%) and narrow LoA across protocols, with the narrowest LoA in the 2 × 20 m protocol (−3.78 to 3.09 m, < 1.8%), as did speed intensity (< 0.3% bias, 1.6% to 3.8% LoA), indicating strong agreement between the units. The maximum speed (< 0.6% bias, 3.1% to 6.4% LoA) metric also shows very low bias and consistently narrow LoA across all protocols, alongside *excellent* ICC values. These findings are consistent with previous studies that report high interunit reliability of GNSS units for measuring distance and speed metrics in field-based sports Beato, Devereux, et al. (2018); Beato et al. (2023); Beato and de Keijzer (2019); Chahal et al. (2022), suggesting practitioners can confidently compare between Apex Pro GNSS units for most distance and speed-related GNSS metrics.***

Total metabolic power, another GNSS derived metric, has also demonstrated *excellent* interunit reliability (ICC: 0.991 to 0.996), STATSports use the calculation 'estimated energy cost per metre multiplied by speed' where the *excellent* interunit reliability of speed measures may contribute to this. The Bland-Altman analysis supports this, for example, in the 4 × 10 m protocol, the bias was – 15.17 W (0.04%) and the LoA spanned from −422.51 (2.7%) to 409.82 W (2.6%). Despite the absolute values appearing high, the minimal percentage discrepancies suggest that variations between units are unlikely to impact load monitoring. This is the first study to directly evaluate the interunit reliability of total metabolic power from GNSS units, however both Buchheit et al. (2015) and Stevens et al. (2016) applied similar equations based in the research of diPrampero et al. (2005) to assessed the reliability of the estimated metabolic power ($W·kg^{-1}$) in a soccer-specific circuit and small-sided soccer games, respectively. Buchheit et al. (2015) reported *poor* test-retest reliability using 4 Hz GPS, while Stevens et al. (2016) found an ICC of 0.78 and CV% of 4.4% when comparing intraunit across multiple small-sided games. Since then, an investigation of STATSports GNSS interunit reliability has reported a similarly high ICC value for average metabolic load (ICC: 0.999), supporting the findings of this study. Given the frequent use of metabolic load metrics in assessing sports performance, establishing definitive evidence of its reliability is essential for practitioners (Brochhagen & Hoppe, 2022; Halson, 2014; Miguel et al., 2021). Nonetheless, practitioners should acknowledge potential variations between units and individual measurements in different contexts, despite these findings suggesting very high interunit reliability.

Acceleration count (ICC: 0.692 to 0.865, *moderate* to *good*) showed the lowest interunit reliability among GNSS-derived metrics, followed by deceleration count (ICC: 0.861 to 0.917, *good* to *excellent*). Notably, acceleration interunit reliability was lowest in the 2 × 20 m protocol (ICC: 0.692, *moderate*), while the Bland-Altman analysis indicated a bias of 0.31 counts (4.0%) with wider LoA (−2.20 [28.5%] to 2.82 counts [36.5%]) in the 2 × 20 m protocol, which is considerably higher than other GNSS-derived metrics, suggesting that acceleration measurements may vary more between units in protocols with fewer changes in direction. The lower interunit reliability in both acceleration and deceleration counts in this study can likely be attributed to the limited number of directional changes in this protocol, which may not fully allow the units to register the few acceleration events. This finding contradicts recent research identifying *excellent* ICC values of 0.993 and 0.991 for accelerations and decelerations, respectively (Beato et al., 2023). This was found in interunit comparisons during a YoYo intermittent recovery test, which involves more changes of direction over a longer duration, potentially supporting that the GNSS has difficulty of recognising accelerations and decelerations in shorter duration, high-intensity activities. It should also be noted that protocols involving longer distances allow athletes to reach greater speeds (Harper et al., 2019). Accordingly, participants produced greater speeds in the 2 × 20 m protocol compared to shorter, more frequent shuttle runs (*2 × 20 m*: 5.44 ± 0.45 m/s; *4 × 10 m*: 4.58 ± 0.3 m/s; *8 × 5 m*: 3.59 ± 0.47 m/s). This may contribute to the limitations in interunit reliability and provide potential for underestimation of acceleration and deceleration counts in the slower protocols with increased directional changes (4 × 10 m and 8 × 5 m), as participants may not have reached STATSports acceleration thresholds (i.e., exceeding ±3 m/s^2). Previous research has highlighted the importance of adjusting speed thresholds based on sex (Gualtieri et al., 2023), playing position (Nyman & Spriet, 2022; Silva et al., 2024), and age group (Harkness-Armstrong et al., 2022). This study also supports the suggestion that acceleration thresholds should be adjusted, with consideration to the activity, in order to improve event recognition (Abbott et al., 2018).

