Improving Base Running Efficiency Amongst Baseball Players



AUT SPORT RESEARCH INSTITUTE NEW ZEALAND

José Antonio Martínez-Rodríguez

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Primary Supervisor: Prof. John B. Cronin
Secondary Supervisor: Dr. Ryan L. Crotin
Tertiary Supervisor: Dr. Jonathon Neville

School of Sport, Exercise and Health

Sports Performance Research Institute New Zealand (SPRINZ)

Abstract

Base running performance in baseball is traditionally assessed using total-time measures from the pro-agility test, t-test, or linear sprint tests. Although useful, these approaches provide limited insight into the segmental, spatiotemporal, and foot-specific movement strategies that underpin efficient base running, particularly during the curvilinear sprinting associated with running multiple bases. Recent developments in wearable technologies, including Global Navigation Satellite Systems (GNSS) and inertial measurement unit (IMU) foot pods, offer opportunities to assess base running in greater detail. In addition, researchers have found sprint training using calf loaded wearable resistance (WR) found that this light rotational overload improved linear acceleration. However, the reliability and diagnostic value of these wearable technologies, and the application of WR to curvilinear training remain for the most part unexplored. Therefore, this thesis examined whether base running efficiency can be assessed and improved in baseball players through better linear and curvilinear diagnostics using wearable technology, and training with wearable resistance.

The thesis was structured across four sections. Section 1 reviewed current evidence on linear sprinting, change of direction (COD) ability, curvilinear running mechanics, and baseball-specific base running performance. Analyses of Major League Baseball data indicated that linear tasks (stolen bases) were important for single-base running; however, did not necessarily distinguish players who advanced multiple bases (doubles). This suggested that multiple-base running requires additional curvilinear, technical, and movement-strategy qualities beyond linear sprint characteristics alone. The Curvilinear Ability Test (CAT) was introduced as a more specific assessment option for capturing the combined curvilinear and COD demands of baseball.

Section 2 examined the reliability and applied value of GNSS and IMU foot pod technologies for assessing linear and curvilinear base running. GPS-derived split-time and velocity measures were found to have acceptable between-session reliability during linear and home-to-second-base sprinting. A base running efficiency ratio (BREr) was also proposed to evaluate how effectively players preserved linear sprint capacity while negotiating curvilinear base running demands. IMU foot pod data provided reliable and

practically meaningful measures of speed, ground contact time (GCT), stride length (SL), push-off acceleration, and impact acceleration, allowing segment-specific and foot-specific interpretation of base running mechanics. In addition, segment-by-segment percent difference between linear and curvilinear sprinting and percent asymmetries between the inside and outside feet analysis were presented to better understand the mechanical qualities of the linear and curvilinear sprints.

Section 3 first investigated calf-loaded WR through a case study comparing two high-school baseball players who completed the same intervention either two or three times per week. The athlete training three times per week was found to have the clearest retained adaptations at two weeks post training (2POST), including improvements of 9.86% in first-to-second-base time and 4.02% in home-to-second-base time, supported by a higher peak velocity after first base and favorable mechanical changes during the first-to-second-base segment. In contrast, the athlete training twice per week demonstrated some improvements at MID and POST testing, but these were not retained at 2POST. These individual responses suggest that weekly training frequency may influence the retention of adaptation, although this interpretation remains exploratory. The subsequent group-based intervention compared baseball-specific sprint training performed with and without calf-loaded WR. From BASE to MID, both groups demonstrated several practically relevant within-group changes in curvilinear outcomes, but no statistically significant or practically relevant between-group differences were observed. From BASE to POST, WRT demonstrated 10 practically relevant curvilinear changes compared with five in CON group; however, this broader response did not result in statistically significant between-group superiority. From BASE to 2POST, home-to-second-base time and the minimum velocity between peaks improved significantly and practically within WRT by 3.57% ($d = -0.64$, $p = 0.022$) and 8.26% ($d = 0.68$), respectively. In addition, the between-group change in minimum velocity between peaks favoured WRT by 9.25% ($d = 0.67$). Therefore, the findings suggest a possible delayed WRT response at 2POST, characterized by an improvement in home-to-second-base time and a velocity preservation around first base.

Section 4 translated the thesis findings into practical recommendations for coaches, strength and conditioning practitioners, and sport scientists. Collectively, this thesis demonstrated that base running should be assessed and trained as a baseball-specific movement skill involving both intersegmental linear

speed and curvilinear sprinting efficiency. GNSS and IMU foot pod technologies can provide reliable diagnostic information beyond total sprint time, while calf-loaded WR may offer a practical training method for improving selected components of curvilinear base running performance. Future research should further expand normative datasets using the technology implemented in this study. Furthermore, a great deal more WR research is needed to understand the long-term effects of this training modality on curvilinear sprint performance, injury risk, and game outcomes.

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List of common abbreviations

AI	Artificial intelligence
ANOVA	Analysis of variance
AUTEC	Auckland University of Technology Ethics Committee
BBCOR	Ball-bat coefficient of restitution
BRE	Base running efficiency
BREr	Base running efficiency ratio
CV	Coefficient of variation
CAT	Curvilinear Ability Test
CBBA	Carlos Beltrán Baseball Academy
CI	Confidence interval
COD	Change of direction
CODS	Change of direction speed
CoM	Centre of mass
CV	Coefficient of variation
CV%	Percent coefficient of variation
ES	Effect size
GCT	Ground contact time
GNSS	Global Navigation Satellite System
ICC	Intraclass correlation coefficient
IMU	Inertial measurement unit
KPI	Key performance indicators
kg	Kilograms
m	Metres
$m.s^{-1}$	Metres per second
MLB	Major League Baseball
MiLB	Minor League Baseball
N	Newtons
NCAA	National Collegiate Athletic Association
NSCA	National Strength and Conditioning Association
RFD	Rate of force development
s	Seconds
SD	Standard deviation
SL	Stride length

SWC	Smallest Worthwhile Change
TE	Typical error
WR	Wearable resistance

Attestation of authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgments), nor used artificial intelligence tools or generative artificial intelligence tools (unless it is clearly stated, and referenced, along with the purpose of use), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Chapters 2 to 11 of this thesis represent separate papers that have either been published or have been submitted to peer-reviewed journals for consideration for publication. The contributions of myself and the various co-authors of these papers are outlined at the beginning of each chapter. All co-authors have approved the inclusion of the joint work in this doctoral thesis.

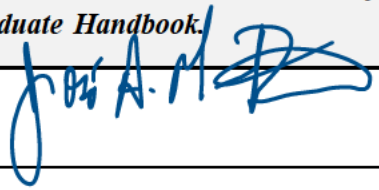


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Student Name:	**Jose Antonio Martinez-Rodriguez**	**Signature:**		**Date:**	**August 3rd, 2026**

Publications and presentations

The publications listed below are a result of the research performed in fulfilment of the degree of Doctor of Philosophy:

Published articles

Chapter 2	Martinez-Rodriguez JA, Crotin RL, Neville J, Cronin JB. The need for speed: Linear and curvilinear characteristics in Major League Baseball players. *Phys Act*. 2024;2(2):3-10. (Jose A. Martinez-Rodriguez - 85%, Ryan Crotin - 2%, Jonathon Neville – 5%, John Cronin - 8%)
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Chapter 8	Martinez-Rodriguez JA, Crotin RL, Neville J, Cronin JB. New perspective on analysing and interpreting base running efficiency: An IMU foot pod methodological case approach. *Appl Sci* 16: 5668, 2026.

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Manuscripts ready for submission for publication

Chapter 10	Base running responses to calf-loaded wearable resistance in baseball: A case study comparison of two versus three sessions per week
Chapter 11	Training the curve: Calf-loaded wearable resistance sprint training altered pattern of adaptation in base running performance in high school baseball players.

Conference proceedings

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Martínez-Rodríguez JA. (2026**).** Puerto Rico Sports Performance Summit Panelist: El futuro del deporte boricua*,* San Juan, Puerto Rico, USA.

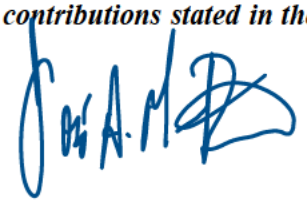
The student was the main contributor (85%) to the research and subsequent analysis and interpretation of the research in this thesis. Additionally, the student was the primary contributor (85%) to the writing of research ethics applications, progress reports, and papers, as well as the main presenter at conferences.

Declaration of collaboration

Chapters 2 to 11 of this thesis represent separate papers that have either been published or have been submitted to peer-reviewed journals for consideration for publication. My contribution and the contributions of various co-authors to each of these papers are outlined below. All co-authors have approved the inclusion of the joint work in this doctoral thesis.

STUDENT AND SUPERVISOR APPROVALS

By signing you are confirming that the co-author contributions stated in the table(s) below are accurate.

Student Name	José Antonio Martínez-Rodríguez	**Signature**		**Date**	July 31, 2026
Supervisor Name	John Barry Cronin	**Signature**		**Date**	01/08/2026

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AUTHOR SURNAME	**CONTRIBUTION**
MARTÍNEZ-RODRÍGUEZ	Conception and design of the project or output; acquisition, curation, and/or processing of research data; analysis or interpretation of research data; drafting significant parts of the research output; revision of the research output to contribute to its quality and interpretation; project administration.
CROTIN	Contribution of sport-specific knowledge; analysis or interpretation of research data.

NEVILLE	Analysis or interpretation of research data and/or literature; drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation.
CRONIN	Conception and design of the project or output; drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation.

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AUTHOR SURNAME	**CONTRIBUTION**
MARTÍNEZ-RODRÍGUEZ	Conception and design of the project or output; literature searching and synthesis; contribution of sport-specific knowledge; analysis or interpretation of the literature; drafting significant parts of the research output; revision of the research output to contribute to its quality and interpretation; project administration.
CROTIN	Conception and design of the project or output; contribution of sport-specific knowledge; analysis or interpretation of research data and/or literature; drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation.
SZYMANSKI	Contribution of sport-specific knowledge; analysis or interpretation of research data and/or literature; drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation.

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AUTHOR SURNAME	**CONTRIBUTION**
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NEVILLE	Analysis or interpretation of research data and/or literature; drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation.
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- 31 May 2024: Ethical approval (reference number 24/69) for Chapters 5–9 (Appendix A)
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Chapter 1: Introduction

1.1 Background

This section briefly reviews existing knowledge, gaps, and limitations concerning: 1) the occurrence of running multiple bases in baseball and the outcomes of these events in terms of match wins; 2) the assessment of curvilinear base running efficiency (BRE); and, 3) the training of base running speed and efficiency. It needs to be acknowledged from the outset that there is a paucity of research that has investigated BRE (103); consequently, this is an emerging area of research.

1.1.1 The occurrence of running multiple bases in baseball and the outcomes of these events in terms of match wins

In addition to batting skills, base running ability is important for scoring runs and winning games (9). The impact of base running skills on run-scoring ability in Major League Baseball (MLB) players is typically 70 runs per season (9). One year later, Baumer and Terlecky (10) estimated the impact of the ability of a base runner to improve the team's run-scoring performance, concluding that more skilled base runners added around 10 runs per season, improving their offensive performance by more than 20%. Recently, Athanasakis et al. (6) examined important offensive softball variables and their association with winning and losing games in an Olympic Softball tournament, concluding that base running ability was important for scoring a run and winning an Olympic game. It should be noted, however, that recent analyses of the importance of base running to match and competition outcomes have not been reported, and the impact of baseball running ability likely differs from 2010. Furthermore, there are two available websites related to Major League Baseball (MLB): Baseball Savant, with StatCast data about time (97) and speed (98) and Baseball-Reference with baseball objective variables (130). Using these public-data websites, the analysis of base running impact can be more comprehensive and granular in the information provided.

1.1.2 The assessment of curvilinear base running efficiency

BRE is one of the base running assessment qualities that has emerged in recent years. BRE provides insight into how a baseball player maintains their maximal linear sprint ability while rounding the bases (103). To determine BREr, the base runner performs a linear sprint matching the distance to the 54.7 m home-to-second-base sprint, and it is calculated by dividing the curvilinear sprint segment time by the matched linear sprint segment time (103). A value closer to 1.00 indicates that the base runners maintained their linear capacity through the curve, reflecting high efficiency relative to their linear capacity, whereas a value farther from 1.00 may indicate a substantial loss in performance during the curvilinear segment, reflecting low efficiency relative to their linear capacity. The BREr reflects how efficient athletes transfer linear sprinting characteristics into the curvilinear sprinting characteristics.

Miyaguchi et al. (103) evaluated the BRE between baseball players and track and field athletes with no baseball experience and the relationship between base running and straight-line running time in college baseball players. The straight-line sprint time was evaluated at 54.7 m and 109.6 m, corresponding to the distance when running to the second base and the home plate. In addition, the base running time was evaluated for each base in the home run test. The researchers reported that track and field athletes are faster than baseball players in a linear sprint (54.7 m sprint: 7.49 s vs. 7.76 s, respectively; 109.6 m sprint; 13.95 s vs. 14.84 s, respectively). However, baseball players were significantly superior in BRE compared to track and field athletes in both second base distance (1.10 vs. 1.15, $p < 0.05$; ES = 1.33) and home plate distance (1.14 vs. 1.22, $p < 0.05$; ES = 2.00). Baseball players who were fast in a straight line were believed to be fast base runners because they could maintain high speed during curved sprint due to curvilinear learned skill (103). However, there was a large effect size for each distance, indicating meaningful between-group differences in pure linear speed and BRE. The authors concluded that baseball players could run to the next base while maintaining their curvilinear speed due to the base running technique learned from playing the game. It seems that differences exist between pure linear speed and BRE, as maintained high speed is considered critical in sprinting to the next base efficiently, decreasing the base running

time. It needs to be noted that such conclusions were made from a sample size of 25 college baseball players, as larger and more diverse sample sizes are needed to fully comprehend the importance of BRE.

Hoffman et al. (56) evaluated 343 professional baseball players from Minor League Baseball (MiLB) and MLB. The authors reported a significant direct relationship between the vertical jump peak power ($r = 0.28$; $p \leq 0.05$) and mean power ($r = 0.27$; $p \leq 0.05$) with total bases and a significant inverse relationship between the vertical jump mean power ($r = -0.25$; $p \leq 0.05$) with stolen bases. However, approximately 8% of the variation in total bases was associated with vertical-jump peak power, while approximately 6% of the variation in stolen bases was associated with vertical-jump mean power. Thus, other methodological strategies should be implemented to analyse how baseball jump characteristics and baseball objective variables explain each other. Furthermore, a significant inverse relationship between the pro-agility times ($r = -0.48$; $p \leq 0.05$) and 10-yard sprint time ($r = -0.42$; $p \leq 0.05$) with stolen bases have been reported (56). However, as well as with the jump test, approximately 23% and 18% of the variation in stolen bases were explained by the variation in pro-agility time and the 9.1 m sprint time, respectively. Thus, apart from jumping and change of direction (COD) speed tests, more relevant factors may be related to stolen bases. In addition, this study did not consider the number of multiple bases running events (double, triple, and inside-the-park home run), where curvilinear running is important. Moreover, using the pro-agility test as an assessment to compare base running data could be less specific, as it is focused on linear movement rather than curvilinear movement, as the latter is required for scoring beyond reaching first base.

Hoffman et al. (56) reported that just 6 to 8% of the variation in the stolen bases and total bases was explained by the variation in jump tests. The researchers used a Vertec to calculate the vertical jump mean and estimate peak force. Thus, advanced technology with a high sampling frequency (Hz) enhances data collection capabilities, allowing for more granular information. Recently, Teske et al. (148) evaluated the relationship between countermovement jump-developed algorithms and advanced statistical metrics among MLB position players ($n = 138$) during the 2013 to 2017 seasons. The researchers used a piezoelectric force plate with a sampling frequency of 1000 Hz to collect ground-reaction force data, including the eccentric rate of force development (load), concentric vertical force (explode), and concentric vertical impulse (drive), as well as the Sparta Score. The Sparta Score is a single metric to assess dynamic movement efficiency based on load, drive, and explode. The researchers

reported that the weighted stolen base (wSB) metric significantly correlated with the Sparta Score, with a predicted increase of 0.04 wSB for each 1-point increase in the Sparta Score. The wSB estimates the number of runs an individual player contributes to the team by stealing bases compared to the average player (68). Also, there was a positive correlation between the Sparta Score and stolen bases, with a mean predicted increase of 1 stolen base for every 3-point increase in the Sparta Score after adjusting for age and plate appearances. Furthermore, players with plate appearances of greater than 362 indicated that the mean stolen bases were statistically higher in the group that had a Sparta Score greater than 89 compared with the group with a Sparta Score lower than 89 ($p = 0.001$). Thus, position players with plate appearances of greater than 362 who had a Sparta Score greater than or equal to 89 may be the best base stealers, followed by younger players (<29 years) with a Sparta Score greater than or equal to 86. These findings suggest that a force-plate-derived composite measure of countermovement-jump performance was associated with stolen-base outcomes in MLB batters, with the relationship most apparent among players with more than 362 plate appearances. However, the retrospective observational design does not establish causation, and stolen-base totals also reflect playing opportunities, tactical decisions, player roles, and game context. More importantly, neither the Sparta Score nor stolen-base totals explain how players accelerate, negotiate the curve around first base, or preserve velocity while running multiple bases.

Recently, Szymanski et al. (145) determined whether change of direction speed, speed, and power correlated with curvilinear ability in 27 collegiate baseball players in NCAA Division I during the offseason. CODS was evaluated using a traditional CODS test in baseball, the pro-agility test. Speed was evaluated by players bunting and hitting a baseball and sprinting to first base using a hand-held stopwatch. Absolute power tests included standing long jump and estimation of standing long jump peak power, drive and stride leg lateral-to-medial jump, bilateral vertical jump, bilateral estimation of vertical jump peak power, actual bilateral vertical jump peak power, unilateral vertical jump from the drive and stride legs, and unilateral vertical jump peak power from the drive and stride legs. Bilateral and unilateral vertical jump tests were recorded using a Vertec. Curvilinear running ability was evaluated indoors on a basketball court using a novel field test, the Curvilinear Ability Test (CAT). The CAT is a multi-component CODS test that evaluates the ability of curvilinear (maneuverability) and CODS (COD that

requires linear sprint) demands (87). The researchers reported, among other correlation analyses, a high positive relationship between the CAT and the pro-agility test turning with the right foot ($r = 0.83$; $p < 0.05$; 69% of shared variance) and the pro-agility test turning with the left foot ($r = 0.81$; $p < 0.05$; 66% of shared variance). In speed terms, the researchers reported a moderately high positive relationship with bunting and then sprinting to first base ($r = 0.76$; $p < 0.05$; 58% of shared variance) and a moderate positive relationship with hitting and sprinting to first base ($r = 0.50$; $p < 0.05$; 25% of shared variance). Furthermore, for the lower extremity power, the researchers reported a moderately high negative relationship between the CAT and standing long jump to body mass ratio ($r = -0.73$; $p < 0.05$; 53% of shared variance) and standing long jump ($r = -0.72$; $p < 0.05$; 52% of shared variance). The researchers concluded that significant relationships exist between CODS, home to first base speed with different hitting situations, and power and the CAT. Also, more than 50% of the variation in the CAT was explained by the variation in the pro-agility test, bunting a baseball and then sprinting to first base, and standing long jump test methods. The researchers recommended that strength and conditioning coaches use the CAT when assessing the running ability of baseball players as it highly relates to the traditional (pro-agility test) CODS test and base running speed situational condition of running to first base and jumping tests.

As observed from this brief review, current assessments of base running speed and efficiency remain relatively basic. A valuable next step would be to use the CAT as a curvilinear training tool as it shared more than 50% of the variation with the traditional CODS test used in the baseball field, the pro-agility test. The CAT includes the most unique characteristic of base running, curvilinear running. In addition, the technology used to describe the determinants of BRE is simplistic e.g., hand-held stopwatch, timing lights, and Vertec. However, advanced wearable technology with high sampling frequency could provide better insights into the kinematics of curvilinear base running. Advanced technology needs to be introduced to provide a deeper understanding of the technical cues and strength qualities that improve BRE.

1.1.3 The training and monitoring of curvilinear base running speed and efficiency

Strength, power, CODS, and speed training are essential for improving base running speed (40,95,116,148,153). McEvoy and Newton (95) evaluated the effect of a 10-week plyometric training program on base running

performance in 18 national-level baseball players. One group received plyometric exercises (EXP); the other underwent a usual baseball training program (CON). The authors reported that both groups increased running speed between bases, but the plyometric-trained group improved even more (CON: 6.1% vs. EXP: 9.1%; $p < 0.05$). Recently, Nimphius et al. (116) examined the performance changes during 20 weeks of softball training (14 weeks of strength and power-focused resistance training). The authors also examined the relationship between percent change in muscle architecture variables (vastus lateralis including muscle thickness and fascicle length) and percent change in speed performance in 10 elite female softball players. Softball players were tested for first-base and second-base sprint performance. The authors reported a significant increase in pre- to post-training (6.52 s to 6.30 s) second-base sprint time. In addition, very large relationships were found between the percent change in vastus lateralis/muscle thickness and first-base sprint time ($r = -0.80$) and a large relationship with second-base ($r = -0.55$) sprint time. In addition, a large relationship was found between the percent change in vastus lateralis-fascicle length and first-base sprint time ($r = -0.53$) and a very large relationship with second-base ($r = -0.84$) sprint time. The authors concluded that increased strength and power could improve base running performance because of a strength- and power-focused resistance training program. As for Miyaguchi et al. (2011), it needs to be noted that such conclusions were made from a sample size of 10 elite female softball players; larger and more diverse sample sizes are needed to fully comprehend the effectiveness of a training program periodization to base running improvement. Thereafter, Fathoni and Rachman (40) determined the effect of a speed and CODS training program on base running speed on 28 high school softball players. The speed training program consisted of a 30-meter run at full speed with 5 to 6 reps per exercise and 2 to 4 times a week during the competition phase. The CODS training program consisted of running as fast as possible from one point to another by changing the direction and position of the body and speed. The authors reported that speed training significantly affected the base running speed. In addition, a significant difference between speed-training and CODS-training methods for base running speed in softball players, with the speed-training method being more specific for improving base running speed ($p = 0.036$). However, a high CODS level has a greater effect on base running speed than those with a low CODS level. The authors concluded that a specific speed training method could improve base running speed.

Training plans must be monitored to evaluate how the athletes are physiologically responding and adapting (51). Recently, Hornsby et al. (59) monitored maximal strength measures using the isometric mid-thigh pull conducted on a force plate at 1000 Hz and home runs (total and home runs per game). Four NCAA Division 1 baseball players with a minimum of 100 at-bats were part of the monitoring program across the 2009, 2010, and 2011 training and competitive seasons. The researchers reported that large to very large significant increases in peak force were noted from 2009 to 2010 ($d = 1.83$; $p = 0.031$) and 2011 ($d = 2.83$; $p = 0.004$) and a moderate increase from 2010 to 2011 ($d = 0.86$). Regarding home runs, the four baseball players had a positive percentage of change from 2009 to 2010 and 2011. Home runs per game improved from 0.32 in 2009 to 1.35 in 2010 and then declined to 1.07 in 2011. The decline in home run per game performance could be related to the ball-bat coefficient of restitution (BBCOR), a baseball bat performance standard that the NCAA adopted (59). Thus, stronger hitters may have an advantage in handling the more challenging hitting ability without the help of a "more recoil" bat. Regardless of the BBCOR, the four subjects contributed 89% in 2009, 87% in 2010, and 79% in 2011 of the team's total home runs. The researchers concluded that strength influenced hitting performance. Nevertheless, the implementation of advanced technology (using the isometric mid-thigh pull test) helped to identify the strength characteristics in each season and the possible BBCOR effect. As a limitation of the study, the researchers did not report the acute and long-term details of the training program. To our knowledge, no study has monitored strength using the isometric mid-thigh pull and compared it with base running speed and efficiency longitudinally. This thesis will monitor the participants' acute and longitudinal strength changes using the isometric mid-thigh pull with a load cell at a sampling frequency of 1000 Hz to investigate how strength qualities are affected by the wearable resistance (WR) training and how these changes explain variations in BRE and speed.

Training methods that resemble the mechanical specificity of a movement, such as base running, have greater potential to transfer to performance. Specific strength training using WR attached to the limbs may transfer to speed and agility (33) and as such, WR training allows athletes to train within a game-specific context (15). Nevertheless, Bustos et al. (15) examined this resisted sprint training method in 31 national-level soccer players aged 15–18 years, who were randomly allocated to a calf-loaded WR group (EXP: $n = 15$) or an unloaded control group (CON: $n = 16$). After eight weeks of WR incorporated into the warm-up, three times per week, the WR

group improved 10- and 20-m sprint performance by 1.64% and 1.23%, respectively. These improvements were significantly greater than those observed after unloaded warm-ups (10-m: ES = 0.97 and 20-m: 0.64; $p < 0.05$). These findings support the integration of calf-loaded WR into routine training to improve linear acceleration. However, improvements in soccer-specific linear sprinting cannot be assumed to transfer to baseball-specific curvilinear base running. To our knowledge, the effects of calf-loaded WR while performing the base running task have not been investigated, providing a rationale for the intervention examined in this thesis. To our knowledge, the effect of WR training while executing the base running task has not been investigated.

No mainstream literature currently explains how to improve base running ability in a baseball-specific manner. Training methods used thus far have been relatively generic and non-specific and have paid little attention to specific cueing and strengthening in relation to base running. Thus, the CAT and calf-loaded WR training should allow baseball players to train in a game-specific context. More research is needed that integrates a mechanical determinant approach to the training of base runners.

1.2 Thesis rationale and significance

Base running ability is important for scoring runs and winning games (6,9,10). Furthermore, baseball players who are fast in a linear sprint are believed to be fast base runners because they can maintain high speed due to learned technical skills. During curvilinear sprinting, maintaining high-speed allows them to sprint to the next base efficiently, separating pure linear speed and BRE (103). Current assessment and monitoring methods used in base running at this stage are relatively fundamental as most of the CODS tests are linear-focused and advanced technology with high sampling frequency is not routinely used. To date, it is well established in the literature that base running is important, however, there is a gap in defining how important base running ability is and how technology could improve it through an improved kinematic and kinetic understanding of this motor task. With better diagnostics, there is the opportunity to individualize exercise prescriptions to optimize base running through improved BRE, base running ability, run scoring, and game outcomes. Therefore, this research will investigate whether BRE can be improved in baseball players.

1.3 Purpose and research questions

The overarching question of this thesis was, "Can BRE be improved in baseball players?" To answer this question, three specific research questions were formulated:

- What is the current status of the literature on linear and curvilinear base running in baseball?
- Can GNSS and IMU foot pod technologies provide reliable and practically useful information for assessing linear and curvilinear base running performance and mechanical demands?
- Can calf-loaded wearable resistance, integrated into baseball-specific training, improve linear sprinting, curvilinear base running, and BRE?

1.4 Research design

This thesis follows AUT's Pathway 2 thesis-by-publication format, in which the research chapters are presented as individual manuscripts that have been published, submitted, or prepared for publication in peer-reviewed journals. Due to this thesis-by-publication approach, there may be some repetition both between chapters and throughout the thesis. This repetition is primarily associated with the need for each manuscript to provide sufficient background and methodological context to be understood independently. Nevertheless, the chapters have distinct objectives and contributions to answering the overarching question of the thesis. Three reviews, two reliability studies, two perspective articles, one cross-sectional study, and two experimental studies were used to answer the thesis research questions:

1. A retrospective observational, exploratory analysis of MLB players-season data was undertaken to describe base running characteristics and associated patterns.
2. A narrative review was undertaken to review the methods used to assess base running in baseball and softball.
3. A narrative review was undertaken to review the training methods to improve curvilinear base running in baseball players.

4. A repeated-measures design was used to quantify the reliability of a high-frequency Global Navigation Satellite System (GNSS) unit for base running assessments (i.e. CAT, base running, and straight-line sprint)
5. A methodological case-study design was used to demonstrate how GPS-derived velocity–time profiles can be interpreted to evaluate base running efficiency during linear and home-to-second-base curvilinear sprint assessments.
6. A repeated-measures design was used to quantify the reliability of the foot pod inertial sensor for base running assessments (i.e. CAT, base running, and linear sprint)
7. A methodological case-study design was used to demonstrate how bilateral inertial measurement unit (IMU) foot pods can be used to interpret inside- and outside-foot mechanics during linear and curvilinear base running assessments, including ground contact time, stride length, push-off acceleration, and impact acceleration.
8. A descriptive study was used to kinematically profile (i.e., speed, time, distance, and acceleration) base running in baseball players using high-frequency GNSS and foot pod inertial sensors, and to determine which variables were associated with high BRE.
9. A case-study design comparing the effects of two versus three WR training sessions per week.
10. A randomized, controlled, parallel-group longitudinal intervention design was used to quantify the training effect of an 8-week baseball-specific calf-loaded WR intervention on base running performance in high-school baseball players.

Figure 1.1 Thematic diagram of proposed research section flow and chapter titles.

<table>
<tr><th colspan="2">The effect of curvilinear training methods to improve base running efficiency amongst baseball players</th></tr>
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<tr><td colspan="2">Section 1: Reviewing the literature and public databases</td></tr>
<tr><td>Chapter 2: Retrospective observational correlational study: "The need for speed: Linear and curvilinear characteristics in Major League Baseball players"
Published in Physical Activity</td><td>Chapter 3: Narrative review: "Introduction to an advanced change of direction test in baseball and softball: The Curvilinear Ability Test"
Published in Strength and Conditioning Journal</td></tr>
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<tr><td>Chapter 7: Repeated measure: "Improving base running diagnostics with foot pod technology: Intersession reliability of linear and curvilinear running performance"
Published in Journal of Strength and Conditioning Research</td><td>Chapter 8: Methodological case-study: "New perspective on analysing and interpreting base running efficiency: An IMU foot pod methodological case approach"
Published in: Applied Sciences</td></tr>
<tr><td colspan="2">Chapter 9: Cross-sectional: "Functional asymmetries in inside-outside foot mechanics when curvilinear sprinting in baseball"
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<tr><td>Chapter 10: Case study: "Base running responses to calf-loaded wearable resistance in baseball: A case study comparison of two versus three sessions per week"
Ready for submission</td><td>Chapter 11: Randomized controlled trial design study: "Training the curve: Calf-loaded wearable resistance sprint training altered pattern of adaptation in base running performance in high-school baseball players"
Ready for submission</td></tr>
<tr><td colspan="2">Section 4: Summary, Practical Application, Limitations, Future Research Directions, and Conclusion</td></tr>
</table>

Chapter 2: The need for speed: Linear and curvilinear characteristics in major league baseball players

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This chapter comprises the following published paper in the *Physical Activity* journal

Reference:

Martinez-Rodriguez JA, Crotin RL, Neville J, Cronin JB. The need for speed: Linear and curvilinear characteristics in Major League Baseball players. Physical Activity. 2024;2(2):3-10.

