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Functional asymmetries in inside-outside foot mechanics when curvilinear sprinting in baseball

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Highlights:

- Foot-specific asymmetries differ between linear and curvilinear sprinting.
- Outside foot was found to have greater push-off and shorter SL in linear sprints.
- Segment-dependent inside–outside foot asymmetries were found during curvilinear sprints.
- Ground contact time differed by foot and running path.
- Inside–outside foot asymmetry peaked in Segment 3 of curvilinear sprinting.

Abstract: The purpose of this study was to determine whether inside-outside foot asymmetries were observed when running multiple bases in baseball. Fifty-four trained male high school baseball position players performed two linear 54.7-meter sprints and two home-to-second base sprints. Ground contact time (GCT), stride length (SL), and average push-off and impact were quantified using inertial measurement unit foot pod technology. The sprints were divided into four segments (0–13.7 m; 13.7–27.4 m; 27.4–41.1 m; 41.1–54.7 m) for both curvilinear segments (C):C1–C4, and linear segments (L):L1–L4. The primary findings of this study were that for linear sprinting, GCT was not significantly different between feet across all segments, but SL was significantly shorter (L2–L4) in the outside foot (−0.76% to −1.34%; ES = −0.20 to −0.37) and push-off were significantly greater (L1–L4) in the outside foot (2.95% to 4.39%; ES = 0.27 to 0.40), with significantly greater outside-foot impact only in L1 (5.63%; ES = 0.29). In curvilinear sprinting, the inside foot was found to have significantly longer GCT in Segments 2–4 (−3.13% to −7.79%; ES = −0.38 to −1.29), higher push-off (3.83% to 4.39%; ES = 0.31 to 0.41), and segment-specific SL changes. Inside–outside foot asymmetries are driven by the linear-curvilinear demands of specific segments, peaking in Segment 3 where stabilization demands are greatest. These findings highlight the need for segment-specific training that develops inside-foot stability and outside-foot propulsion to optimize base-running performance in base runners.

Keywords: base running biomechanics; foot-specific mechanics; monitoring

1. Introduction

Base running involves both linear sprinting when running single bases and curvilinear sprinting when running multiple bases. While linear sprinting in baseball has been extensively studied in terms of kinematics determinants [1–5], curvilinear running introduces additional biomechanical demands, such as the need to generate centripetal force, altered step kinematics, and asymmetrical loading between the inside and outside limbs [6–11]. Importantly, these inside–outside mechanical differences are not merely descriptive phenomena but represent task-specific adaptations that may directly influence velocity maintenance, curve negotiation efficiency, and overall base running performance. However, despite recent advances in understanding the biomechanical demands of base running, significant limitations remain in the literature. First, most studies have derived their findings from standardized track curvature [6–9], typically using a fixed radius that differs substantially from the narrower and self-selected curvilinear path encountered during base running [12,13]. Second, nearly all investigations have relied on adult competitive sprinters (average of 22.1 years old) rather than baseball players, which makes generalization of finding's problematic. Third, although prior researchers have employed advanced laboratory-based and stadium-based technologies (*e.g.*, three-dimensional motion capture, force plates, high-speed video, and StatCast) [6–9,14,15], these approaches are typically costly, spatially constrained, and inaccessible in many training environments. While these technologies have enhanced biomechanical understanding of sprinting, the primary scientific gap is not technological validation but limited insight into how inside and outside foot mechanics adapt under the specific task constraints of baseball base running. Additionally, the analysis from these technologies have been applied to linear and curvilinear sprints or aggregated analyses and have not been designed to examine step-by-step inside and outside foot spatiotemporal characteristics, during linear and curvilinear base running. Fourth, consequently, previous researchers have primarily reported total or averaged outcomes rather than segmental, foot-specific measures, limiting insight into inside–outside asymmetry and how foot mechanics differ between linear and curvilinear running conditions [6–9]. A clearer understanding of these foot-specific adaptations is necessary to determine whether observed asymmetries represent meaningful mechanical strategies under curve-running demands. These limitations highlight the need for a portable, affordable and practical tool capable of quantifying the segmental step-by-step spatiotemporal characteristics of linear sprint and curvilinear base running.

One such technology that may offer these step-by-step insights into base running is inertial measurement unit (IMU) foot pod technology. Martínez-Rodríguez *et al.* [16], used such technology to quantify the inter-session (three sessions of two trials separated by at least seven days) reliability of foot pod measurements during a 54.7-m linear and curvilinear (home-to-second base sprint). Kinematic measures (time, maximum and average speed and right and left ground contact time (GCT), stride length (SL), total and averaged push-off and total and averaged impact) were collected over a linear (0–54.7 m) and three curvilinear distances segments (0–27.4 m, 27.4–54.7 m, and 0–54.7 m). Across 60 planned comparisons between linear and curvilinear trials, no systematic between-session differences were observed ($p > 0.05$), with 91% of mean percent changes below 2%. Absolute consistency was acceptable, as 94% of coefficients of variation were < 10% and 63% were < 5%. Relative consistency was also acceptable, with intraclass correlation coefficients exceeding 0.74 for 80%, 56%, and 80% of variables in curvilinear segments 1, 2, and the total segment, respectively. Given acceptable reliability, the utility of foot pod technology for exploring base running mechanics, particularly curvilinear running mechanics during four specific segments (0–13.7 m, 13.7–24.7 m, 27.4–41.1 m, 41.1–54.7 m) is unexplored to this point in time, however foot pod technology would seem well placed to provide additional information on inside-outside foot mechanics in base running. Thus, the emphasis of this study is not on validating wearable technology per se, but on leveraging a practical measurement approach to better characterize task-specific mechanical asymmetries during unconstrained base running.