In contrast to the GNSS-derived metrics, the accelerometer-derived metrics of fatigue index (ICC: 0.393 to 0.544) and DSL (ICC: 0.445 to 0.539) exhibited *poor* to *moderate* reliability across all protocols. These metrics are calculated using data collected from the internal accelerometer, therefore the lower interunit reliability of both metrics would suggest improvements can be made to the accelerometer hardware. It should also be acknowledged that the sensor fixation in this study is most likely to have an impact on the accelerometer and not the GNSS capabilities. However, these findings are also in agreement with the findings of Beato et al. (2023), in which the interunit reliability of the DSL metric was identified as *questionable* (ICC: 0.681). The low reliability suggests that these metrics should be interpreted cautiously, particularly in short duration, high-intensity activities and when changes of direction are frequent. The inconsistency could also point to the need for refined algorithms to improve these metrics, especially in team sports environments where the sporting demands can reflect these study protocols. However, there is a recognisable similarity between the Bland-Altman plots for fatigue index and DSL, suggesting the potential for error may lie, in the accelerometer hardware, however previously identified issues with extraneous harness movement (Edwards et al., 2019), sensor fixation (Hughes et al., 2021), sensor positioning and muscle damping (Dawson, Beato, et al., 2024; McErlain-Naylor et al., 2021) could also be attributed. Similar to GNSS-derived accelerations and decelerations, DSL applies thresholds, accumulating a total of weighted impacts above 2 g, applying a convex-shaped weighting function. Future studies should focus on refining these algorithms and adjusting thresholds to enhance the reliability and sensitivity of accelerometer-derived metrics. Until further research can clarify the limitations of accelerometer-derived metrics, it is recommended to avoid interchanging units between athletes and sessions to minimise the impact of poor interunit agreement. Intra-participant comparisons within the same session or drill remain a strength of the technology.

Limitations and future directions

GNSS reliability can be influenced by environmental factors such as weather conditions (Gilgen-Ammann et al., 2020), satellite signal quality (Cummins et al., 2013), and stadium interference (Williams & Morgan, 2009); therefore, it was ensured that weather conditions were clear, data was collected in an open environment, not in a stadium. Horizontal dilution of precision for all units was 0.4, where lower values are better and below 1 indicates excellent accuracy (Specht, 2021). These factors should be acknowledged when applying the findings. While most GNSS-derived metrics demonstrated *good* to *excellent* interunit reliability, accelerometer-derived metrics were less reliable. Inconsistencies in metric outputs between units could be attributed to the positioning of the units, i.e., orientation of the unit both relative to the other unit, and fixation to the participant's body. Finally, the thresholds included in certain metrics such as accelerations and decelerations ($\pm 3\ m\cdot s^{-2}$), may not be most appropriate for short, shuttle run protocols, such as this study. The use of pre-defined thresholds for metrics like accelerations, decelerations, and sprint speeds have been shown to improve load monitoring by tailoring intensity (e.g., classifying low, moderate, and high speeds as < 4, 4–5.5, and $> 5.5\ m\cdot s^{-1}$, respectively); however, this should not impact the assessment of inter-unit agreement in this study as all thresholds remained consistent. In the future, developing methods to personalise these thresholds could enhance metric capability to distinguish different protocol intensities, particularly in scenarios with frequent changes of direction. Future research should expand on these findings by assessing GNSS inter-unit reliability across a wider range of training, competition, and environmental conditions. Additionally, standardising data collection and analysis protocols would improve the consistency and comparability of GNSS-derived metrics in both research and applied settings.