2.1 Prelude

In addition to batting skills, base running ability is important to score runs and win games. However, recent analyses of the importance of base running to match and competition outcomes have not been reported, and the impact of baseball running ability may differ from articles published in 2010 (9,10). With the availability of public data, the impact of base running can be analysed more comprehensively and in greater detail. Therefore, the purpose of this chapter was to describe selected MLB base running statistics and explore their observed associations with stolen-base and doubles outcomes . It sets the foundation for the chapters of this thesis by determining: 1) current values of base running key performance indicators related to home-to-first base running and running multiple bases; 2) how KPIs are related to each other; and, 3) the descriptive patterns of these measures on stealing and running single and multiple bases.

2.2 Introduction

Base running ability impacts offensive performance and team wins (6,9,10,17). Baumer (9) researched the connection between speed and scoring runs in Major League Baseball (MLB) players and concluded that the impact is typically ± 25 runs per season. By grouping the best base runners, a team can score as many as 70 runs per season (9). Therefore, improving base running ability to make players better base runners could maximize run-scoring ability. In the following year, Baumer and Terlecky (10), evaluated ten situations to take an extra base, and concluded that the more skilled base runners added approximately 10 runs per season, improving their offensive performance by more than 20%. Recently, Athanasakis et al. (6) investigated the game-related indicators (batting and base running) contributing to scoring runs and winning games at an Olympic level. The authors mentioned that fast sprinting from home to first base to reach the first base safely, base stealing with optimal technique during the lead-off, and running multiple bases contributed to offensive performance.

To further base running research, base running speed and acceleration have been investigated in multiple studies for MLB players (21,25,26,61). In 1992, Coleman and Lasky (26) tested the running speed (split times at 0 and 27.4 m) in MLB players (Houston Astros) for the 1992 season. The authors reported that the average time in the first half (0 - 27.4 m), in the second half (27.4 – 54.9 m), and the total 54.7 m sprints were 3.75 s, 3.21 s, and 6.96 s, respectively. Although the authors collected running data using photoelectronic sensors, it is important to highlight that sport scientists and strength and conditioning coaches have strongly criticized the 54.7-m linear run test as it is considered irrelevant to actual competitive base running conditions that are more acceleration-driven rather than max velocity-driven (23,29,87). Therefore, collecting players' speed and acceleration at split distances over the run from home plate to first base versus 54.7 m with a curvilinear motion is more specific for profiling and interpretation and may have a greater ability to predict on-field outcomes that lead to wins. This was confirmed by Chernoff (17), who investigated which baseball outcomes were most important for scoring runs. The author concluded that doubles (2B) were a significant explanatory variable, meaning that base running ability from home to second base, a curvilinear pattern, is important to score runs and consequently win games.

Coleman and Amonette (21) further evaluated the time to run from home to first base with a hand-held digital stopwatch that assessed speed in MLB players from 2007 to 2010. The authors reported that the time from home to first base was significantly correlated with acceleration in the first half (0 - 13.7 m) (r = - 0.76; p < 0.001) and second half (13.7 - 27.4m) (r = - 0.23; p < 0.001) on the way to first base. Though both correlations were significant, it must be noted that ~58% of the time a base runner takes to reach the first base from home plate was explained by first half (0 – 13.7 m) acceleration, whereas ~6% was explained by the acceleration in the second half (13.7 – 27.4 m).

Previous researchers have provided a fundamental understanding of base running, yet since 2015, the MLB has used StatCast, a system composed of higher-definition cameras that have enabled additional precision and collection of baseball player movements. In 2020, the StatCast platform added the Hawk-Eye optical tracking system (The Hawk-Eye StatCast system). The Hawk-Eye system consists of twelve high-definition cameras, where seven cameras are dedicated to tracking players' movement in the field at 50 Hz in each MLB stadium. The seven cameras are placed behind the left and right fields (52,62). These higher-definition cameras are based on pose tracking in rapid movements and directional change situations, not just the center or mass, with no indication of arms or legs to track (144). The Hawk-Eye system was evaluated in 2004 by the International Tennis Federation; an error of less than 5 mm was needed to pass the International Tennis Federation tests. It was reported that the technology had an overall uncertainty of ± 0.9 mm (42). With the advancement of higher-definition camera tracking technology, Hawk-Eye elevated the accuracy to ± 0.1 inches to help counteract systematic error and random uncertainty associated with human-operated data collection methods (41,144). Using this data, the StatCast Metrics Engine system filters the location data, computing base running key performance indicators (KPIs), such as player acceleration and speed. Then, the data captured by StatCast is

available to coaches, fans, and players through a website called Baseball Savant (https://baseballsavant.mlb.com/), which provides batting, fielding, pitching, and base running (73).

With this in mind, the main aims of this study using data captured by the StatCast System were to determine: 1) current values of base running key performance indicators (KPIs) related to home-to-first base running (i.e., intersegmental linear time, speed, and acceleration from home to first base and home-to-first base time) and running multiple bases (base running speed and *Competitive Runs*); 2) how KPIs were related to each other; and, 3) the influence of these measures on stealing a base (running one base in a linear sprint) and doubles (running two bases in a curvilinear sprint).

2.3 Methods

2.3.1 Experimental approach to the problem

To extend findings previously published on base running ability, a retrospective observational study was conducted using publicly available MLB player-season records from 2019 – 2023. This study determined current KPIs values: intersegmental linear speed and acceleration from home to first base (4.6, 9.1, 13.7, and 27.4 m split distances speed and acceleration, and home-to-first base time) and KPIs related to running multiple bases (base running maximum speed and Competitive Runs). Spearman correlations were used to determine the relationship between KPIs and the descriptive rank associations between selected running KPIs. The KPIs were separated into quartiles to describe how the mean KPIs varied across stolen-base and doubles quartiles.

2.3.2 Subjects

Professional baseball players who participated in the MLB season from 2019 to 2023 were eligible for inclusion in the study using publicly available data. The range of years selected was chosen to avoid the aging effect; the player's ability is assumed to be roughly constant over a short time span (71). The publicly available data was initially accessed on May 4th, 2023 from the online databases https://baseballsavant.mlb.com/leaderboard/running_splits, https://baseballsavant.mlb.com/leaderboard/sprint_speed, Lahman baseball database, and www.baseball-reference.com, which contains unique identification numbers and the names of every player who has played in the MLB. Only stolen bases and double baseball outcomes relating to base running were considered. Accordingly, all pitchers were omitted from the sample with a focus on position player data. Further exclusion criteria entailed having fewer than 200 plate appearances that reflect injury or irregular play (71). The resulting dataset contained 924 observations on 475 different players with the following positional distribution: 79 first-base, 134 second-base, 125 third-base, 110 short-stops, 71 catchers, 129 center-fielders, 137 left-fielders, 107

right-fielders, and 32 designated hitters. Since the data is publicly available, IRB approval was not required, as similar work could be freely undertaken without institutional association and data permission.

2.3.3 Measurements

Intersegmental linear sprint time to first base, base running speed, Competitive Runs, and home-to-first base sprint time data were downloaded and analysed from Baseball Savant's Sprint speed and 90 ft running split leaderboard data, which contained data on players from all 30 MLB teams. Then, using a unique identification number and the names of each player, the data of stealing a base and running multiple bases was matched with the Baseball Savant Leaderboards data.

2.3.4 Data analysis

The base running KPIs (i.e., base running speed and Competitive Run) variables are described as shown on the Baseball Savant Leaderboard webpage (https://baseballsavant.mlb.com/). The base running KPIs variables are:

1 Average speed:

Formula:

$$\frac{\text{Distance (current segment)}}{\text{Time (current segment)}}$$

2 Average acceleration: The change in speed calculated by individual segment points from the start to the 27.4 m mark, i.e., 0 – 4.6 m segment (approximately 17% of the home to first base distance), 4.6 m—9.1 m segment (33% of the home to first base distance), 9.1 m—13.7 m segment (50% of the home to first base distance), and the 22.8 m—27.4 m segment (100% of the home to first base distance) that spans the entire home-to-first base time.

Formula:

$$\frac{\text{Final speed (current segment)} - \text{Initial speed (previous segment)}}{\text{Elapsed time}}$$

3 Base running speed: How fast a base runner can run in different situations during a game. The best two-thirds of the runs collected when running multiple bases and running from home to first base during the game are averaged for the player's seasonal average. The run situations that are addressed and used to average base running speed are described as follows:

3.1 Running multiple bases: This measures how fast a player can run two or more bases in a non-home run situation, except when a base runner is on second base and a hit with the possibility of running extra bases happens.

3.2 Running from home to first base: This measures how fast a player can run from the point of bat-on-ball contact in the home plate to the moment the batter reaches first base, specifically when a batter hits the ball weakly or not very far.

4 Competitive Run (#): The speed ranges from 7.01 m*s^{-1} (23 ft*s^{-1}; poor) to 9.10 m*s^{-1} (30 ft*s^{-1}; elite), where the base runner needs to run at least ten times within this range to be indexed in the dataset.

2.3.5 Statistical analyses

Descriptive analyses were processed using the RStudio: Integrated Development for R. (version 2023.06.0+421; RStudio, Inc., Boston, USA) in addition to the tidyverse package [19]. Normality and outlier analysis was performed on the data. Means and standard deviations were used as measures of centrality and spread of data. The relationship of base running KPIs intersegmental linear speed and acceleration on 4.6, 9.1, 13.7, and 27.4 m, base running speed, and home-to-first base time was quantified via Spearman rank correlations coefficients (ρ). Because some athletes contributed observations from multiple seasons, the assumption that all observations were independent was not met for conventional inference; therefore, no correlation p-values are presented. Players with more eligible seasons also contributed more observations to the pooled coefficients. To describe the linear running ability on base running, the data were divided into four quartile groups (i.e., 0-25%, 25-50%, 50-75%, and 75-100%) for stolen bases (SB) and doubles (2B). For each quartile group, the average value of base running KPIs within each quartile was calculated and visually analysed to determine trends.

2.4 Results

Intersegmental linear time, speed, and acceleration KPIs over 27.4 m distance for MLB players from 2019 to 2023 seasons are detailed in Table 1. The greatest changes in speed and acceleration occurred in the 0 - 4.6 m segment (approximately 17% of the home to first base distance). In the 9.1 - 13.7 m segment (50% of the home to first base distance), base runners had achieved 84% of their reported 27.4 m speed (5.73 vs. 6.81 m·s^{-1}, which was near their total maximal given the minimal change in acceleration (0.39 m·s^{-2}) in the 22.8 – 27.4 m segment (100% of the home to first base distance).

Table 2.1. Intersegmental linear time, speed and acceleration key performance indicators over 27.4 m distance for MLB players from 2019 to 2023 seasons.

Segment (m)	Time (s) (mean ± SD)	Speed (m·s^{-1}) (mean ± SD)	Acceleration (m·s^{-2}) (mean ± SD)
4.6	1.12 ± 0.04	4.10 ± 0.13	3.66 ± 0.24
9.1	1.80 ± 0.05	5.06 ± 0.15	1.42 ± 0.13
13.7	2.39 ± 0.07	5.73 ± 0.18	1.15 ± 0.10
27.4	4.03 ± 0.14	6.81 ± 0.24	0.39 ± 0.10

The measures for baseball offensive KPIs related to base running are shown in Table 2. The average base running speed of 8.35 $m \cdot s^{-1}$(27.40 $ft \cdot s^{-1}$) was above the average (8.06 $m \cdot s^{-1}$ [26.44 $ft \cdot s^{-1}$) of the *Competitive Run* speed range.

Table 2.2. Base running key performance indicators measure for MLB players from 2019 to 2023 seasons.

Variables	Measure (mean ± SD)
Competitive runs (#)	147.82 ± 57.07
Base running speed ($m.s^{-1}$ [$ft \cdot s^{-1}$])	8.35 ± 0.39 (27.41 ± 1.27)
Home-to-first base time (s)	4.41 ± 0.18

The descriptive Spearman rank associations between segmental speed or acceleration and the two running outcomes are presented in Table 2.3. For speed, the correlation with seasonal base running speed was positive and increased from $\rho = 0.44$ at 4.6 m to $\rho = 0.91$ at 27.4 m; the corresponding association with home-to-first-base time was negative ($\rho = -0.63$ to -0.86).

Table 2.3. Descriptive Spearman rank correlation coefficients (ρ) between intersegmental speeds and accelerations and base running speed and home-to-first-base time

	Base running speed (ρ)	Home-to-first base time (ρ)
4.6 m Speed ($m.s^{-1}$)	0.44	−0.63
0 - 4.6 m Acceleration ($m.s^{-2}$)	0.44	−0.63
9.1 m Speed ($m.s^{-1}$)	0.67	−0.77
4.6 - 9.1 m Acceleration ($m.s^{-2}$)	0.77	−0.62
13.7 m Speed ($m.s^{-1}$)	0.76	−0.82
9.1 - 13.7 m Acceleration ($m.s^{-2}$)	0.88	−0.76
27.4 m Speed ($m.s^{-1}$)	0.91	−0.86
22.8 - 27.4 m Acceleration ($m.s^{-2}$)	0.74	−0.48

Note: Positive coefficients indicate that the two variables tend to increase together; negative coefficients indicate that one tends to decrease as the other increases.

The quartile statistics for the players who stole the least (0-25%) to most (75-100%) bases can be observed in Table 2.4. A linear increase in speed, acceleration, *Competitive Runs*, and base running speed was seen across the quartiles. The players who stole the most bases had the highest speeds and accelerations, *Competitive Runs*, base running speed, and the lowest home to first base time.

Table 2.4. Quartile statistics for the players who stole the least to most bases (means ± standard deviations).

Stolen Bases	0-25%	25-50%	50-75%	75-100%

4.6 m Speed ($m \cdot s^{-1}$)	4.03 ± 0.12	4.06 ± 0.09	4.10 ± 0.10	4.17 ± 0.11
0 – 4.6 m Acceleration ($m \cdot s^{-2}$)	3.53 ± 0.21	3.58 ± 0.16	3.66 ± 0.19	3.77 ± 0.19
13.7 m Speed ($m \cdot s^{-1}$)	5.65 ± 0.15	5.73 ± 0.12	5.78 ± 0.13	5.89 ± 0.13
4.6 –13.7 m Acceleration ($m \cdot s^{-2}$)	1.26 ± 0.08	1.33 ± 0.08	1.35 ± 0.07	1.42 ± 0.07
27.4 m Speed ($m \cdot s^{-1}$)	6.68 ± 0.20	6.81 ± 0.17	6.88 ± 0.17	7.02 ± 0.15
13.7 – 27.4 m Acceleration ($m \cdot s^{-2}$)	0.62 ± 0.07	0.67 ± 0.08	0.68 ± 0.07	0.72 ± 0.06
Competitive Runs (#)	128.76 ± 52.94	143.77 ± 55.02	169.13 ± 53.96	185.04 ± 55.15
Home to first base time (s)	4.55 ± 0.15	4.45 ± 0.13	4.39 ± 0.13	4.30 ± 0.10
Base running speed ($m \cdot s^{-1}$ [$ft \cdot s^{-1}$])	8.16 ± 0.29 (26.78 ± 0.94)	8.40 ± 0.29 (27.57 ± 0.95)	8.47 ± 0.29 (27.79 ± 0.95)	8.66 ± 0.26 (28.40 ± 0.84)

The quartile statistics for the players who ran two bases are detailed in Table 2.5. There was a linear increase in the number of *Competitive Runs* across the quartiles. However, no other trends were observed in any of the variables.

Table 2.5. Quartile statistics for the players who ran two bases (means ± standard deviations).

Two bases	0-25%	25-50%	50-75%	75-100%
4.6 m Speed ($m \cdot s^{-1}$)	4.06 ± 0.12	4.10 ± 0.09	4.09 ± 0.12	4.08 ± 0.13
0 – 4.6 m Acceleration ($m \cdot s^{-2}$)	3.58 ± 0.22	3.66 ± 0.17	3.63 ± 0.22	3.62 ± 0.24
13.7 m Speed ($m \cdot s^{-1}$)	5.71 ± 0.16	5.79 ± 0.13	5.76 ± 0.17	5.74 ± 0.19
4.6 – 13.7 m Acceleration ($m \cdot s^{-2}$)	1.31 ± 0.10	1.36 ± 0.08	1.34 ± 0.09	1.32 ± 0.11
27.4 m Speed ($m \cdot s^{-1}$)	6.77 ± 0.21	6.91 ± 0.17	6.85 ± 0.21	6.80 ± 0.25
13.7 – 27.4 m Acceleration ($m \cdot s^{-2}$)	0.65 ± 0.08	0.70 ± 0.07	0.67 ± 0.07	0.65 ± 0.08
Competitive Runs (#)	101.10 ± 27.72	132.29 ± 39.96	172.77 ± 40.02	220.00 ± 41.44
Home to first base time (s)	4.47 ± 0.16	4.40 ± 0.14	4.44 ± 0.16	4.45 ± 0.19
Base running speed ($m \cdot s^{-1}$ [$ft \cdot s^{-1}$])	8.33 ± 0.33 (27.32 ± 1.07)	8.52 ± 0.30 (27.94 ± 1.00)	8.41 ± 0.32 (27.59 ± 1.04)	8.34 ± 0.37 (27.38 ± 1.22)

2.5 Discussion

Base running ability is an important component of winning games and championships and so it is important to have descriptive reference values from the sampled MLB player-season records for coaches to compare athletes. The first aim of this study was to provide such data by collating and synthesizing data captured by in-stadium technology of MLB players from the 2019-2023 seasons. Data on 475 players across 30 teams involving 924 observations provided the basis of this descriptive reference values from the sampled MLB player-season

records. Several researchers have reported base running time and speed data over past seasons (21,25,26,56). In 1992, Coleman and Lasky (26) evaluated the 54.7 m sprint in MLB players (n = 210). They reported that the first 27.4 m of the 54.7 m sprint was completed in 3.75 ± 0.11 s, which was quicker than the average home-to-first base time (4.41 ± 0.18 s - Table 2.2) of the MLB players of this study. The differences could be attributed to the laboratory-like testing where comprehensive warm-up and stretching took place before the sprints, crouched starts, and technology differences (pressure mats and photoelectric sensors) as opposed to the in-stadium HawkEye system in- game data. Coleman and Dupler (25) reported an average (n = 10 players) home-to-first base time of 5.03 ± 0.98 s and a peak home-to-first base time of 4.30 ± 0.12 s, the data collated from 2,683 times that were recorded during 162 games from the 1998 MLB season. These researchers also reported an average home-to-first base speed of 5.45 ± 1.08 $m \cdot s^{-1}$ and a peak home-to-first base speed of 6.38 ± 0.02 $m \cdot s^{-1}$. The average speed of this cohort, was less than the 27.4 m segment speed (6.81 ± 0.24 $m \cdot s^{-1}$ - Table 1) of the players of this study. Once more, the methodological differences in capturing sprint speed could explain the differences in results. For example, Coleman and Dupler (25) assessed the time to first base with a handheld stopwatch, the tester seated at field level even with first base, and the tester starting the watch at bat contact with the ball. In current practice, handheld timing methods are obsolete in game play that now requires highest sampling frequency data and updated descriptive reference values as presented in this work. Differences could also be attributed to the evolution of player athleticism over the years.

Another focus of this study was on identifying the relationship between intersegmental linear speed and acceleration segments and base running speed and home-to-first base time. The rank correlations indicated that greater 13.7 m speed was generally associated with higher base running speed and shorter home-to-first-base time. Stronger pooled rank associations were observed for later speed segments, particularly at 27.4 m. It would seem that the associations observed at 13.7 m suggest that early sprint indicators warrant attention in baseball-specific assessment. These results are similar to those of Coleman and Amonette (21), who reported that 58% of the characteristics of the first 13.7 m segment (0 – 13.7 m) acceleration explained the home-to-first base time.

To determine the importance of linear running ability on base running, the 2023 MLB players data were divided into four quartile groups (i.e., 0-25%, 25-50%, 50-75%, and 75-100%) for stolen bases (SB) and doubles (2B). Those players who stole the most bases had the highest speeds (4.6 $m \cdot s^{-1}$ = 4.17 $m \cdot s^{-1}$; 13.7 $m \cdot s^{-1}$ = 5.89 $m \cdot s^{-1}$; 27.4 m = 7.02 $m \cdot s^{-1}$) and accelerations (4.6 $m \cdot s^{-2}$ = 3.77 $m \cdot s^{-2}$; 13.7 m = 1.42 $m \cdot s^{-2}$; 27.4 m = 0.72 $m \cdot s^{-2}$), *Competitive Runs* (185.04 times) and base running speed (8.66 $m \cdot s^{-1}$), and the lowest home to first base time (4.30 s). However, when it came to running doubles, there was a linear increase in the number of *Competitive Runs* across the quartiles, but no other trends were observed in any of the speed and acceleration measures (see Table 2.5). It was noted that in fact, values were very similar between quartiles. Players in higher stolen-base quartiles also showed higher group-average linear sprint values in this dataset. However, when running multiple bases (doubles), which involved curvilinear running from home to second base, it seemed that the absence of a

comparable pattern across doubles quartiles may motivate further investigation of curvilinear running characteristics. This finding is supported by other authors who have found differences in kinetics, kinematics, and spatiotemporal variables, including ground contact time (GCT), stride length (SL), and step frequency between curvilinear and straight-line sprint performance (7,11,18,19,36,45,64,65,103,141,142).

2.6 Conclusion

This retrospective analysis provided descriptive reference values for selected MLB player-season running characteristics. Higher stolen-base quartiles generally exhibited greater mean linear speed and acceleration, whereas doubles quartiles did not show the same consistent pattern. It maybe that base runners need to be assessed and trained for linear and curvilinear sprint ability, rather than assume improvement with the assessment and training of linear speed translates to improved multiple base running.

Chapter 3: Introduction to an advanced change of direction test in baseball and softball: The curvilinear ability test

This chapter comprises the following published paper in the *Strength and Conditioning Journal*.

Reference:
Martínez-Rodríguez JA, Crotin RL, Szymanski DJ. Introduction to an advanced change of direction test in baseball and softball: The curvilinear ability test. *Strength Cond J* 46: 279-286, 2023.

3.1 Prelude

In the previous chapter, retrospective analysis of baseball data provided descriptive reference values for selected MLB player-season running characteristics. Higher stolen-base quartiles generally exhibited greater mean linear speed and acceleration, whereas doubles quartiles did not show the same consistent pattern. Baseball base running involves maximal sprinting that at times requires running a curvilinear path with periods of acceleration, deceleration and re-acceleration. Traditionally, the pro-agility test has been used in baseball and softball to evaluate COD ability, however ecologically valid tests and training tools are needed to simulate typical base running movements. The purpose of this chapter was to introduce a new field assessment called the CAT that measures both curvilinear and linear properties of base running and determine the reliability of the variables used in the CAT.

3.2 Introduction

Our current understanding of agility is evolving; thus, clear definitions are needed (155). COD ability is the centre of three interactive components: agility, CODS, and manoeuvrability. COD ability is the ability to change direction independent of the planned or unplanned context. CODS includes only the linear and COD preplanned action, and agility integrates the perceptual-cognitive component. In addition, maneuverability involves COD, focusing on individual tactical techniques. The interaction between CODS and maneuverability contributes to the maintenance of speed (113). Figure 2 displays the interaction between agility, CODS, and maneuverability interrelating an overall COD ability. In addition, it provides base running examples, subdivided by dashed lines in boxes with rounded edges. Baseball and softball are sports that require movements in linear, curvilinear, lateral, and diagonal directions in reaction to visual stimuli and situational commands involving rapid COD and explosive running. Linear, curvilinear, lateral, and diagonal movements require COD ability to accomplish accelerations, decelerations, and redirections of body movement (22,23,29,80,95,103,115,146).

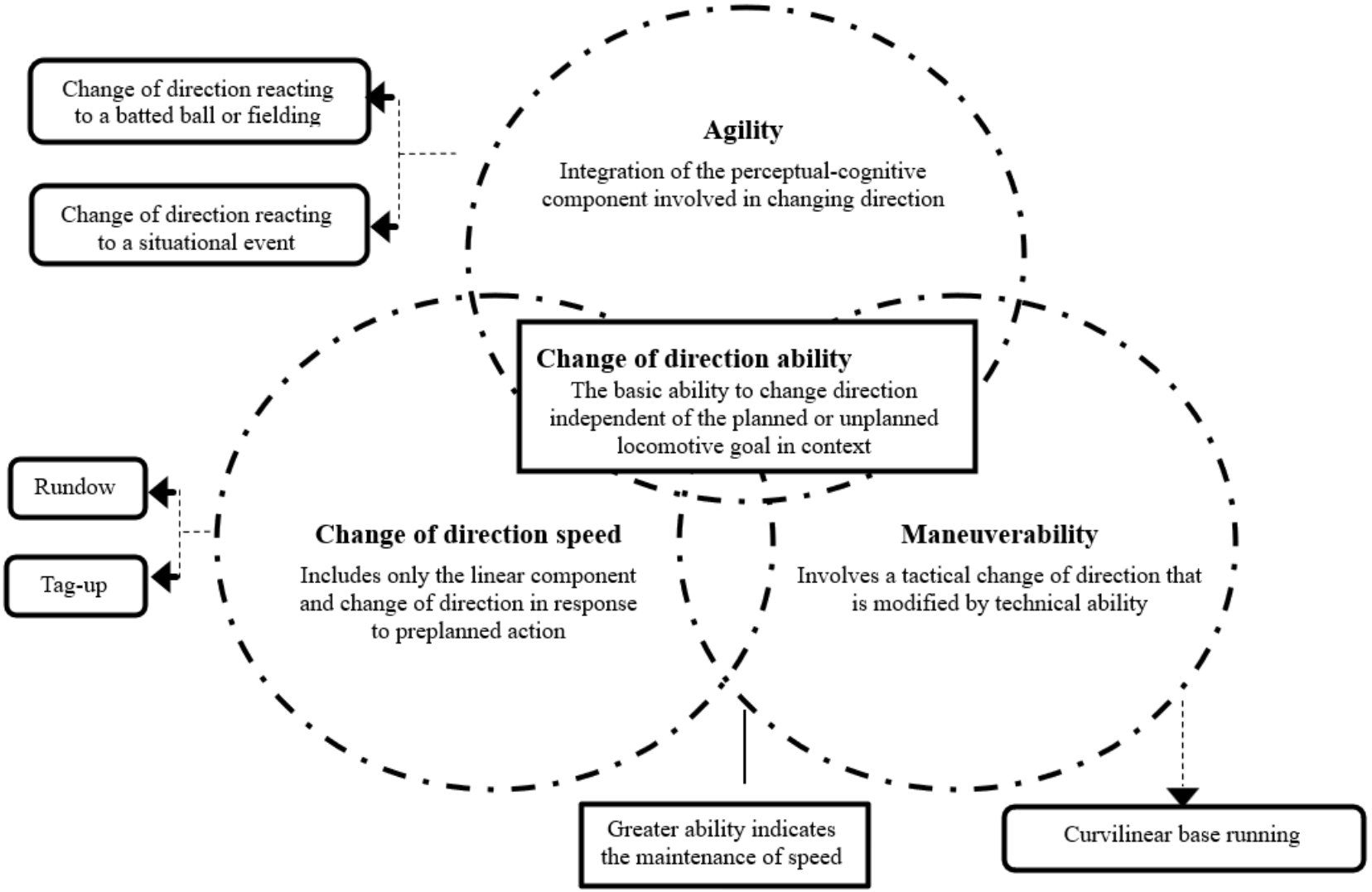


Figure 3.1. Conceptual framework illustrating the interactions among change of direction speed, maneuverability, and agility, with examples of their application to baseball-specific movement tasks

Hoffman et al. (56) evaluated professional baseball players and reported a significant inverse relationship between the pro-agility times (r = -0.482) and 9.1-m (r = -0.422) with stolen bases. In addition, based on regression statistics, the pro-agility test (p = 0.03) and 9.1-m sprint (p = 0.05) were significant predictors of total bases and the 9.1-m sprint (p = 0.05) was the only predictor of stolen bases. As demonstrated by Hoffman et al. (56), the pro-agility test is commonly used to assess CODS in baseball because it simulates the base running starting position stance and cross-over movement in base running and stolen bases and, at present, is still considered the gold standard CODS test (56,82). However, the pro-agility test is void of the tactical element of base running and does not account for curvilinear movement, as this test only requires a maximum linear distance of 18.3 m (60 ft) and two 180° COD. Furthermore, Coleman and Amonette (22,23) stated that quickness (starting time) and acceleration (running in the first 13.7 m [45 ft]) are more important than pure speed since most offensive and defensive runs in game situations are under five seconds. Specific game performance variables can be improved with effective starts, acceleration, curvilinear, and CODS ability with a specific body position.

In baseball base running, the goal of reaching a base that is 27.4 m (90 ft) away in the shortest time possible depends on the initial linear speed and maximum acceleration during the first 13.7 m (45 ft) (23). The offensive movement in baseball from a lead-off stance begins with a jab step with the right foot and cross-over with the left foot that transitions to a linear sprint position with increasing acceleration for the first 13.7 m (45 ft) towards the base to maximize the opportunity to reach the 27.4 m (90 ft) base in the shortest possible time (23). However, before reaching the next base (first base to second base), a curvilinear movement to the left occurs when rounding a base as the runner travels toward home plate.

