



Article

Between-Session Reliability of GPS Technology for Quantifying Linear and Curvilinear Base-Running Performance

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Abstract

The purpose of this study was to quantify the between-session reliability of time, velocity, and distance measures over 54.7 m straight-line and home-to-second base sprints (curvilinear), using global positioning satellite (GPS) technology. Twelve trained male high school baseball position players attended four sessions: one familiarization session and three identical testing sessions, separated by at least two days, each consisting of two linear and two curvilinear trials. There was no statistically significant evidence ($p < 0.05$) of systematic change in any of the variables between sessions, with the majority of the mean percent changes ranging from -2.7 to 2.5% , and only four between-session comparisons greater than 2% (-6.2 to 3.4%). In terms of absolute consistency, no measure exceeded a coefficient of variation (CV) of 10% , with the majority (93%) of the CVs under 5% . With regard to relative consistency, 66% of the measures had intraclass correlation coefficients (ICCs) greater than 0.74 , ranging from 0.76 to 0.98 . Comparison of smallest worthwhile change (SWC) values with CV-derived typical error indicated that several key time- and speed-based metrics were sensitive to meaningful performance changes, with error estimates that were comparable to or smaller than SWC. In contrast, event-timed typical errors (e.g., time to peak speed) were substantially greater than the SWC, indicating limited sensitivity for detecting small performance changes. The non-significant changes in the mean, low CVs, and high ICCs, for the most part, over repeated testing occasions, indicate acceptable between-session reliability for many of the procedures and GPS-derived variables examined in this study. Practitioners should prioritize linear time at 41.1 m and 54.7 m and velocity at 27.4 m and 41.1 m for return-to-play and short-term performance tracking. For curvilinear running, peak speed before first base, peak speed before second base and after first base, and speed at 41.1 m are the most suitable monitoring metrics based on the results. Specifically, speed at 41.1 m should be considered for return-to-play and short-term performance tracking, while peak speed before first base and peak speed before second base and after first base may be used cautiously when larger performance changes are expected.

Keywords: velocity-time-distance measures; high school; baseball



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1. Introduction

In the baseball offensive phase, the base runner needs to hit the ball and run between bases to reach home plate to score runs to win games. This base running involves both linear sprints from home to first base, as well as curvilinear sprints when running multiple bases. As such, it would seem important to measure and improve players' linear and curvilinear base-running abilities [1]. In terms of assessing base-running performance, timing gate technology is the most common technology used to evaluate linear and curvilinear sprint ability [2–4]. In terms of home-to-first-base (linear) sprinting, timing gates would seem ideally suited to provide accurate and reliable information, though much of the research in this area has not reported reliability statistics [4]. However, timing gate accuracy during multiple-base curvilinear sprinting could be affected by gate placement and misalignment with the base runner's trajectory, as the technology requires the runner to pass through timing gates approximately one metre apart. These factors may alter the base runner's natural curvilinear sprinting and influence sprint mechanics. Researchers examining the kinematic characteristics of unconstrained curvilinear sprinting in baseball are limited, as is the research quantifying the reliability of the measures used to describe this motion. These observations provide the focus of this paper.

It needs to be noted that, though the use of timing gates is popular, the technology provides a very limited kinematic understanding of base running [2,5]. For example, home to first base is reported as a single time and speed measure, which offers little insight into sprint kinematics [4,6,7]. Furthermore, timing gates are rarely used in curvilinear sprints because of the varying paths athletes take to run multiple bases. A more sensitive technology is needed to provide a more nuanced understanding of linear and particular curvilinear base-running characteristics. One device that may provide a more granular understanding of base running is GPS technology. Between-session reliability of GPS-derived base-running variables is critical for their applied use in base-running performance, as practitioners require stable measures to monitor training adaptations, detect meaningful changes in performance, inform talent development decisions, and support return-to-play assessment following injury. In the absence of adequate between-session reliability, changes in base-running metrics cannot be confidently attributed to true performance change rather than measurement error (biological and technological variability), limiting their practical utility. To the author's knowledge, GPS has been used to evaluate and compare baseball athletes' external load during pitching [8–10], but its application to base running, especially curvilinear paths, has not been explored. Therefore, the purpose of this study was to determine the between-session reliability of 10 Hz GPS technology for quantifying distance-time-velocity measures over linear and curvilinear paths of a similar distance—home to second base (54.7 m). Reliable quantification of base-running metrics will enable the evaluation and comparison of athletes, facilitating a more targeted approach to exercise prescription.

2. Materials and Methods

2.1. Experimental Approach to the Problem

A cross-sectional, repeated measures design was used for comparative analysis of linear and curvilinear sprint data. A wearable sensor collecting GPS data (VX Sport, Wellington, New Zealand), at a sampling rate of 10 Hz, was worn by participants in a vest worn over their training attire. A familiarization session was conducted before data collection to ensure a consistent technique. Trained male high school baseball players with an average of 2.9 years of structured strength and 11.8 years of baseball training were recruited, given that baseball players represent a performance-relevant population for examining curvilinear base-running mechanics. Participants were tested on a turf baseball

field, wearing baseball cleats and completing a standardized dynamic warm-up before each session. Data was collected over three testing occasions, separated by at least two days. Researchers compared performance between the three consecutive sessions (i.e., sessions one and two and sessions two and three) and determined the reliability of the GPS technology for base-running linear assessments, using change in the mean, intraclass correlation coefficients (ICCs), and coefficient of variations (CVs).

2.2. Participants

Twelve trained male high school baseball position players (age = 14.67 ± 0.89 years, height = 169.29 ± 9.03 cm, weight = 63.98 ± 10.29 kg) volunteered to participate in this study. Baseball players trained at a high school baseball academy in Puerto Rico and had an average of 11.8 years of baseball experience. Participants were required to be healthy and free of injury at the time of testing. Before participating in this study, all participants were provided with an information sheet, and their written assent and the consent of a legal guardian were required before participating in the study. Participants were notified that they were free to withdraw from the study at any time. This research was approved by the Auckland University of Technology Ethics Committee (24/69).

2.3. Procedures

Testing sessions were conducted with a minimum of two days and a maximum of twenty-five days ($n = 2$ participants) apart, at the same time of the day, under the same experimental conditions, and tested in the same order (i.e., linear running first and then curvilinear running). The interval between sessions ranged from two to twenty-five days because of unforeseen scheduling challenges at the baseball academy. No injuries or physical overload were reported that would confound the results. Each testing session lasted approximately 25 min. Participants performed a standardized warm-up at the beginning of the session (Table 1), which consisted of lower-body dynamic movements.