Practical application

This study confirms that GNSS-derived metrics such as all distance and speed-related metrics, and total metabolic power and can be used confidently by practitioners for athlete monitoring in team sports. While acceleration and deceleration count metrics demonstrated mostly *good* to *excellent* interunit reliability (except 2×20 m accelerations), counts may be underestimated, particularly in drills with frequent directional changes. Developing methods to adjust these thresholds could enhance event recognition and therefore improve reliability and load monitoring accuracy. Accelerometer-derived metrics, including Fatigue Index and Dynamic Stress Load, showed *poor* reliability, particularly in short, high-intensity shuttle run drills, and should be interpreted with caution. Practitioners are advised to avoid interchanging devices between athletes and sessions and instead assign specific units to individuals. These findings support the inter-unit reliability of GNSS-derived metrics while highlighting the need for further developments of accelerometer-derived metrics.

Ethics approval and informed consent

The study was performed in accordance with the Declaration of Helsinki for studies on human subjects. The study protocol received ethical approval from the University of Suffolk Research Ethics Committee (RETH20/074). Written informed consent and physical activity readiness questionnaire was obtained from all participants prior to testing. Participant inclusion required the absence of serious musculoskeletal injury in the 6 months preceding testing.

Acknowledgments

We would like to thank all the study participants for their time and effort in participating in this study.

Disclosure statement

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

Funding

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

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References

Abbott, W., Brickley, G., Smeeton, N. J., & Mills, S. (2018). Individualizing acceleration in English Premier league Academy soccer players. *The Journal of Strength and Conditioning Research*, *32*(12), 3503–3510. https://doi.org/10.1519/JSC.0000000000002875

Akenhead, R., & Nassis, G. P. (2016). Training load and player monitoring in high-level football: Current practice and perceptions. *International Journal of Sports Physiology and Performance*, *11*(5), 587–593. https://doi.org/10.1123/ijspp.2015-0331

Armitage, M., McErlain-Naylor, S. A., Devereux, G., Beato, M., Iga, J., McRobert, A., Roberts, S., & Buckthorpe, M. (2024). On-field rehabilitation in football: Current practice and perceptions. A survey of the English Premier League and Football League. *Science and Medicine in Football*, *9*(2), 1–10. https://doi.org/10.1080/24733938.2024.2313529

Beato, M., Coratella, G., Stiff, A., & Iacono, A. D. (2018). The validity and between-unit variability of GNSS units (STATSports Apex 10 and 18 Hz) for measuring distance and peak speed in team sports. *Frontiers in Physiology*, *9*. https://doi.org/10.3389/fphys.2018.01288

Beato, M., & de Keijzer, K. (2019). The inter-unit and inter-model reliability of GNSS STATSports Apex and Viper units in measuring peak speed over 5, 10, 15, 20 and 30 meters. *Biology of Sport*, *36*(4), 317–321. https://doi.org/10.5114/biolsport.2019.88754

Beato, M., Devereux, G., & Stiff, A. (2018). Validity and reliability of global positioning system units (STATSports viper) for measuring distance and peak speed in sports. *The Journal of Strength and Conditioning Research*, *32*(10), 2831–2837. https://doi.org/10.1519/JSC.0000000000002778

Beato, M., & Drust, B. (2021). Acceleration intensity is an important contributor to the external and internal training load demands of repeated sprint exercises in soccer players. *Research in Sports Medicine*, *29*(1), 67–76. https://doi.org/10.1080/15438627.2020.1743993

Beato, M., Wren, C., & de Keijzer, K. L. (2023). The inter-unit reliability of global navigation satellite systems Apex (STATSports) metrics during a standardized intermittent running activity. *The Journal of Strength and Conditioning Research*, *Epub ahead*. *38*(2), e49–e55. https://doi.org/10.1519/JSC.0000000000004613

Boyd, L. J., Ball, K., & Aughey, R. J. (2011). The reliability of MinimaxX accelerometers for measuring physical activity in Australian football. *International Journal of Sports Physiology and Performance*, *6*(3), 311–321. https://doi.org/10.1123/ijspp.6.3.311