Similar to professional baseball, which has used the pro-agility test to assess CODS (56,82), softball has used the 505 agility test as a general test to assess the relationship between CODS and base running (115,116). Nimphius et al. (115) also evaluated the CODS, sprint to first base (18.3 m or 60 ft), and sprint to second base (36.8 m or 120 ft). The authors reported a significant positive relationship between second base performance and 505 agility test performance from the non-dominant side. Therefore, curvilinear ability needs to be evaluated uniquely as the run from first base to second base requires curvilinear and CODS components and validates the need for sport-specific COD testing to give feedback to the players and coaches for better decision making.

Softball is a sport that includes base running, similar to baseball, but with a shorter distance between bases. As demonstrated by Nimphius et al. (115), the 505 agility test is commonly used to assess base running CODS performance (first base and second base). It is approximately the first half of the run to first base in softball. However, similar to the pro-agility test, the 505 agility test is void of the tactical element of base running in softball and does not account for curvilinear movement having a maximum distance of 18.3 m

(60 ft) and one 180° COD. Furthermore, the significant positive relationship between the second base and 505 agility test performance could be because the player is recovering the lost time in the linear phase due to a poor ability at the curvilinear phase (111).

The performance in softball first base and second base running depends on the first 10.1 m (33 ft) over the sprint to first base and second base (115). Base running in softball consists of starting position, leading off the base, base running ability and performance, and body position. Another way to advance the base runners around the bases is to steal a base (6,54,83,92,115). Softball has a distance between bases of 18.3 m (60 ft), a difference of 9.1 m (30 ft) between bases in baseball. However, softball and baseball have a characteristic in common: a curvilinear movement to the left when rounding a base as the runner travels around bases toward home plate. When evaluating the curvilinear and CODS component in base running, it is advisable to evaluate the base running ability between each base path segment and not rely solely on the linear sprint as the major determinant of the total time. For this reason, instead of emphasizing the total base running ability, the various COD segments can provide valuable information to analyse the players' curvilinear and CODS to minimize deceleration and the centrifugal force that may take the runner offline between bases (110,115).

Some base running examples include: 1) running to first base after hitting a baseball or softball (batted ball), 2) running between bases, and 3) running back and forth to a base changing direction similar to a run-down or going back to a base to tag-up on a fly ball to the outfield (146). A base runner must maximize the opportunity to reach each base faster than the ball being received by a defender to ultimately score a run, be aware of another teammate who is also running between bases, and know where and how defensive players are positioned (80). Figure 3 proposes a modified base running ability model based on related COD articles, as in Martínez-Rodríguez et al. (91). The flow chart goes from base running ability to key outcomes of interest arriving at the measure of increased probability of championship wins.

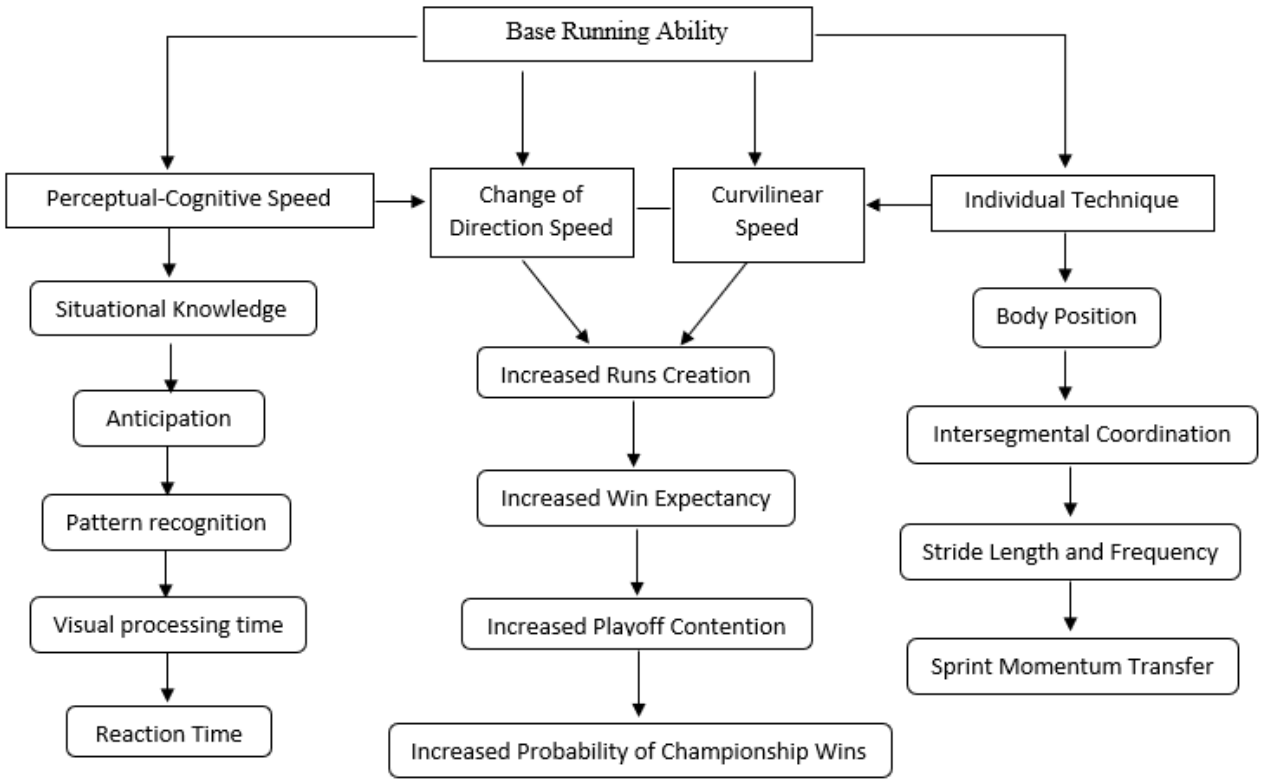


Figure 3.2. Proposed base running ability model diagram.

Although specific exercises to improve base running are available (80), to our knowledge, no curvilinear and CODS test integrating specific baseball and softball base running locomotive demands has been developed and published. Martínez-Rodríguez et al. (91) designed a new curvilinear and CODS multi-component test named Baseball-Specific Agility Test. However, the Baseball-Specific Agility Test did not investigate the efficacy and validity of on-field performance. Furthermore, the perceptual-cognitive ability was not involved in the test. Moreover, the Baseball-Specific Agility Test did not represent softball and baseball base running. Thus, a new name, Curvilinear Ability Test (CAT), has been proposed to be more inclusive. The CAT will be accepted as the appropriate name for the test going forward.

The CAT requires four cones and boundaries (Figure 3) beginning with participants in a lateral, lead-off stance at cone number one, located 1.2 m (4 ft) away from the reference cone. The right foot should be in front of cone number one, toes lined up with the reference cone, and perpendicular to the first segment of the test. From this starting position, base runners quickly initiate a movement with a drop/jab step with the right foot followed by a cross-over step (left foot crossing the right foot), running towards cone number two in a curvilinear movement similar to running from the first to third base. To define the laneways where the athlete must stay, boundaries A and B were implemented to control the area where athletes have to

perform the curvilinear movement. Athletes then touch cone number two with the right hand and quickly perform a COD towards cone number three, touch it with the left hand, and finally perform a COD and sprint past cone number four. The opposite hand should not touch the ground while the player touches a cone. The reason is that the corresponding author learned from previous experience that players performed the test differently when touching the cones as they were not provided the guidelines in this article. Therefore, to have greater reliability, further guidelines were needed to standardize the CAT.

Ideally, the CAT should be performed on a turf or gym flooring for a consistent running surface while wearing multi-directional turf or gym shoes. If turf or gym flooring is unavailable, the test can be performed on the dirt part of the infield while wearing either metal spikes or plastic cleats (specific shoes). Performing the CAT on turf or gym flooring is highly recommended for consistent data and safety. Times should be expected to be slower when running on dirt due to the less stable dirt conditions compared to turf or gym flooring.

The CAT highlights the difference between curvilinear and CODS locomotive demands in CODS tests, and that curvilinear running may be considered more skill-based that requires greater individual curvilinear running technique. Total time data mask different athletic properties between the curvilinear and CODS that may indicate a lack of acceleration and body position or individual technique between curvilinear and CODS (117). At least three timing gates should be used. One timing gate at the cone identified as both the second and fourth and the other two timing gates by the third cone. The timing gate at the second-fourth cone should be facing boundary B in a position that can detect the athlete touching cone number two after the curvilinear movement has been completed and then when running past cone number four to finish the test. The other two timing gates should be placed in the following fashion: one facing the third cone in line with the second-fourth cone and the other facing toward boundary B (Figure 3). Based on the test set-up in Figure 3, specific differences in cumulative and individual time points can indicate different athletic properties between the curvilinear and CODS that may indicate a lack of acceleration and proper body position between curvilinear and CODS. Therefore, dissecting the sprint performances for each segment can indicate the degree of concentration an athlete must have in their speed development program to improve their CAT ability, which is believed to transfer to base running ability. layer begins at cone number 1. Then, runs toward cone number 2 in a curvilinear movement touching cone number 2 with the right hand and stays within boundaries A and B defined as the laneways to perform the curvilinear movement. After the curvilinear movement, the player immediately performs a 180° COD toward cone number 3 while touching the cone with their left hand, then performs another 180° COD and sprints past cone number 4. The opposite hand should not touch the ground while the player is touching a cone. The timing gates must be facing the direction the dashed arrows are facing. The dashed arrows are located next to the timing gates.

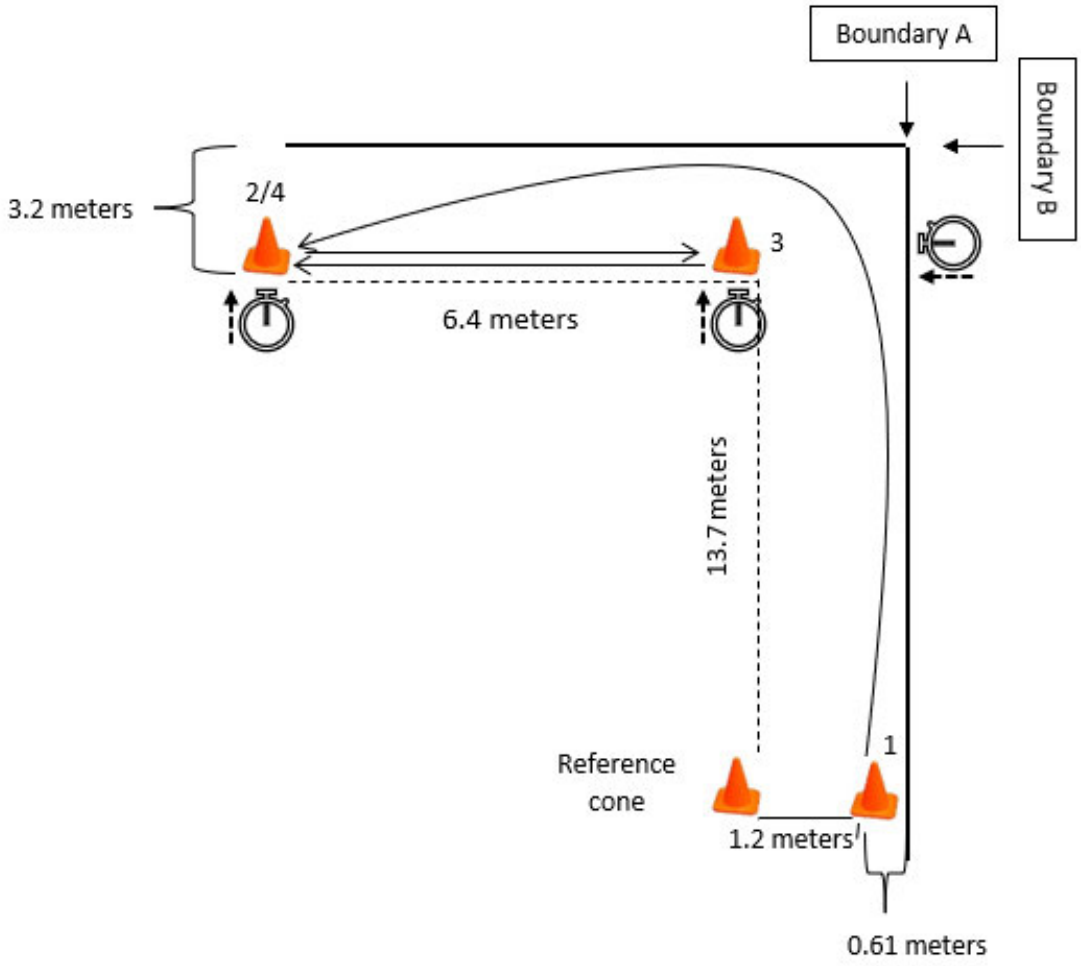


Figure 3.3. Curvilinear Ability Test setting

Timing gates at the second-fourth cone allow time from a curvilinear COD movement and then from adding two 180° CODS movements. In addition, the curvilinear section time could be measured from both timing gates at the third cone, as Miyaguchi et al. (103), where athletes were evaluated in a curved 3 m (9.8 ft) section that was timed before and after rounding and stepping on first base while running to second base. The curvilinear section time could be used to evaluate how much time it takes the athlete to make the curvilinear movement as it contributes to shortening curvilinear time and improving curvilinear technique. Furthermore, the time at the second cone (20.1 m [66 ft]) could be compared with a 20.1 m (66 ft) straight-line sprint and evaluate the COD deficit introduced by Nimphius et al. (117). In this case, a more direct association between curvilinear and straight-line sprint timing could be perceived as the curvilinear COD deficit. Moreover, Miyaguchi et al. (103) stated that BRE was measured by dividing base running time by

straight sprint time. Thus, using the same times collected for COD deficit, dividing curvilinear COD time by the 20.1 m (66 ft) straight-line sprint time can determine curvilinear running efficiency.

On the other hand, the two 180° CODS movements of the CAT describe a straight-line sprint ability. Base running has two movements, among others, consisting of running back and forth to a base in a direction similar to a run-down and going back to a base to tag-up on a fly ball to the outfield. Both examples integrate CODS mentioned early in this article. On these segments, base running coaches and sport scientists could monitor curvilinear time vs. straight-line sprint time for curvilinear and CODS and determine what locomotive property needs greater improvement. Moreover, curvilinear and CODS could be monitored in curvilinear sections as in Miyaguchi et al. (103) vs. 180° CODS time section as in Nimphius et al. (117) and evaluate how much time base runners spent in each section. These sections could be analysed by sport scientists to describe, understand, and predict the behavior between base runners' performance and CAT to make better decisions to guide specific interventions by strength coaches to enhance straight-line and curvilinear ability that could be translated to base running. For example, Magrini et al. (80) included a series of drills that explain how to train speed and CODS in baseball and softball players. At present, we noted a far greater number of movements required to assess base running ability that are currently not comprehensively assessed in any single CODS test described in the literature.

3.3 Base running specificity

Coleman and Amonette (21) suggested that physical capacity for base running may decline by the stage of the athlete (years of experience). However, as athletes become more experienced, they become more skilled in running to the first base, thus preserving speed. Therefore, skilled performance measures, such as base running, are different than physical capacity measures, and their relationship can vary by stage of athletic development. In addition, Miyaguchi et al. (103) stated that linear sprint ability does not translate to base running curvilinear speed. It is important to evaluate body position while players run bases as specific body positions and movements are more advantageous to increase speed around the base.

To evaluate base running ability in baseball and softball, curvilinear and CODS motion characteristics of base running must be tested (29,103,146). A curvilinear and CODS test for base running ability requires identifying the game situation and specific movements. Many locomotive tasks in baseball and softball require curvilinear and CODS, including accelerating out of the batter's box after batted ball contact, the cross-over step or drop/jab step to steal bases, base running, catching fly balls, fielding ground balls, and other sprinting strategies to complete defensive plays in the field.

3.4 Speed in baseball and softball

3.4.1 Baseball speed

Batting and base running ability affect the probability of scoring a run in baseball. Aside from the decision-making element of hitting that adds motor complexity, once the ball is contacted, base running ability is essential in scoring runs (6,9). Baumer (9) estimated the impact of base running skills on run-scoring ability in Major League Baseball (MLB), reporting that the best base runner has two characteristics: runs often and has a high success rate. In addition, the impact of base running skills on run scoring ability is typically 70 runs per season.

In MLB, athletes' speed has traditionally been measured using time in the 54.9 m (180 ft) dash. However, strength and conditioning coaches have questioned the specificity and validity of measuring 54.9 m linear direction speed as an objective baseball performance metric as bases are 27.4 m (90 ft) apart and are located at 90° angles to one another (23,29). The initial acceleration phase in base running begins when a player at-bat hits a baseball and runs the first 13.7 m (45 ft) from home plate toward first base. Then, the initial acceleration phase changes to a transitional acceleration phase from 16 m (52.5 ft) to 27.4 m (90 ft) when the baseball player reaches the first base (29). Coleman and Amonette (21) evaluated the time to run from home to first base in MLB players from 2007 to 2010. The authors evaluated 1,896 runs in 324 games over four seasons. Timing began at a batted ball, and two times were taken, one at 13.7 m (45 ft) and the other at 27.4 m (90 ft) while running to first base. Each player had at least two runs to first base, and the fastest time was recorded and used as data. The authors reported that the average time to first base was 4.36 s, with the first 13.7 m (45 ft) segment recorded as 2.62 s, and with the last 13.7 m (45 ft) segment recorded as 1.75 s. Furthermore, left-handed hitters were faster than right-handed hitters because the distance they travel is less since the left-handed batter's box is closer to first base than the right-handed batter's box. The authors concluded that acceleration from home plate to first base is crucial for the runner to be safe. If the first 13.7 m (45 ft) is performed at sub-maximal capacity for various reasons, it automatically puts the baseball player at a disadvantage as the first segment of the 27. 5 m (90 ft) distance is the most significant determinant in the run to first base (21).

Furthermore, Miyaguchi et al. (103) evaluated the base running performance in 25 college baseball players and 15 male track and field athletes with no baseball experience. The sprint time taken at 54.8 m (180 ft) and 109.6 m (360 ft) was evaluated, corresponding to the distance to second base and home plate. In addition, the time to reach each base in the home run test, the three-meter section time around first base on the way to second base and BRE (dividing the base running time by the straight sprint time) were evaluated. The authors reported that track and field athletes had better sprint times ($p < 0.05$, ES = 1.35) than baseball

players at 109.6 m. As for BRE, baseball players were significantly superior to track and field athletes in both run to second base/54.8 m sprint (1.10 ± 0.04 vs. 1.15 ± 0.05, $p < 0.05$; ES = 1.33) and run to home/109.6 m, sprint (1.14 ± 0.04 vs. 1.22 ± 0.06, $p < 0.05$; ES = 2.00). However, in the three-meter section, the baseball players had a significantly shorter time compared to the track and field athletes (0.86 ± .08 s vs. 0.95 ± 0.08 s, $p < 0.05$; ES = 1.17, respectively). The authors mentioned no significant difference between both groups when running to second base and home plate. However, baseball players were superior in BRE. Thus, superiority in BRE means that the declining rate of speed was smaller in baseball players. In addition, the author discussed that baseball players can run to the next base maintaining their speed (curvilinear manoeuvre) due to using base running technique learned from playing the game. Ultimately, such insights can indicate the expected run production to potentially improve as a result of a player's ability to reach a scoring position and having better base running technique (9).

3.4.2 Softball speed

Speed and acceleration are crucial as they relate to first and second base running performance, which can be the difference between winning and losing softball games (83,115). To win a softball game, a team needs to score one more run than their opponent, which can be accomplished by hitting, yet also through walking, which can lead to base stealing, and eventually scoring by contacting home plate (83). Athanasakis et al. (6) examined important offensive softball variables determining winning and losing games in the 2004 Athens Olympic Softball tournaments. The authors concluded that, in addition to batting ability, base running tactics such as base stealing are important to score a run and win an Olympic softball game.

Similar to Coleman and Amonette (21) who evaluated the time of the first segment of a run to first base in baseball players, Nimphius et al. (115) also evaluated the split time at 10 m (33 ft) over the distances of a sprint to first base (17.9 m) and during a sprint to second base (35.8 m) in competitive softball players. The authors reported acceleration ability as the most important factor with a positive relationship between 10 m split time and first base and second base performance (115). The authors reported a significant positive relationship between 10 m split time and first base and second base performance. Therefore, the first 10 m over the sprint to first base and second base are critical on first base and second base running performance.

3.5 Curvilinear ability test expectations and implications

The CAT is a new/novel test undergoing further scientific evaluation. In a preliminary study, Martínez-Rodríguez et al. (91) assessed baseball players' CAT ability and collected segment sprint times. Table 1 presents the expected CAT total and segment times for baseball players while running on grass.

Table 3.1. Mean times to complete the CAT segments for collegiate baseball players.

Segments	Mean Time (s)
1. CAT – 13.7 m	2.82
2. CAT – 20.1 m	4.28
3. CAT – 26.5 m	6.28
4. CAT – 32.9 m	7.80

CAT = Curvilinear Ability Test

The CAT testing protocol, as described in the introduction section, requires a familiarization session to be completed before testing. A standardized warm-up must be conducted before each CAT testing session to prepare the body for high-speed acceleration and decelerations. The warm-up consisted of 5-min jogging at a low-intensity speed, 8-min dynamic stretching of the lower limbs, and at least one practice run completing the CAT distances for a total preparation time between 13-15 minutes. Each participant must perform three maximal attempts with 3 minutes of rest between each trial. Time is scored to the nearest 0.01 s. In addition, a Certified Strength and Conditioning Specialist (CSCS) should administer the delivery of the CAT protocol. The CAT was assessed on a grass/dirt field, but it is recommended that other surfaces should be used, such as turf and gym flooring. Metal or plastic cleats are recommended for grass/dirt and turf baseball surface, while multi-purpose gym shoes can be worn on gym flooring or a basketball court. However, it is important to note that a time variation will be present due to the differences between surfaces and the interaction of such surfaces with shoe types. Maintaining specificity and consistency with testing surface and footwear is recommended when assessing the CAT.

The CAT has a curvilinear segment distance of 20.1 m (66 ft) and a total of 32.9 m (108 ft) of distance that has an average completion time on grass/dirt of 4.28 s (min = 3.84 s, max = 4.81 s) and 7.80 s (min = 7.03 s, max = 8.66 s,), respectively. In baseball, the distance to reach first base is 27.4 m (90 ft) and second base is 54.8 m (180 ft), which takes a median time to complete of 4.36 s (21) and an average of 7.76 s (103), respectively. In softball, the distance to reach the first base is 18.3 m (60 ft) and second base is 36.6 m (120 ft), which takes an average time to complete of 3.21 s and 6.30 s (116), respectively. The phosphagen system is the predominant energy supply for events lasting 10 seconds or less, which is most applicable for this event (2,9). Given the time window for the CAT, the phosphagen and fast glycolysis energy system interact to provide anaerobic energy responsible for supplying adenosine triphosphate for the event. The CAT segmental and total distances are within the distances base runners travel between baseball and

softball base paths. Suppose CAT performance takes more than 9 s to complete. In that case, the player may have poor individual base running technique, poor anaerobic capacity, and deficits in curvilinear and CODS, as well as variations in acceleration and deceleration ability.

The 13.7 m (45 ft) CAT segment was implemented because of the importance of the acceleration in the first 13.7 m (45 ft) in baseball players (21) and the subsequent segments were implemented because the pro-agility test has been commonly used to assess CODS (56). The pro-agility test simulates the base running starting position stance and cross-over movement in baseball running and stealing. In addition, the pro-agility test is the most used standardized CODS test to simulate offensive movements in baseball (56,82). The 505 agility test has been commonly used in softball to assess CODS and has correlated with the run times from home plate to second base (21). The pro-agility and 505 agility tests have a 180° COD like the third and fourth segments of the CAT. The CAT was created from baseball literature and assessed with collegiate baseball players. However, it can be used to assess softball players since they have the same base running movement patterns to baseball. Table 2 presents collegiate baseball players' CAT reliability (CV%) for the various segment times and total time (91).

Ideally, all segment times of the CAT should be tested with electronic timers; however, this was not done with the data presented in Table 1 as only one electronic timing system was available and each segment could not be analysed using the same timing system. The first (13.7 m) and third (26.5 m) timing segments were completed with a hand-held stopwatch. In comparison, the second (20.1 m) and fourth (32.9 m) segments were completed with an electronic timing system. Table 2 displays how the coefficient of variation (CV) and percent of coefficient of variation (CV%) decrease as players advance to each segment of the CAT (91); however, future work involving a consistent timing method may yield different results.

Table 3.2. Reliability between trials in the Curvilinear Ability Test.

Segments	*CV*	*CV%*
1. CAT – 13.7 m	0.0425	4.25
2. CAT – 20.1 m	0.0255	2.55
3. CAT – 26.5 m	0.0189	1.89
4. CAT – 32.9 m	0.0158	1.58

CAT = Curvilinear Ability Test; CV = coefficient of variation; CV% = percent of coefficient of variation

3.6 Practical application

The newly developed CAT could help identify base running talent in baseball and softball and effectively evaluate players' curvilinear ability and CODS. In addition, the CAT requires greater curvilinear sprinting skill, as ineffective technique leads to far more braking steps than would be observed in typical curvilinear running. By understanding the deceleration points between curvilinear ability and CODS, coaches can properly identify curvilinear ability and CODS in athletes and add further information to scouting models that can indicate where prospects may have deficiencies in negotiating curves. The CAT intends to fill the gap between base running ability assessments and the practicality of carrying out linear field tests in baseball and softball. The CAT can measure the curvilinear section time, curvilinear COD deficiencies, and curvilinear running efficiency (the decreased rate to straight sprint time in curvilinear running time) to inform curvilinear ability and what aspect of the curvilinear ability should be trained.

3.7 Conclusion

The CAT offers new insights in evaluating COD sprint ability that can infer discrepancies in base running ability in baseball and softball players. The CAT adds curvilinear and CODS times and movement information related to base running that other CODS tests, such as the pro-agility test and the 5-0-5 agility test, cannot offer due to their linearity in testing design. Future research is recommended to present the reliability and validity of the CAT and determine its relationship to on-field base running performance. If proven consistent and applicable, normative data from the CAT would offer a breakthrough in talent identification for Olympic, professional, and collegiate organizations.

Chapter 4: A review of the training and monitoring methods for base running efficiency in baseball

4.1 Prelude

Following the introduction of the CAT in Chapter 3, which highlighted the need for more specific assessment of curvilinear and COD qualities in baseball, Chapter 4 broadens the focus to the training and monitoring methods that may be used to improve BRE. Given that base running performance depends on more than linear sprint speed alone, this chapter reviews the current literature relating to the physical, technical, and monitoring approaches that may enhance curvilinear sprinting ability and, in turn, inform more individualized assessment and training strategies in baseball players. This knowledge is foundational for ensuing chapters, particularly the training studies.

4.2 Introduction

In baseball, base running plays a crucial role in offensive performance by helping base runners to run multiple bases, create scoring opportunities, and secure team victories (6,9,10). Baumer (9) reported that player speed contributes approximately 25 runs per season in Major League Baseball. Baumer and Terlecky (10) further reported that concentrating elite base runners within a lineup may increase seasonal run totals by up to 70 runs. Baumer and Terlecky (10) also examined ten scenarios intaking an extra base, concluding that skilled base runners added roughly 10 runs per season. This equates to improvement in offensive performance by over 20% (9). More recently, Athanasakis et al. (6) analysed indicators like batting and base running that contributed to scoring and winning at the Olympic level. They noted that factors such as rapid sprints from home to first base, effective base stealing during the lead-off, and advancing multiple bases helped improve offensive outcomes. Thus, focusing on improving players' linear (home to first base) and curvilinear sprinting (running multiple bases) would be an important strategy in winning more games. In terms of training more efficiently, it would be useful to understand players' linear sprint ability in relation to curvilinear and how one influences the other. Findings across other sports (e.g., soccer and basketball) are mixed, with studies reporting low to high shared variance (r^2 = ~35%) (45) and significant differences ($p < 0.001$) (7) between linear and curvilinear sprint ability, whilst others have reported moderate to high shared variance (r^2 = ~27– 67%) (75) and (r^2 = ~86 – 90%) (69). Shared variance describes how much two tests overlap; for example, an r^2 of 35% means that approximately 35% of performance in one test is explained by the other test. However, there are several reasons as to why these findings may not be generalizable to baseball. Firstly, the curved paths used for the tests in previous research are different from

the curvilinear paths taken by baseballers, and second, soccer and basketball players do not typically run such curvilinear paths in gameplay.

Baseball-specific research on curvilinear running remains limited; however, existing evidence around curved running is sparse, however, there is some evidence that linear and curvilinear sprinting are relatively separate motor qualities (86,103). For example, Miyaguchi et al. (103) have shown that base running efficiency (curvilinear time divided by linear time) was superior in baseballers compared to track athletes because track athletes had a faster linear time (54.8 m: 7.76 vs 7.49 s [ES = 0.66]; 109.6 m: 14.84 vs. 13.95 s [ES = 1.35]) than baseballers. Track athletes had a higher ratio, with a more developed linear ability compared to base runners. Furthermore, Martinez-Rodriguez et al. (86) analysed 475 players across 30 teams of the 2019 to 2023 MLB season and reported that players who stole the most bases had the highest linear speeds and accelerations. However, higher linear speeds and accelerations were not observed amongst players who ran two bases consecutively (curvilinear running). It was concluded that traditional linear running metrics are key performance indicators when running single bases, but other factors may play a role in curvilinear running over two bases. Progressing this line of thought, it may be that base runners should be evaluated and trained for linear and curvilinear sprinting abilities (i.e., base running efficiency) rather than if linear speed enhancements will automatically improve base running ability.

Given the aforementioned findings, the focus of this review is to: 1) review the available literature to identify the mechanical determinants/technical demands associated with curvilinear running and how these might differ from linear running; 2) identify in-field technology that may provide diagnostic insight into some of these determinants and the efficacy of various training methods to optimize baseball base running ability; and, 3) determine training methods that are currently used for the training of curvilinear running and suggest alternative options.