Table 1. Warm-up exercises prior to baseball base running.

Exercises	Distance	Reps
Linear running	13.7 m	2
Running hip out	13.7 m	2
Butt kicks	13.7 m	2
Skipping	13.7 m	2
Lateral shuffles	13.7 m	2
Quick forwards and backwards	13.7 m	2
Walking lunges	13.7 m	1
Linear sprints	13.7 m	3
Curvilinear sprints	13.7 m	3

After warming up, the participants performed the straight-line sprint test, decelerating after passing through the final cones at the 54.7 m mark. Participants started from a lead-off stance with their feet positioned shoulder-width apart, a position used for stealing bases. After ten minutes of rest, the participants performed the home-to-second base sprint test by running from home to the second base (54.7 m), rounding the first base, and decelerating after touching the second base. The starting position for the home-to-second base sprint test was a lead-off position for stealing a base, with the right foot placed in the middle of home base and the left foot positioned shoulder-width apart. Participants were instructed to run

at maximum speed through the second base, decelerate, and stand still for five seconds to have a zero-velocity point, indicating the trial ended. Two trials for the straight-line sprint and home-to-second base tests were collected and averaged for further analysis. Three minutes of passive rest between trials and ten minutes between tests were provided to limit fatigue effects, performance fluctuations and decrease the risk of injury [2,3]. Participants used the same plastic cleats for all trials, and all trials were performed on the same formal turf-surface baseball diamond. Instructions were to complete the test as fast as possible.

2.4. Equipment

GPS wearable technology (VX Sport, Wellington, New Zealand) was affixed posteriorly between the scapulae in a specialized polyester and elastane vest supplied by the manufacturer (see Figure 1). Prior to each testing session, the researcher powered on the GPS device approximately 5 to 10 min before the first activity to allow for satellite signal recognition [11] and calibration by placing the GPS unit for 30 s at the start of each test, the end of each test, and the first base. The VX Sport GPS device collected data at 10 Hz. The data was uploaded to the VX Sports software 7.2.0.11, trimmed, and split for analysis. VX Sport GPS units (4–10 Hz) have been found reliable for measuring total distance and speed metrics in recreational and female collegiate athletes ($CV < 5\%$) [12,13]. In youth soccer players, the technology has been reported to have high reliability for peak linear velocity ($ICC = 0.97$) but low rank order reliability for high-speed running distance ($ICC = -0.31$). However, despite this low reliability, the difference in total distance compared with other GPS technologies remains small [14].

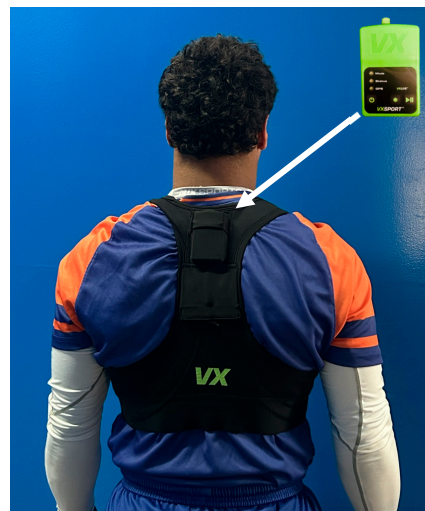


Figure 1. GPS device and location.

To calibrate the trial GPS data so that the stationary location points of home, first base, and second base could be used as event/location markers, a common reference point was used. As the accuracy of GPS for absolute position is subject to drift over time, each trial was location normalized. This was achieved by taking the sample prior to velocity increase (starting sample for the trial) and subtracting the latitude and longitude difference from the known ‘Google Maps’ home base location. By doing this, not only could reference points for first and second base also be used from Google Maps, but the location plots could be overlaid over the Google Maps satellite view. This process was also implemented for start-of-day calibrations collected by leaving the GPS sensor resting on each of the bases for 30 s to 1 min. As drift would occur throughout the day, each trial was location-normalized to the start of that day’s calibration file. This did not allow for clean plotting of trials across

days, but ensured the first and second base event triggers were accurate, independent of Google Maps.

2.5. Data Analysis

Calibration data were processed by reading trial-specific calibration periods, extracting positional coordinates (home, first, second base, and start/end calibration points), and calculating means and standard deviations for each calibration location, which were saved for future reference. GPS samples associated with each event (home, first, second base, and start/end calibration points) were taken as the GPS location sample closest to the reference point for the associated event. Each trial was processed iteratively, using time-series GPS and velocity data. The start of the trial was identified as the first sample in which the athlete's velocity exceeded $0.152 \text{ m} \times \text{s}^{-1}$, and the corresponding end of the trial was identified using the 30 s calibration point at the end of each test. The five preceding samples were averaged to establish the trial's starting location. All GPS coordinates were then aligned to a predefined "home" reference point (from Google Maps) to normalize spatial orientation across trials. GPS samples were then matched to predefined base locations (first and second base). Two midpoints were calculated for each trial: (1) the midpoint between home and first base and (2) the midpoint between first and second base. Raw velocity data were smoothed using a zero-phase 4th-order Butterworth low-pass filter with a cutoff frequency of 0.5 Hz to reduce noise and improve signal clarity. Velocity data were numerically integrated to determine cumulative distance. Specific distance thresholds were used to extract split times. Figure 2 presents a representative speed–time profile of a home-to-second-base sprint, illustrating the key phases of base running and the derivation of the analyzed variables. The profile highlights the initial acceleration phase (H–A), peak speed before first base (B), speed modulation when approaching and rounding first base (C–D), and the subsequent increase to peak speed before second base (E–F), followed by passing through the second base (G). The curvilinear segments (C1–C4) illustrate how distance- and time-based variables were derived across successive base-running intervals, providing context for the observed reliability outcomes, particularly for peak, minimum, and segment-specific measures. Distance was calculated by multiplying speed and time data. For each trial, temporal markers and velocity metrics were stored and used for analysis. Specifically, the following variables (Table 2) were included in the final analysis, some of which are depicted in Figure 2. Also, the experimental design is illustrated in Figure 3.

Table 2. Description of curvilinear variables.