Brochhagen, J., & Hoppe, M. W. (2022). Metabolic power in team and racquet sports: A systematic review with best-evidence synthesis. *Sports Medicine - Open*, *8*(1), 133. https://doi.org/10.1186/s40798-022-00525-9

Brosnan, R. J., Watson, G., Stuart, W., Twentyman, C., Kitic, C. M., & Schmidt, M. (2022). The validity, reliability, and agreement of global positioning system units-can we compare research and applied data? *The Journal of Strength and Conditioning Research*, *36*(12), 3330–3338. https://doi.org/10.1519/JSC.0000000000004139

Buchheit, M., Manouvrier, C., Cassirame, J., & Morin, J.-B. (2015). Monitoring locomotor load in soccer: Is metabolic power, powerful? *International Journal of Sports Medicine*, *36*(14), 1149–1155. https://doi.org/10.1055/s-0035-1555927

Bujang, M. A., & Baharum, N. (2017). A simplified guide to determination of sample size requirements for estimating the value of intraclass correlation coefficient: A review. *Archives of Orofacial Science*, *12*(1), 1–1.

Chahal, A. K., Lim, J. Z., Pan, J.-W., & Kong, P. W. (2022). Inter-unit consistency and validity of 10-Hz GNSS units in straight-line sprint running. *Sensors*, *22*(5), 1888. https://doi.org/10.3390/s22051888

Clubb, J., Towlson, C., Barrett, S., & Gonçalves, B. (2022). Measurement properties of external training load variables during standardised games in soccer: Implications for training and monitoring strategies. *PLOS ONE*, *17*(1), e0262274. https://doi.org/10.1371/journal.pone.0262274

Colby, M. J., Dawson, B., Heasman, J., Rogalski, B., & Gabbett, T. J. (2014). Accelerometer and GPS-derived running loads and injury risk in elite Australian footballers. *The Journal of Strength and Conditioning Research*, *28*(8), 2244–2252. https://doi.org/10.1519/JSC.0000000000000362

Crang, Z. L., Duthie, G., Cole, M. H., Weakley, J., Hewitt, A., & Johnston, R. D. (2022). The inter-device reliability of global navigation satellite systems during team sport movement across multiple days. *Journal of Science & Medicine in Sport*, *25*(4), 340–344. https://doi.org/10.1016/j.jsams.2021.11.044

Cummins, C., Orr, R., O'Connor, H., & West, C. (2013). Global positioning systems (GPS) and microtechnology sensors in team sports: A systematic review. *Sports Medicine*, *43*(10), 1025–1042. https://doi.org/10.1007/s40279-013-0069-2

Dalen, T., Sandmæl, S., Stevens, T. G. A., Hjelde, G. H., Kjøsnes, T. N., & Wisløff, U. (2021). Differences in acceleration and high-intensity activities between small-sided games and peak periods of official matches in elite soccer players. *The Journal of Strength and Conditioning Research*, *35*(7), 2018–2024. https://doi.org/10.1519/JSC.0000000000003081

Dawson, L., Beato, M., Devereux, G., & McErlain-Naylor, S. A. (2024). A review of the validity and reliability of accelerometer-based metrics from upper back-mounted GNSS player tracking systems for athlete training load monitoring. *The Journal of Strength and Conditioning Research*, *38*(8), e459–e474. https://doi.org/10.1519/JSC.0000000000004835

Dawson, L., McErlain-Naylor, S. A., Devereux, G., & Beato, M. (2024). Practitioner usage, applications, and understanding of wearable GPS and accelerometer technology in team sports. *The Journal of Strength and Conditioning Research*, *38*(7), e373–e382. https://doi.org/10.1519/JSC.0000000000004781

Delaney, J. A., Cummins, C. J., Thornton, H. R., & Duthie, G. M. (2018). Importance, reliability, and usefulness of acceleration measures in team Sports. *The Journal of Strength and Conditioning Research*, *32*(12), 3485–3493. https://doi.org/10.1519/JSC.0000000000001849