4.3 Mechanical considerations for curvilinear running

The biomechanics of base running has not been researched in depth, even though its understanding is critical to examining the differences between linear and curvilinear sprinting occurrences and scoring runs in baseball (17,87,103,149). Given this paucity of baseball specific research, comparing the linear and curvilinear running of track athletes may provide insights that can be transferred to baseball. When running multiple bases however, base running path is not denoted by lanes compared to track running, therefore the curvilinear paths are much less regulated, and each player can have their own technique for running between bases (149). Given this scarcity of literature on base running, and the reader cognizant of the differences between baseball and track curvilinear running, the differences between track linear and curvilinear movement will be discussed. Specifically, this section will focus primarily showcasing the

differences between inside and outside leg mechanics when comparing linear and curvilinear running, with some coaching recommendations based on the interpretation of the findings, rounding out this section.

4.4 Inside vs outside leg comparisons

A primary mechanical difference between linear and curvilinear sprinting is the inward body lean during curved running (149). During linear sprinting, both legs typically share the load evenly, which helps produce equal force and maintain a straight path. During curved running, inward lean shifts greater load to the inside leg, shifting more weight to the inside leg, creating asymmetrical loading and changing how each foot interacts with the ground (149). To better understand how the foot and leg muscles adapt during curved sprinting, researchers have used tools like Statistical Parametric Mapping (SPM) (to track how forces change during each step) (64).

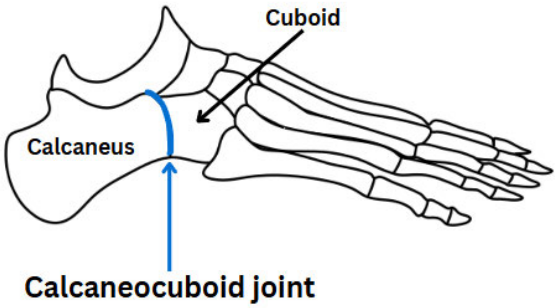
Statistical parametric mapping studies demonstrate reduced anteroposterior force and increased mediolateral force during curvilinear sprinting (64). These force shifts happen because the inside leg needs to redirect force laterally to help the body stay on the curved path. This reduces the amount of forward propulsion and requires the foot to adjust its position, reorienting push-off toward a more stable, transverse alignment (64). This helps with balance but limits how much forward force can be applied. Meanwhile, the outside leg produces more forward (anteroposterior) force, helping keep the athlete moving along the curve (19,64). Step-by-step analysis also showed the outside leg creates more lateral force early in stance (1–12%), while the inside leg takes over later in stance (75–100%) (64).

4.4.1 Foot mechanics

Foot–ground interaction during push-off plays a critical role in force transmission during curvilinear sprinting. When pushing off during movement, especially when using the inside of the foot, the calcaneocuboid joint (see Figure 4.1) plays a key role in how force is transferred (9). When the foot inverts as during the asymmetrical loading from the inward lean, the inside foot is placed in a loose-packed position to allow absorption, increased braking impulse, and mediolateral force expression. As the athlete leans inward, the foot usually lands laterally. Then, there is an ankle eversion to control the body and accommodate the orientation of the ground reaction force. Lastly, the outside foot will reach the ground in a strong, "locked" (close-packed) position, the heel bone (calcaneus) sits firmly over the cuboid in an hourglass shape, stabilizing the joint to act like a solid lever (3,11). This configuration enhances push-off efficiency and power through peroneus longus activation and plantar aponeurosis engagement (11). This locked position helps the foot generate greater forward (anteroposterior) and curved (curvilinear) force

through the transverse axis (see Figure 4.2), aiding in speed and directional control (11,16,18,19,64,65,99,120,127).

Figure 4.1. Diagram of the calcaneocuboid joint location.



4.4.2 Leg mechanics

With regards to inside-outside leg mechanics, researchers have shown that the inside leg tends to use the oblique push-off axis (see Figure 2) with the foot in a loose-packed calcaneocuboid joint, allowing more mobility and absorption, while the outside leg uses the transverse axis (see Figure 2) with a close-packed joint, offering more stiffness for powerful push-off (64). In Judson et al. (64) the inside leg showed:

- A significant increase in midfoot eversion (↑956%) and ankle internal rotation (↑346%).
- Non-significant increases in ankle eversion (↑55%) and a slight drop in toe joint (MTP) angular velocity (↓11%).

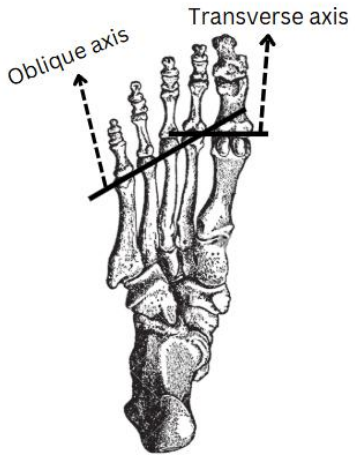
Whereas the outside leg showed:

- A significant decrease in midfoot eversion (↓1271%) and a significant increase in midfoot inversion (↑69%)
- A non-significant drop in ankle internal rotation (↓108%)

Although the percent changes reported for midfoot and ankle movement were large, these values should be interpreted alongside the absolute angular changes because small baseline values can inflate percent-change calculations. For example, the increase in inside-leg midfoot eversion represented a shift from approximately 0.3° to 4°, whereas ankle internal rotation increased from approximately 2° to 12°. Practically, these changes suggest that the inside foot adopted a loose and absorptive position to help manage inward lean, braking, and mediolateral force redirection during curve sprinting. In contrast, the outside foot demonstrated a shift toward greater midfoot inversion and reduced midfoot eversion, suggesting a stiffer foot position that may better support forward propulsion through the transverse push-

off axis. Therefore, the key interpretation is not the magnitude of the percent change alone, but the functional difference between the inside foot acting more as a braking and redirection structure and the outside foot acting more as a propulsive structure.

Figure 4.2. Transverse and oblique axes in the right and left feet.



4.5 Inside and outside leg muscle activation

During curved sprinting, muscle activation patterns differ between the inside and outside legs due to the body's inward lean and shifting force demands (44,55,67,124). Using surface EMG, researchers have found that the outside leg had significantly greater activation of the gluteus medius (ES = 1.32) and biceps femoris (ES = 0.81), helping with hip stability and horizontal propulsion (124) during curvilinear running. The biceps femoris, in particular, was found to support hip extension to drive the body forward on the curve (45). Meanwhile, the inside leg was found to have more activity in the semitendinosus (ES = 0.23) and adductor (ES = 0.21) muscles that helped stabilize against sideways (centrifugal) forces during turning (45).

The vastus lateralis and tibialis anterior muscular activity (sEMG) did not demonstrate statistically significant between-leg differences during curvilinear sprinting. However, both muscles had significant activation during the acceleration phase, when force output was high, with meaningful activity reported for the outside leg ($p = 0.001$, $g = 0.67$) and inside leg ($p = 0.004$, $g = 0.48$) (124).

The inside leg gastrocnemius medialis was especially active (g = 1.08) during curved running, playing a key role in absorbing ground reaction forces, slowing the body, and redirecting momentum (124). On the outside leg, this same muscle helped stabilize the foot and ankle, enabling efficient force transfer into the ground.

4.5.1 Summary

Curved sprinting requires specific movement adjustments to maintain speed. When sprinting around a curve, the inward lean of the body results in a cascade of biomechanical adaptations in both the inside and outside leg, from foot anatomical position to differences in muscle activation. The inward lean of the body creates different demands for the inside and outside legs, including changes in foot position, force application, and muscle activation. The following coaching recommendations summarize the key practical takeaways:

Foot mechanics. Strengthen the lateral foot and arch-support muscles to improve force transfer, propulsion and reduce injury risk.

Leg mechanics. Train both mobility and absorption (inside leg) and stiffness and propulsion (outside leg) to improve curvilinear sprint performance.

Muscle activation. Train the outside glute medius and biceps femoris for propulsion and stability, and the inside leg's adductors and medial gastrocnemius for braking and directional control.

Stride mechanics. Train each leg for its specific role: the inside leg for redirection and lateral force control, and the outside leg for curve stability and forward drive.

4.6 Physical training considerations for curvilinear running

4.6.1 Research summary

To gain an understanding of what training methods were being used to train base running, a systematic search was conducted and the authors found eight research groups (baseball = 5; softball = 3) (24,40,49,50,95,116,129,139) (see Supplementary Table 4.2). The majority of the research groups measured and reported on home to first base running performance i.e., linear sprint performance. Given the focus of this review is curvilinear running ability, the authors expanded their search from baseball and softball-specific training to all sports that had trained and assessed curvilinear running ability. Six studies were found and reviewed to determine the training methods used to train curvilinear running. The methodological quality of the studies was assessed and is attached as supplementary information (see Supplementary Table 4.1 and 4.3), to help with the interpretation of the results. The majority of the curvilinear research (n = 5) involved male soccer players (4,8,53,122,143), and one included female softball players (116). The age of the participants (n = 127) ranged from 15 to 26 years of age, with the majority (92.1%) of participants being male. The most common piece of technology used to measure curvilinear performance was dual beam timing gates (8,53,114,122), with four of the six studies reporting

only total base running time. There was also variation in the surfaces (grass, artificial grass and sand), directions (left and right sides), stance position, radius (i.e., soccer penalty arc versus softball home to second base) and distances covered (soccer = 17 m, softball = 18.3 m), making it difficult for comparisons between studies.

4.6.2 Training methods summarized

The curvilinear sprint training research can be grouped into three categories: resisted sprint training (n = 2), sprint training (n = 3) and powerlifting (n = 1). The summary of the training methods used for each study are presented in Table 1. In this section, negative percent changes in sprint time indicate faster performance, whereas effect size (ES) describe the magnitude of change. Therefore, results should be interpreted by considering the direction of the percentage change, the effect-size magnitude, and whether the study design and testing task are relevant to baseball base running. Researchers that employed resisted sprinting (8,53) in soccer players using sled towing at light (15-25% velocity loss) and heavy loads (50-75% velocity loss) reported significant improvements in curvilinear performance to the left (Heavy sled: % change = -4.21 – - 5.90; ES = 0.90 – 1.39, light sled: % change = -2.54 – - 5.90, ES = 0.75 - 1.06), with no significant difference between load types, suggesting both may be beneficial in improving curvilinear base running. Three research groups (4,122,143) investigated the effect of unresisted sprint training on curvilinear sprint performance. Altmann et al. (4) and Solleiro-Duran et al. (143) both compared linear sprint training to curvilinear sprint training. Altmann et al. (4) reported the greatest improvements in the control group (% change = -1.00--4.01, ES = 0.25-0.61) as compared to the linear sprint (% change = -4.03-2.88%, ES = -0.76 – 0.47) and curvilinear sprint group (% change = -2.32 – 4.30, ES = -0.38 – 0.88). Although greater improvements were observed in the control group, Altmann et al. (4) was designed as a pilot study with a small final sample size and limited inferential statistical analysis. Therefore, conclusions regarding the comparative effectiveness of the interventions remain tentative. Conversely, Solleiro-Duran et al. (143) reported superior results in the curvilinear sprint group (% change = -3.36 - -4.16, ES -0.90 - -1.05, $p < 0.05$) compared to linear sprint group % change = 0.02-0.13, ES = 0 – 0.05, $p > 0.05$). Nimphius et al. (116) were the only researchers to determine the effects of a powerlifting intervention on curvilinear sprint performance in female softball athletes. The authors reported a 2.88% improvement (ES = -0.53; $p < 0.05$) in curvilinear home to second base performance and a 0.32% improvement (ES = -0.29; $p < 0.05$) in linear home to first base performance after 20-weeks of powerlifting. It is worth noting to highlight that curvilinear performance had greater improvement than linear performance. However, results have limited generalization due to the single-sex, small cohort (n = 10 females).

Overall, existing studies are limited by methodological inconsistencies, small sample sizes, non-baseball-specific tasks, and limited female representation (7.9% of 127 total athletes). Most studies were conducted

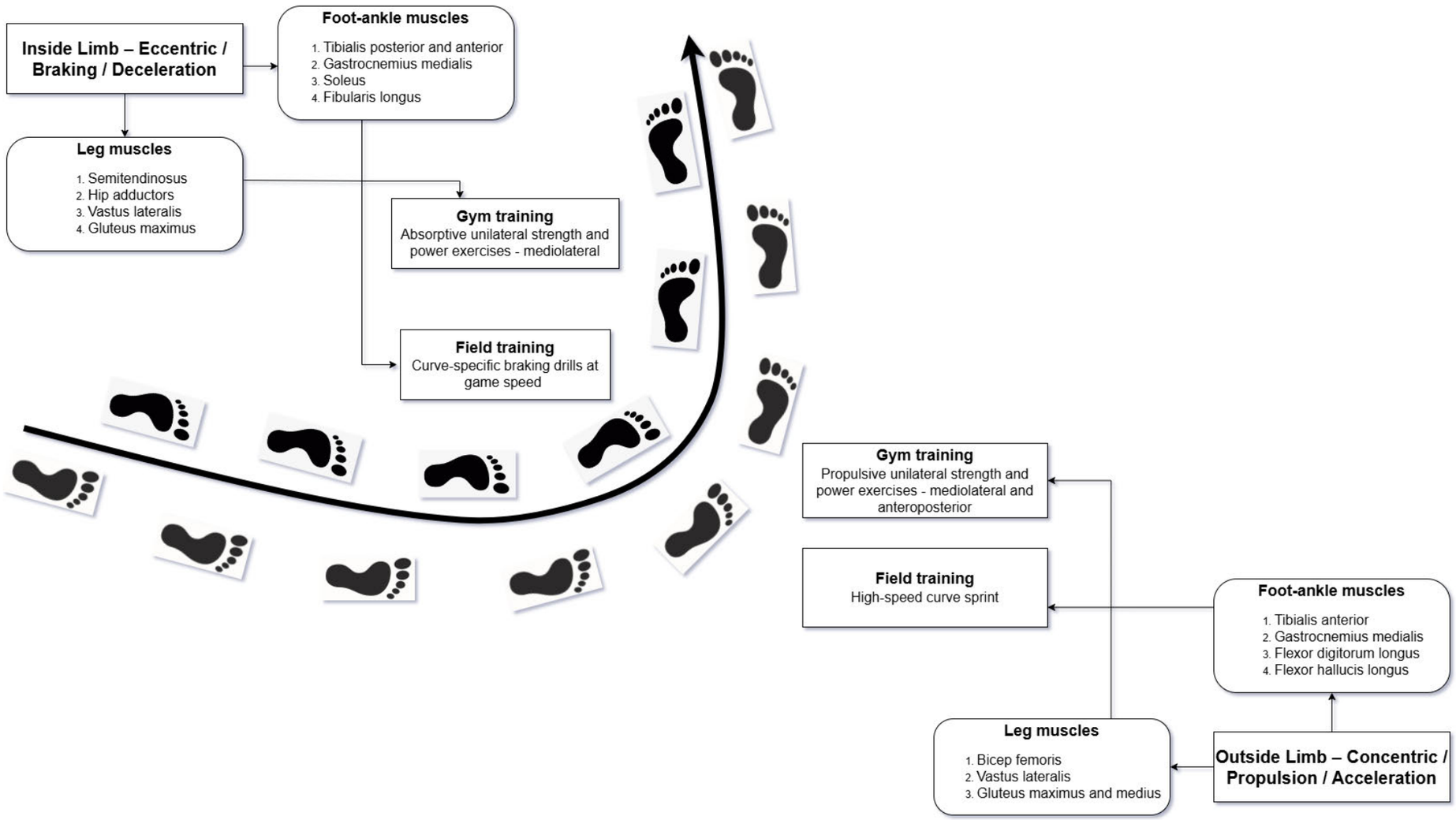
in male soccer players aged 20 or younger, often using movements (e.g., penalty arc runs), surfaces (grass/sand), directions (clockwise or counter-clockwise), and starting positions (unspecified stance) that differ significantly from baseball base running.

4.7 New perspective for training curvilinear running in baseball

There are clear differences in inside- and outside-leg mechanics between curvilinear and linear sprinting (18,19,64,65). While the biomechanics of curvilinear sprinting have been investigated in track and soccer athletes, research specifically investigating baseball base running remains non-existent. Nevertheless, these techniques must be understood through the lens of physical capability, as an athlete's ability to meet technical demands is often limited or enhanced by strength, mobility and coordination.

Two principal methods are typically used to develop lower-limb force production: 1) gym-based isolated muscle training; and 2) on-field motor pattern training. Gym-based, leg-specific strength training can enhance the muscle's intrinsic ability to generate force, while curvilinear sprinting patterns demand a more coordinated, sport-specific expression of that force to effectively direct the CoM through the curvilinear sprint. With this in mind, this section presents an integrated gym and on-field approach to training curvilinear running in baseball, including exercise examples for foot-ankle complex and the inside and outside leg. In Figure 4.3, the organization of the inside and outside legs, detailing the foot–ankle complex and muscle contributions to curvilinear running, along with the aims of targeted training purposes are detailed.

Figure 4.3. Inside and outside foot-ankle muscles and inside and outside leg muscle utilization during curvilinear sprints and aims of training prescription



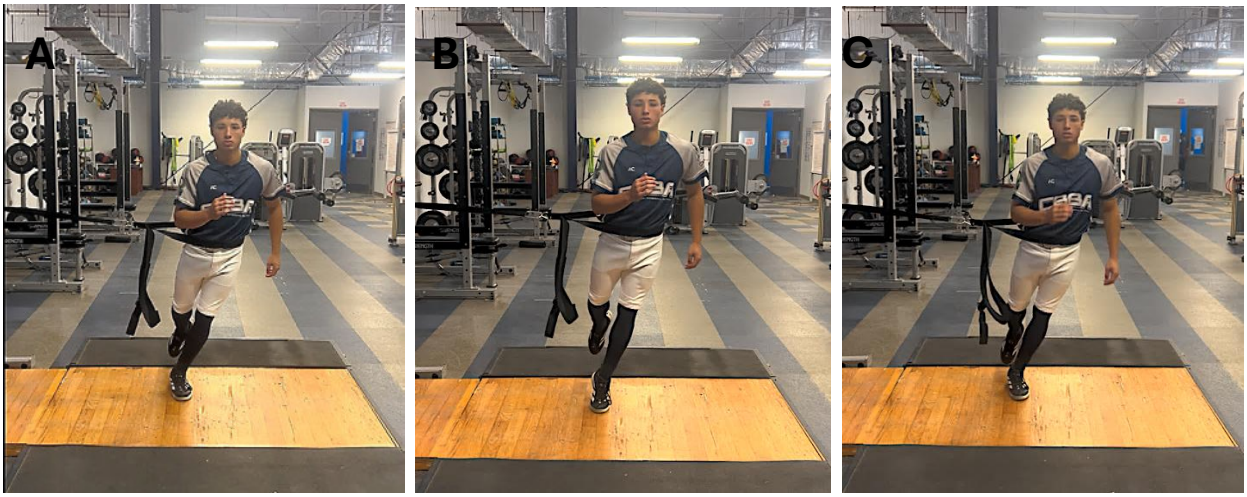
4.8 Foot–ankle complex

The foot–ankle complex is foundational to curvilinear running due to its critical role in force transfer, directional control, and stability (11,64,140). Propulsive and absorptive functions underpin adaptations during the eccentric/braking and concentric/propulsive stance phases. Muscles such as the soleus, gastrocnemius medialis, tibialis anterior and posterior, and fibularis longus are heavily involved in absorbing mediolateral forces (19,44,64,124). In contrast, the flexor hallucis longus, flexor digitorum longus, soleus, tibialis anterior, and gastrocnemius medialis play a dominant role in propelling the body, stiffening the forefoot to generate push-off forces (38,39). Therefore, strength training for the foot-ankle complex should reflect its dual function: eccentric-decelerative qualities for the inside foot, and concentric-propulsive strength for the outside foot.

4.8.1 Inside foot training

The inside foot primarily absorbs mediolateral forces and stabilizes the body during inward lean, operating on an oblique axis (11,140). During the stance phase, triphasic loading occurs i.e. eccentric, isometric, and concentric contractions, with the soleus, tibialis anterior, and gastrocnemius medialis supporting absorption and stabilization (44,124). Training should therefore emphasize braking capacity and frontal-plane control in the gym. A principal foundational exercise to teach the base runner how to lean and load the inside foot to isolate the plantar flexors as shown in the tethered inward-leaning rack exercise shown in Figure 4.4.

Figure 4.4. Inward lean inside foot plantar flexion using a waist harness and tether attached to the rack.



Key: A) Starting position; B) end of concentric phase; C) end of breaking eccentric phase.

4.8.2 Outside foot training

The outside foot primarily generates propulsive forces, pushing the CoM forward through the transverse axis and creating a closed-packed position for force transfer (11,140). Accordingly, training should emphasize unilateral anteroposterior force application. As previously mentioned for the inside foot training, a principal foundational exercise to teach the base runner how to lean and load the outside foot is the tethered inward-leaning rack exercise shown in Figure 4.5.

Figure 4.5. Inward lean outside foot plantar flexion using a waist harness and tether attached to the rack.



Key: A) Starting position; B) end of concentric phase; C) end of breaking eccentric phase.

4.9 Inside and outside leg muscle system

The foot-ankle complex primes the upper leg musculature for subsequent propulsive or absorptive actions through the curve (3,44,124). Proximally, the biceps femoris, semitendinosus, hip adductors, vastus lateralis, and gluteus maximus contribute to stabilization and propulsion. The inside and outside legs have their own roles when sprinting curvilinearly (3,18,19,44,64,65,125). To the authors' knowledge, no exercises have been specifically prescribed for inside- and outside-leg curvilinear sprint demands. Therefore, the following section introduces coordination-specific exercises for each leg and how to progress them for experienced base runners.

4.9.1 Inside leg training

Gym-based training for base runners should emphasize absorptive unilateral strength training in the mediolateral plane to enhance braking capacity and stability. The inside leg primarily manages braking and mediolateral stability (19,64). Accordingly, exercises such as the Nordic hamstring exercise, glute-ham raise, Romanian deadlift, and Copenhagen adduction exercise are recommended to target the posterior

chain and hip adductors, improving eccentric strength and dynamic stability (74,94,152). Given the high incidence of hamstring injuries in baseball athletes (121), emphasizing absorptive strength at long muscle lengths may reduce injury risk. Nevertheless, base running has a specific inward lean requirement during the curve. As mentioned in the foot-ankle complex section, if the athlete does not have experience or has weakness leaning inward, foundational exercises such as inside leg inward lean landmine squat (Figure 4.6) and tethered squat (Figure 4.7) could be programmed to increase stability and movement control. The difference between exercise options is that the tethered squat is less constrained and therefore requires more intermuscular co-ordination from the synergists and co-contracting antagonists.

Figure 4.6. Inward lean, inside leg landmine squat.



Figure 4.7. Inward lean, inside leg tethered squat.

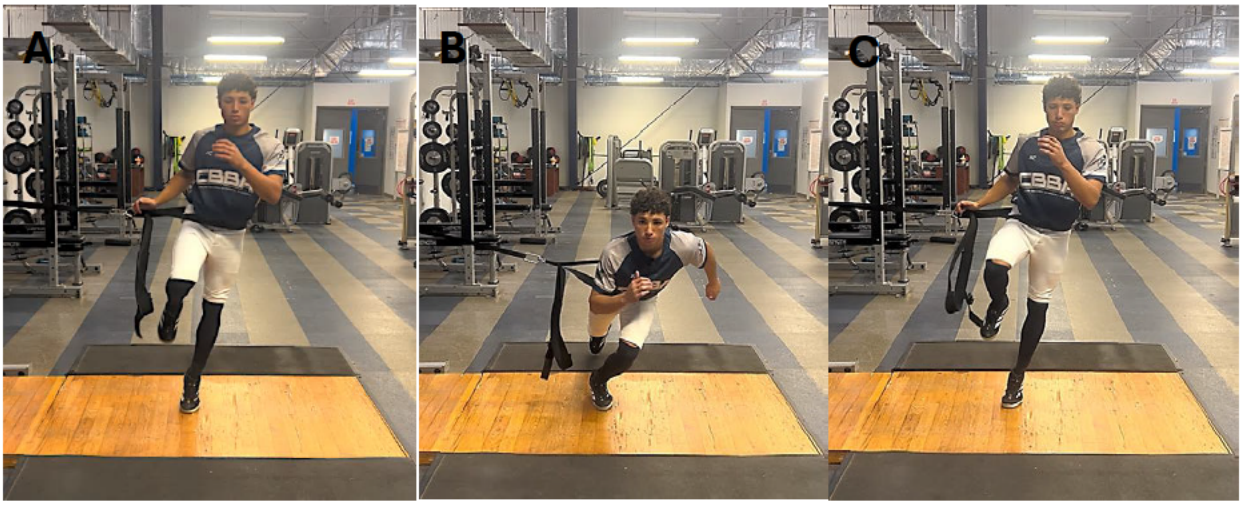


Key: A) Starting position; B) end of eccentric phase; C) end of propulsive concentric phase.

These exercises can be progressed by the strength and conditioning coach to integrate the plantar flexion foot-ankle complex training, by requesting the players to extend through the hip, knee and ankle (triple extension), improving the specificity of the exercise and likely resulting in more efficient curvilinear mechanics (29). This integrated approach places major emphasis on unilateral strength and power exercises that challenge both the frontal plane (to improve inside leg stability) and the anteroposterior plane (to

enhance outside leg propulsion) (29). An example of the tethered inward lean squat with a triple extension is shown in Figure 4.8.

Figure 4.8. Inward lean, inside leg tethered squat with triple extension.



Key: A) Starting position; B) end of eccentric phase; C) end of propulsive concentric phase.

This plantar-flexion variation could be further progressed for more experienced players by introducing a ballistic element to the exercise. The tethered inward lean inside-leg squat jump, as shown in Figure 4.9 requires the athlete to become airborne at the end of the propulsive phase, which is an inside leg movement more relevant to curvilinear running and additionally overloads eccentric strength and stabilization during the landing. By incorporating an inside-leg squat pattern with an explosive jump, the speed and power of the movement become more of a focus rather than maximal strength/force capability. Furthermore, there are greater co-ordination demands associated with such exercises in terms of propulsion and mediolateral stabilization, so implementation of such exercises should be predicated on players having adequate strength and motor coordination.

Figure 4.9. Tethered inside-leg squat jump



Key: A) Starting position; B) end of eccentric phase; C) jump; D) landing position

4.9.2 Outside leg training

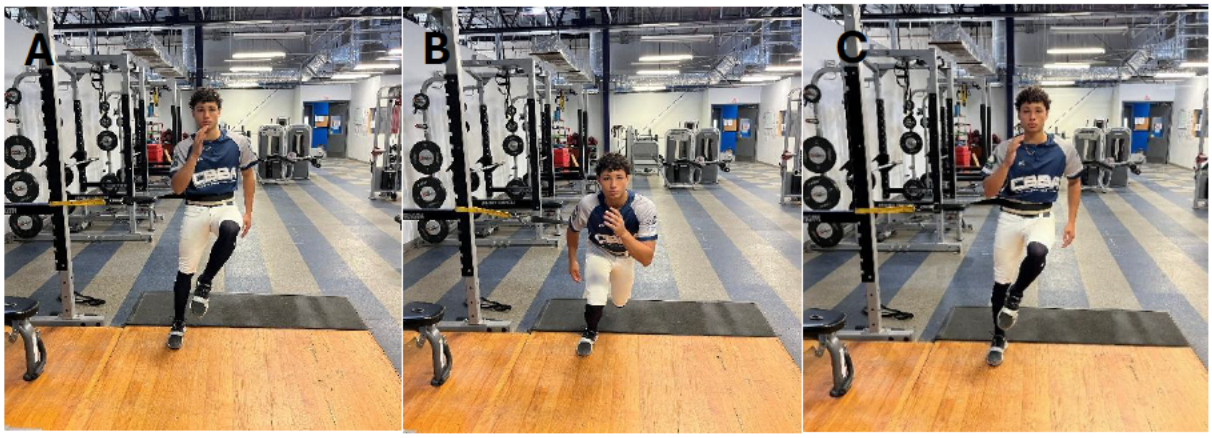
The outside leg is the primary concentric propulsive driver during the curvilinear sprint, generating anteroposterior force to move the CoM forward through the coordinated action of the tibialis anterior, gastrocnemius medialis, soleus, biceps femoris, gluteus maximus, gluteus medius, and vastus lateralis (19,44,125). Training should therefore focus on outside leg strength and power development. As mentioned in the previous section, foundational exercises could be implemented if the base runner is not experienced leaning inward. The outside leg inward lean landmine squat (Figure 4.10) and tethered outside-leg squat (Figure 4.11) exercise can be used in the first instance to increase stability and movement control. Similar to the inside leg, the tethered squat is less constrained and therefore requires more intermuscular co-ordination from the synergists and co-contracting antagonists and can be used as a progression to the landmine.

Figure 4.10. Inward lean landmine outside leg squat exercise without plantar flexion



Key: A) Starting position; B) end of eccentric phase; C) end of propulsive concentric phase.