Curvilinear Variables	Shorthand	Description
Time to 13.7 m	A	Time from home plate to the first 13.7 m to first base.
Time to reach peak speed before first base	B	Time to maximum speed between the home plate and first base.
Time to first base	C	Time from home plate to first base.
Time to the minimum speed between peaks	D	Time to the minimum speed between the first and second peak.
Time to 41.1 m	E	Time from home plate to the first 41.1 m to second base.
Time to peak speed before second base and after first base	F	Time to maximum speed between the first base and the second base.

Table 2. Cont.

Curvilinear Variables	Shorthand	Description
Time to second base	G	Time from home plate to second base.
Peak speed before first base	B	Maximum speed between the home plate and first base.
Speed at first base	C	Speed when the base runner was passing through first base.
Peak speed before second base and after first base	F	Maximum speed between the first base and the second base.
Speed at second base	G	Speed when the base runner was passing through second base.
Minimum speed between peaks	D	Minimum speed between the first and second peak.

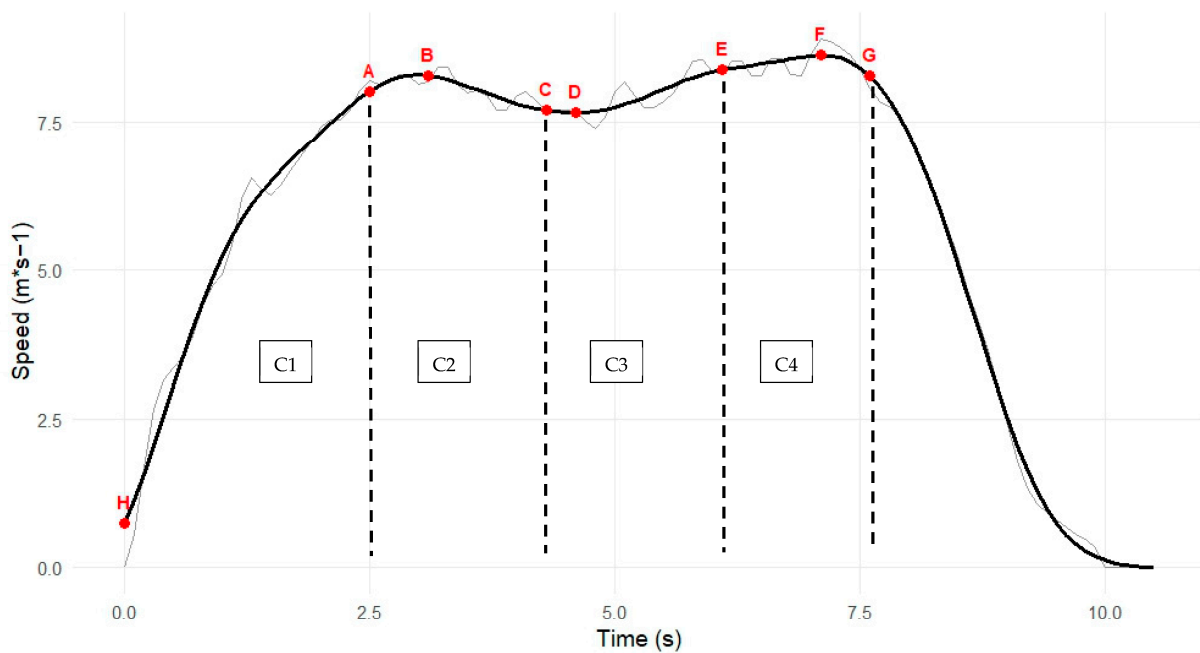


Figure 2. Speed-time profile of a baseball player performing a home-to-second base sprint. Key: H = Home; A = Time at 13.7 m; B = Peak speed before first base; C = Time and speed at first base; D = Minimum speed between bases; E = Time at 41.1 m; F = Peak speed before second base and after first base; G = Time and speed at second base; C1 = Curvilinear segment 1; C2 = Curvilinear segment 2; C3 = Curvilinear segment 3; C4 = Curvilinear segment 4. Grey line = Raw signal; Black thick line = zero-phase 4th-order Butterworth low-pass filter signal; Dashed lines = Curvilinear segments division.

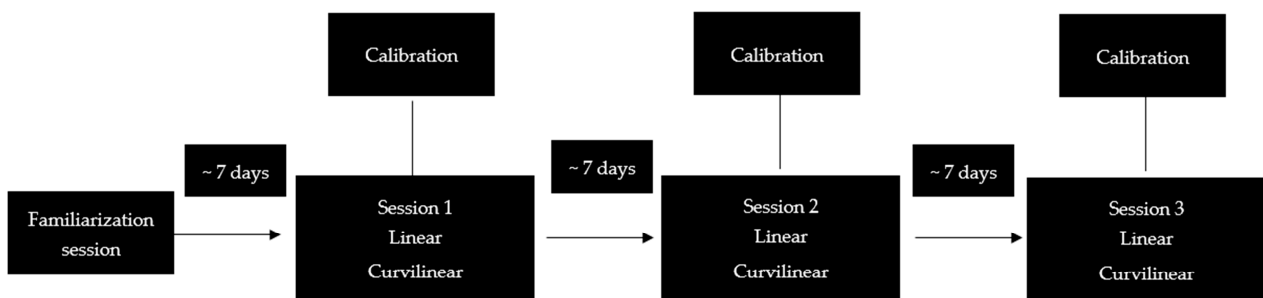


Figure 3. Assessment process overview.

2.6. Statistical Analyses

An a priori sample size estimate was conducted to determine the number of participants required to assess the reliability of key performance metrics using intraclass correlation coefficients (ICCs). Although G*Power 3.1 does not provide a direct calculation for ICC-based designs, a conservative estimate was derived using the correlation-based model with an anticipated ICC of 0.70, an alpha level of 0.05, and power set at 0.80. This approach yielded a minimum requirement of 13 participants to detect a statistically significant correlation. One subject suffered an unrelated injury during the course of the study, leaving 12 subjects for the final analysis, resulting in an estimated power of 0.77.