Dennison, L., Duthie, G. M., Ehrmann, F., & Psarakis, M. A. (2025). Concurrent validity and interunit reliability of 25-Hz GNSS units for profiling sprinting performance. *The Journal of Strength and Conditioning Research*, *39*(1), 107–114. https://doi.org/10.1519/JSC.0000000000004961

diPrampero, P. E., Fusi, S., Sepulcri, L., Morin, J. B., Belli, A., & Antonutto, G. (2005). Sprint running: A new energetic approach. *Journal of Experimental Biology*, *208*(14), 2809–2816. https://doi.org/10.1242/jeb.01700

Edwards, S., White, S., Humphreys, S., Robergs, R., & O'Dwyer, N. (2019). Caution using data from triaxial accelerometers housed in player tracking units during running. *Journal of Sports Sciences*, *37*(7), 810–818. https://doi.org/10.1080/02640414.2018.1527675

Fessi, M. S., Farhat, F., Dellal, A., Malone, J. J., & Moalla, W. (2018). Straight-line and change-of-direction intermittent running in professional soccer players. *International Journal of Sports Physiology and Performance*, *13*(5), 562–567. https://doi.org/10.1123/ijspp.2016-0318

Giavarina, D. (2015). Understanding Bland Altman analysis. *Biochemia Medica*, *25*(2), 141–151. https://doi.org/10.11613/BM.2015.015

Gilgen-Ammann, R., Schweizer, T., & Wyss, T. (2020). Accuracy of distance recordings in eight positioning-enabled sport watches: Instrument validation study. *JMIR mHealth and Uhealth*, *8*(6), e17118. https://doi.org/10.2196/17118

Gómez-Carmona, C. D., Bastida-Castillo, A., Ibáñez, S. J., Pino-Ortega, J., & Cortis, C. (2020). Accelerometry as a method for external workload monitoring in invasion team sports. A systematic review. *PLOS ONE*, *15*(8), e0236643. https://doi.org/10.1371/journal.pone.0236643

Gualtieri, A., Rampinini, E., Dello Iacono, A., & Beato, M. (2023). High-speed running and sprinting in professional adult soccer: Current thresholds definition, match demands and training strategies. A systematic review. *Frontiers in Sports and Active Living*, *5*. https://doi.org/10.3389/fspor.2023.1116293

Halson, S. L. (2014). Monitoring training load to understand fatigue in athletes. *Sports Medicine*, *44*(S2), 139–147. https://doi.org/10.1007/s40279-014-0253-z

Harkness-Armstrong, A., Till, K., Datson, N., & Emmonds, S. (2022). Determining age-specific velocity thresholds for elite youth female soccer players. *Science and Medicine in Football*, *6*(5), 581–588. https://doi.org/10.1080/24733938.2021.1991585

Harper, D. J., 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*, *49*(12), 1923–1947. https://doi.org/10.1007/s40279-019-01170-1

Hughes, G. T. G., Camomilla, V., Vanwanseele, B., Harrison, A. J., Fong, D. T. P., & Bradshaw, E. J. (2021). Novel technology in sports biomechanics: Some words of caution. *Sports Biomechanics*, *23*(4), 1–9. https://doi.org/10.1080/14763141.2020.1869453

Jackson, B. M., Polglaze, T., Dawson, B., King, T., & Peeling, P. (2018). Comparing Global positioning System and Global navigation satellite System measures of team-Sport movements. *International Journal of Sports Physiology and Performance*, *13*(8), 1005–1010. https://doi.org/10.1123/ijspp.2017-0529

Koo, T. K., & Li, M. Y. (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

Luteberget, L. S., & Gilgien, M. (2020). Validation methods for global and local positioning-based athlete monitoring systems in team sports: A scoping review. *BMJ Open Sport and Exercise Medicine*, *6*(1), e000794. https://doi.org/10.1136/bmjsem-2020-000794

Mara, J. K., Thompson, K. G., Pumpa, K. L., & Morgan, S. (2017). Quantifying the high-speed running and sprinting profiles of elite female soccer players during competitive matches using an optical player tracking system. *The Journal of Strength and Conditioning Research*, *31*(6), 1500–1508. https://doi.org/10.1519/JSC.0000000000001629