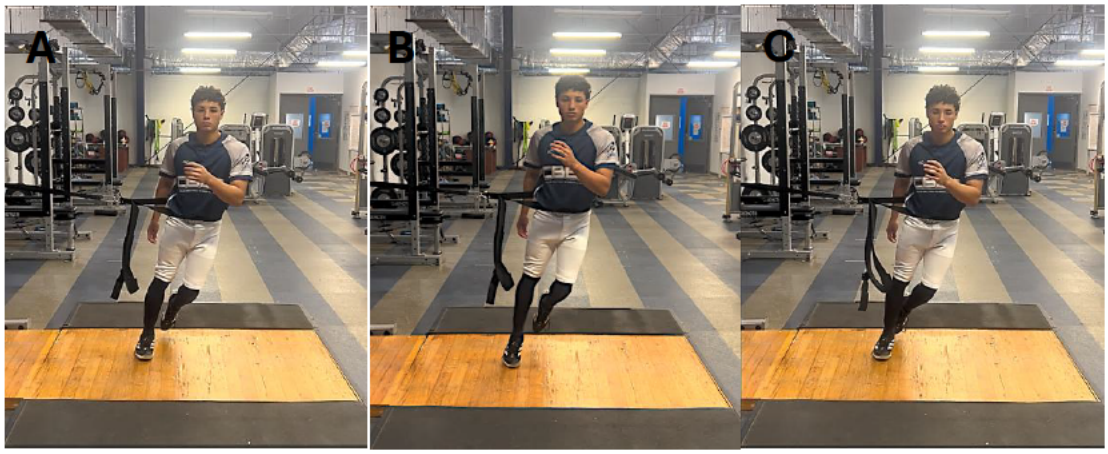
Figure 4.11. Tethered outside-leg squat without plantar flexion



Key: A) Starting position; B) end of eccentric phase; C) end of propulsive concentric phase

As with the inside-leg an outside leg triple extension squat (Figure 4.12) and a ballistic outside leg triple extension squat jump (Figure 4.13) can be integrated into the outside leg training, improving foot-ground interaction/co-ordination and increasing movement specificity which potentially could have flow onto more efficient curvilinear mechanics (29).

Figure 4.12. Outside leg inward-leaning rack attached via a waist harness and tether with triple extension



Key: A) Starting position; B) end of concentric phase; C) end of breaking eccentric phase

Figure 4.13. Outside leg inward-leaning rack attached via a waist harness and tether jumps



During these exercises, the athlete coordinates forward propulsion while resisting lateral drift, maintaining the tether-induced lean to simulate the outside leg's requirement to generate forward momentum during baseball curvilinear sprinting. Table 4.1 summarizes the recommended training exercises, target muscles, and their rationale within curvilinear running development.

Table 4.1. Curvilinear training exercises, targeted muscles, curvilinear sprint emphasis, and rationale

Exercise	Targeted muscles	Curvilinear emphasis	Training rationale
Inward-lean landmine squat – inside and outside leg alternating	Inside leg: • Tibialis anterior • Hip adductor Outside leg: • Gluteus maximus • Biceps femoris • Vastus lateralis	Inside leg: • Mediolateral stability Outside leg: • Concentric - propulsion	Simulates the inside leg's loaded position during a curvilinear sprint Simulates the outside leg's propulsion position during a curvilinear sprint Strength exercise – injury prevention
Waist-harness tether lean squat	Inside leg: • Tibialis anterior • Hip adductor Outside leg: • Gluteus maximus • Biceps femoris • Vastus lateralis	Inside leg stability during inward lean Outside leg propulsion during inward lean	Simulates the inside leg's loaded position during a curvilinear sprint Simulates the outside leg's propulsion position during a curvilinear sprint Strength exercise – injury
Progression: Waist-harness tether lean – plantar flexion/triple extension (Progress further to jumps - advanced power exercise)	Inside leg: • Fibularis longus • Gastrocnemius medialis • Hip adductor Outside leg: • Flexor hallucis and digitorum longus • Gastrocnemius medialis	Whole-body curvilinear sprint lean mechanics.	Leaned-angle force production. Athletes must sustain a curvilinear-lean posture every jump

	• Gluteus maximus • Biceps femoris • Vastus lateralis		

4.9.3 On-field training and wearable resistance applications

While gym-based strength and power development is essential, such training is typically isolated and non-specific to the motor demands of curvilinear running. To effectively translate these gains to on-field performance, sport-specific on-field training that expresses curvilinear motor patterns is required. Drills should emphasize coordinated movement at the hip, knee, and the foot-ankle complex, with the dual aim of reducing speed loss during curvilinear running and reducing the risk of knee and hamstring injuries (120,121,135).

Foundational drills can be used to develop kinesthetic awareness of inward lean mechanics and foot placement under game-speed conditions. Examples include running in controlled arcs—such as full, half, or quarter circles (29). As athletes progress, more advanced variations can involve rounding a sharp 90° path over a minimum distance of 13.7 meters, using marked boundaries to encourage precise control of the turning arc. These drills should initially be performed at low speeds to allow athletes to adapt their foot placement and body orientation, with gradual increases in intensity/speed as technical proficiency improves. Once foundational movement patterns are well established, base running drills that replicate the self-selected optimal arcs and direction changes of gameplay should be incorporated (87,103). This progressive approach builds dynamic strength, refines techniques, and reduces injury risk through improved control of braking and propulsion. Wearable resistance (WR) is a training tool that can be implemented to further enhance movement-specific strength and technical proficiency during curvilinear running. WR should not replace foundational youth athlete development training methods, including sprint mechanics, strength training, coordination, and movement skills. Nevertheless, WR involves the application of external micro-loads to specific body segments during dynamic movement, and represents a practical example (on-field) of the training specificity principle (33). Gamble (48) emphasized specific points to possibly elicit mechanical effects and adaptations, which could be adopted on WR base running training design, and should follow:

- Metabolic specificity: short high intensity sprints of approximately 5 to 10 seconds with rest intervals 2 to 3 minutes (15,34,147).
- Biomechanical specificity: This includes the muscular contraction (eccentric/braking and concentric/propulsive) (106), joint angles (106), velocity (106), body position (48,149), and unilateral and bilateral strength load (37,95,109).

Typically, light resistive loads equivalent to 1%–5% of body mass (133) or 200-600 grams (15) are incorporated into wearable garments that centrally (e.g., vests) or peripherally load the body (e.g., thigh, calf and arm sleeves). This approach is designed to selectively overload musculature specific to an on-field

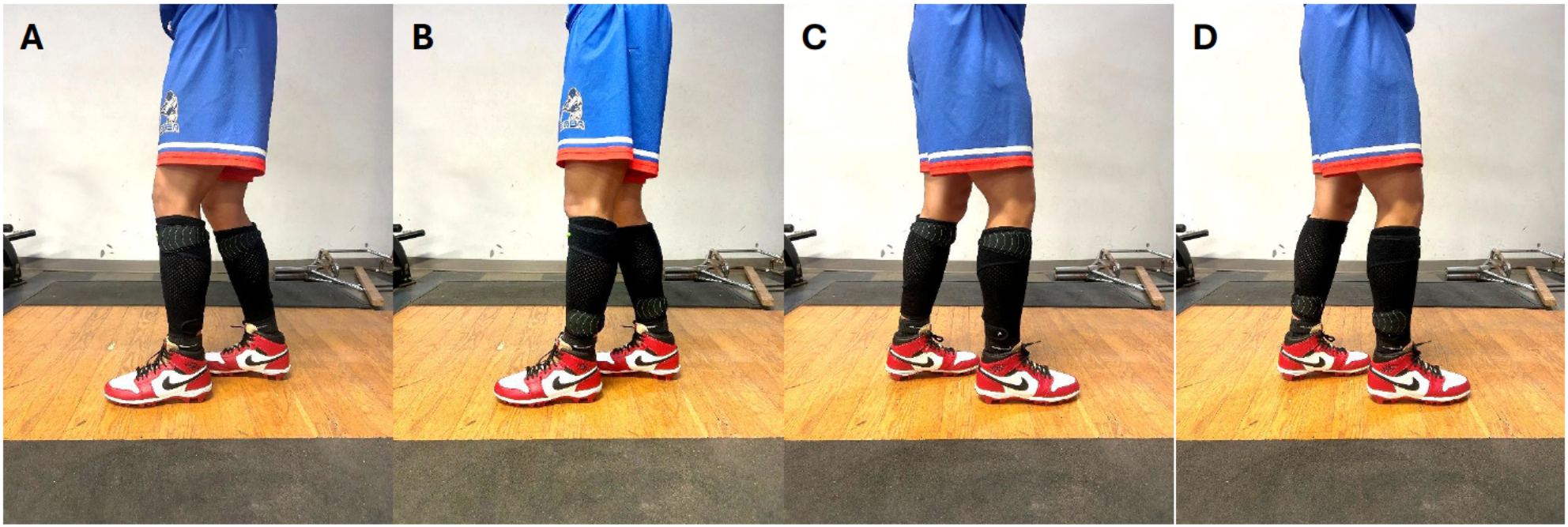
movement pattern without substantially altering natural biomechanical behaviour. Unlike external resistance methods such as sled towing which primarily load the stance phase and restrict the athlete's ability to run along a curvilinear path, WR allows resistance to be affixed directly to the body, enabling base runners to move freely along curved paths while loading both the stance and airborne phases of curvilinear sprinting. Additionally, WR allows for strategic load placement to target specific adaptations: for example, applying resistance to the torso, thighs and calf to overload the inside leg (see Figure 4.14), or applying medial-lateral, proximal-to-distal calf loading on the inside-outside leg to challenge resistive and assistive control (see Figure 4.15). This asymmetrical stimulus can also increase motor control demands by promoting leg flailing, requiring enhanced neuromuscular coordination (33). A detailed exploration of wearable resistance biomechanics lies beyond the scope of this review; however, interested readers are directed to recent literature providing comprehensive analyses of its applications and mechanisms (15,33,60,76,126).

Figure 4.14. Wearable resistance placement for the torso, thighs and calf



Key: A) inside-leg side torso, lateral-proximal thigh, and lateral-proximal calf overload; B) outside-leg lateral-distal thigh and lateral-distal calf

Figure 4.15. Bilateral resistive and assistive wearable resistance placement



Key: A) Assistive-Proximal; B) Assistive-Distal; C) Resistive-Proximal; D) Resistive-Distal

Bustos et al. (15) reported that 8 weeks of lower-body WR during warm-up improved 10- and 20-m sprint performance in 16–18-year-old soccer players compared with an unloaded group. These findings suggest a practically relevant acceleration benefit, although the evidence remains indirect for baseball-specific curvilinear sprinting. A continuous limitation in the literature is the lack of curvilinear sprint training information in baseball players. A practical recommendation based on professional communication (33) is that the WR micro-loads could be placed proximally or distally on the left side of the shank i.e., to the left side of each leg (towards the inside of the curve [assistive]) or on the right lateral i.e., to the right side of each foot (away from the curve [resistive]) (see Figure 4.16). The rationale for these alternations is to challenge assistive and resistive aspects of the curvilinear running. On the left side, towards the turn, it will stabilize turning, but on the right side, away from the turn, will cause the leg to flail out, demanding more control. The proximal placement of the WR offers a decrease in intensity due to less rotational inertia.

Figure 4.16. Single-leg wearable resistance placement for the inside and outside leg



Key: A) Inside Leg-Assistive-Proximal; B) Inside Leg-Assistive-Distal; C) Inside Leg-Resistive-Proximal; D) Inside Leg-Resistive-Distal; E) Outside Leg-Assistive-Proximal; F) Outside Leg-Assistive-Distal; G) Outside Leg-Resistive-Proximal; H) Outside Leg-Resistive-Distal

4.10 Future research

Future research should examine baseball-specific curvilinear sprinting using tasks that reflect actual base running demands, including the approach to first base, curve negotiation, and re-acceleration toward the next base. Although track and soccer studies provide useful insight into curved sprinting mechanics, baseball base running differs because athletes use self-selected paths, round around the bases and transition between acceleration, redirection, and re-acceleration phases. Therefore, future studies should quantify inside- and outside-leg mechanics during baseball-specific base running using direct biomechanical measures, such as foot pod inertial sensors, GNSS or a combination of technologies.

Additional intervention studies are also needed to determine which training methods most effectively improve curvilinear base running performance. These studies should compare linear sprint training, curvilinear sprint training, resisted sprint training, strength and power training, and WR training in baseball base running across different ages, positions, and competitive levels. Future work should also examine how maturity status, training history, and baseline linear sprint ability influence adaptation to curvilinear training. Finally, WR should be studied as a light, progressive, and supervised adjunct to baseball-specific movement training, with attention to load placement, loading scheme, training volume, movement quality, and transfer to game-relevant base running outcomes.

4.11 Conclusion

Research on curvilinear sprinting in baseball remains limited and is largely extrapolated from other sports. Despite these limitations, examining foot–ankle mechanics and leg-specific force roles provide a valuable framework for curvilinear sprint analysis to guide on-field training interventions to promote base running performance, as well as optimize force production, coordination, and injury prevention.

4.12 Practical applications

Strength and conditioning coaches should incorporate targeted interventions that address the asymmetric biomechanical demands of curvilinear sprinting. Key interlimb differences must be acknowledged in a periodized plan. The inside leg and foot-ankle complex is the shock absorber, decelerator and resists inversion to mitigate being pulled into the turn with an everted foot. Conversely, the outside leg and foot-ankle complex is the propulsion engine, accelerating the athlete toward the inner radius of the curve with concentric muscle actions in inversion that pushes the CoM into the turn. Integration of portable technology will enable the generation of advanced diagnostic information, support a deeper biomechanical understanding of base running mechanics and allow practitioners to be aware of emerging asymmetries that

can arise. To quantify these asymmetries, practitioners may employ high-sampling inertial sensors capable of tracking CoM motion such as foot-pod inertial sensors that are capable of tracking the CoM and providing step-by-step analytics along the curvilinear path (84). Ultimately, a data-rich approach can refine exercise prescriptions, enhance athletic performance, and increase both safety and effectiveness of curvilinear speed training specific to baseball athletes.

Chapter 5: Between-session reliability of GNSS technology for quantifying linear and curvilinear base running performance

This chapter comprises the following published paper in the *Applied Sciences* journal.

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5.1 Prelude

The findings from Chapters 2 to 4 indicated that base running performance is influenced by factors beyond linear sprint ability alone, and that coaches require field-based monitoring methods capable of describing how players accelerate, maintain speed, lose speed, and negotiate the curve when running multiple bases. However, traditional timing gates and stopwatches provide only total or split times and offer limited insight into the velocity, distance, and path-related characteristics that underpin BRE. GNSS technology was therefore introduced because it can provide time, velocity, and distance-derived measures across the full linear and curvilinear sprint in an applied baseball setting. Accordingly, Chapter 5 examined the between-session reliability of GPS-derived measures during 54.7 m linear sprinting and home to second base curvilinear sprinting. Establishing the stability of these variables was necessary before GNSS could be used in later chapters to interpret meaningful change, support practitioner decision-making, and monitor training responses in baseball players.

5.2 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 (149). In terms of assessing base running performance, timing gate technology is the most common technology used to evaluate linear and curvilinear sprint ability (87,95,103). 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 (95). 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 (87,111). For example, home to first base is reported as a single time and speed measure, which offers little insight into sprint kinematics (21,25,95). 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 GNSS 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, GNSS has been used to evaluate and compare baseball athletes' external load during pitching (14,107,128), 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 GNSS 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.

5.3 Methods

5.3.1 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 GNSS 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 GNSS technology for base running linear assessments, using change in the mean, intraclass correlation coefficients (ICCs), and coefficient of variations (CVs).

5.3.2 Subjects

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).

5.3.3 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 5.1. 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 (87,103). 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.

5.3.4 Equipment

A 10 Hz multi-constellation GNSS receiver (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 GNSS receiver approximately 5 to 10 min before the first activity to allow for satellite signal recognition (35) and calibration by placing the GNSS unit for 30 s at the start of each test, the end of each test, and the first base. The VX Sport GNSS receiver 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 GNSS units (4–10 Hz) have been found reliable for measuring total distance and speed metrics in recreational and female collegiate athletes (CV < 5%) (2,81). 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 GNSS technologies remains small (12).



Figure 5.1. GNSS receiver and location.

To calibrate the trial GNSS 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 GNSS 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 GNSS 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.

5.3.5 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. GNSS samples associated with each event (home, first, second base, and start/end calibration points) were taken as the GNSS location sample closest to the reference point for the associated event. Each trial was processed iteratively, using time-series GNSS and velocity data. The start of the trial was identified as the first sample in which the athlete's velocity exceeded 0.152 $m \times s^{-1}$, 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 GNSS coordinates were then aligned to a predefined “home” reference point (from Google Maps) to normalize spatial orientation across trials. GNSS 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 analysed 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.

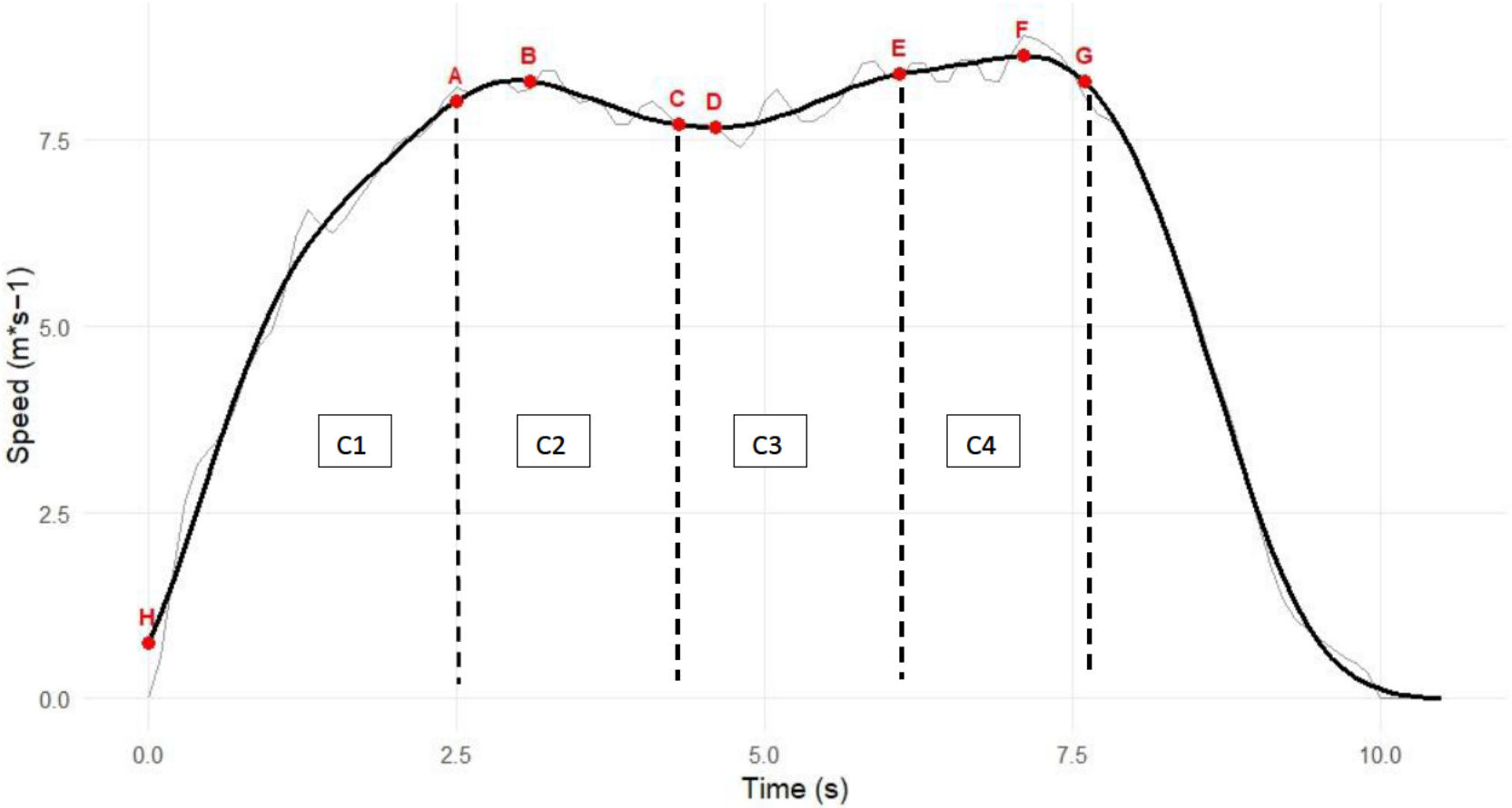


Figure 5.2. Speed-time profile of a baseball player performing a home-to-second base sprint.

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.

Table 5.2. 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.
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.

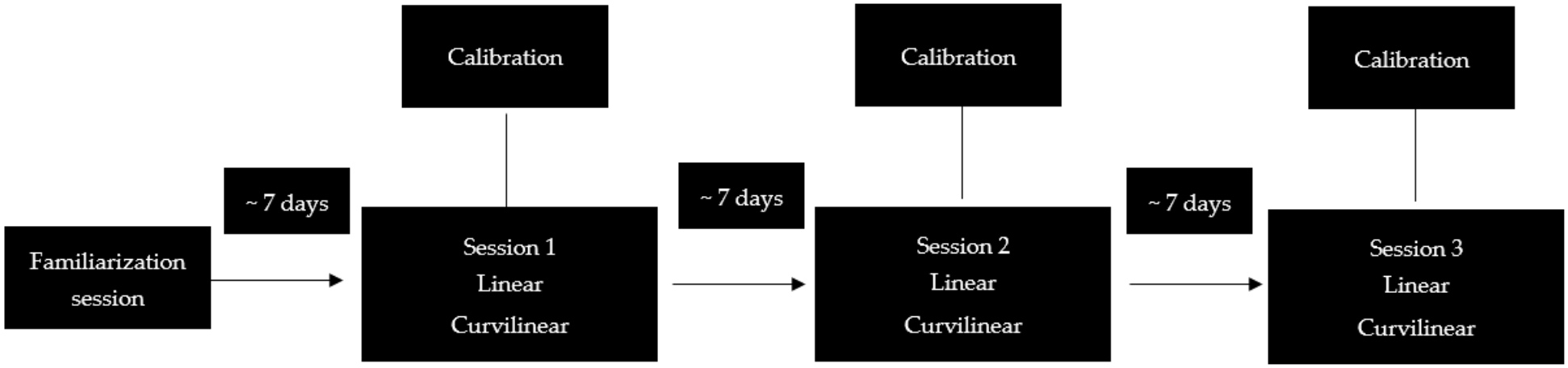


Figure 5.3. Assessment process overview.

5.4 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 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 (58) 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 (108). Absolute consistency was quantified as a CV, where measures less than or equal to 10% were deemed acceptable (66). Relative consistency between consecutive sessions was assessed using the Hopkins pairwise reliability spreadsheet, which calculates ICC based on a two-way mixed-effect, single measure consistency model (ICC(3,1) for each adjacent pair of sessions (70). Categorization of ICC was deemed as follows: ‘poor’ (≤0.50), ‘moderate (0.50–0.74), ‘good’ (0.75–0.90), or ‘excellent’ (≥0.90) (13). 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 (57). 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× the between-subject standard deviation and expressed in the original measurement units to provide decision-relevant performance change thresholds (57). Alpha levels of 0.05 and 95% confidence intervals were used where appropriate.

5.5 Results

The between-session variability of these curvilinear GNSS 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.

Table 5.3. Between-session reliability of GNSS curvilinear variables.

Variable	Mean ± SD			% Change in Mean (95% CI)		CV (95% CI)		ICC (95% CI)	
	Session 1	Session 2	Session 3	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 (s)	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)
Time to peak speed before first base (s)	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)
Time to first base (s)	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)
Time to minimum speed between bases (s)	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)
Time to 41.1 m (s)	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)
Time to peak speed before second base and after first base (s)	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)
Time to second base (s)	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)
Time from first to second base (s)	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)
Speed at 13.7 m ($m.s^{-1}$)	6.89 ± 0.55	6.94 ± 0.45	6.96 ± 0.45	0.8	0.2	1.8	1.7	0.95	0.94

				(−0.8–2.5)	(−1.3–1.7)	(1.3–3.1)	(1.2–2.9)	(0.85–0.99)	(0.82–0.98)
Peak speed before first base ($m.s^{-1}$)	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)
Speed at first base ($m.s^{-1}$)	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)
Minimum speed during curvilinear movement ($m.s^{-1}$)	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)
Peak speed before second base and after first base ($m.s^{-1}$)	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)
Speed at 41.1 m ($m.s^{-1}$)	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)
Speed at second base ($m.s^{-1}$)	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)
Distance from home to 13.7 m (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)
Distance from 13.7 m to first base (m)	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)
Distance from first base to 41.1 m (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)
Distance from 41.1 m to second base (m)	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)

The between-session variability of the linear GNSS 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 5.4. Between-session reliability of GNSS linear variables.

Variable	Mean ± SD			% Change in Mean (95% CI)		CV (95% CI)		ICC (95% CI)	
	Session 1	Session 2	Session 3	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)
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)
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)
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)
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)
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)
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)
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)

5.6 Discussion

The purpose of this study was to quantify the between-session reliability of GNSS 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 (100,136) using GNSS (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 (100) 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 (136) 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, like the data of other researchers (100,136).

Although there is no preset standard for acceptable CV values, many researchers set a goal of <10% for acceptable reliability (63). The CVs associated with the linear and curvilinear measures were all under 10%, and 93% of the measures were under 5%. Additionally, most of the comparisons had a 95% CI less than 10%, indicating that the typical error between sessions was minimal. Two groups of researchers (100,136) using GNSS (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 (100,136) differed from this study, making direct comparisons problematic (100,136).

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 GNSS technology itself.

Two groups of researchers (100,136) using GNSS (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 ≤ SWC were judged suitable for return-to-play decisions and for short- and long-term performance monitoring.

5.7 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 GNSS 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.

5.8 Conclusion

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.

5.9 Practical applications

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 GNSS 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 GNSS 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 GNSS 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.

Chapter 6: New perspectives on analysing and interpreting base running efficiency: A GNSS approach

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6.1 Prelude

In Chapter 5 the between-session reliability of GPS-derived base running metrics was established. Chapter 6 extended this work by presenting an applied perspective on how GNSS technology can be used to assess and interpret linear and curvilinear base running performance in baseball. Moving beyond reliability, Chapter 6 uses a case study approach to demonstrate the practical utility of GPS-derived measures for identifying segment-specific movement characteristics, which in turn are used to inform better assessment, monitoring, and training decisions later in the thesis.

6.2 Introduction

Teams with good hitters will allow runners on base, and those runners will create opportunities to take extra bases and score runs. The ability to run between and around bases, therefore, will impact offensive performance and team success in baseball, highlighting the critical importance of both linear and curvilinear sprint abilities (9,10,86). Given that base running involves both linear and curvilinear sprinting characteristics, it is important to understand if these motor qualities have distinct technical and physical demands (86,103). Martinez-Rodriguez et al. (86) investigated the influence of linear and base running speed measures on stealing a base (linear) and running two bases (curvilinear) from Baseball Savant, Baseball Reference, and Lahman databases from 475 Major League Baseball players. The authors reported that a linear increase across the speed, acceleration, and base running speed metrics quartiles was observed from players who stole the least (0–25%) to the most (75–100%) bases. In contrast, no linear increase in the metrics was observed across the quartiles from players who ran the least (0–25%) to the most (75–100%) doubles (running two bases). It would seem those players who were fast in a straight line (running single bases) were different to those running curvilinear paths (running multiple bases).

Although base running-specific sprinting remains under-researched, 200 m sprinters who run curves present with an inward body lean, asymmetrical force application, and different functional roles for the inside and outside foot to maintain speed while redirecting the center of mass (CoM) (3,18,19,64,65,119,120,124). Compared with straight sprinting, curvilinear sprinting is characterized by reduced anteroposterior force, increased mediolateral force, and altered lower-limb kinematics, with the inside foot contributing more to redirection and stabilization and the outside foot to forward propulsion of the CoM (18,19,64,65). Researchers studying the electromyography of elite sprinters have reported specific muscle activation of the gluteus medius and bicep femoris in the outside leg, and the semitendinosus and adductor muscles in the inside leg. Specifically, the vastus lateralis and tibialis anterior were activated, while the gastrocnemius medialis was highly activated in both legs during the curvilinear sprint segment (44,124). This supports the notion that curvilinear sprinting is a distinct neuromechanical task rather than simply linear sprinting performed on a curved path (44,124,125). Although base running differs from a lane-constrained sprint compared to a 200 m track event, base runners similarly need to maintain speed while negotiating the curve around the bases. Therefore, evidence from curvilinear track events provides an important theoretical framework for understanding the technical demands of baseball-specific curvilinear sprinting and transfer of capacities between linear and curvilinear sprints (87,103,149).

Given these differences between linear and curvilinear sprinting and inside–outside foot mechanics, it was concluded that there was a need to implement base running assessments to understand linear and curvilinear sprinting base running ability. Current methods for evaluating base running typically rely on timing gates or stopwatch technology, which limit the depth of understanding of spatiotemporal and kinematic characteristics across the curvilinear sprint (21,35,86). These timing technologies are unable to capture critical aspects that might indicate a lack of technique, such as speed loss during the curvilinear segment, and do not map individual approaches and self-selected curvilinear paths when running multiple bases. Therefore, other diagnostic methods are needed that provide detailed information about the time and speed during linear and curvilinear sprinting. Global Navigation Satellite System (GNSS) devices are one such technology that can potentially provide more granular information about in situ base running. In this paper, the utility of GNSS technology as a tool for the implementation, collection, and interpretation of segment-specific velocity and time metrics for diagnostic base running performance is explored. Using representative athlete case-study examples, the analysis illustrates how GPS-derived data can be used to examine differences between linear single-base sprinting and curvilinear multi-base running. The purpose of this work is therefore to present a practical analytical framework for interpreting GPS-derived base running metrics, rather than to establish generalized performance principles.

6.3 Collecting Base Running Data Using GNSS Technology

GNSS technology determines the position of a receiver using trilateration, whereby the receiver estimates its location based on measured distances from multiple satellites. To resolve the three-dimensional position (X, Y, and Z axes) of the unit and the receiver clock bias, signals from at least four satellites are required. The GNSS receiver used sampled positional and velocity data at 10 Hz using an eighth-generation Swiss high-precision chipset (VX Sport, Wellington, New Zealand). The unit supports multiple satellite constellations, including GPS, GLONASS, QZSS, Galileo, and BeiDou, as well as satellite-based augmentation services (SBAS) where available. This multi-constellation capability can improve satellite visibility and positioning robustness during outdoor athletic performance monitoring. The receiver operates as a multi-constellation GNSS receiver but does not utilize real-time kinematic (RTK), precise point positioning (PPP), or differential GNSS correction methods. The unit includes a nine-axis inertial measurement unit (IMU) composed of three-axis accelerometers, gyroscopes, and magnetometers, each sampled at 100 Hz, allowing detailed monitoring of body motion. The GNSS receiver was affixed posteriorly between the scapulae in a vest to maintain antenna orientation and minimize movement. Approximately 30 min prior to data collection, calibration coordinates were recorded for home, first and second base locations along with the start and end of the 54.7 m sprint (see Figure 1). The unit was then powered off to save the calibration data in a separate file, and subsequently powered on again to enable satellite signal recognition and stabilization approximately 15 min before each testing session (35).