Outlier and normality analysis using the Shapiro–Wilk test was performed prior to any further statistical analysis. The mean of two trials was used for analysis, and data were reported as mean and standard deviations for each variable of interest. Hopkins spreadsheet [15] was used to quantify measures of reliability; the log-transformed outputs were used to normalize the distribution and stabilize the variance, thereby improving the accuracy of reliability estimates. In this study, reliability is considered from a complementary perspective. Absolute reliability was quantified using the CV and percentage change to describe within-subject measurement error. Relative reliability was assessed using ICCs to evaluate rank-order consistency between sessions. Together, these metrics inform the stability of GPS-derived variables. Systematic change between sessions was quantified using mean percentage change and repeated measures analysis of variance (ANOVA) with Bonferroni post hoc contrasts [16]. Absolute consistency was quantified as a CV, where measures less than or equal to 10% were deemed acceptable [17]. Relative consistency between consecutive sessions was assessed using the Hopkins pairwise reliability spreadsheet, which calculates intraclass correlation coefficients based on a one-way random-effects model [ICC(1,1)] for each adjacent pair of sessions [18]. Categorization of ICC was deemed as follows: ‘poor’ (≤ 0.50), ‘moderate’ (0.50–0.74), ‘good’ (0.75–0.90), or ‘excellent’ (≥ 0.90) [19]. CV-derived absolute error estimates were used as a proxy for typical error and were compared with smallest worthwhile change (SWC) values to determine the practical importance of performance change [20]. This approach acknowledges that acceptable stability depends on the magnitude of change practitioners aim to detect, such that the usefulness of a metric must be interpreted relative to both SWC and CV-derived measurement error. The SWC was calculated as $0.2 \times$ the between-subject standard deviation and expressed in the original measurement units to provide decision-relevant performance change thresholds [21]. Alpha levels of 0.05 and 95% confidence intervals were used where appropriate.

3. Results

The between-session variability of these curvilinear GPS variables can be observed in Table 3. In terms of systematic change for the curvilinear variables, only three between-session comparisons were greater than 2%, with -6.2% being the largest between-session change observed for Session 2-1 time to reach minimum velocity. Also, the average between-session change in mean across all variables was -0.71% for Sessions 2-1 and 0.14% for Sessions 3-2. No statistically significant change in the mean in any variable was observed between sessions ($p = 0.15$ to 0.99). In terms of absolute consistency, no variable exceeded the 10% threshold, with 74% of CVs under 5%. Additionally, only 4 of the comparisons had a 95% CI greater than 10%. The average between-session change across all variables was 3.91% for Sessions 2-1, and 3.78% for Sessions 3-2. With regard to relative consistency, the ICCs ranged from 0.07 (time to peak speed before first base—Sessions 2-1) to 0.97. Most of the variables (58%) had ICCs greater than 0.74. Wider ICC 95% CIs were observed for several distance-based, peak- and minimum-speed timing variables, indicating reduced

precision of the reliability estimates compared with time- and speed-based measures. In terms of the SWC values, several time- and speed-based measures (e.g., speed at 41.1 m, peak speed before first base, and time to 41.1 m) were found to be practically useful, as CV-derived typical error was comparable to or smaller than SWC. Conversely, event-timed variables such as time to peak speed and time to minimum speed showed typical errors substantially greater than the SWC, suggesting limited sensitivity for detecting small performance changes.

The between-session variability of the linear GPS variables is detailed in Table 4. In terms of systematic change for the linear variables, no statistically significant change in the mean in any variable was observed between sessions ($p = 0.11$ to 0.94), the average between-session change in the mean across all variables was -0.07% for Sessions 2-1 and 0.50% for Sessions 3-2. In terms of absolute consistency, no variable exceeded the 10% threshold, with 94% of the linear CVs under 5%. Additionally, only one of the comparisons had a 95% CI greater than 10%. The average between-session change in CV across all variables was 2.26% for Sessions 2-1 and 2.58% for Sessions 3-2. With regard to relative consistency, the ICCs ranged from -0.01 (time to 13.7 m—Sessions 3-2) to 0.98. Most of the variables (83%) had ICCs greater than 0.74. Again, the width of the 95% confidence intervals (CIs) for ICCs varied across linear sprint variables. Wider ICC CIs were primarily observed for the acceleration-phase time measure (e.g., 13.7 m), indicating reduced precision of these reliability estimates compared with transition, maximal, and maintenance phases. Comparison of SWC values with CV-derived typical error showed that several key linear sprint metrics, including time to 41.1 m and 54.7 m and velocity at 27.4 m and 41.1 m, were found practically meaningful, as typical error was equal to or smaller than the SWC. In contrast, early acceleration-phase measures (e.g., time and velocity at 13.7 m) more frequently exhibited typical error greater than the SWC, indicating reduced ability to detect small but meaningful performance changes in these variables.

Table 3. Between-session reliability of GPS curvilinear variables.