In base running, one of the biggest differences between linear and curvilinear sprinting is the inward lean of the body [12]. When running multiple bases (curvilinear), changes in direction occur across distinct movement segments, and prior analyses suggest that Segments 2 and 3 account for most of the total angular change, whereas Segment 4 contributes the least [12]. Curvilinear running requires a combination of mediolateral and anteroposterior force to produce the inward-lean effects associated with running curves. The inward lean during curvilinear base running shifts the body's mass toward the inside foot [12], creating asymmetrical loading that alters foot mechanics, muscle activation, and joint rotations for both the inside and outside feet to maintain velocity during centripetal/centrifugal forces activity on the curve [6–9,14,17,18]. This inward lean also increases inside-foot braking and mediolateral force demands, while positioning the outside foot as a stable lever for more effective push-off [6–9]. The inside foot is typified by longer GCT, high breaking impulse, inward force, and reduced propulsive impulses, whereas the outside foot commonly exhibits shorter GCT. It needs to be noted, however, that most of the evidence on differences between inside and outside foot curvilinear running has come from athletes running curves on the track. Whether baseball players exhibit similar characteristics when running multiple bases *in situ*, where the curvature is unconstrained, is unknown.

Asymmetries within sport performance context can be classified as functional or non-functional. Functional asymmetries are common in many sports given the high volume and intensities of unilateral work associated with activities such as, tennis [19] and baseball pitching/throwing [20]. In these contexts, inter-limb differences may reflect task-specific adaptations aligned with the mechanical and technical demands of the sport rather than maladaptive imbalances. Consequently, such asymmetries are not inherently viewed as deficits requiring correction. Conversely, non-functional asymmetries are generally characterized as inter-limb differences that exceed acceptable variability and are associated with reduced performance capacity and impaired movement efficiency. When sufficiently pronounced, these asymmetries may warrant targeted intervention. Importantly, this study does not directly evaluate the relationship between asymmetry magnitude and sport performance outcomes. Therefore, interpretations regarding functional or non-functional classifications should be understood as conceptual distinctions within the literature rather than evidence of causal effects on performance. Of interest to the authors is determining if there are any notable functional asymmetries between inside and outside foot, whilst running multiple bases. Linear sprints over the same distances will be used for a baseline understanding of asymmetry and whether any functional asymmetry exists. If functional asymmetries are noted, then there is potentially a case to train the feet to optimize inside-outside foot mechanics.

From this brief treatise of the literature, it is apparent there is limited information regarding the kinematic and kinetic characteristics of curvilinear base running and in particular the asymmetrical differences in inside and outside foot mechanics while running unconstrained curved paths. The aim of this study therefore was to determine whether inside and outside foot functional asymmetries were associated with curvilinear base running, using IMU foot pod technology. Linear sprints over the same distances will be used for a baseline understanding of asymmetry and whether any functional asymmetry exists. It is hypothesized that given the training history of the participants there would be longer GCT in the inside foot and greater push-off in the outside foot during curvilinear segments and reduced asymmetry during linear sprinting.

2. Methods

2.1. Experimental approach to the problem

A cross-sectional design was used to determine the magnitude of inside and outside foot asymmetry during a linear 54.7 m and curvilinear home-to-second base sprint. No familiarization session was provided because all participants were well-familiarized with linear and curvilinear sprinting based on their daily training and routine testing. Participants were tested on a turf baseball field, wearing baseball cleats and completed a standardized dynamic warm-up before each session. Researchers compared spatiotemporal asymmetries between the inside (foot closest to the center of curvature) and outside foot (foot furthest away from the center of curvature),_across linear and curvilinear movements, between four different linear and curvilinear distances (0–13.7 m; 13.7–27.4; 27.4–41.1 m; 41.1–54.7 m). All athletes ran counterclockwise (standard baseball base running direction).

2.2. Participants

Fifty-four trained males high school baseball position players (age = 15.15 ±1.17 years, height = 169.34 ±10.38 cm, weight = 72.33 ±13.78 kg) volunteered to participate in this study. Baseball players trained at a high school baseball academy in Puerto Rico. For inclusion in the study, participants were required to be healthy and free of injury at the time of testing. Before participating in this study, all participants received an informational sheet, and written assent and consent of a guardian were obtained before starting participation in the study. Participants were informed that participation was voluntary and that they were free to withdraw from the study at any point. Ethical approval was granted by the Auckland University of Technology Ethics Committee (24/267).

2.3. Procedures

All testing sessions were completed under consistent environmental and experimental conditions, with the sprint assessments performed in the same order for all participants: linear sprinting followed by curvilinear sprinting. This order was intentionally selected because linear sprinting required maximal sprinting at higher velocities and greater overall mechanical demand; performing this task under fatigued conditions could compromise sprint mechanics and increase injury risk. Please note, it is acknowledged that this fixed order introduces a potential order and/or fatigue effect that may systematically influence the curvilinear trials. Irrespective of the rest periods, accumulated neuromuscular fatigue or potentiation effects cannot be ruled out, therefore the reader should be cognizant of this limitation. No injuries or physical overtraining were reported that would have affected test outcomes. Each testing session lasted approximately 25 minutes. At the start of each session. participants completed a standardized warm-up consisting of lower-body dynamic movement drills. The warm-up protocol was detailed in Martínez-Rodríguez *et al.* [16].