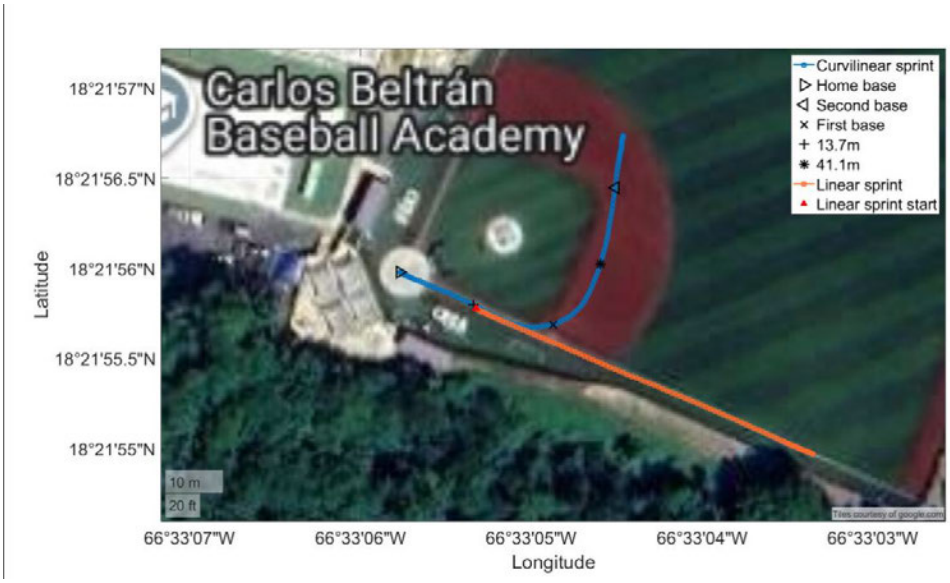


Figure 6.1. Samples collected during the straight-line and curvilinear sprints.

Both linear and curvilinear (home to second base) sprint tests were recorded over 54.7 m (collected in the same session), with linear sprint ability assessed first. Each session began with a standardized dynamic warm up focused on lower body movements. Two trials for each test were performed, separated by three minutes of rest between trials and ten minutes of rest between tests. The home-to-second-base sprint starting position was a stealing-base lead-off position at home plate with the front foot on top of the home plate. The participant would then sprint, rounding first base, before reaching and passing through second base. The linear sprint starting position was a stealing-base lead-off position at home plate with the front foot on top of the middle of the starting line. Therefore, the linear test was complementary to the curvilinear test, as the linear sprint reflects the raw capacity to sprint and the curvilinear sprint demonstrates the body's technical and physical curve negotiation, from which BREr can be calculated.

All trials were conducted in baseball-specific shoes on a turf surface, and athletes were instructed to run maximally without slowing down before reaching the endpoint. After each data collection, the data was uploaded and stored in the cloud for later analysis. GNSS curvilinear data was processed using a custom data-processing algorithm (93).

Understanding the core variables for each segment allows for calculation of the peak before first base and peak after first base. The speed data between the home plate and the first base reference location was used to identify the highest recorded speed, which was defined as the peak speed before first base (see Figure 1). Next, within the first and second bases, the search was iterated to determine the highest recorded speed after the first base and before the second base. To capture any change in speed that occurred between these two peaks in speed, the data was examined to identify the lowest recorded speed, defined as the minimum speed between the two bases.

The reliability of the GNSS-derived measures used in the following sections was previously established by Martínez-Rodríguez et al. (85). The authors evaluated 12 male high school baseball players, who completed three testing sessions separated by at least 48 h. In each testing session players performed 54.7 m linear and curvilinear base running (home-to-second base) sprints. The authors evaluated multiple performance variables derived from the GNSS receiver velocity–time profile, including split times, peak sprint velocities, minimum velocities during curve negotiation, and segment-specific running speeds and distances at standardized points along the running path (e.g., 13.7 m, 27.4 m, and 41.1 m). Reliability was quantified using ICC to assess relative reliability and coefficients of variation (CV%) to assess absolute reliability across the three testing sessions. Acceptable between-session reliability for most of the GNSS-derived variables was reported, with coefficients of variation ranging from 1.3–7.7% for linear sprint measures and 1.6–8.4% for curvilinear base running variables. ICC for most measures were reported as moderate to high

(ICC~0.74–0.98), indicating consistent ranking of participants across testing sessions. Additionally, the authors calculated the smallest worthwhile change (SWC) to determine the sensitivity of the GPS-derived metrics for detecting meaningful performance changes. The analysis showed that several key metrics, particularly time and velocity measures at distances of 41.1 m and 54.7 m, as well as running speed at 27.4 m, were adequately sensitive to detect performance changes. Collectively, these findings indicated that the GPS-based measurement system provided reliable and consistent estimates of time-, speed-, and distance-based variables during both linear and curvilinear baseball sprinting tasks. It would seem that GNSS might be appropriate for applied performance monitoring and diagnostic analysis in baseball athletes.

The next three sections will focus on the analysis and interpretation of the data processed from the GNSS receiver, specifically focusing on the curvilinear and linear differences between segments (i.e., the time in the current segment minus the time in the previous segment). These differences provide insight into how base runners change their speed across successive running segments.

- A positive difference reflects an increase in speed, indicating the base runner accelerated into the next segment.
- A negative difference reflects a decrease in speed, indicating the base runner decelerated into the next segment.
- A difference close to zero suggests the base runner maintained similar speed between segments.

This approach allows identification of where speed is gained, maintained, or lost throughout the sprint and provides a clearer understanding of segmental performance.

6.4 Analysing and interpreting linear base running ability

Three high school baseball players (Player A, Player B, and Player C) from a baseball academy in Puerto Rico were selected for in-depth performance comparison. The players varied in time to second base, which allowed the demonstration of the utility of the GNSS data analysis across different performance profiles. This approach illustrates how baseball coaches and sport scientists can apply the comparative framework to their baseball players, enabling individualized monitoring.

As can be observed in Table 1, the distance was divided into four linear sprint (L) segments (see Figure 2), and the velocities for each linear distance quantified via GPS:

- L1 (0–13.7 m)—indicative of initial acceleration
- L2 (13.7–27.4 m)—indicative of transitional acceleration to maximum speed
- L3 (27.4–41.1 m)—indicative of maximal speed
- L4 (41.1–54.7 m)—indicative of speed endurance

Linear sprint data is reported in Table 1, the differences in speed development among Players A, B, and C highlighted. Player A had the fastest performance overall, maintaining higher speeds consistently between segments. Player C decelerated early from L2 to L3, indicating poor transitional acceleration. The three players decelerated before passing the 54.7 m mark.

Table 6.1 Linear sprint segments: time and speed for three players different in performance.

	Player A	Player B	Player C
L1: Speed at 13.7 m ($m \cdot s^{-1}$)	8.22	6.96	5.95
L1: Time at 13.7 m (s)	2.60	2.95	3.30
L2: Speed at 27.4 m ($m \cdot s^{-1}$)	9.02	7.39	6.32
L2: Time at 27.4 m (s)	4.20	4.90	5.50
L3: Speed at 41.1 m ($m \cdot s^{-1}$)	9.12	7.45	6.13
L3: Time at 41.1 m (s)	5.70	6.70	7.70
L4: Speed at 54.7 m ($m \cdot s^{-1}$)	8.72	7.13	5.95
L4: Time at 54.7 m (s)	7.20	8.55	9.90

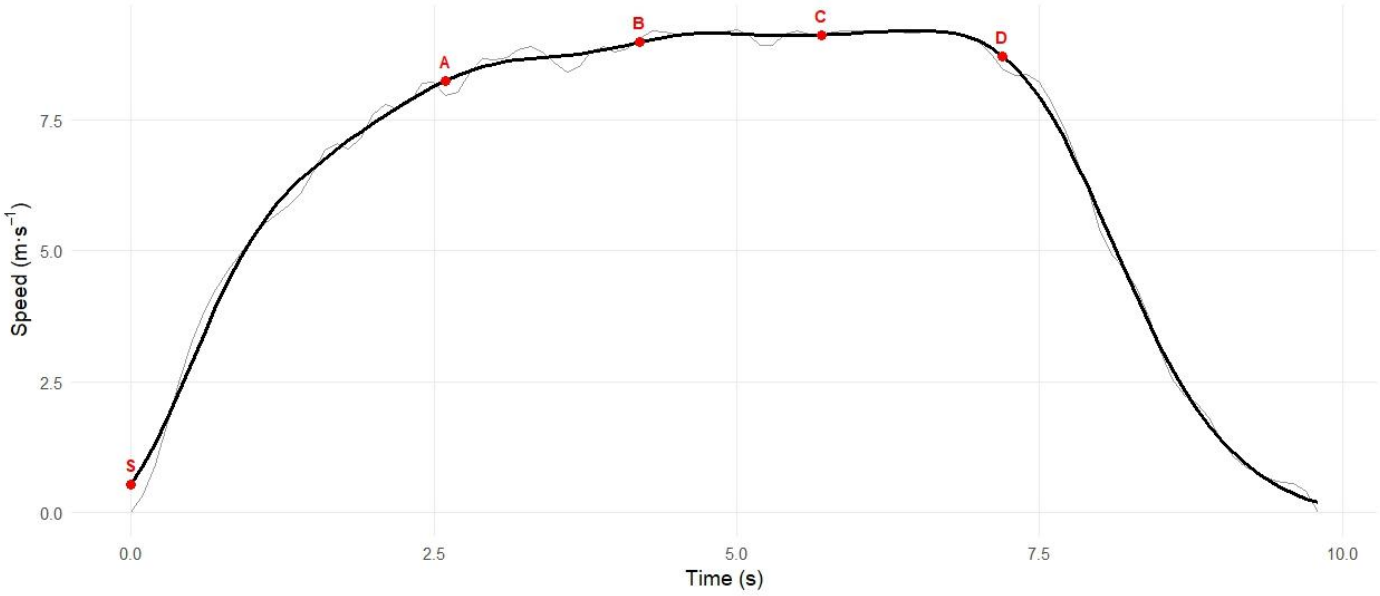


Figure 6.2. Speed–time profiles of a baseball player performing a 54.7 m linear sprint.

Key: S = Start; A = Time and speed at 13.7 m; B = Time and speed at 27.4 m; C = Time and speed at 41.1 m; D = Time and speed at 54.7 m.

To evaluate how each player transitions between bases, calculating the difference between segments provides a clear indication of whether the base runner is increasing or decreasing speed across these segments. Specifically:

- L2–L1—This phase reflects how much speed changes when moving from initial acceleration to transitional acceleration.
- L3–L2—This phase reflects the transition from acceleration toward maximal speed.
- L4–L3—This phase reflects the player's ability to maintain maximal speed during the later portion of the sprint.

The linear sprint speed changes across successive segments (L1, 2, 3, and 4) are presented in Table 2, and three observations can be made from these data:

- L2–L1: Player A demonstrated the largest increase in speed (0.80 $m \cdot s^{-1}$) during this phase as compared to Players B and C, indicating greater speed development during the transition from initial acceleration.
- L3–L2: There was very little increase in speed during this phase (−0.19 to 1.0 $m \cdot s^{-1}$), indicating that players were approaching maximal speed; however, most notable was that Player C was already decelerating during this phase.
- L4–L3: Speed decreased during this phase in all three players, indicating a reduction in speed during the later stages of the sprint, with the largest decrease observed in Player A (−0.40 $m \cdot s^{-1}$).

From a practical perspective, these linear segment-specific velocity profiles illustrate how practitioners might interpret GPS-derived sprint data to identify potential areas of performance development. Specifically:

1. The speed reduction observed in the later phase of the sprint for Player A may suggest a potential focus on speed endurance capacity.
2. The relatively smaller speed increases during the early sprint phases for Players B and C may indicate areas where initial or transitional acceleration development could be considered.
3. The reduction in speed observed for Player C during the L3–L2 phase illustrates how practitioners might examine maximal speed development or speed maintenance characteristics when interpreting segment-specific sprint profiles.

Table 6.2. Linear segments: change comparison across three players.

	Player A	Player B	Player C
L2–L1 ($m \cdot s^{-1}$)	0.80	0.43	0.37
L3–L2 ($m \cdot s^{-1}$)	0.10	0.06	−0.19
L4–L3 ($m \cdot s^{-1}$)	−0.40	−0.32	−0.18

6.5 Analysing and interpreting curvilinear base running ability

As can be observed in Table 3, the distance was divided into four curvilinear (C) segments (Figure 3), and the speed for each curvilinear distance quantified via GPS:

- C1 (Home plate—13.7 m)—indicative of initial acceleration.
- C2 (13.7 m—first base)—indicative of curvilinear deceleration.
- C3 (First base—41.1 m)—indicative of curvilinear reacceleration.
- C4 (41.1 m—second base)—indicative of maximal speed.

Curvilinear sprint data is reported in Table 3, the differences in speed, time and distance among Players A, B, and C highlighted. Player A demonstrated the best overall performance relative to Players B and C. From C1 to peak speed, Player A exhibited the smallest increase in velocity (+0.17 $m \cdot s^{-1}$) compared with Player B (+0.37 $m \cdot s^{-1}$) and Player C (+0.34 $m \cdot s^{-1}$). After reaching peak speed, Player A also was found to have substantially lower deceleration toward first base (−0.45 $m \cdot s^{-1}$) than Player B (−1.15 $m \cdot s^{-1}$) and Player C (−1.56 $m \cdot s^{-1}$), suggesting less deceleration during the transition. After C2, Player A again maintained speed more effectively, with lower deceleration (−0.61 $m \cdot s^{-1}$) than Player B (−1.21 $m \cdot s^{-1}$) and Player C (−1.78 $m \cdot s^{-1}$). In contrast, Player C displayed the greatest reacceleration after peak speed (+1.59 $m \cdot s^{-1}$), indicating greater reliance on linear sprint ability compared with Player A (+0.79 $m \cdot s^{-1}$) and Player B (+1.07 $m \cdot s^{-1}$). All players decelerated before reaching second base.

In terms of distance covered across the four segments, distinct curvilinear path strategies were observed between players. In C1 (0–13.7 m), Player C covered the greatest distance (13.32 m), followed by Player A (13.15 m) and Player B (12.54 m), indicating a slightly longer initial path for Player C. During C2 (13.7 m to first base), Player C again covered the greatest distance (14.66 m), while Player B (14.20 m) and Player A (13.88 m) followed, suggesting a wider approach into first base for Player C. In contrast, Player A covered the greatest distance in C3 (first base to 41.1 m: 14.97 m) compared with Player B (14.43 m) and Player C (13.22 m), indicating a more progressive curvilinear trajectory between bases. During the final segment (C4), Player C (13.48 m) and Player B (13.42 m) covered greater distances than Player A (12.51 m), suggesting that Player A adopted a tighter running line when approaching second base. When comparing

Player A with Players B and C, Player A demonstrated a wider running path in C3 exiting the first base, whereas Players B and C consistently adopted wider running paths in C2 approaching first base.

Table 6.3. Curvilinear sprint segments: time, speed and distance for three players.

	Player A	Player B	Player C
C1: Speed at 13.7 m ($m \cdot s^{-1}$)	8.14	6.38	5.58
C1: Time at 13.7 m (s)	2.45	2.90	3.20
Peak speed before first base ($m \cdot s^{-1}$)	8.31	6.75	5.92
C2: Speed at first base ($m \cdot s^{-1}$)	7.86	5.61	4.36
C2: Time at first base (s)	4.15	5.15	5.85
Minimum speed between peaks ($m \cdot s^{-1}$)	7.70	5.54	4.14
C3: Speed at 41.1 m ($m \cdot s^{-1}$)	8.09	6.46	5.79
C3: Time at 41.1 m (s)	6.05	7.45	8.65
Peak speed after first base and before second base ($m \cdot s^{-1}$)	8.49	6.61	5.73
C4: Speed at second base ($m \cdot s^{-1}$)	8.08	5.00	4.65
C4: Time at second base (s)	7.55	9.60	11.10
C1: Distance covered from 0–13.7 m (m)	13.15	12.54	13.32
C2: Distance covered from 13.7 m to first base (m)	13.88	14.20	14.66
C3: Distance covered from first base to 41.1 m (m)	14.97	14.43	13.22
C4: Distance covered from 41.1 m to second base (m)	12.51	13.42	13.48

To evaluate how each player transitions between sprint segments, calculating the difference between segments provides a clear indication of whether the base runner is increasing or decreasing speed.

- C2–C1—This phase reflects the change in speed when the base runner enters the curve approaching first base.
- C3–C2—This phase reflects the change in speed associated with reacceleration after negotiating the curve.
- C4–C3—This phase reflects the base runner's ability to accelerate to maximum speed or maintain speed when exiting the curve toward second base.

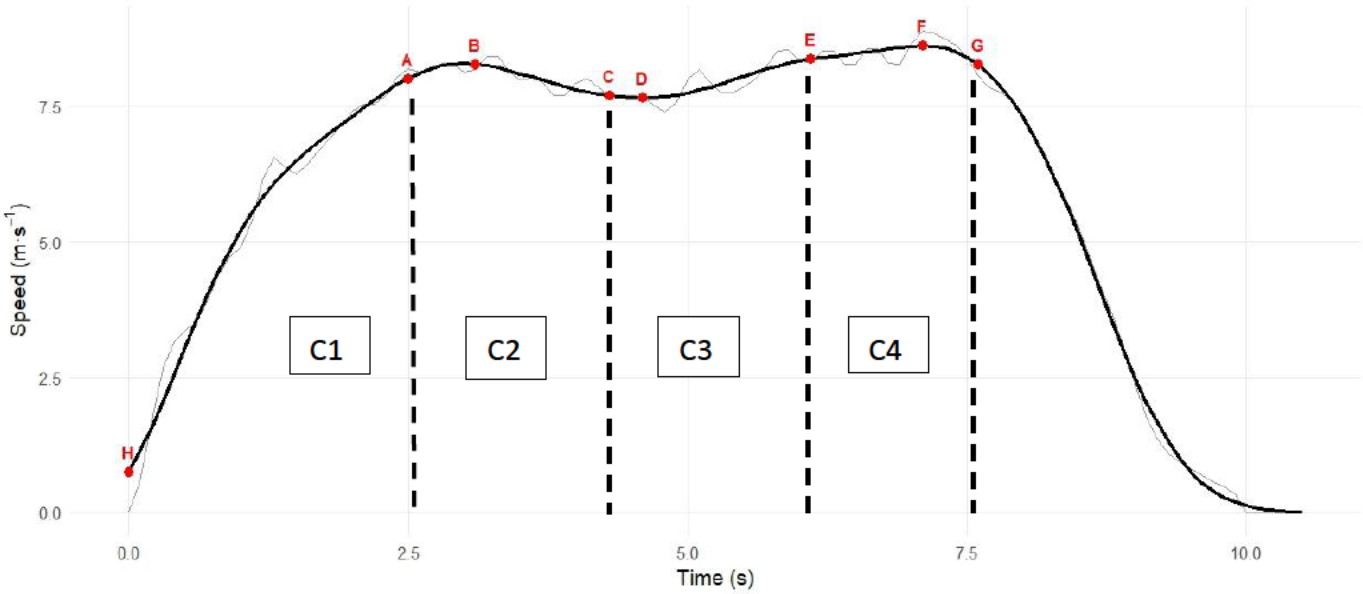


Figure 6.3. Speed–time profiles of a baseball player performing a home-to-second-base sprint.

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.

The curvilinear sprint speed changes across successive segments (C1, 2, 3, and 4) are shown in Table 4, and three points are important to highlight:

- C2–C1: Player A demonstrated the smallest reduction in speed (−0.28 m·s^{-1}) during the entry into the curve and covered the shortest distance during this phase as compared to Players B and C. This may suggest a tighter running path with less disruption to speed. In contrast, Players B and C appeared to adopt a different strategy where they covered more distance with a larger reduction in speed to set themselves up with a different exit path/strategy around first base.
- C3–C2: Player A was observed to have minimal speed change (−0.05 m·s^{-1}), indicating stable speed in this phase. Players B and Player C demonstrated greater increases in velocity during this phase, suggesting a more pronounced reacceleration after first base. Player C also exhibited a slightly flatter curve (i.e., −1.44 m).
- C4–C3: Players B and C exhibited substantial reductions in speed, whereas Player A ran a shorter distance, probably due to the wider path taken in the previous phase. Differences in segment distance across this phase may reflect variations in running trajectory following the curve.

From a practical perspective, these curvilinear segment-specific speed profiles illustrate how practitioners might interpret GPS-derived sprint data to identify potential areas of performance development. Specifically:

1. The minimal speed developed observed during the curve phase for Player A may suggest opportunities to examine physical/technical strategies after negotiating the curve.
2. The speed patterns observed in the later segment for Player B illustrate how practitioners might focus on reacceleration capacity when exiting the curve toward second base.
3. The trajectory and velocity changes observed for Player C across segments may warrant emphasis on curved-running mechanics and path selection.

Table 6.4. Differences in speed and distance between successive curvilinear segments (C1–C4) during the home-to-second-base sprint.

	Player A	Player B	Player C
	Speed ($m \cdot s^{-1}$)		
C2–C1	−0.28	−0.77	−1.22
C3–C2	0.23	0.85	1.43
C4–C3	−0.01	−1.46	−1.14
	Distance (m)		
C2–C1	0.73	1.66	1.34
C3–C2	1.09	0.23	−1.44
C4–C3	−2.46	−1.01	0.26

Key: Negative values indicate that the preceding segment had a greater value than the subsequent segment, reflecting reductions in speed or distance between phases.

6.6 Base running efficiency ratio: Curvilinear/linear diagnostics

Of interest is how a base runner's raw linear ability translates to curvilinear base running performance, revealing the extent to which linear speed potential is preserved or lost when sprinting a curved path. This potential can be calculated as a BRE metric derived from the ratio of curvilinear to linear sprint in each of the phases. BREr provides insight into how a baseball player maintains their maximal linear sprint ability while rounding the bases (103). To determine BREr, the base runners performed a linear sprint covering a distance equivalent to the 54.7 m home-to-second-base sprint. BREr is calculated by dividing the curvilinear sprint segment time over each segment by their linear sprint segment time:

BREr = (Curvilinear segment time)/(Linear segment time)

This ratio normalizes the result to each athlete's base running ability. A value closer to 1.00 indicates that the base runners maintained a similar performance to their straight sprint performance, reflecting high efficiency (maneuverability) relative to their linear capacity (continuous acceleration) (87,103,154). In contrast, a value farther from 1.00 suggests a substantial loss in performance during the curvilinear segment (drop in speed), reflecting low efficiency relative to their linear capacity (deceleration instead of maintenance). The BREr reflects how efficient athletes transfer linear sprinting characteristics into the curvilinear technical and physical demands of base running. It captures not only raw speed but also highlights physical and technique fluctuations when rounding bases. Therefore, a BREr of 1.05 means the runner maintains 95% of their straight-line sprint time, indicating a 5% reduction in time during curvilinear sprinting.

BRE has typically been expressed as a ratio of total time of both the linear and curvilinear 54.7 m sprints (103,149). When computing and understanding BREr, time is the best measure to use, as neither distance nor speed are good representations of efficiency on their own; taking a wider line could increase speed, or decreasing speed could flatten the line. It therefore makes sense to look at time to each specific point as the best measure of efficiency, as it incorporates both distance and speed. However, there is a need to distinguish between global efficiency (the fastest possible time to second base vs. linear) and segmented performance. At the global level, efficiency is unambiguous, being the run that reaches the end point with the least time lost compared to linear sprinting. When broken into quarters (for any variable) it is no longer valid to assume that the smallest difference in time, distance or speed between linear and curvilinear represents better efficiency. Practitioners could fall into the trap where a participant can appear "inefficient" in one quarter (larger linear–curvilinear gap) yet still be globally efficient if that strategy reduces the gap in later quarters. It may be more prudent to break efficiency down into an early (home to first), late (first to second) phase, and total (home to second) phase because it may offer greater ecological validity. These phases closely reflect the principal base running demands encountered in baseball game situations and may therefore be easier for practitioners to interpret and apply. However, further research is needed to determine optimal segmentation strategies. This does not necessarily indicate what is most efficient, but optimal efficiency may reflect a balance of efficiency in these zones (i.e., BREr closer to 1.00 in each zone), which is potentially easier to understand than a complex balancing act between four split segments.

As can be observed in Table 6.5, the home-to-second-base sprint was divided into three BREr segments, and the ratio for each segment was quantified via BREr calculation ([curvilinear segment time]/[linear segment time]):

- BREr1 from home to first base—indicative of efficiency in maintaining speed under increasing curvilinear demands
- BREr2 from first to second base—indicative of efficiency after curvilinear demands to maximal speed.
- BREr3 from home to second base—indicative of how effective the athlete is across multiple bases and is a combination of BREr1 and BREr2.

Given the information in Table 6.5, several interpretations can be drawn. Player A demonstrated the highest efficiency across all three ratios, suggesting a strong ability to maintain speed given the curvilinear demands of running multiple bases. The highest BREr was observed in the first-to-second-base segment. This segment may represent a potentially relevant area for further exploration in a practice context. For example, practitioners might consider examining inside–outside foot mechanics or related strength qualities, or exploring alternative approach paths in the preceding segment, to determine whether such adjustments influence efficiency in the subsequent phase. However, these considerations should be interpreted as exploratory and context-dependent rather than prescriptive.

Table 6.5. BREr for three players of different curvilinear performance.

	Player A	Player B	Player C
BREr1	0.99	1.05	1.06
BREr2	1.13	1.22	1.19
BREr3	1.05	1.12	1.12

Limitations. Several limitations should be acknowledged when interpreting the present findings. First, the detailed comparative analysis presented in this case study is based on three high school baseball players, and therefore the results should be interpreted as illustrative examples of the analytical framework rather than general performance characteristics. Second, the participants were drawn from a specific population of high school players, which may limit the applicability of these observations to other competitive levels or sports contexts, and should be interpreted with this in mind. Finally, although GPS-derived velocity and trajectory data provide valuable information about running dynamics, the technology does not directly measure biomechanical variables such as joint kinematics, force production, or ground reaction forces (84). Consequently, interpretations regarding movement strategies should be considered indirect inferences based on velocity–time data rather than direct biomechanical measurements.

6.7 Conclusion

GPS-derived velocity–time variables can provide a useful framework for examining the dynamics of base running performance during both linear and curvilinear sprinting. Specifically, the framework illustrates how GPS-derived data can be used to examine where athletes accelerate, maintain velocity, or experience reductions in speed while transitioning from linear sprinting into curved running around the bases. This segmented approach allows practitioners to visualize how velocity changes across different phases of the base running path and to identify potential differences in how athletes negotiate the transition from a linear to curvilinear movement.

GPS-derived metrics can reveal individual differences in segment-specific running characteristics. These characteristics include initial acceleration, transitional velocity changes approaching first base, velocity reduction during curve negotiation, subsequent reacceleration toward second base, and deceleration in the late phase associated with fatigue-related constraints on force production and stride mechanics (104). These examples illustrate how the velocity–time profile might be interpreted to examine different base running strategies across athletes. The BREr provides an example of how relative performance between linear and curvilinear sprinting segments may be quantified to assess how effectively athletes maintain linear sprint capability while negotiating the technical demands associated with rounding bases. Therefore, the use of GNSS to enhance base running ability diagnostics represents a novel method to advance understanding of linear–curvilinear interaction in base running and potentially could better inform individualized assessment and training decisions.

Chapter 7: Improving base running diagnostics with foot pod technology: Intersession reliability of linear and curvilinear running performance

This chapter comprises the following published paper in the *Journal of Strength and Conditioning Research*.

Reference: Martínez-Rodríguez JA, Crotin RL, Neville J, Barcelo RA, and Cronin JB. Improving base running diagnostics with foot pod technology: Intersession reliability of linear and curvilinear running performance. *J Strength Cond Res*, 40: e714-e720, 2026.

7.1 Prelude

Chapters 5 and 6 highlighted that GNSS technology could provide useful external measures of base running performance, including time, velocity, distance, path behaviour, and segment-specific efficiency. However, GNSS is worn on the trunk and therefore cannot describe the step-by-step foot-specific strategies that may explain why a base runner accelerates, maintains, or loses speed during linear and curvilinear sprinting. This limitation is important because Chapters 3 and 4 highlighted that curvilinear base running involved distinct inside- and outside-leg demands, including braking, stabilization, and propulsion. Chapter 7 therefore introduced IMU foot pod technology as a complementary method to GNSS-based monitoring. Whereas GNSS identifies where performance changes occur across the sprint, foot pods can provide more detailed spatiotemporal variables such as ground contact times, stride length, push-off, impact, and inside–outside foot behaviour. The purpose of Chapter 7 was to determine whether these IMU-derived variables could be measured reliably so as to support more refined diagnostics of the mechanical patterns underpinning base running performance.

7.2 Introduction

In baseball, base running proficiency hinges on metrics like time, speed, and acceleration. The StatCast system in Major League Baseball stadiums capture base running movement to calculate such data using multiple high-sampling frequency cameras (21,46,62,87,103). However, coaches and sports scientists have limited access to such technology. Consequently, there is a need for more portable and cost-effective solutions. Timing gate technology has been widely adopted to assess linear and curvilinear sprint ability, offering insights into sprint times and speeds between bases (5,8,53,91,116,122,143). These time-based

data, however, provide little insight into movement descriptives, given that only one data point is quantified over many seconds (1). These spatial and temporal limitations highlight the necessity for more advanced step-by-step assessment methods, especially for quantifying curvilinear movements by segments such as dividing home to second base into 2 segments e.g., home to first and first to second (87,95,103). Segmental information enables a better understanding of specific curvilinear and linear kinematics characteristics (112,117). One technology that may provide such segmental kinematic information is IMU foot pod technology. High reliability has been found on foot pod technology in walking (102), running (47), and change of direction (COD) (134). However, the reliability of such technology has not been used to quantify the reliability of variables that are important in describing base running performance.