Variable	Mean ± SD			% Change in Mean (95% CI)		CV (95% CI)		ICC (95% CI)		SWC	
	Session 1	Session 2	Session 3	Session 2-1	Session 3-2	Session 2-1	Session 3-2	Session 2-1	Session 3-2	Session 2-1	Session 3-2
Home-to-Second Base Sprint											
Time to 13.7 m	2.83 ± 0.19	2.82 ± 0.16	2.77 ± 0.13	−0.1 (−2.6–2.4)	−1.7 (−4.0–0.5)	2.8 (2.0–4.8)	2.6 (1.8–4.4)	0.82 (0.48–0.94)	0.79 (0.42–0.94)	0.038	0.032
Time to peak speed before first base	3.75 ± 0.29	3.68 ± 0.26	3.59 ± 0.28	−1.8 (−7.8–4.7)	−2.6 (−8.0–3.1)	7.4 (5.2–12.8)	6.6 (4.6–11.5)	0.07 (−0.51–0.60)	0.25 (−0.35–0.70)	0.058	0.052
Time to first base	4.97 ± 0.32	4.96 ± 0.30	5.08 ± 0.49	−0.2 (−2.4–2.1)	2.1 (−2.7–7.1)	2.5 (1.8–4.3)	5.5 (3.8–9.4)	0.86 (0.59–0.96)	0.58 (0.04–0.86)	0.064	0.06
Time to minimum speed between bases	5.96 ± 0.72	5.57 ± 0.38	5.77 ± 0.61	−6.2 (−11.8–−0.2)	3.4 (−0.8–7.8)	7.1 (5.0–12.4)	4.7 (3.3–8.1)	0.50 (−0.07–0.83)	0.76 (0.35–0.92)	0.144	0.076
Time to 41.1 m	7.23 ± 0.53	7.20 ± 0.45	7.23 ± 0.58	−0.3 (−2.6–2.1)	0.3 (−2.2–2.8)	2.6 (1.9–4.5)	2.8 (2.0–4.8)	0.87 (0.62–0.96)	0.87 (0.62–0.96)	0.106	0.09
Time to peak speed before second base and after first base	8.10 ± 0.66	7.76 ± 0.37	7.86 ± 0.35	−4.1 (−8.7–0.9)	1.5 (−1.5–4.3)	5.7 (4.0–9.9)	3.2 (2.3–5.6)	0.28 (−0.32–0.72)	0.55 (0.00–0.85)	0.132	0.074
Time to second base	9.25 ± 0.76	9.21 ± 0.66	9.25 ± 0.87	−0.4 (−3.1–2.4)	0.3 (−2.1–2.8)	3.1 (2.2–5.3)	2.7 (1.9–4.7)	0.87 (0.60–0.96)	0.91 (0.72–0.97)	0.152	0.132
Time from first to second base	4.35 ± 0.61	4.22 ± 0.47	4.27 ± 0.42	−2.7 (−8.8–3.9)	1.4 (−3.4–6.3)	7.5 (5.3–13.1)	5.5 (3.9–9.5)	0.71 (0.25–0.91)	0.78 (0.40–0.93)	0.122	0.094
Speed at 13.7 m	6.89 ± 0.55	6.94 ± 0.45	6.96 ± 0.45	0.8 (−0.8–2.5)	0.2 (−1.3–1.7)	1.8 (1.3–3.1)	1.7 (1.2–2.9)	0.95 (0.85–0.99)	0.94 (0.82–0.98)	0.11	0.09
Peak speed before first base	7.19 ± 0.54	7.24 ± 0.52	7.18 ± 0.50	0.7 (−0.7–2.1)	−0.8 (−2.7–1.2)	1.6 (1.1–2.7)	2.2 (1.6–3.8)	0.97 (0.88–0.99)	0.92 (0.76–0.98)	0.108	0.104
Speed at first base	6.58 ± 0.68	6.48 ± 0.59	6.57 ± 0.55	−1.5 (−5.6–2.7)	1.5 (−3.9–7.2)	4.8 (3.4–8.4)	6.2 (4.4–10.8)	0.79 (0.42–0.93)	0.56 (0.01–0.85)	0.136	0.118
Minimum speed during curvilinear movement	6.14 ± 0.66	6.19 ± 0.55	6.16 ± 0.86	1.0 (−3.0–5.1)	−0.7 (5.2–4.1)	4.5 (3.2–7.8)	5.3 (3.8–9.2)	0.81 (0.46–0.94)	0.69 (0.21–0.90)	0.132	0.11

Table 3. Cont.

Variable	Mean ± SD			% Change in Mean (95% CI)		CV (95% CI)		ICC (95% CI)		SWC	
	Session 1	Session 2	Session 3	Session 2-1	Session 3-2	Session 2-1	Session 3-2	Session 2-1	Session 3-2	Session 2-1	Session 3-2
Home-to-Second Base Sprint											
Peak speed before second base and after first base	7.00 ± 0.66	7.05 ± 0.60	7.07 ± 0.65	0.8 (−1.1–2.9)	0.2 (−1.6–2.0)	2.2 (1.6–3.8)	2.0 (1.4–3.5)	0.95 (0.84–0.99)	0.96 (0.87–0.99)	0.132	0.12
Speed at 41.1 m	6.71 ± 0.74	6.85 ± 0.54	6.79 ± 0.60	2.4 (−0.8–5.8)	−0.9 (−2.3–0.5)	3.6 (2.6–6.3)	1.6 (1.1–2.7)	0.89 (0.67–0.97)	0.97 (0.91–0.99)	0.148	0.108
Speed at second base	6.11 ± 0.77	6.00 ± 1.00	6.01 ± 1.10	−2.3 (−6.5–2.0)	−0.2 (−7.2–7.3)	4.9 (3.5–8.5)	8.4 (5.9–14.7)	0.92 (0.76–0.98)	0.84 (0.55–0.95)	0.154	0.20
Distance from home to 13.7 m	13.09 ± 0.51	13.08 ± 0.50	13.03 ± 0.80	−0.1 (−3.1–3.0)	−1.5 (−3.3–2.5)	3.5 (2.5–6.0)	1.3 (2.3–5.7)	0.23 (−0.37–0.69)	0.88 (0.08–0.87)	0.102	0.10
Distance from 13.7 m to first base	14.73 ± 0.3	14.76 ± 0.32	14.80 ± 0.44	0.2 (−1.5–1.9)	0.3 (−2.0–2.6)	1.9 (1.4–3.3)	2.6 (1.8–4.5)	0.39 (−0.21–0.78)	0.04 (−0.53–0.58)	0.06	0.064
Distance from first base to 41.1 m	14.41 ± 0.74	14.54 ± 0.62	14.40 ± 0.65	0.9 (−2.6–4.4)	−1.0 (−3.6–1.7)	3.9 (2.8–6.8)	3.0 (2.1–5.2)	0.37 (−0.23–0.77)	0.58 (0.04–0.86)	0.148	0.124
Distance from 41.1 m to second base	13.38 ± 0.44	13.32 ± 0.43	13.33 ± 0.74	−0.5 (−3.0–2.1)	−0.1 (−3.5–3.5)	2.9 (2.0–4.9)	4.0 (2.8–6.9)	0.29 (−0.31–0.73)	0.26 (−0.34–0.71)	0.088	0.086

Note: SWC = Smallest Worthwhile Change.

Table 4. Between-session reliability of GPS linear variables.