McErlain-Naylor, S. A., King, M. A., & Allen, S. J. (2021). Surface acceleration transmission during drop landings in humans. *Journal of Biomechanics*, *118*, 110269. https://doi.org/10.1016/j.jbiomech.2021.110269

McLean, B. D., Cummins, C., Conlan, G., Duthie, G., & Coutts, A. J. (2018). The fit matters: Influence of accelerometer fitting and training drill demands on load measures in Rugby league players. *International Journal of Sports Physiology and Performance*, *13*(8), 1083–1089. https://doi.org/10.1123/ijspp.2017-0729

Mejuto, G., Gómez-Carmona, C. D., Gracia, J., & Rico-González, M. (2024). Surfing time-motion characteristics possible to gain using global navigation satellite systems: A systematic review. *Sensors*, *24*(11), 3455. https://doi.org/10.3390/s24113455

Miguel, M., Oliveira, R., Loureiro, N., García-Rubio, J., & Ibáñez, S. J. (2021). Load measures in training/match monitoring in soccer: A systematic review. *International Journal of Environmental Research and Public Health*, *18*(5), 2721. https://doi.org/10.3390/ijerph18052721

Nyman, D. L. E., & Spriet, L. L. (2022). External training demands in women's varsity rugby union players quantified by wearable microtechnology with individualized speed thresholds. *The Journal of Strength and Conditioning Research*, *36*(11), 3151–3158. https://doi.org/10.1519/JSC.0000000000004084

Sarmento, H., Clemente, F. M., Harper, L. D., Costa, I. T. D., Owen, A., & Figueiredo, A. J. (2018). Small sided games in soccer - a systematic review. *International Journal of Performance Analysis in Sport*, *18*(5), 693–749. https://doi.org/10.1080/24748668.2018.1517288

Scott, M. T. U., Scott, T. J., & Kelly, V. G. (2016). The validity and reliability of global positioning systems in team sport. *The Journal of Strength and Conditioning Research*, *30*(5), 1470–1490. https://doi.org/10.1519/JSC.0000000000001221

Silva, H., Nakamura, F. Y., Loturco, I., Ribeiro, J., & Marcelino, R. (2024). Analyzing soccer match sprint distances: A comparison of GPS-based absolute and relative thresholds. *Biology of Sport*, *41*(3), 223–230. https://doi.org/10.5114/biolsport.2024.133663

Specht, M. (2021). Experimental studies on the relationship between HDOP and position error in the GPS system. *Metrology and Measurement Systems*, 17–36. https://doi.org/10.24425/mms.2022.138549

Stevens, T. G. A., De Ruiter, C. J., Beek, P. J., & Savelsbergh, G. J. P. (2016). Validity and reliability of 6-a-side small-sided game locomotor performance in assessing physical fitness in football players. *Journal of Sports Sciences*, *34*(6), 527–534. https://doi.org/10.1080/02640414.2015.1116709

Theodoropoulos, J. S., Bettle, J., & Kosy, J. D. (2020). The use of GPS and inertial devices for player monitoring in team sports: A review of current and future applications. *Orthopedic Reviews*, *12*(1). https://doi.org/10.4081/or.2020.7863

Thornton, H. R., Nelson, A. R., Delaney, J. A., Serpiello, F. R., & Duthie, G. M. (2019). Interunit reliability and effect of data-processing methods of global positioning systems. *International Journal of Sports Physiology and Performance*, *14*(4), 432–438. https://doi.org/10.1123/ijspp.2018-0273

West, S. W., Williams, S., Kemp, S. P. T., Cross, M. J., & Stokes, K. A. (2019). Athlete monitoring in rugby union: Is heterogeneity in data capture holding us back? *Sports*, *7*(5), 98. https://doi.org/10.3390/sports7050098

Williams, M., & Morgan, S. (2009). Horizontal positioning error derived from stationary GPS units: A function of time and proximity to building infrastructure. *International Journal of Performance Analysis in Sport*, *9*(2), 275–280. https://doi.org/10.1080/24748668.2009.11868483