Kinematic variables, such as time, speed, SL, GCT, push-off, and impact, provide valuable insight into the mechanical and performance demands of base running. Time, speed, and SL measures reflect the base runner's ability to generate and maintain speed, whereas GCT, push-off, and impact characterize force application and breaking patterns associated with linear and curvilinear movement. Collectively, these variables help identify and explain changes in performance and hence can guide exercise prescription to better effect. To the authors' knowledge, however, no researchers have quantified the kinematic characteristics of base running using IMU foot pod technology, and no comprehensive analysis of the reliability of these measures has been reported, such analysis providing the focus of this article. The purpose of this study was to determine the intersession reliability of foot pod technology for quantifying kinematic measures over the 54.7-m straight-line sprint (linear) and home-to-second base sprint (curvilinear).

7.3 Methods

7.3.1 Experimental approach to the problem

A cross-sectional, repeated measures design was used for comparative analysis of linear and curvilinear foot pod data. A familiarization session was conducted before data collection to ensure consistent technique. Trained male high school baseball players with 11.83 years of structured strength and 2.92 years of baseball training were recruited, given baseball players represent a performance-relevant population for examining curvilinear base running mechanics. Subjects were tested on a turf baseball field, wearing baseball cleats and completing a standardized dynamic warm-up before each session. Data were collected over 3 testing occasions, separated by at least 2 days and a maximum of 25 days. Researchers quantified the reliability of inside and outside leg mechanics over 3 consecutive sessions using change in the mean, coefficients of variation (CVs), and ICCs.

7.3.2 Subjects

Twelve trained male high school baseball position players (age =14.67 ± 0.89 [14 – 16] years old, height = 169.29 ± 9.03 cm, weight = 63.98 ± 10.29 kg) volunteered to participate in this study. Baseball players trained at a baseball academy in Puerto Rico and had a minimum of 1 year of baseball experience. Subjects were required to be healthy and free of injury at the time of testing. Before participating in this study, all subjects were provided with an information sheet, and their written assent and consent of a legal guardian were required before participating in the study. The research was approved by the Auckland University of Technology Ethics Committee (24/69).

7.3.3 Procedures

Testing sessions were conducted with a minimum of 2 days and a maximum of 25 days apart, at the same time of the day, and tested in the same order (i.e., linear running first and then curvilinear running). The interval between sessions ranged from 2 to 25 days because of unforeseen scheduling challenges at the baseball academy. Each testing session lasted approximately 25 minutes.

All subjects wore cleats and performed a standardized warm-up at the beginning of the session (Table 1), which consisted of lower-body dynamic movements. After warming up, the subjects performed 2 straight-line sprints separated by a 3-minute rest period (26). Each sprint began in a lead-off shoulder-width position in which subjects were instructed to run maximally until passing the end cones at 54.7 m. After 10 minutes of rest, the subjects performed 2 trials, test. The starting position for the home-to-second base sprint test was a lead-off position, placing the right foot in the middle of the home base and the left foot shoulder-width. This starting position was the normal position a baseball player uses when prepared to run during the offensive phase. Subjects were instructed to run at maximum speed through the second base and then decelerate. Two trials for the straight-line sprint and home-to-second base tests were collected and averaged for further analysis.

Table 7.1. Warm-up exercises – Baseball base running.

Exercises	Distance	Reps	Rest (seconds)
Linear running	13.7 m	2	30
Running hip out	13.7 m	2	30
Butt kicks	13.7 m	2	30

Skip	13.7 m	2	30
Lateral shuffles	13.7 m	2	30
Quick forwards and backwards	13.7 m	2	60
Walking Lunges	13.7 m	1	30
Linear sprints	13.7 m	3	60
Curvilinear sprints	13.7 m	3	60

7.3.4 Equipment

Foot pod technology (Plantiga Technologies, Vancouver, Canada) comprising of a 6-axis IMUs (triaxial accelerometer and triaxial gyroscope) were placed in the subjects' shoes before the warm-up (26) as shown in Figure 1. The IMU collected data at a sampling rate of 416 Hz and at the end of testing, the data were uploaded to Plantiga cloud, where the manufacturer software was used to quantify the variables of interest.

7.3.5 Data analysis

Each trial was recorded using an iPad video camera with 1080p HD video recording at 30 frames per second, capturing a lateral view. The video recordings were used to count individual steps accurately and to identify the start and end times of each segment. Specifically, the average metrics were calculated for the following segments and were included in the final analysis:

- Home-to-first base sprint: Curvilinear running segment 1
- First-to-second base sprint: Curvilinear running segment 2
- Home-to-second base sprint: Curvilinear running total segment
- Start-to-end 54.7-m sprint: Linear running segment

The video-determined step counts for each segment were selected within the IMU signal in the Plantiga Explore feature. The start and end steps of each segment were masked manually using the masking tool. This allowed precise isolation of the 4 distinct segments from the larger activity trace.

Eight different kinematic measures were extracted from the Plantiga cloud and used for analysis. The manufacturer's definitions for the metrics assessed and included in the final analysis are described in Table 2.

7.3.6 Statistical analysis

An a priori sample size estimate was conducted to determine the number of subjects required to assess the reliability of key performance metrics using ICCs. Although G*Power 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 subjects to detect a statistically significant correlation. One subject suffered and injury unrelated to the base running testing during the study, leaving 12 subjects for the final analysis, resulting in an estimated power of 0.77.

Outlier and normality analysis using the Shapiro-Wilks test was performed before any further statistical analysis. The mean of 2 trials for each subject was used for analysis, and data were reported as mean and standard deviations for each variable of interest. Reliability was quantified using the Hopkins spreadsheet for reliability analysis (9). Before analysis, measures were log transformed to normalize the distribution and stabilize the variance, thereby improving the validity of reliability estimates.

Figure 7.1. IMU sensor and insole.



Table 7.2. Manufacturer's definitions for the metrics assessed

Metric	Manufacturer's definition
Maximum speed ($m*s^{-1}$)	Calculated for each foot based on the horizontal accelerations, and then the speed of both feet was averaged to estimate the CoM speed. Speed was reported every tenth of a second as a summary of the activity.
Average speed ($m*s^{-1}$)	Calculated as the median speed over the duration of the activity.
Right and left foot average ground contact time (s)	The amount of time the foot spent on the ground in each stride cycle, defined by time from foot strike to toe-off.

Right and left foot average stride length (m)	The distance the foot travelled in one stride, calculated from toe off to foot strike of the same foot.
Right and left foot average and total push-off (g)	The peak acceleration as the foot leaves the ground.
Right and left foot average and total impact (g)	The peak acceleration as the foot contacts the ground.

Systematic change between sessions were quantified using mean percentage change and repeated measures analysis of variance (ANOVA) with Bonferroni post hoc contrasts (20). Absolute consistency, the degree of variability in absolute scores was quantified as a CV, where measures less than or equal to 10% were deemed acceptable (11). Relative consistency reflects the stability of subjects' rank order across repeated testing occasions and was determined using ICC (3,1) using a two-way mixed-effect single measures model (12). ICCs were calculated for consecutive testing-session comparisons (sessions 1–2 and 2–3), using the mean of two trials per player at each session. Categorization of ICC was deemed as follows: "poor" (< 0.50), "moderate" (0.50–0.74), "good" (0.75–0.90), or "excellent" (> 0.90) (4). Alpha levels of 0.05 and 95% confidence intervals were used where appropriate.

7.4 Results

The between-session variability of the linear IMU variables are detailed in Table 7.3. In terms of systematic change for the linear running segment, 13% (4/30) between-session comparisons were 0.2%. The average between-session change across all variables was 0.09% for sessions 2-1, and 20.40% for sessions 3-2. No statistically significant change in the mean of any variable was observed between sessions. In terms of absolute consistency, no variable exceeded the 10% threshold, in fact approximately 60% of CVs were < 5%. The average between-session CVs across all variables were 4.75% for sessions 2-1, and 3.56% for sessions 3-2. Regarding relative consistency, all 30 between-session comparisons were above 0.70, only one ICC was below 0.74 (right total push-off), and all session 3-2 had ICCs .0.85.

Table 7.3. Between-session reliability of IMU variables for the 54.7-m linear sprint

Variable	Mean ± SD			% Change in mean (95% CI)		CV (95% CI)		ICC (95% CI)	
	Session 1	Session 2	Session 3	Session 2-1	Session 3-2	Session 2-1	Session 3-2	Session 2-1	Session 3-2
Start-to-end 60-yard sprint									
Time (s)	7.9 ± 0.6	7.8 ± 0.5	7.9 ± 0.6	-1.2 (-2.3- -0.2)	1.3 (0.1-2.6)	1.2 (0.8-2.0)	1.4 (1.0-2.3)	0.98 (0.93-0.99)	0.97 (0.90-0.99)
Max speed ($m*s^{-1}$)	7.9 ± 0.6	7.9 ± 0.6	7.9 ± 0.7	-0.4 (-1.1-0.4)	-0.1 (-1.2-1.0)	0.8 (0.6-1.4)	1.2 (0.8-2.0)	0.99 (0.97-1.00)	0.98 (0.95-1.00)
Average speed ($m*s^{-1}$)	7.6 ± 0.6	7.5 ± 0.6	7.6 ± 0.6	-0.7 (-1.6-0.2)	0.2 (-0.9-1-3)	1.1 (0.7-1.8)	1.3 (0.9-2.2)	0.99 (0.95-1.00)	0.98 (0.93-0.99)
Right average GCT (s)	95.0 ± 13.8	96.6 ± 12.8	97.8 ± 14.6	1.8 (-0.3-3.9)	1.0 (-1.8-4.0)	2.3 (1.6-4.0)	3.2 (2.3-5.5)	0.98 (0.94-0.99)	0.97 (0.88-0.99)
Left average GCT (s)	97.9 ± 11.9	96.8 ± 10.9	96.7 ± 12.8	-1.1 (-3.6-1.5)	-0.3 (-3.2-2.6)	2.9 (2.1-5.0)	3.3 (2.3-5.6)	0.96 (0.86-0.99)	0.95 (0.84-0.99)
Right average stride length (m)	3.8 ± 0.4	3.7 ± 0.3	3.8 ± 0.3	-1.0 (-3.3-1.4)	1.5 (-0.4-3.4)	2.7 (1.9-4.6)	2.1 (1.5-3.6)	0.92 (0.76-0.98)	0.94 (0.79-0.98)
Left average stride length (m)	3.7 ± 0.3	3.8 ± 0.3	3.8 ± 0.3	-0.8 (-2.5- 1.0)	1.3 (-0.6-3.2)	2.0 (1.4-3.4)	2.1 (1.5-3.6)	0.95 (0.83-0.98)	0.94 (0.82-0.98)
Right total impact (g)	430.42 ± 62.61	432.18 ± 48.92	427.38 ± 59.24	0.8 (-5.3-7.3)	-1.4 (-5.6-3.1)	7.2 (5.0-12.5)	5.0 (3.5-8.7)	0.75 (0.34-0.92)	0.87 (0.62-0.96)

Left total impact (g)	438.91 ± 62.17	424.31 ± 41.82	425.06 ± 48.25	-2.9 (-8.2-2.7)	0.0 (-3.7-3.9)	6.5 (4.5-11.2)	4.3 (3.0-7.4)	0.77 (0.38-0.93)	0.87 (0.61-0.96)
Right total push-off (g)	278.95 ± 42.25	283.52 ± 55.32	278.59 ± 46.23	1.1 (-7.1-10.0)	-1.4 (-6.6-4.1)	9.9 (6.9-17.4)	6.2 (4.4-10.8)	0.73 (0.29-0.91)	0.90 (0.69-0.97)
Left total push-off (g)	271.69 ± 30.20	276.36 ± 54.34	269.00 ± 47.69	0.6 (-6.6-8.4)	-2.4 (-7.3-2.7)	8.6 (6.0-15.1)	5.9 (4.1-10.2)	0.75 (0.34-0.92)	0.92 (0.75-0.98)
Right average impact (g)	28.61 ± 3.66	28.81 ± 2.43	28.68 ± 3.15	1.1 (-3.9-6.3)	-0.6 (-3.9-2.7)	5.8 (4.1-10.0)	3.7 (2.6-6.4)	0.77 (0.37-0.93)	0.89 (0.65-0.97)
Left average impact (g)	28.57 ± 3.68	28.27 ± 2.83	28.22 ± 3.36	-0.8 (-5.6-4.4)	-0.4 (-3.4-2.8)	5.8 (4.0-10.0)	3.6 (2.5-6.1)	0.81 (0.46-0.94)	0.92 (0.75-0.98)
Right average push-off (g)	18.46 ± 2.89	19.08 ± 3.53	18.53 ± 3.28	3.0 (-3.5-9.9)	-2.8 (-7.0-1.7)	7.5 (5.3-13.1)	5.1 (3.6-8.8)	0.85 (0.55-0.95)	0.94 (0.80-0.98)
Left average push-off (g)	17.80 ± 2.52	18.31 ± 3.73	17.95 ± 3.52	1.9 (-4.0-8.3)	-1.9 (-6.1-2.6)	6.9 (4.9-12.1)	5.0 (3.5-8.7)	0.87 (0.61-0.96)	0.95 (0.83-0.98)

The between-session variability of the curvilinear IMU variables can be observed in Table 7.4. In terms of systematic change for the curvilinear variables in curvilinear running segments 1 and 2, and total segment, 18% (16/90) of the between-session comparisons were 0.2%. The averaged between-session change across all variables was 0.23% for sessions 2-1 and 0.49% for sessions 3-2 for curvilinear running segment 1, 20.07% for sessions 2-1, and 1.32% for sessions 3-2 for curvilinear running segment 2, and 0.15% for sessions 2-1 and 0.96% for sessions 3-2 for curvilinear running total segment. No statistically significant ($p > 0.05$) change in the mean in any variable was observed between sessions. In terms of absolute consistency, only one CV of 30 was greater than 10% (session 2-1 left average impact) in segment 1, 6/30 CVs were greater than 10% in the curvilinear segment 2, and no CV was greater than 10% for the curvilinear total segment. Regarding the relative consistency of curvilinear running, 20% (0.47–0.73), 43% (0.26–0.73), and 27% (0.66–0.73) of the between-session comparisons were below 0.74 for the curvilinear segments 1 and 2, and total segment, respectively, and 70% (63/90) of all ICCs were above 0.74.

Table 7.4. Between-session reliability of IMU variables for home-to-second-base sprint by segments

Variable	Mean ± SD			% Change in mean (95% CI)		CV (95% CI)		ICC (95% CI)	
	Session 1	Session 2	Session 3	Session 2-1	Session 3-2	Session 2-1	Session 3-2	Session 2-1	Session 3-2
Segment 1: Home-to-first base sprint									
Time (s)	4.6 ± 0.3	4.6 ± 0.3	4.6 ± 0.3	-0.3 (-2.5-1.8)	-0.5 (-2.0-1.0)	2.4 (1.7-4.2)	1.7 (1.2-2.9)	0.88 (0.63-0.96)	0.93 (0.77-0.98)
Max speed (m*s^{-1})	7.4 ± 0.6	7.3 ± 0.5	7.4 ± 0.5	-1.0 (-2.8-0.8)	0.5 (-1.4-2.5)	2.0 (1.4-3.5)	2.2 (1.5-3.7)	0.93 (0.79-0.98)	0.91 (0.72-0.97)
Average speed (m*s^{-1})	6.8 ± 0.5	6.7 ± 0.4	6.8 ± 0.4	-1.2 (-2.3-0.2)	1.2 (-1.1-3.6)	1.2 (0.8-2.0)	2.6 (1.8-4.5)	0.97 (0.91-0.99)	0.85 (0.57-0.96)
Right average GCT (s)	111.5 ± 14.6	110.0 ± 15.1	110.4 ± 12.3	-1.5 (-4.5-1.6)	0.6 (-3.5-4.9)	3.6 (2.5-6.1)	4.8 (3.4-8.3)	0.95 (0.82-0.98)	0.89 (0.67-0.97)
Left average GCT (s)	116.4 ± 12.5	115.3 ± 11.64	113.3 ± 11.0	-0.9 (-3.1-1.3)	-1.7 (-4.7-1.3)	2.5 (1.8-4.3)	3.5 (2.5-6.0)	0.95 (0.85-0.99)	0.90 (0.70-0.97)
Right average stride length (m)	3.2 ± 0.3	3.2 ± 0.22	3.2 ± 0.2	-1.1 (-4.5-2.3)	-0.4 (-3.2-2.6)	3.9 (2.8-6.7)	3.3 (2.3-5.6)	0.80 (0.44-0.94)	0.81 (0.46-0.94)
Left average stride length (m)	3.3 ± 0.2	3.3 ± 0.2	3.2 ± 0.2	-1.9 (-3.9- -0.2)	-1.2 (-3.5-1.2)	2.4 (1.7-4.0)	2.6 (1.9-4.5)	0.87 (0.62-0.96)	0.87 (0.61-0.96)
Right total impact (g)	219.04 ± 38.18	224.28 ± 31.87	216.95 ± 35.05	2.8 (-1.6-7.4)	-3.5 (-8.5-1.9)	5.0 (3.5-8.6)	6.2 (4.3-10.7)	0.92 (0.75-0.98)	0.86 (0.60-0.96)
Left total impact (g)	220.87 ± 31.48	216.14 ± 22.99	219.74 ± 27.94	-1.7 (-8.2-5.2)	1.4 (-5.9-9.3)	7.8 (5.5-13.7)	8.7 (6.1-15.2)	0.68 (0.21-0.90)	0.56 (0.02-0.85)
Right total push-off (g)	132.66 ± 18.20	131,91 ± 20.09	136.43 ± 21.39	-0.7 (-7.1-6.0)	3.4 (-3.1-10.3)	7.6 (5.3-13.3)	7.5 (5.3-13.1)	0.77 (0.38-0.93)	0.80 (0.43-0.94)
Left total push-off (g)	130.07 ± 17.69	132.28 ± 23.16	133.87 ± 18.02	1.2 (-5.8-8.8)	1.7 (-2.1-5.7)	8.3 (5.8-14.6)	4.3 (3.0-7.4)	0.77 (0.38-0.93)	0.94 (0.80-0.98)
Right average impact (g)	27.15 ± 4.36	27.45 ± 3.36	27.77 ± 3.57	1.6 (-3.0-6.5)	1.1 (-2.6-5.0)	5.3 (3.7-9.1)	4.3 (3.0-7.4)	0.90 (0.69-0.97)	0.91 (0.73-0.97)
Left average impact (g)	26.95 ± 4.43	27.08 ± 2.37	27.38 ± 3.17	1.4 (-7.2-10.8)	0.9 (-6.0-8.2)	10.3 (7.2-18.2)	8.1 (5.7-14.2)	0.51 (-0.05-0.83)	0.47 (-0.11-0.81)
Right average push-off (g)	15.46 ± 1.87	15.97 ± 2.74	16.44 ± 2.64	2.7	3.1	9.9	6.9	0.61	0.85

				(-5.7-11.8)	(-2.9-9.5)	(6.9-17.4)	(4.8-12.0)	(0.09-0.87)	(0.57-0.96)
Left average push-off (g)	14.95 ± 2.10	15.64 ± 2.84	15.69 ± 2.29	4.1	0.8	9.3	5.5	0.73	0.91
				(-3.9-12.7)	(-3.9-5.8)	(6.5-16.3)	(3.9-9.6)	(0.30-0.91)	(071-0.97)
Segment 2: First-to-second base sprint									
				2.1	-1.6	3.6	3.6	0.87	0.89
Time (s)	4.2 ± 0.4	4.3 ± 0.4	4.2 ± 0.4	(-1.1-5.5)	(-4.7-1.6)	(2.6-6.3)	(2.6-6.3)	(0.62-0.96)	(0.66-0.97)
				-1.6	1.7	2.0	2.8	0.95	0.90
Max speed (m*s^{-1})	7.3 ± 0.7	7.2 ± 0.6	7.3 ± 0.6	(-3.4-0.1)	(-0.7-4.3)	(1.4-3.5)	(2.0-4.7)	(0.85-0.99)	(0.68-0.97)
				-0.9	0.7	3.1	2.8	0.89	0.69
Average speed (m*s^{-1})	7.0 ± 0.6	6.9 ± 0.5	7.0 ± 0.6	(-3.5-1.8)	(-1.7-3.2)	(2.2-5.3)	(2.0-4.7)	(0.66-0.97)	(0.69-0.97)
				-1.1	-1.0	6.2	5.1	0.83	0.88
Right average GCT (s)	112.0 ± 14.4	110.7 ± 13.1	109.5 ± 13.3	(-6.3-4.4)	(-5.3-3.5)	(4.4-10.7)	(3.6-8.8)	(0.51-0.95)	(0.64-0.96)
				-2.2	-1.4	4.4	4.8	0.87	0.85
Left average GCT (s)	119.5 ± 12.3	116.9 ± 12.4	115.3 ± 12.9	(-5.9-1.7)	(-5.5-2.8)	(3.1-7.6)	(3.4-8.3)	(0.61-0.96)	(0.57-0.96)
				0.0	0.4	3.6	3.5	0.72	0.62
Right average stride length (m)	3.6 ± 0.3	3.6 ± 0.2	3.6 ± 0.2	(-3.1-3.3)	(-2.7-3.5)	(2.6-6.2)	(2.5-6.0)	(0.28-0.91)	(0.11-0.88)
				0.1	-0.7	2.6	2.6	0.88	0.87
Left average stride length (m)	3.6 ± 0.3	3.6 ± 0.2	3.6 ± 0.3	(-2.2-2.4)	(-3.0-1.6)	(1.8-2.4)	(1.8-4.5)	(0.64-0.96)	(0.62-0.96)
				0.0	3.4	11.6	11.2	0.26	0.32
Right total impact (g)	212.36 ± 30.65	211.32 ± 21.52	219.70 ± 32.52	(-9.3-10.4)	(-6.0-13.7)	(8.1-20.4)	(7.8-19.8)	(-0.34-0.71)	(-0.28-0.74)
				0.9	-2.3	9.5	8.7	0.69	0.72
Left total impact (g)	222.59 ± 36.06	223.80 ± 30.20	219.02 ± 32.57	(-7.0-9.5)	(-9.3-5.3)	(6.7-16.7)	(6.1-15.7)	(0.23-0.90)	(0.28-0.91)
				-1.0	7.0	11.7	9.0	0.58	0.81
Right total push-off (g)	127.5 ± 18.23	126.99 ± 23.99	136.01 ± 25.84	(-10.3-9.3	(-1.0-15.7)	(8.1-20.6)	(6.3-15.8)	(0.04-0.86)	(0.47-0.94)
				-1.3	-0.1	15.5	9.5	0.35	0.83
Left total push-off (g)	122.34 ± 19.18	121.11 ± 22.61	121.94 ± 27.42	(-13.3-12.4)	(-7.9-8.4)	(10.8-27.8)	(6.6-16.6)	(-0.25-0.76)	(0.52-0.95)
				2.0	5.3	10.5	6.5	0.08	0.45
Right average impact (g)	25.57 ± 3.16	25.97 ± 1.95	27.38 ± 2.41	(-6.7-11.6)	(-0.5-11.5)	(7.3-18.4)	(4.6-11.3)	(-0.50-0.60)	(-0.14-0.80
				0.5	-0.9	8.7	5.0	0.76	0.90
Left average impact (g)	27.25 ± 4.59	27.25 ± 3.77	27.00 ± 3.66	(-6.8-8.2)	(-5.1-3.5)	(6.1-15.1)	(3.5-8.6)	(0.35-0.92)	(0.70-0.97)
				1.4	5.5	7.9	5.6	0.73	0.92
Right average push-off (g)	15.42 ± 1.75	15.72 ± 2.52	16.65 ± 3.05	(-5.3-8.6)	(0.4-10.8)	(5.6-13.8)	(4.0-9.8)	(0.30-0.92)	(0.74-0.98)
				1.1	3.8	10.2	6.0	0.72	0.93
Left average push-off (g)	14.47 ± 2.12	14.72 ± 2.85	15.31 ± 3.11	(-7.4-10.2)	(-1.5-9.4)	(7.1-17.8)	(4.2-10.4)	(0.27-0.91)	(0.77-0.98)

Total segment: Home-to-second base sprint									
Time (s)	8.8 ± 0.7	8.8 ± 0.6	8.7 ± 0.7	-0.9 (-1.6-3.4)	-1.4 (-3.4-0.6)	2.8 (2.0-4.8)	2.3 (1.6-3.9)	0.88 (0.64-0.96)	0.92 (0.76-0.98)
Max speed (m*s^{-1})	7.5 ± 0.6	7.4 ± 0.5	7.4 ± 0.5	-1.3 (-3.1-0.5)	0.6 (-1.2-2.4)	2.0 (1.4-3.5)	2.0 (1.4-3.4)	0.95 (0.82-0.98)	0.93 (0.79-0.98)
Average speed (m*s^{-1})	7.0 ± 0.6	6.9 ± 0.5	7.0 ± 0.5	-0.6 (-3.0-1.8)	0.3 (-1.9-2.6)	2.7 (1.9-4.7)	2.5 (1.8-4.4)	0.91 (0.71-0.97)	0.90 (0.70-0.97)
Right average GCT (s)	111.1 ± 13.6	109.8 ± 12.8	109.6 ± 12.3	-1.1 (-4.8-2.8)	-0.2 (-3.7-3.5)	4.3 (3.0-7.5)	4.1 (2.9-7.1)	0.91 (0.71-0.97)	0.91 (0.72-0.97)
Left average GCT (s)	118.0 ± 12.4	116.5 ± 12.1	114.7 ± 10.9	-1.3 (-4.4-2.0)	-1.5 (-4.7-1.9)	3.7 (2.6-6.3)	3.8 (2.7-6.5)	0.91 (0.71-0.97)	0.89 (0.66-0.97)
Right average stride length (m)	3.5 ± 0.3	3.5 ± 0.2	3.5 ± 0.2	-0.5 (-3.2-2.3)	0.6 (-1.6-3.0)	3.1 (2.2-5.3)	2.6 (1.8-4.4)	0.80 (0.44-0.99\4)	0.79 (0.43-0.94)
Left average stride length (m)	3.5 ± 0.2	3.5 ± 0.2	3.5 ± 0.2	0.1 (-1.9-2.1)	0.1 (-2.2-2.4)	2.3 (1.6-3.9)	2.6 (1.8-4.5)	0.89 (0.66-0.97)	0.83 (0.52-0.95)
Right total impact (g)	430.92 ± 63.69	432.83 ± 32.85	434.64 ± 51.52	1.2 (-4.7-7.4)	0.0 (-5.3-5.7)	6.9 (4.8-12.0)	6.3 (4.4-11.0)	0.71 (0.27-0.91)	0.66 (0.17-0.89)
Left total impact (g)	438.39 ± 59.74	437.08 ± 35.20	437.59 ± 49.52	0.3 (-5.1-5.9)	-0.2 (-4.6-4.4)	6.3 (4.4-10.9)	5.1 (3.6-8.8)	0.74 (0.32-0.92)	0.79 (0.42-0.93)
Right total push-off (g)	257.01 ± 31.84	258.92 ± 40.68	271.36 ± 44.19	0.4 (-6.0-7.2)	4.7 (-0.7-10.4)	7.6 (5.3-13.2)	6.1 (4.3-10.5)	0.76 (0.36-0.93)	0.88 (0.64-0.96)
Left total push-off (g)	245.34 ± 34.12	252.39 ± 41.60	254.73 ± 42.38	2.6 (-4.6-10.2)	0.9 (-3.0-5.0)	8.3 (5.8-14.5)	4.6 (3.2-7.9)	0.76 (0.36-0.93)	0.94 (0.81-0.98)
Right average impact (g)	26.57 ± 3.61	26.71 ± 2.50	27.35 ± 2.80	1.0 (-4.7-7.0)	2.3 (-2.8-7.7)	6.7 (4.7-11.6)	5.8 (4.1-10.1)	0.74 (0.32-0.92)	0.70 (0.24-0.90)
Left average impact (g)	27.29 ± 4.37	26.92 ± 2.86	26.97 ± 2.95	-0.7 (-7.8-7.0)	0.1 (-4.5-5.0)	8.6 (6.1-15.1)	5.4 (3.8-9.4)	0.69 (0.22-0.90)	0.81 (0.45-0.94)
Right average push-off (g)	15.41 ± 1.69	15.72 ± 2.59	16.57 ± 2.76	1.4 (-5.7-8.9)	5.4 (0.1-11.0)	8.3 (5.8-14.5)	6.0 (4.2-10.3)	0.71 (0.25-0.91)	0.90 (0.68-0.97)
Left average push-off (g)	14.73 ± 2.02	15.07 ± 2.77	15.46 ± 2.66	1.7 (-6.1-10.1)	2.8 (-1.2-6.9)	9.3 (6.5-16.3)	4.5 (3.2-7.7)	0.73 (0.29-0.91)	0.95 (0.83-0.98)

7.5 Discussion

The purpose of this study was to determine the between-session reliability of IMU foot pod technology for measuring kinematic variables, thought important to characterize base running. The main findings were (a) no systematic change ($p > 0.05$) between any of the linear (linear running segment) and curvilinear (curvilinear running segments 1, 2, and total segment) measures across sessions was observed; (b) absolute consistency was acceptable (CV, 10%) for all linear (linear running segment) and 92% of curvilinear (curvilinear running segments 1, 2, and total segment) measures; and (c) in terms of relative consistency as quantified via an ICC, good to excellent reliability was observed for the curvilinear (63/90) and linear (29/30) running data.