Variable	Mean ± SD			% Change in Mean (95% CI)		CV (95% CI)		ICC (95% CI)		SWC	
	Session 1	Session 2	Session 3	Session 2-1	Session 3-2	Session 2-1	Session 3-2	Session 2-1	Session 3-2	Session 2-1	Session 3-2
54.7 m Linear Sprint											
Time to 13.7 m	2.83 ± 0.19	2.77 ± 0.19	2.84 ± 0.14	−2.1 (−5.4–1.3)	2.5 (−2.6–7.9)	3.9 (2.7–6.7)	5.9 (4.1–10.2)	0.71 (0.26–0.91)	−0.01 (−0.56–0.55)	0.038	0.038
Time to 27.4 m	4.66 ± 0.32	4.61 ± 0.31	4.69 ± 0.29	−0.9 (−2.8–1.1)	1.7 (−1.6–5.0)	2.2 (1.6–3.8)	3.6 (2.6–6.3)	0.91 (0.72–0.97)	0.73 (0.29–0.91)	0.064	0.062
Time to 41.1 m	6.42 ± 0.43	6.41 ± 0.46	6.43 ± 0.43	−0.1 (−1.3–1.0)	0.3 (−1.0–1.6)	1.3 (0.9–2.2)	1.4 (1.0–2.4)	0.97 (0.90–0.99)	0.97 (0.89–0.99)	0.086	0.092
Time to 54.8 m	8.18 ± 0.60	8.16 ± 0.63	8.12 ± 0.65	−0.3 (−1.6–1.1)	−0.5 (−2.5–1.6)	1.5 (1.1–2.6)	2.3 (1.6–3.9)	0.97 (0.89–0.99)	0.93 (0.78–0.98)	0.12	0.126
Velocity at 13.7 m	7.23 ± 0.50	7.17 ± 0.53	7.21 ± 0.53	−0.9 (−2.7–0.9)	0.5 (−1.2–2.3)	2.1 (1.5–3.5)	2.0 (1.4–3.4)	0.94 (0.79–0.98)	0.94 (0.82–0.98)	0.10	0.106
Velocity at 27.4 m	7.65 ± 0.69	7.82 ± 0.60	7.81 ± 0.62	2.3 (−1.0–5.6)	−0.1 (−1.4–1.2)	3.7 (2.6–6.3)	1.5 (1.0–2.5)	0.85 (0.56–0.95)	0.97 (0.91–0.99)	0.138	0.12
Velocity at 41.1 m	7.83 ± 0.66	7.90 ± 0.70	7.92 ± 0.68	0.8 (−0.5–2.2)	0.3 (−1.1–1.7)	1.5 (1.1–2.6)	1.6 (1.1–2.7)	0.98 (0.92–0.99)	0.98 (0.92–0.99)	0.132	0.14
Velocity at 54.8 m	7.32 ± 0.77	7.32 ± 0.87	7.30 ± 0.81	−0.3 (−2.6–2.0)	−0.2 (−3.2–3.0)	2.6 (1.8–4.5)	3.5 (2.5–6.0)	0.96 (0.87–0.99)	0.93 (0.79–0.98)	0.154	0.174

4. Discussion

The purpose of this study was to quantify the between-session reliability of GPS technology for measuring distance-time-velocity variables, considered important for characterizing base running. For a comprehensive understanding of the reliability of a variable, measures of systematic change, absolute, and relative consistency should be reported [22]. The main findings were: (1) no statistically significant systematic change ($p < 0.05$) between any of the linear and curvilinear measures across sessions was noted; (2) absolute consistency was acceptable ($CV < 10\%$) for all variables, and 93% of CVs were under 5%; and (3) relative consistency was more variable for the curvilinear running data; however, on average 66% of ICC values of the linear and curvilinear variables had good to excellent rank order reliability.

The systematic error was found to be statistically non-significant ($p < 0.05$), with a small percentage change in the mean between testing days (89% of the measures lower than or equal to 2%), indicative of no consistent shift in participant performance between sessions. Two groups of researchers [23,24] using GPS (18 Hz) with soccer players have found similar between-session percent changes in the mean with linear (-0.27 to -2.96%) and curvilinear sprinting (-0.18 to -2.44%) across 10-20-30-40 m segments. It needs to be noted, however, that the linear and curvilinear methodologies and variable measures differed between the studies. One of the research groups [23] used the theoretical maximal velocity to estimate what the athlete could theoretically achieve under optimal conditions over a 40 m distance. The other research group [24] measured time and maximal speed over a distance of 30 m. Moreover, the two research groups conducted curvilinear movement tests using a semi-circle. This study utilized raw coordinate data to measure the velocity of the sprint directly, and the curvilinear movement test and distances (27.4 to 54.7 m) matched the in-game running path of baseball players. It is important to measure similar base-running distances to identify specific kinematic characteristics. Nevertheless, participants in this study followed a self-selected curvilinear pathway without increasing variability, similar to the data of other researchers [23,24].

Although there is no preset standard for acceptable CV values, many researchers set a goal of $<10\%$ for acceptable reliability [25]. The CVs associated with the linear and curvilinear measures were all under 10%, and 93% of the measures were under 5%. Additionally, the majority of the comparisons had a 95% CI less than 10%, indicating that the typical error between sessions was minimal. Two groups of researchers [23,24] using GPS (18 Hz) have found similar between-session CVs with linear (1.5 to 10.2%) and curvilinear (1.5 to 7.8%) sprinting across 10-20-30-40 m segments. Similar to the change in mean data, the linear and curvilinear tasks, and the variables measured in these studies [23,24] differed from this study, making direct comparisons problematic [23,24].

The ICCs were used as measures of relative consistency or the degree to which individuals maintain their rank order in a sample with repeated measures. Most ICCs (66%) were greater than 0.74, ranging from 0.76 to 0.98, indicating good to excellent reliability. The curvilinear variables exhibited the greatest between-session rank changes. In particular, the time to peak speed before first base ($ICC = 0.07$) and time to peak speed between first and second base ($ICC = 0.28$) in session 2-1. When looking at the signals, it was observed that for some subjects there was considerable separation between the time to peaks for each trial, which no doubt affected the rank order. This wide distribution increased within-subject variability and contributed directly to instability in rank order, thereby reducing ICC values. Interestingly, the ICCs improved for the Session 3-2 comparison, the time to peak speed before first base ($ICC = 0.25$), and time to peak velocity before second base and after first base ($ICC = 0.55$); however, both were still under the 0.74 threshold. Furthermore, the distance covered within each 13.7 m segment from home to second base was found to have

low ICC values (0.04–0.39), indicating substantial changes in rank order for both time and distance measures across sessions. This change in rank order in both time and distance measures is more likely a function of biological rather than technological variability. For example, the athletes were young and relatively homogeneous, and therefore, there is likely a lot of movement variability associated with their base running, which could be a function of maturation and physical/technical expertise. Associated with this is that base runners make subtle adjustments when preparing to round first base; these adjustments alter the trajectory in and out of first base. From a biomechanical perspective, base running, particularly when approaching and rounding first base, requires subtle adjustments in foot placement strategy to accommodate changes in running direction. These small but natural strategic variations alter distance-time outcomes, and if a population is relatively homogeneous, which is the case with the cohort of athletes used in this study, these small changes in distance-time measures will be reflected in rank order changes despite acceptable measurement precision. Collectively, these findings indicate that the low reliability observed for certain curvilinear variables most likely reflects the inherent sensitivity of complex base-running tasks to biological variability rather than limitations of the GPS technology itself.