Following the warm-up, participants completed two trials of 54.7 m straight-line sprinting, with three minutes of passive rest between trials [16]. After ten minutes of recovery [13,16], participants completed two trials of a 54.7-m home-to-second base sprinting, rounding the first base, again with three minutes of passive rest between trials [16]. The starting position for home-to-second base sprint test was a lead-off position, placing the right foot in the middle of the home base, left foot shoulder-width apart, the body facing the second base, and right shoulder aligned with the first base. After each trial, participants remained stationary for five seconds so the end of the movement could be identified from a near-zero speed value, indicating the trial ended. The mean of two trials for each test was used for subsequent analysis [13].

2.4. Equipment

Spatiotemporal sprint data were collected using foot pod technology (Plantiga Technologies, Vancouver, Canada), comprised of a 6-axis IMUs (triaxial accelerometer and triaxial gyroscope) placed in an insole as detailed in Martínez-Rodríguez *et al.* [16]. These insoles were fitted inside each participants' shoes before starting the warmup [16]. For all sprint trials, participants wore a GPS device to provide positional data for segment identification.

2.5. Data analysis

Each sprint trial was recorded with an iPad camera using 1080p HD video at 30 frames per second from a lateral viewpoint. Video footage was used to count steps and identify the start and end of each segment.

For the curvilinear sprint, the following segments were analyzed:

- Home to 13.7 m: Curvilinear segment 1 (C1)
- 13.7 m to first base sprint: Curvilinear segment 2 (C2)
- First to 41.1 m: Curvilinear segment 3 (C3)
- 41.1 m to second base: Curvilinear segment 4 (C4)

For the linear sprint, the following segments were analyzed:

- Start to 13.7 m: Linear segment 1 (L1)
- 13.7 to 24.7 m: Linear segment 2 (L2)
- 24.7 to 41.1 m: Linear segment 3 (L3)
- 41.1 to 54.7 m: Linear segment 4 (L4)

The step counts obtained from the video for the 27.4 m and 54.7 m segments of the linear and curvilinear sprint segments were matched to the IMU signal within the Plantiga Explore feature. Segment boundaries were then manually masked according to the corresponding start and end steps. The start and end steps of each segment were masked manually using the masking tool. This allowed precise isolation of the four distinct segments from the larger activity trace. The 13.7-m and 41.1-m segments were also masked manually. However, the exact time was determined using the concurrently collected GPS data and then applied to the IMU-derived trace.

Right and left GCT, SL, average push-off, and average impact measures were obtained from the Plantiga Cloud. Description for these variables are detailed in Martínez-Rodríguez *et al.* [16].

2.6. Statistical analyses

Outlier and normality analysis were performed using the Kolmogorov-Smirnov test [21]. The mean of two trials was calculated for each variable and descriptive results are reported as mean ± standard deviations. Paired-sample t-tests were used to determine within-subject differences/asymmetries in running mechanics across segments. For each distance segment, paired t-tests were used to compare inside and outside foot outcomes within the same athletes. In addition, paired t-tests were conducted to compare linear and curvilinear sprint conditions across segments for each foot. All comparisons were performed separately for each outcome variable. Effect sizes were calculated using Cohen's *d* for paired samples to provide a standardized measure of the magnitude of differences between two conditions. Cohen's *d* was computed as the mean of the within-subject difference scores divided by the standard deviation of those difference scores. Effect sizes were interpreted according to the thresholds proposed by Hopkins *et al.* [22]: trivial ($d < 0.19$), small ($0.2 \leq d < 0.59$), moderate ($0.6 \leq d < 1.19$), large ($1.2 \leq d < 1.99$), and very large (> 2.0) [23]. Within-session reliability of the foot pod derived variables was assessed using trial-to-trial data. Relative reliability was quantified using intraclass correlation coefficients (ICC), while absolute reliability was evaluated using a coefficient of variation (CV%). Relative consistency reflects the stability of subjects' rank order across repeated testing occasions and was determined using ICC (3,1) based on a two-way mixed-effects single-measure consistency model. Categorization of ICC values was interpreted as poor (≤ 0.50), moderate (0.50–0.74), good (0.75–0.90), or excellent (≥ 0.90). All statistical analyses were conducted using the statistical software Rstudio: Integrated Development Environment for R (version 2023.06.0+421; Posit Software, PBC, Boston, MA, USA). The significance level for all analyses was set at $p \leq 0.05$.

3. Results

Reliability varied across running segments (see Table 1). In terms of absolute consistency, CV values between 2.0%–5.0% were observed for GCT, SL between 7.1%–9.3%, push-off acceleration between 3.2%–8.3%, and impact acceleration between 5.4%–10.5%. In terms of relative consistency, ICC ranged from 0.45–0.94 for GCT, 0.60–0.77 for SL, 0.75–0.95 for push-off acceleration, and 0.52–0.76 for impact acceleration. According to established thresholds, these values indicate moderate to excellent reliability across most variables and segments, with the highest reliability generally observed for push-off acceleration and ground contact time. Collectively, the low CV values (absolute consistency) and moderate-to-excellent ICC values (relative consistency) indicate acceptable within-session reliability of the foot-pod derived variables across the sprint segments.

Table 1. Within-session reliability of foot-pod derived running variables across curvilinear and linear segments.

Segments	Inside-foot ICC	Outside-foot ICC	Inside-foot CV%	Outside-foot CV%
		Average ground contact time (ms)		
C1: 0–13.7 m	0.83	0.88	3.6	2.9
L1: 0–13.7 m	0.45	0.47	5.0	4.5
C2: 13.7–27.4 m	0.79	0.80	2.9	2.7
L2: 13.7–27.4 m	0.80	0.94	2.3	2.0
C3: 27.4–41.1 m	0.91	0.86	2.2	2.1
L3: 27.4–41.1 m	0.91	0.92	2.3	2.1
C4: 41.1–54.7 m	0.80	0.81	2.6	2.8
L4: 41.1–54.7 m	0.91	0.91	2.3	2.5
		Average stride length (m)		
C1: 0–13.7 m	0.67	0.67	7.9	7.7
L1: 0–13.7 m	0.60	0.68	9.3	9.0
C2: 13.7–27.4 m	0.64	0.65	8.6	9.2
L2: 13.7–27.4 m	0.72	0.70	8.3	8.5
C3: 27.4–41.1 m	0.66	0.69	7.5	7.8
L3: 27.4–41.1 m	0.73	0.74	8.1	8.0
C4: 41.1–54.7 m	0.70	0.77	7.6	7.1
L4: 41.1–54.7 m	0.76	0.76	8.2	8.1
		Average push-off (g)		
C1: 0–13.7 m	0.89	0.86	4.7	5.1
L1: 0–13.7 m	0.88	0.76	4.1	6.1
C2: 13.7–27.4 m	0.81	0.85	6.0	6.0
L2: 13.7–27.4 m	0.95	0.82	3.2	5.0
C3: 27.4–41.1 m	0.90	0.88	4.5	4.8
L3: 27.4–41.1 m	0.91	0.81	3.7	5.2
C4: 41.1–54.7 m	0.75	0.75	7.8	8.3
L4: 41.1–54.7 m	0.84	0.76	6.0	6.6
		Average impact (g)		
C1: 0–13.7 m	0.73	0.73	8.7	9.6
L1: 0–13.7 m	0.66	0.54	10.5	10.2
C2: 13.7–27.4 m	0.67	0.53	6.5	7.1
L2: 13.7–27.4 m	0.76	0.71	6.1	5.9
C3: 27.4–41.1 m	0.61	0.58	7.9	6.7
L3: 27.4–41.1 m	0.75	0.66	6.3	5.4
C4: 41.1–54.7 m	0.67	0.60	7.3	7.0
L4: 41.1–54.7 m	0.66	0.52	5.9	6.0

Key: ICC = Intraclass correlation coefficient; CV% = % Coefficient of variation; yds = yards.

When comparing the inside-outside foot across linear segments (L1–L4), no significant differences were observed in GCT. However, small, but significant reductions in SL (~0.8%–1.3%) and significant greater push-off acceleration (~3.0%–4.4%) across all segments was noted. A between-foot difference in impact was only observed in L1, where the outside foot exhibited significant moderately greater impact (~5.6%) (see Table 1 for detailed statistics).

In terms of the curvilinear inside-outside foot analysis, asymmetries were segment-specific and more pronounced. In Segment 1, no significant GCT differences were detected, although small, but significant increases in SL in the inside foot (~1.5%) were noted. In Segment 2, significant moderate greater GCT (~3.1%) and significant greater push-off (~4.4%) were observed in the outside foot. In Segment 3, the largest asymmetries were observed, with significant greater GCT in the inside foot (~7.8%), significant small-to-moderate increases in push-off in the outside foot (~4.2%), and SL in the inside foot (~1.1%). In Segment 4, a significant and small greater GCT and SL in the inside foot (~3.6% and ~0.5%, respectively) were noted, while push-off remained significantly greater in the outside foot (~3.8%). Full statistical details are presented in Table 1. With regards to the linear-curvilinear sprint analysis (Table 2), the higher velocities associated with the linear sprinting, was generally characterized by significant shorter GCT (~3%–13%), longer SL (~1%–10%), and greater push-off (~4%–23%) and impact (~2%–11%) in both feet relative to curvilinear segments. Effect sizes ranged from small to large depending on the variable and segment. Full statistical details are provided in Table 2.

In terms of inter-limb asymmetry (right *vs.* left; %), distance- and variable-specific magnitudes were observed across the sprints (see Figure 1). During 13.7–27.4 m (Column A), GCT (A1) was predominantly left-dominant (central tendency ~−5% to −10%) with substantial dispersion approaching −20% to −25%. SL (A2) was centered near symmetry (~−2% to +2%), whereas push-off (A3) showed a slight right-dominant bias (~+3% to +6%) with values extending beyond ±15%–20%. In the 27.4–41.1 m segment (Column B), GCT (B1) remained modestly left-dominant (~−4% to −8%), while SL (B2) shifted slightly positive (~+1% to +4%). Push-off (B3) demonstrated greater right-dominant asymmetry (~+5% to +10%) exceeding +20%–30%. In the 41.1–54.7 m segment (Column C), GCT (C1) had left-dominant asymmetry (~−3% or greater), whereas SL (C2) stayed in the middle (symmetry) and push-off (C3) displayed larger right-dominant magnitudes (~+5% to +12%), with values surpassing +25%–30%.