Two groups of researchers [23,24] using GPS (18 Hz) have found similar between-session results for most of our ICC values with linear (0.92 to 0.98) and curvilinear (0.77 to 0.96) sprinting across 10-20-30-40 m segments. However, it needs to be noted that the methodological approaches differed substantially from those of the current study, limiting direct comparison. For example, the researcher did not include distance-time measures that resembled the 13.7 m segment analysis used in this study, nor did they assess curvilinear base-running movement. Instead, tests used standardized, continuous circular running paths with a fixed radius, which impose different mechanical and coordinative demands compared to the volitional home-to-second base path travelled by the athletes in this study. In addition, their cohorts consisted of adult student-athletes with developed neuromuscular control and greater familiarity with repeated sprinting tasks. In contrast, participants in this study are still developing the technical proficiency required in a movement pattern that is not yet deeply ingrained. This developmental difference potentially contributed to the greater rank-order variability observed in the curvilinear measures, particularly time to peak speed and distance covered in each segment. These metrics are sensitive to subtle fluctuations in the segmental approach strategy and trajectory adjustments before and after the first base.

In addition to traditional reliability metrics, SWC values were calculated to determine whether each performance metric was sensitive enough to detect practically meaningful changes. Sensitivity was evaluated by comparing SWC with the magnitude of measurement error estimated from the CV. Metrics were considered practically useful when CV-derived typical error (TE) was equal to or smaller than SWC, indicating that true performance changes of interest could be distinguished from normal measurement noise. For linear sprint measures (i.e., time to 41.1 and 54.7 m and velocity at 27.4 and 41.1 m), measurement error was generally small relative to SWC. These variables were found to have high relative reliability (ICC = 0.85–0.98) and low absolute error (CV = 1.3–1.5%). Importantly, CV-derived error estimates (0.08–0.13) were comparable to or smaller than SWC values (0.09–0.14), indicating that these metrics are sensitive enough to detect meaningful performance changes. Similar findings were observed for several curvilinear sprint metrics, including peak speed before first base, peak speed before second and after first base, and speed at 41.1 m., which also demonstrated combined reliability and sensitivity. These measures showed excellent reliability (ICC = 0.89–0.97) with acceptable absolute error (CV = 1.6–2.0%). For these variables, CV-derived error magnitudes (0.11–0.14) were again

approximately equal to or smaller than SWC values (0.10–0.13), supporting their practical sensitivity. Collectively, these comparisons indicate that key time- and speed-based metrics possess both strong reliability and adequate sensitivity to detect worthwhile changes. Metrics for which TE approached or exceeded SWC were interpreted more cautiously, whereas variables meeting the criterion of $TE \leq SWC$ were judged suitable for return-to-play decisions and for short- and long-term performance monitoring.

Limitations

This study has several limitations that should be considered when interpreting the findings. First, the sample size was relatively small, and although consistent with prior reliability studies, this may have influenced the stability and precision of some reliability estimates. Second, the cohort comprised adolescent athletes, and ongoing maturation and developing base-running technique may have contributed to increased biological and movement variability between sessions, especially for complex curvilinear tasks. Third, the SWC estimates used in this study are distribution-based and should be considered provisional, as true, meaningful performance change thresholds for base-running metrics have not yet been empirically established (baseball outcomes). Fourth, the authors did not isolate biological and technical sources of variability; the findings should be interpreted as such. Finally, while the GPS system demonstrated acceptable reliability for most variables, potential signal error associated with rapid directional changes and curvilinear movement cannot be entirely excluded and may have influenced the reliability of selected segment-specific measures.

Therefore, the results of this study must be viewed within the constraints of a developing youth cohort performing a base-running curvilinear-specific task. Future work should continue to refine baseball-specific movement assessments and track how reliability improves as athletes mature and acquire more consistent curve-running mechanics.

5. Conclusions

The non-significant changes in the mean, low CVs, and high ICCs, for the most part, over repeated testing occasions, indicate acceptable between-session reliability for several GPS-derived variables examined in this study. Specifically, practitioners are recommended to use these linear and curvilinear measures: linear time to 41.1 m and 54.7 m, and velocity at 27.4 m; and curvilinear running speed at 41.1 m, peak speed before first base, and peak speed before second base and after first base. Importantly, statistical reliability alone does not imply sensitivity to detect a practically meaningful performance change, and applied usefulness depends on whether measurement error is smaller than the SWC. With this in mind, the practitioner may consider using the more stable linear and curvilinear running time- and speed-based metrics for monitoring base-running performance when interpreted relative to CV-derived absolute error. Implementing such an approach provides an expanded capacity to quantify curvilinear locomotion, which may inform training analysis and exercise prescription for better outcomes.

Practical Application

There are several applications of this research to advance the field of monitoring baseball players, improving talent identification, generating specific prescriptions, and coaching approaches among baseball position players. However, statistical reliability does not by itself ensure sensitivity to detect meaningful performance change, and applied interpretation should consider measurement error and SWC thresholds. Given that this study detailed acceptable between-session reliability of some GPS-derived base-running measures, practitioners may consider applying the more stable metrics in applied performance settings where expected changes exceed measurement error. First, practitioners can use GPS time

and velocity measures between segments to advance base-running diagnostics and improve exercise prescription for the optimization of base-running efficiency and performance, particularly for variables demonstrating stronger reliability profiles. Second, practitioners can use GPS technology for base running and speed sessions to determine cumulative workloads and prescribe undulations in training volume, intensity, frequency, or a combination of the aforementioned load factors to reduce injury risk while interpreting session-to-session changes relative to measurement error. The demonstrated reliability of these measures provides a foundation for monitoring workload changes across sessions and over time, rather than relying on single-session changes. Third, practitioners can use GPS technology to create longitudinal databases on speed characteristics in players across their amateur and professional careers for the purpose of talent identification, scouting, and recruiting purposes, with greater confidence placed on variables demonstrating higher stability. The confirmed between-session stability of the selected variables enables longitudinal tracking when interpreted alongside error bounds. Lastly, practitioners can use these reliable GPS-derived base-running metrics to support return-to-play decision-making by objectively comparing post-injury base-running performance to pre-injury or normative benchmarks across testing sessions, provided observed differences exceed the measurement error threshold.

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Abbreviations

The following abbreviations are used in this manuscript:

ICC	Intraclass correlation coefficient
GPS	Global Positioning System
CV	Coefficient of variation
CI	Confidence intervals

References

1. Tsuno, T.; Nagahara, R.; Mizutani, M.; Matsuo, A.; Nakamoto, H.; Maeda, A. Relationship of base running performance with running direction and its change. In Proceedings of the 34 International Conference on Biomechanics in Sports, Tsukuba, Japan, 18–22 July 2016; pp. 1074–1077.
2. Martínez-Rodríguez, J.A.; Crotin, R.L.; Szymanski, D.J. Introduction to an advanced change of direction test in baseball and softball: The curvilinear ability test. *Strength Cond. J.* **2024**, *46*, 279–286. [[CrossRef](#)]

3. Miyaguchi, K.; Demura, S.; Nagai, K.; Uchida, Y. Comparison of base running in baseball players and track-and-field athletes. *Health* **2011**, *3*, 26–31. [[CrossRef](#)]
4. McEvoy, K.P.; Newton, R.U. Baseball throwing speed and base running speed. *J. Strength. Cond. Res.* **1998**, *12*, 216–221. [[CrossRef](#)]
5. Nimphius, S.; Callaghan, S.J.; Bezodis, N.E.; Lockie, R.G. Change of direction and agility tests: Challenging our current measures of performance. *Strength Cond. J.* **2018**, *40*, 26–38. [[CrossRef](#)]
6. Coleman, A.E.; Amonette, W.E. Pure acceleration is the primary determinant of speed to first-base in major-league baseball game situations. *J. Strength Cond. Res.* **2012**, *26*, 1455–1460. [[CrossRef](#)]
7. Coleman, A.E.; Dupler, T. Changes in running speed in game situations during a season of Major League Baseball. *J. Exerc. Physiol. Online* **2005**, *8*, 10–15.
8. Bullock, G.S.; Schmitt, A.C.; Chasse, P.; Little, B.A.; Diehl, L.H.; Butler, R.J. Differences in PlayerLoad and pitch type in collegiate baseball players. *Sports Biomech* **2021**, *20*, 938–946. [[CrossRef](#)]
9. Qin, S.; Ren, D.; Li, Z.; Zhang, B. Differences in external loads of different pitch types in Chinese male college baseball players. *Front. Sports Act. Living* **2025**, *7*, 1724517. [[CrossRef](#)]
10. Murray, N.B.; Black, G.M.; Whiteley, R.J.; Gahan, P.; Cole, M.H.; Utting, A.; Gabbett, T.J. Automatic detection of pitching and throwing events in baseball with inertial measurement sensors. *Int. J. Sports Physiol. Perform* **2017**, *12*, 533–537. [[CrossRef](#)]
11. Duffield, R.; Reid, M.; Baker, J.; Spratford, W. Accuracy and reliability of GPS devices for measurement of movement patterns in confined spaces for court-based sports. *J. Sci. Med. Sport* **2010**, *13*, 523–525. [[CrossRef](#)]
12. Malone, S.; Doran, D.; Collins, K.; Morton, J.; McRoberts, A. Accuracy and reliability of the VXSport Global Positioning System in intermittent activity. In Proceedings of the 19th Annual Congress for the European College of Sport Science, Amsterdam, The Netherlands, 2–5 July 2014.
13. Alphin, K.L.; Sisson, O.M.; Hudgins, B.L.; Noonan, C.D.; Bunn, J.A. Accuracy assessment of a GPS device for maximum sprint speed. *Int. J. Exerc. Sci.* **2020**, *13*, 273–280. [[CrossRef](#)]
14. Buchheit, M.; Allen, A.; Poon, T.K.; Modonutti, M.; Gregson, W.; Di Salvo, V. Integrating different tracking systems in football: Multiple camera semi-automatic system, local position measurement and GPS technologies. *J. Sports Sci.* **2014**, *32*, 1844–1857. [[CrossRef](#)]
15. Hopkins, W.G. Spreadsheets for analysis of validity and reliability. *Sportscience* **2017**, *21*, 36.
16. Nanda, A.; Mohapatra, D.B.B.; Mahapatra, A.P.K.; Mahapatra, A.P.K.; Mahapatra, A.P.K. Multiple comparison test by Tukey's honestly significant difference (HSD): Do the confident level control type I error. *Int. J. Stat. Appl. Math* **2021**, *6*, 59–65. [[CrossRef](#)]
17. Kang, C.W.; Lee, M.S.; Seong, Y.J.; Hawkins, D.M. A control chart for the coefficient of variation. *J. Qual. Technol* **2017**, *39*, 151–158. [[CrossRef](#)]
18. Koo, T.K.; Li, M.Y. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J. Chiropr. Med.* **2016**, *15*, 155–163. [[CrossRef](#)]
19. Buchheit, M.; Mendez-Villanueva, A. Reliability and stability of anthropometric and performance measures in highly-trained young soccer players: Effect of age and maturation. *J. Sports Sci.* **2013**, *31*, 1332–1343. [[CrossRef](#)] [[PubMed](#)]
20. Panoutsakopoulos, V.; Athanasopoulos, E.; Li, T.; Kitsikoudis, P.; Chalitsios, C. Field-based monitoring of linear sprint performance: Agreement between the K-Power sensor and timing gates in trained youth sprinters. *Appl. Sci.* **2026**, *16*, 1268. [[CrossRef](#)]
21. Hopkins, W.G. How to interpret changes in an athletic performance test. *Sportscience* **2004**, *8*, 1–7.
22. Hopkins, W.G. Measures of reliability in sports medicine and science. *Sports Med.* **2000**, *30*, 1–15. [[CrossRef](#)]
23. Miras-Moreno, S.; García-Ramos, A.; Sašek, M.; Cvjetičanin, O.; Šarabon, N.; Kavčič, I.; Smajla, D. Individual acceleration-speed profile variables: Comparison and reliability between linear and curvilinear sprints. *J. Strength Cond. Res.* **2025**, *39*, e538–e545. [[CrossRef](#)] [[PubMed](#)]
24. Sašek, M.; Miras-Moreno, S.; García-Ramos, A.; Cvjetičanin, O.; Šarabon, N.; Kavčič, I.; Smajla, D. The concurrent validity and reliability of a global positioning system for measuring maximum sprinting speed and split times of linear and curvilinear sprint tests. *Appl. Sci.* **2024**, *14*, 6116. [[CrossRef](#)]
25. Job, T.; Cross, M.R.; Cronin, J.B. Shoulder internal and external rotation strength assessment in baseball pitchers: Normative data and reliability. *J. Strength Cond. Res.* **2025**, *39*, e634–e638. [[CrossRef](#)] [[PubMed](#)]

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