Table 2. Spatiotemporal inside and outside foot measures during linear and curvilinear segments sprint.

Segment	Inside foot	Outside foot	Inside-outside feet analysis			Linear-curvilinear analysis					
							Inside foot			Outside foot	
			Asym (%)	*p*	ES (*d*)	% Diff	*p*	ES (*d*)	% Diff	*p*	ES (*d*)
Average ground contact time (ms)											
C1: 0–13.7 m	143 ±28.4	141 ±28.6	−1.50	0.12	−0.16	1.48	0.29	0.07	2.49	0.09	0.12
L1: 0–13.7 m	145 ±29.8	144 ±29.2	−0.49	0.51	−0.06						
C2: 13.7–27.4 m	127 ±29.4	123 ±30.4	−3.13	< 0.001	−0.49	−2.96	0.07	−0.13	−0.21	0.79	−0.02
L2: 13.7–27.4 m	123 ±29.9	123 ±28.7	−0.43	0.46	−0.07						
C3: 27.4–41.1 m	137 ±28.2	127 ±27.9	−7.79	< 0.001	−1.29	−12.88	< 0.001	−0.52	−5.24	0.00	−0.21
L3: 27.4–41.1 m	121 ±30.3	120 ±29.0	−0.46	0.43	−0.08						
C4: 41.1–54.7 m	131 ±28.8	126 ±30.1	−3.58	< 0.001	−0.38	−5.79	0.00	−0.22	−2.61	0.13	−0.11
L4: 41.1–54.7 m	124 ±31.4	123 ±31.2	−0.46	0.68	−0.04						
Average stride length (m)											
C1: 0–13.7 m	2.74 ±0.30	2.70 ±0.30	−1.46	0.01	−0.27	1.81	0.02	0.17	1.83	0.05	0.14
L1: 0–13.7 m	2.79 ±0.30	2.75 ±0.30	−1.43	0.04	−0.20						
C2: 13.7–27.4 m	3.65 ±0.28	3.63 ±0.30	−0.55	0.11	−0.16	1.90	< 0.001	0.31	1.10	0.01	0.19
L2: 13.7–27.4 m	3.72 ±0.29	3.67 ±0.29	−1.34	0.00	−0.34						
C3: 27.4–41.1 m	3.51 ±0.29	3.55 ±0.28	1.13	0.00	0.33	10.27	< 0.001	1.73	8.37	< 0.001	1.45
L3: 27.4–41.1 m	3.89 ±0.31	3.86 ±0.31	−0.77	0.00	−0.28						
C4: 41.1–54.7 m	3.80 ±0.32	3.78 ±0.33	−0.53	0.02	−0.24	4.38	< 0.001	0.63	4.15	< 0.001	0.60
L4: 41.1–54.7 m	3.97 ±0.34	3.94 ±0.34	−0.76	< 0.001	−0.37						
Average push-off (g)											
C1: 0–13.7 m	14.3 ±2.41	14.5 ±2.39	1.45	0.15	0.14	3.71	< 0.001	0.38	5.24	< 0.001	0.45
L1: 0–13.7 m	14.8 ±2.24	15.3 ±2.73	2.95	0.01	0.27						
C2: 13.7–27.4 m	16.4 ±3.09	17.1 ±2.95	4.39	< 0.001	0.38	12.50	< 0.001	0.93	12.50	< 0.001	1.03
L2: 13.7–27.4 m	18.5 ±3.31	19.4 ±3.58	4.39	< 0.001	0.40						
C3: 27.4–41.1 m	15.3 ±2.55	15.9 ±2.60	4.21	< 0.001	0.41	20.52	< 0.001	1.41	20.36	< 0.001	1.45
L3: 27.4–41.1 m	18.8 ±3.85	19.5 ±3.91	4.04	< 0.001	0.37						
C4: 41.1–54.7 m	14.4 ±2.91	15.0 ±3.31	4.19	0.00	0.31	22.65	< 0.001	1.34	22.27	< 0.001	1.18
L4: 41.1–54.7 m	18.1 ±3.94	18.8 ±4.16	3.83	0.00	0.31						
Average impact (g)											
C1: 0–13.7 m	22.4 ±4.67	23.2 ±5.43	3.32	0.13	0.15	4.49	< 0.001	0.27	6.91	< 0.001	0.38
L1: 0–13.7 m	23.6±5.37	24.9 ±5.10	5.63	0.00	0.29						
C2: 13.7–27.4 m	27.6 ±3.65	27.5 ±3.63	−0.43	0.72	−0.04	−1.20	0.51	−0.05	2.23	0.01	0.18
L2: 13.7–27.4 m	27.3 ±4.11	28.1 ±3.92	2.95	0.05	0.19						
C3: 27.4–41.1 m	26.2 ±3.92	25.6 ±3.27	−2.14	0.16	−0.14	6.82	< 0.001	0.44	11.02	< 0.001	0.77
L3: 27.4–41.1 m	28.1 ±3.95	28.6 ±3.64	2.03	0.10	0.16						
C4: 41.1–54.7 m	26.3 ±4.30	26.4 ±3.62	0.11	0.89	0.01	9.10	< 0.001	0.59	9.74	< 0.001	0.75
L4: 41.1–54.7 m	28.8 ±3.76	29.1 ±3.12	0.76	0.52	0.06						

Key: yds = yards; Asym = Asymmetry; Diff = Difference.

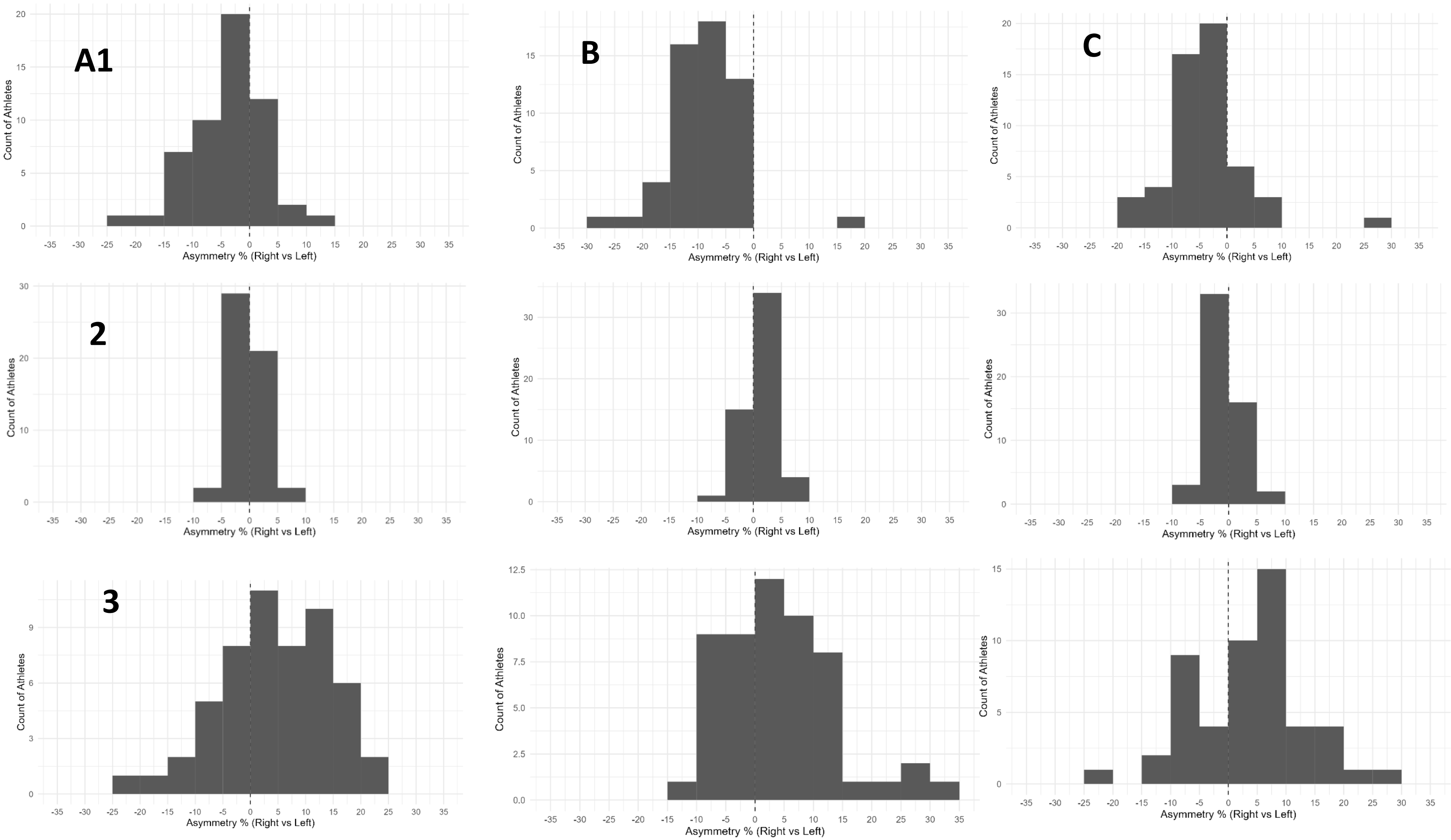

Figure 1. Distribution of athletes' asymmetry among three segments on the home-to-second base sprint. Key: Column A: 13.7 to 27.4 m; Column B: 27.4 to 41.1 m; Column C: 41.1 to 54.7 m; Row 1: Ground Contact Time; Row 2: SL; Row 3: Push-off.

4. Discussion

Of particular interest was whether GCT, SL, impact and push-off accelerations (g) of the inside-outside foot differed across linear and curvilinear paths of the same distance. Linear sprints over the same distances/segments were used for a baseline understanding of asymmetry between inside and outside feet, and whether any functional asymmetry existed. It was hypothesized that given the training history of the participants there would be longer GCT in the inside foot and greater push-off in the outside foot during curvilinear segments and reduced asymmetry during linear sprinting. Whilst no significant differences were found in GCT, the average SL was significantly shorter (−0.76% to −1.34%; ES = −0.20 to −0.37) for the outside foot in all linear segments and push-off accelerations were significantly greater (2.95% to 4.39%; ES = 0.27 to 0.40) in the outside foot across all linear segments Whether these differences are a function of the curvilinear running that baseball athletes engage in is difficult to discern, however, in this cohort small ($p < 0.05$) functional inside-outside foot asymmetries were observed in terms of SL and push-off forces, during linear sprinting.

The sprinting path is predominantly linear in Segment 1 (C1), therefore minimal inside–outside asymmetry would typically be expected. A significantly longer inside foot SL (−1.46%; ES = −0.27) was observed, nonetheless, there was no significant difference between inside and outside foot for GCT and push-off and impact acceleration. A possible explanation is that base runners sprint predominantly linear to the right, away from the home to first base straight line, changing the angle to enter the curved segment (C2) and as a result the inside foot needing to take a slightly longer SL. Researchers [9] studying curvilinear sprinting have reported that curve-specific kinematics adaptations may start before the curve segment during early acceleration. However, in contrast to previous research [6–9,14], that reported measurements at a specific point of the curvilinear sprint, the authors of this study quantified spatiotemporal characteristics using step-by-step derived values averaged across the curvilinear segment. This segment-based approach was chosen to provide a representative estimate of the inside and outside foot asymmetry during the preparation phase immediately preceding the curve. Therefore, these asymmetries in SL may be a function of the adjustments needed to prepare to run a predominantly curved path and specific to base running.

In Segment 2 (C2) the athlete transitioned from a predominantly linear acceleration to the right into the start of the curvilinear segment around the first base [12], this alteration in the running path reflected by significant increases in the inside foot GCT (−3.13%; ES = 0.58) and the outside foot push-off acceleration (4.39%; ES = 0.38) and no significant difference between inside and outside foot for SL. These observations were similar to the curvilinear sprint segment adaptations described by previous researchers, where the inside foot played a stabilizing role and the outside foot played a propulsive role to prepare the body for transition from linear to curvilinear running [6–9]. Increased inside foot GCT reflects the effects of the inward lean to maintain the speed, stabilizing the hip to manage the mediolateral shifts with the intention of reducing excessive path deviation. This interpretation aligns with the findings of Tsuno *et al.* [12], who reported that minimizing sudden or sharp changes of direction to the left and decreasing the distance covered during Segment 2 reduced the base running efficiency ratio in Segment 3. It would seem therefore that any asymmetries in Segment 2 represent the inside foot assuming greater stabilizing and directional control roles and the outside foot assuming greater propulsive role.

During Segment 3 (C3) the base runner was typically ending their curvilinear phase, where GCT asymmetry was at its peak. Specifically, while the changes in outside-foot SL (ES = 0.33) and push-off acceleration (ES = 0.41) were small, there was a large reduction in inside-foot GCT (ES = −1.290). These segment-specific changes are biomechanically consistent with elevated centripetal acceleration demands during the apex of the curve, which would theoretically require greater stabilizing contribution from the inside limb and continued propulsive contribution from the outside limb to preserve forward velocity. These results align with the evidence of researchers investigating curvilinear sprinting, reporting increased midfoot eversion, ankle internal rotation, and inward force production in the inside foot [7,8], reflecting a stabilizing role. Within this context, the larger asymmetry observed in Segment 3 may represent the point at which mechanical adjustments are most pronounced. The increased inside-foot GCT may theoretically correspond to greater stabilization demands required to preserve trajectory, whereas the longer SL and elevated push-off metrics in the outside foot may reflect its continued propulsive contribution to maintain forward velocity. However, because joint kinematics and force vectors were not directly quantified in this study, these interpretations remain inferential and should be viewed as biomechanically plausible explanations rather than direct confirmation of segment-specific force strategies.

In Segment 4 (C4) the asymmetries should decrease as the running path becomes more linear. Specifically in this phase, there was a longer GCT (−3.58%; ES = −0.38) and SL (−0.53%; ES = 0.24) on the inside foot and higher push-off (3.83%; ES = 0.31) on the outside foot, indicating a mechanical transitioning after the directional changes of Segment 3. These results align with Tsuno *et al.* [12], who reported that Segment 4 accounted for 6.62% of the total angle of direction changes in running multiple bases, whereas Segment 2 and 3 accounted for 31.5% and 58.10% of the total angle of direction change respectively. In this segment therefore there is less inward lean, running gait will become more symmetrical and linear in nature, however there are still inside-outside foot mechanical adjustments taking place as the athlete lines up his trajectory with the second base.

With regards to the linear-curvilinear comparison, the inside and outside foot during the curvilinear sprint, for the most part, was characterized by longer GCTs (−2.96% to −12.88%), shorter SLs (1.10%–10.27%), and lower impact and push-off (3.71%–22.65%). Specifically, the largest deviations occurred in Segment 3 with a longer GCT in the inside (−12.88%; ES = −0.52) and outside foot (−5.24%; ES = −0.21), shorter SL in the inside (10.27%; ES = 1.73) and outside foot (8.37%; ES = 1.45), lower push-off acceleration in the inside (20.52%; ES = 1.41) and outside foot (20.36%; ES = 1.45) and impact acceleration in the inside foot (6.82%; ES = 0.44) and outside foot (11.02%; ES = 0.77), indicating that the apex of the curve imposed the greatest mechanical cost relative to linear sprinting. In Segment 4, these characteristics persisted, although less pronounced for GCT, with a longer GCT in the inside foot (−5.79%; ES = −0.22), shorter SL in the inside foot (4.38%; ES = 0.63) and the outside foot (4.15%; ES = 0.60), and lower push-off acceleration in the inside foot (22.65%; ES = 1.34) and the outside foot (22.27%; ES = 1.34) and impact acceleration in the inside foot (9.10%; ES = 0.59) and the outside foot (9.74%; ES = 0.75), indicating a mechanical transition back toward more linear sprinting. These findings align with previous researchers who showed that curvilinear sprinting is associated with longer GCT, shorter SLs, lower propulsion, and greater inside-foot stabilizing characteristic due to inward lean [6–9].

5. Conclusion

The asymmetries observed in this study were not unexpected given the higher velocities associated with the linear movement. These patterns align with researchers reporting longer GCT and shorter SL during curvilinear sprinting [6,9]. However, comparison with the existing literature is complicated as almost all available data is from track-and-field curvilinear sprinting, and not the unconstrained curve running of baseball. In addition, the track studies [6–9,14] collected data in a single fixed location (often the apex of the curvilinear sprint), disparate to the averaged step-by-step segment analysis undertaken in this study. In summary, the most meaningful deviations from linear sprinting occurred in Segment 3, where directional control was a priority, and inside-outside foot symmetry became highly impacted. The linear-curvilinear comparison was segment dependent, with the largest differences evident in Segments 3 and 4, where curvilinear sprinting was characterized by longer GCT, shorter SL, and lower push-off and impact accelerations.

6. Practical application

The findings of this study highlight that curvilinear base running is an asymmetric sequence of mechanical adjustments through the segments, placing different demands on the inside and outside feet. Now that it is known that functional asymmetries exist between feet across segments and differences exist between linear and curvilinear movement across segments, coaches may consider whether training tasks align with the stabilizing and propulsive requirements of each segment. The following recommendations should be interpreted as biomechanically informed suggestions rather than evidence-based exercise prescription.

Base running may be considered as a series of segment-specific tasks rather than a single action. Coaches may consider emphasizing efficient acceleration patterns in Segment 1, encouraging smooth and controlled transition mechanics into the curve for Segment 2, exposing athletes to high-speed curve-running proficiency in Segment 3, and reinforcing practice opportunities to re-establish linear sprint mechanics during the high-velocity exit in Segment 4 [12]. Whether this segment-based approach improves performance requires further experimental investigation.

Specifically, coaches should consider:

(1) Developing inside-foot stability and force production for curvilinear base running

The consistent increases in inside-foot GCT and outside-foot push-off acceleration during the curved segments underscore the importance of developing inside-foot stability and control and outside-foot propulsive capability. Training programs may incorporate single-leg strength exercises, particularly those emphasizing medial-lateral stability. Curvilinear sprinting drills that progressively challenge the inside foot's ability to manage inward lean and outside foot's ability to propel the body forward could be explored as practical strategies, though their direct impact on asymmetry magnitude or performance enhancement was not examined in this study [24–26].

(2) Preparing athletes for the high mechanical demands of segment 3 (C3)

Given that the greatest mechanical demands and asymmetries occurred in Segment 3, training may prepare athletes for the high centripetal force requirements present in this phase. High-speed curvilinear sprint sessions, focusing on the apex of the curve with a small radius but uncontrolled specific base running curve may be integrated to expose athletes to these demands, although the efficacy of this type of training is yet to be determined [24]. This exposes base runners to the demands of maintaining speed while leaning into the curve. Additionally, repeated curvilinear sprints with wearable resistance may be considered as a method to increase sport specific mechanical loading, but this recommendation has been extrapolated from the linear sprinting literature and the efficacy of this type of training is yet to be determined for base running [25,26].

(3) Early-segment training to improve curve preparation

Strength coaches may consider emphasizing preparatory adjustments by teaching optimal linear acceleration to the right from home to the first 13.7 m and providing visual cues to guide consistent curve-entry angles [12]. Practicing this approach may help improve consistency during the transition into Segment 2.

(4) Integrate IMU-based foot technology to monitor asymmetry

In this study, GPS data were used solely to identify and mask the 0–13.7 and 27.4–41.1 m segments of interest, whereas all spatiotemporal and mechanical metrics were derived from the IMU foot pod. This approach highlights the capacity of IMU-based systems to independently quantify foot-specific variables such as GCT, SL, impact, and push-off, once the segment boundaries are defined. Importantly, these metrics can be collected automatically and repeatedly across sessions, supporting longitudinal mechanical profiling and monitoring. Asymmetry values should be interpreted within the broader context of athlete performance and injury risk rather than assumed to require correction.

Data availability statement

The data that support the findings of this study are not publicly available due to privacy, but are available from the corresponding author upon reasonable request.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used generative AI tools only to improve language and readability. The authors take full responsibility for the content of the manuscript.

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Authors' contribution

Conceptualization, J.A.M.R. and J.B.C.; methodology, J.A.M.R.; software, J.A.M.R. and J.N.; validation, J.N.; formal analysis, J.A.M.R.; investigation, J.A.M.R.; resources, J.B.C. and J.A.M.R.; data curation, J.A.M.R.; writing—original draft preparation, J.A.M.R.; writing—review & editing, J.A.M.R., J.N. and J.B.C.; visualization, J.A.M.R.; supervision, J.B.C.; project administration, J.A.M.R. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

Ethical statement

The study was performed in accordance with the Declaration of Helsinki and approved by the name of the Auckland University of Technology Ethics Committee (14 February 2025, 24/267).

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