In terms of systematic error between testing days, the percentage change in the mean between testing days was small (all comparisons, 2%) and nonsignificant, indicative of no consistent shift in subjects performance between sessions. The testing procedures appear stable and not influenced by external factors such as familiarization, motivation, or environmental conditions. Higher between-session percent changes in the mean with right (22.8 to 26.5%) and left (27.0 to 24.9%) GCTs and similar between-session percent changes in averaged maximum speed (20.9 to 23.6%) during the modified linear 5-0-5 COD test were observed by Ryan et al. (134) using similar foot pod technology. Riglet et al. (131) examined fast speed overground running using IMU (104 Hz) in healthy subjects; their percent changes in the mean for speed, GCT, propulsion time, impact force, and SL ranged from 0.4 to 1.0%. It needs to be noted that making comparisons between studies is problematic given different technical and physical demands (linear vs. curvilinear running), analysis (inside vs. outside leg), and distances travelled (9.1 vs. 54.7 m) in each test.

Although there is no preset standard for acceptable CV values, many researchers set a goal of ,10% for acceptable reliability (100,136). The CVs associated with linear and curvilinear (curvilinear running segments 1, 2, and total segment) measures were all under 5%. In addition, the majority of the comparisons had 95% CI ,10%, indicating that the typical error between sessions is minimal. Several previous studies have found similar between-session CVs (7,19,26) using similar foot pod technology. Although these other studies examined treadmill running and COD, their CVs for speed and acceleration ranged from 2.1 to 10.4%, and GCTs were higher (6.4–14.4%) during COD. These differing results are once more explained by the methodological differences between studies.

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 of the variables in curvilinear running segment 1 (80%) and curvilinear total segment (73%), and some of the variables in curvilinear running segment 2

(57%) had ICCs greater than 0.74, indicating good to excellent reliability. Conversely, 27 of the 90 between-session comparisons (30%) had ICCs less than or equal to 0.74. One group of researchers (47) using foot pod technology have found similar ICCs albeit for different movements and testing procedures. For example, over a 3-month interval, between-session ICCs have been reported for peak resultant acceleration (0.74–0.88), peak vertical acceleration (0.85–0.94), and peak anteroposterior acceleration (0.79–0.87) for 30 consecutive steps on a treadmill running at 2.5, 3.0, and 3.5 $m \cdot s^{-1}$. Another research group (134) reported similar between-session CVs with max speed (0.93–0.94) and right and left GCT (0.81–0.94) during 5-0-5 COD sprinting.

7.6 Conclusion

The nonsignificant changes in the mean, low CVs, and high ICCs for the most part indicate a high degree of reliability between testing days for the procedures and IMU foot pod technology used in this study. It needs to be noted that the reliability statistics were generated from 14-16 year-old baseball athletes and whether the same results could be generalized across adult populations needs consideration from the reader.

7.7 Practical applications

Timing gates or the use of handheld stopwatches are limited in assessing curvilinear sprint ability and identifying determinants that can be trained to impact curvilinear running performance. It would seem that the use of IMU foot pod technology can be used to provide a deeper kinematic understanding of curvilinear and linear running. As such, practitioners will have information that can provide deeper insight into interlimb asymmetry and how the inside and outside legs may differ given the inward lean during curve running. IMU foot pod technology may provide complementary spatiotemporal information to assist in describing linear and curvilinear running characteristics. Measures such as ground contact time, stride length, and push-off acceleration outputs may help identify movement patterns associated with differences in running velocity across segments. Further validation is required before these measurements can be used confidently to guide individual training interventions or monitor longitudinal biomechanical adaptations.

Chapter 8: New perspectives on analysing and interpreting base running efficiency: An IMU foot pod methodological approach

This chapter comprises the following published paper in the *Applied Science* journal.

Reference: Martinez-Rodriguez JA, Neville J, and Cronin J. New perspectives on analyzing and interpreting base running efficiency: An IMU foot pod methodological approach. *Applied Science* 16: 5668, 2026.

8.1 Prelude

Given the reliability findings presented in Chapter 7, a logical next step was to inform practitioners how they could translate foot pod outputs into meaningful information about individual movement strategies. Chapter 8 therefore used an IMU new perspective study to explain how GCT, SL, and push-off acceleration could be analysed across linear and curvilinear sprint segments. This chapter provided a practical interpretation of the foot-specific mechanics that could explain how baseball players enter, negotiate, and exit the curve during base running.

8.2 Introduction

Linear sprint mechanics provide a useful baseline for understanding a base runner's straight-line acceleration and maximal speed capacity. However, running multiple bases in baseball requires athletes to express that capacity while negotiating curved trajectories and redirecting the CoM around the bases. During curvilinear running, athletes must coordinate body lean, foot placement, and force application to maintain velocity while limiting excessive braking. These requirements can produce foot-specific differences between the inside and outside limbs, particularly as athletes enter and progress through the curved portion of the path. Therefore, comparing linear and curvilinear sprinting provides a useful framework for identifying how base runners maintain, reorganize, or lose mechanical efficiency across multiple-base running tasks.

Previous curvilinear-sprinting research has shown that curvilinear sprinting differs from linear sprinting in ground contact time (GCT), stride length (SL), and inter-foot asymmetries during sprint acceleration and maximal velocity phases (18,19,65). Recently, researchers have further emphasized the neuromuscular specificity of curvilinear sprinting. Sašek et al. (137) examined the relationships between lower-limb strength, strength asymmetries, linear sprinting, and curvilinear sprinting in student-athletes in team sports.

They reported very large associations between hip adductor and abductor strength and 30 m curvilinear sprint performance to the left ($r = -0.75$ and -0.71), while hip abductor strength symmetry was also related ($r = -0.71$, $p < 0.001$) to faster curvilinear sprint times. It seems that curvilinear sprinting may be influenced by hip strength; therefore, the interpretation of inside–outside foot mechanics during base running should be considered within the broader context of lower-limb strength, asymmetry, and task-specific curvilinear running demands. Moreover, specifically in baseball base running, Martinez-Rodriguez et al. (88) further reported that inside–outside foot asymmetries are segment-dependent, with group-level patterns varying across phases of the home-to-second route. Together, these findings support the need to examine base running as a task-specific movement pattern rather than as a simple extension of straight-line sprinting. Importantly, asymmetry should be interpreted in relation to task demands and segment context rather than automatically treated as dysfunction.

Although prior curvilinear-sprinting studies provide important kinetic and kinematic context, they do not provide a practitioner-oriented foot pod workflow for base-ball base running. One portable and cost-effective technology that could be used in gaining a better understanding of multiple base running and inside–outside foot mechanics are inertial measurement units (IMUs), in the form of foot pods. Such technology can enable detailed step-by-step analysis of spatiotemporal variables, including GCT, SL, and push-off accelerations (1,134). The novelty of this article is not the use of the inertial measurement unit (IMU) foot pod technology alone, but the organization of these variables into a base running-specific interpretative work-flow. Unlike timing-only-based analyses, this framework complements segment-specific base running time and speed data with foot-specific spatiotemporal and acceleration-derived analyses. The intended contribution is therefore a practical model for translating wearable sensor outputs into applied understandings about entering, negotiating, and exiting the curve during base running.

The aim is not to generalize performance outcomes but to describe how practitioners may interpret IMU-derived spatiotemporal data within applied baseball environments. Implicit in this approach is a deeper understanding of the determinants and differences between linear-single base and curvilinear-multiple base running mechanics, which in turn can be used to inform specialized exercise prescription based on these attributes.

8.3 Collecting base running data using IMU foot pod technology

IMU foot pods (42 × 47 × 3.4 mm; Plantiga Technologies, Vancouver, BC, Canada) were used to describe inside–outside foot mechanics by recording accelerometer and gyroscope quantifying motion in the X, Y,

and Z planes (see Figure 1). The foot pods were secured within custom insoles placed under each base runner's foot to maintain consistent positioning throughout sprint testing (134).

Figure 8.1. IMU sensor inserted in the insoles.



The reliability of the IMU foot pod measures used in this article have been established and published previously (84). Between-session absolute reliability was acceptable for the variables of interest, with coefficients of variation ranging from 0.8% to 9.9% for linear measures and from 1.2% to 9.9% for curvilinear measures. Relative re-liability was also acceptable, with intraclass correlation coefficients ranging from 0.75 to 0.99 for linear measures and from 0.77 to 0.97 for curvilinear measures. In addition, Dasso et al. (30) examined the validity of foot-mounted IMU systems with a 3D motion-capture during maximal 10 m linear sprints and reported an acceptable level of agreement between the two technologies. Between the reported variables, SL demonstrated a wide level of agreement, and peak velocity and instantaneous velocity demonstrated moderate level of agreement. The baseball-specific curvilinear application used in this study has not yet been independently validated against 3D motion capture or floor-embedded force plates. Accordingly, the acceleration-derived interpretations in this article should be considered exploratory and hypothesis-generating within this context. Linear and curvilinear sprints were completed during the same session over a total distance of 54.7 m (home to second-base regulation distance of 54.7 m). The linear trial was completed first to establish an unfatigued straight-line baseline before the more technically constrained home-to-second-base sprint condition. The same order was used for all players to standardize comparisons across sprint conditions. Before testing, base runners completed a standardized dynamic warm-up focused on the lower extremity as detailed in Martinez-Rodriguez et al. (84). Two maximal trials were performed for each sprint condition, with 3 min of recovery between trials, and 10 min between test types were taken to avoid fatigue (84,103). For the home-to-second-base trial, participants started from a stealing lead-off stance at home plate with the front foot positioned on home plate, then rounded first base and continued through second base. The linear 54.7 m sprint began from the same starting

stance but followed a straight path. All runs were completed on turf while wearing baseball-specific footwear, and base runners were instructed to maintain maximal effort through the finish line to avoid deceleration before the endpoint.

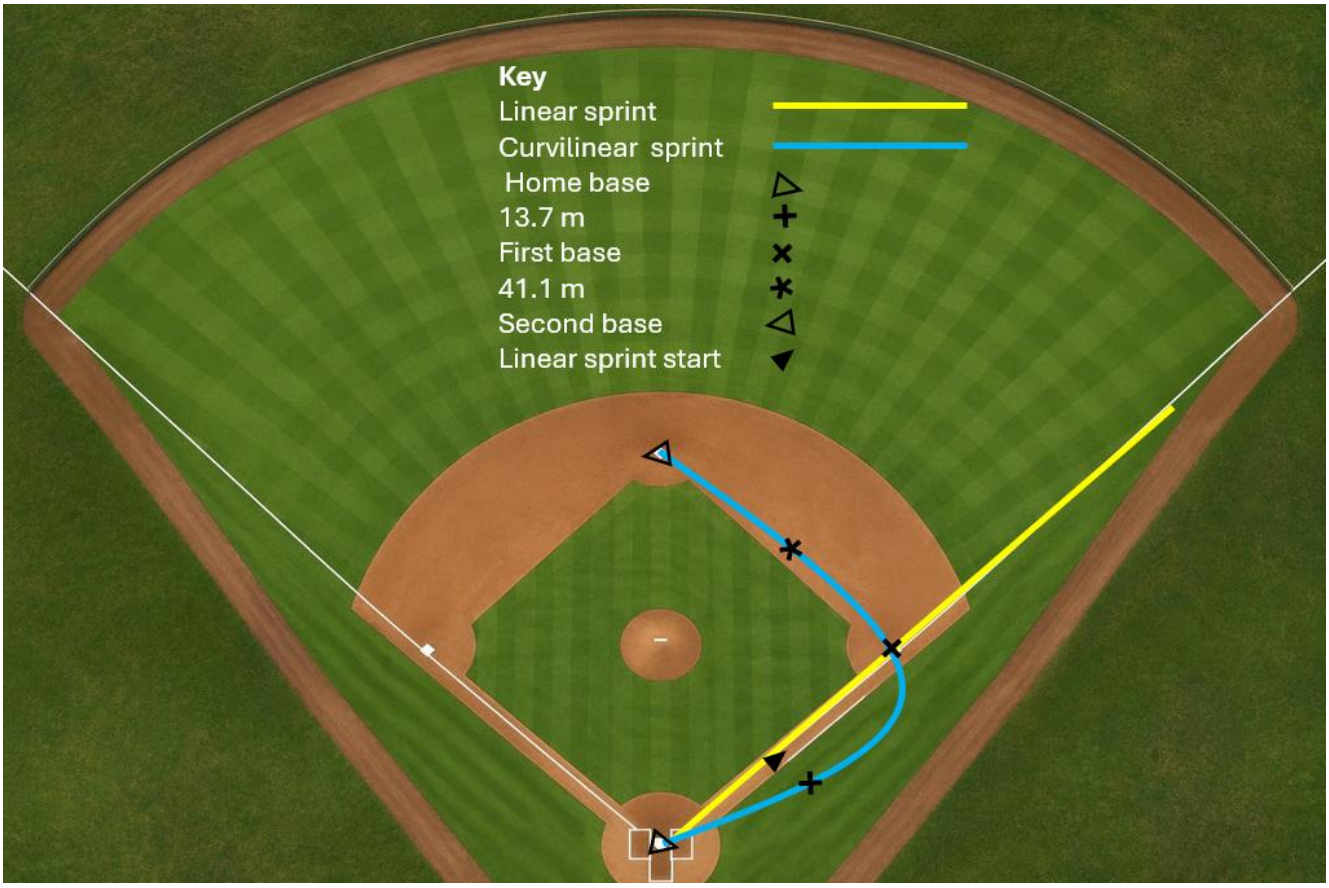
The 54.7 m linear sprint was selected as the comparison condition for the home-to-second-base trial for three reasons. First, it matched the total distance covered from home to second base and therefore provided a gameplay-relevant assessment of straight-line sprint capacity. Second, linear sprint ability contributes to curvilinear running performance (120). In this way, the linear sprint represented straight-line sprint capacity, whereas the curvilinear trial reflected how that capacity was ex-pressed while negotiating the turn around first base.

Each trial was also recorded with an iPad camera at 1080p resolution and 30 frames per second from a lateral view. After data collection, the pods were docked and uploaded to the Plantiga cloud for subsequent processing. Video footage was used to determine step counts for the 27.4 m (home to first distance) and 54.7 m (home to second-base distance) portions of both sprint conditions, and those step counts were aligned with the corresponding IMU signals in Plantiga Explore. The GNSS receiver used sampled data at 10 Hz using a high-precision chipset (VX Sport, Wellington, New Zealand). Details of the GNSS can be found in Martínez-Rodríguez et al. (89). GPS-derived timestamps were used to identify when each base runner crossed the 13.7 m and 41.1 m distance markers at the same timestamp provided by the Plantiga soft-ware (version: 2026.05.26.a0ca0f7) as players wore a GNSS unit during the sprints (85). Segment boundaries were then manually identified with the masking tool to isolate each portion of the sprint from the full activity trace. All performance out-comes were ultimately obtained through the Plantiga Explore platform and the data were stored on their password-encrypted cloud servers.

Six foot-specific kinematic and spatiotemporal metrics were extracted from the Plantiga cloud for analysis as follows: inside- and outside-foot GCT, SL, and average push-off acceleration. For the home-to-second-base trial, base runners ran counterclockwise around the first base. Therefore, the left foot functioned as the inside foot and the right foot as the outside foot during curve negotiation. Within this framework, GCT and SL describe the spatiotemporal organization of each step, whereas push-off acceleration describes foot-acceleration characteristic around toe-off. These proprietary measurements may support exploratory interpretations of foot-specific movement patterns but do not directly quantify ground-reaction forces or their directional components. Variables were calculated using the manufacturer's proprietary signal-processing algorithms, which identify toe-off events based on accelerometer and gyroscope signatures. Descriptions for these variables are detailed in Martinez-Rodriguez et al. (84).

The following sections focus on the linear and curvilinear differences between segments (i.e., changes in spatiotemporal characteristics from the previous segment) as quantified by the foot pods. To help explain the potential reasons for the increases or decreases in speed observed in each player, the authors also included GPS-derived speed and distance data collected simultaneously with the foot pod data (see Figure 2). Within this framework, segmental comparisons were interpreted as indicators of mechanical reorganization across the sprint. Importantly, a recent group-level study by Martinez-Rodriguez et al. (88) provided a useful reference pattern for inside- vs. out-side-foot asymmetry, but the case examples in this article are intended to illustrate that individual base runners may not always conform to that average profile. Practitioner considerations are made and must be interpreted in the context of being examples in how diagnostic information could be potentially used.

Figure 8.2. Home to second base and linear sprint segments.



8.4 Analysing and Interpreting Linear Base Running Mechanics

Three competitive base runners (X, Y, and Z) were selected from a larger dataset of n = 54 base runners from a baseball academy in Puerto Rico. They were tested using the same protocol with distinct home-to-second-base performance profiles noted as follows: the fastest case, an intermediate case, and the slowest case based on total home-to-second-base time. The players were not selected to represent population-level performance norms, and no inferential comparison between players was intended. The cases were selected purposively to demonstrate the application of the IMU interpretation framework, including ground contact time (GCT), stride length (SL), and push-off acceleration. The 54.7 m sprint was divided into four equal 13.7 m segments, consistent with previous base running analyses (1). The four segments were thought indicative of:

- L1 (0–13.7 m)—early-phase acceleration;
- L2 (13.7–27.4 m)—transitional acceleration;
- L3 (27.4–41.1 m)—maximal speed;
- L4 (41.1–54.7 m)—ability to maintain maximal speed—speed endurance.

The averaged linear inside–outside foot data for each of the three variables across the four segments is reported in Table 1, which summarizes foot-specific mechanical characteristics across the four linear sprint segments. Because the linear sprint did not impose curve-specific directional demands, foot differences were interpreted as individual tendencies rather than inside–outside curve effects.

Table 8.1. Mechanical characteristics during linear sprint segments for inside and outside foot and % change between segments for Players X, Y, and Z.

Seg	Player X			Player Y			Player Z		
	Inside Foot (% Change)	Outside Foot (% Change)	% Asym	Inside Foot (% Change)	Outside Foot (% Change)	% Asym	Inside Foot (% Change)	Outside Foot (% Change)	% Asym
					Average GCT (ms)				
L1	105	98	−6.67	125	121	−3.59	195	186	−4.36
L2	79 (−25%)	77 (−21%)	−2.53	99 (−21%)	99 (−18%)	0.00	184 (−6%)	176 (−5%)	−4.09
L3	75 (−5%)	68 (−12%)	−8.67	99 (0%)	100 (1%)	0.50	185 (1%)	167 (−5%)	−9.46
L4	77 (3%)	67 (−1%)	−12.3	102 (3%)	95 (−5%)	−6.86	185 (0%)	178 (7%)	−3.25
					Average SL (m)				
L1	2.77	2.72	−1.81	2.63	2.59	−1.52	2.73	2.65	−2.93

L2	3.82 (38%)	3.76 (38%)	−1.57	3.74 (42%)	3.55 (37%)	−5.08	3.35 (23%)	3.37 (27%)	0.59
L3	4.09 (7%)	3.98 (6%)	−2.69	3.79 (1%)	3.80 (7%)	0.26	3.49 (4%)	3.51 (4%)	0.57
L4	4.18 (2%)	4.04 (2%)	−3.35	3.75 (−1%)	3.79 (−0.3%)	1.06	3.56 (2%)	3.67 (5%)	3.00
Average push-off acceleration (g)									
L1	19.2	17.9	−7.02	13.1	13.9	5.54	11.0	12.1	9.34
L2	23.6 (23%)	23.4 (31%)	−0.72	16.2 (24%)	15.2 (9%)	−6.23	14.7 (34%)	14.4 (19%)	−2.24
L3	25.3 (7%)	25.6 (9%)	1.17	16.1 (−1%)	15.2 (0%)	−5.34	13.7 (−7%)	14.3 (−1%)	4.00
L4	25.6 (1%)	26.3 (3%)	2.70	15.1 (−6%)	15.2 (0%)	0.59	12.7 (−7%)	12.6 (−12%)	−1.41

Note: Seg = segments; Asym = Asymmetry% change = (next segment − previous segment)/previous segment × 100. Asymmetry symbol = negative value means asymmetry to the inside foot.

The use of IMU-derived step metrics in the present linear sprint analysis is supported by previous sprint-specific validation and application research. de Ruiter and van Dieën (31) demonstrated that IMUs can be used to obtain SL and step length during maximal sprint acceleration from 30 m and 60 m sprint times, supporting the use of wearable IMU sensors for step-by-step sprint analysis. de Ruiter et al. (32) later extended this work by validating SL estimates during maximal linear overground sprint acceleration using foot-mounted IMUs. In addition, van den Tillaar et al. (150) compared step-by-step sprint kinematics from an IMU-based system with force plate data during a 50 m sprint, further supporting the use of IMU approaches for analysing sprint mechanics across successive steps. Therefore, the linear sprint data in the present article provides a relevant baseline from which curvilinear base running adjustments can be interpreted.

Ground contact time (GCT)

- GCT decreased from L1 to L3 in all players, reflecting the expected transition from early acceleration to maximal velocity running;
- Player X had the lowest GCTs (inside foot: 75–105 ms; outside foot: 67–98 ms) across all segments, particularly in L3 and L4, consistent with efficient force ap-plication at high speed;
- Player Z maintained substantially longer GCTs (35–60%) across all segments, with limited reduction beyond L1, suggesting constraints in force production at higher running speeds [18];
- As expected for linear sprinting, inside–outside foot asymmetries in GCT are generally small, though Player X had slightly larger negative asymmetries in later segments, possibly reflecting individual running mechanics rather than systematic directional bias.

Stride length

- All players increased SL progressively (L2–L1: 22–42%; L3–L2: 1–7%; and L4–L3: 2–5%) from L1 to L4, reflecting the typical acceleration-to-higher-velocity transition, where SL increases as running speed rises [5];
- Player X achieved the greatest absolute SL (L1: 2.72 to L4: 4.18 m), especially in L3 and L4, and may indicate an effective translation of force into horizontal dis-placement;
- Player Z's SL remained comparatively limited (L1: 2.65–L4: 3.67 m) across all segments, reinforcing their reduced maximal speed capability and horizontal dis-placement;
- Inside–outside SL asymmetries were minimal and inconsistent, supporting the in-itial assumption of symmetry in straight-line sprinting.

Push-off acceleration

- Push-off acceleration increased from L1 to L3 in all players, with Player X achieving substantially higher (22–52%) values than Players Y and Z throughout;
- Player X also maintained high push-off acceleration into L4 (L1 vs. L4: 33–47%; L2 vs. L4: 8–12%; and L3 vs. L4: 1–3%), which may indicate superior speed endurance and the ability to sustain propulsive force at near-maximal speed;
- Player Z demonstrated both lower peak values (L1: 13–43%; L2: 5–38%; L3: 6–45%; and L4: 16–52%) and a plateauing or decline in later segments, consistent with reduced push-off acceleration and speed maintenance capacity [19];
- As with other variables, push-off acceleration asymmetries remain small overall, reinforcing the expectation of mechanical symmetry during linear sprinting.

Linear sprint transition

To evaluate how the player transitions from one segment to the next, calculating the difference between each segment (see Table 1) provides a clear indication of whether the base runner is changing strategies to adjust the body across the segments, which were illustrated in Martinez-Rodriguez et al. (84):

- L2-L1—ability to advance from initial acceleration mechanics into transitional sprint patterns;
- L3-L2—ability to progress from accelerating to establishing maximal sprinting mechanics;
- L4-L3—ability to maintain stable spatiotemporal patterns after reaching maximal sprinting mechanics.

Overall, the data highlight distinct individual strategies in how each athlete progresses from early acceleration to maximal velocity and then attempts to maintain linear sprint mechanics.

Transition from Early to Transitional Acceleration (L2–L1)

Across all players, this transition is characterized by the largest mechanical adjustments, consistent with the shift from initial acceleration mechanics to more upright sprinting patterns.

- Ground contact time (GCT) decreased substantially for all players, particularly Players X (−25% and −21% for the inside and outside foot, respectively) and Y (−21% and −18%), and may indicate a greater rate of force development application as velocity increases. Player Z showed smaller reductions, suggesting a more conservative acceleration strategy;
- Stride length (SL) increased largely in this phase for all players, most notably in Players X (38% and 38%) and Y (42% and 37%) (>1.0 m), suggesting effective conversion of horizontal force into forward displacement;
- Push-off acceleration increased markedly in Players X (inside foot: 23%; outside foot: 31%) and Z (inside foot: 34%; outside foot: 19%), inferring more aggressive forces being imparted into the ground.

Interpretation: L2–L1 is the most mechanically demanding transition. Players differ in how they balance propulsion and stride reorganization, with Players X and Y demonstrating more explosive acceleration profiles versus Player Z.

Transition to maximal speed mechanics (L3–L2)

This transition reflects the shift from acceleration to the establishment of maximal sprinting mechanics.

- GCT changes are minimal for Player Y and Z, with values close to zero or slightly negative, and may indicate stabilization of contact timing. Conversely, Player X had −5% and −12% for the inside and outside foot, respectively. This change may indicate rapid force generation for maximal speed transition;
- Stride length (SL) continued increasing, but to a much smaller extent than in L2–L1, consistent with nearing maximal velocity;
- Push-off acceleration trends diverge: Player X (7% and 9%) had positive changes, Player Y (−1% and 0%) remained relatively constant, and Player Z (−7% and −1%) showed negligible or negative changes. Player X may increase propulsion transitioning to max speed;
- Interpretation: By L3, players are largely refining rather than restructuring sprint mechanics. Player X continues to increase propulsion, while Players Y and Z appear to prioritize mechanical stability over further propulsion gains.

Ability to maintain maximal sprint mechanics (L4–L3)

The final transition assesses speed endurance and the capacity to maintain stable mechanics after reaching maximal speed.

- Ground contact time (GCT) changes were small and consistent, and may reflect ei-ther maintenance or slight deterioration, depending on the player and foot;
- Stride length (SL) changes were minimal, with Player Y showing slight reductions and Players X and Z maintaining or modestly increasing SL;
- Push-off acceleration trends diverge: Player X (1% and 3%) had positive changes, Player Y (−6% and 0%) tended to decrease, specifically for the inside foot, and Player Z (−7% and −12%) showed negligible or negative changes. Player X may increase propulsion when transitioning to maintain speed.

Interpretation: L4–L3 revealed each player's ability to maintain maximal speed. Player X for the most part maintained relatively stable mechanics, whereas Players Y and Z showed more pronounced signs of mechanical decay that we assume to be reduced propulsion.

8.5 Analysing and interpreting curvilinear base running ability

In Table 2, the home to second-base distance has been divided into four curviline-ar sprint (C) segments, and the GCT, SL, push-off acceleration, and impact acceleration for each curvilinear distance quantified via IMU foot pods:

- C1 (home plate—13.7 m)—initial acceleration preparing for the curvilinear phase;
- C2 (13.7 m—first base)—curvilinear initiation;
- C3 (first base—41.1 m)—curvilinear finalization;
- C4 (41.1 m—second base)—curve exit and reacceleration toward second base.

Table 2 summarizes the inside–outside foot kinematic and kinematic responses of three baseball players across four curvilinear sprint segments (C1–C4) from home to second base. The table reports GCT, SL, push-off acceleration, and corresponding asymmetry values for each segment, allowing changes in foot-specific mechanics to be compared across the curvilinear running task.

Table 8.2. Kinematic characteristics during curvilinear sprint segments for inside and outside foot and % change between segments for Players X, Y, and Z.

Player X			Player Y			Player Z		
Inside Foot (% Change)	Outside Foot (% Change)	% Asym	Inside Foot (% Change)	Outside Foot (% Change)	% Asym	Inside Foot (% Change)	Outside Foot (% Change)	% Asym

Average GCT (ms)									
C1	125	98	−21.6	144	139	−3.47	193	197	1.78
C2	84 (−33%)	72 (−27%)	−14.2	121 (−16%)	114 (−18%)	−6.17	189 (−2%)	182 (−8%)	−3.69
C3	92 (10%)	83 (15%)	−9.78	135 (12%)	129 (13%)	−4.44	199 (5%)	183 (1%)	−8.27
C4	89 (−3%)	80 (−4%)	−10.1	119 (−12%)	111 (−14%)	−6.69	193 (−3%)	185 (1%)	−3.89
Average stride length (m)									
C1	2.61	2.62	0.38	2.68	2.68	0.00	2.47	2.41	−2.43
C2	3.68 (41%)	3.53 (35%)	−4.08	3.55 (32%)	3.64 (36%)	2.47	3.22 (30%)	3.25 (35%)	0.92
C3	3.63 (−1%)	3.63 (3%)	0.00	3.43 (−3%)	3.63 (−0.3%)	5.51	3.17 (−2%)	3.22 (−1%)	1.55
C4	3.79 (4%)	3.68 (1%)	−2.90	3.63 (6%)	3.66 (1%)	0.82	3.45 (9%)	3.55 (10%)	2.82
Average push-off acceleration (g)									
C1	20.0	18.4	−8.13	12.2	12.0	−1.40	11.5	10.6	−8.23
C2	24.4 (22%)	21.5 (17%)	−12.0	14.1 (16%)	14.8 (23%)	4.34	14.5 (26%)	11.4 (8%)	−21.3
C3	22.3 (−9%)	21.0 (−2%)	−6.0	13.5 (−4%)	13.2 (−11%)	−2.22	13.0 (−10%)	11.9 (4%)	−8.82
C4	22.2 (−0.5%)	21.3 (1%)	−3.9	12.8 (−5%)	11.8 (−11%)	−8.27	11.3 (−13%)	11.8 (−1%)	4.40

Note: Seg = segment; Asym = Asymmetry; % change = (next segment − previous segment)/previous segment × 100. Asymmetry symbol = negative value means asymmetry to the inside foot.

Ground contact time (GCT)

Across all players, outside-foot GCT was consistently shorter (2–22% asymmetry) than inside-foot GCT, particularly during the early and middle curvilinear segments (C1–C3). This effect was most pronounced in Player X, who demonstrated large negative asymmetries (up to −22% in C1), and may indicate a rapid unloading of the out-side foot during curve-entry and mid-curve segments (C2–C3). Player Y displayed smaller but consistent asymmetries (3–6%), while Player Z showed minimal or occasionally reversed asymmetry in early segments. C1 occurred before the main curved portion of the route; asymmetry in this segment may reflect the base runner's approach strategy, including whether they begin preparing for the curve earlier or opt for late entry until they are closer to first base. Importantly, asymmetry generally diminished by C4 in all players, suggesting a convergence of foot function due to the linear nature of reacceleration towards second base became the priority.

Stride length

SL asymmetry was highly individualized. Player X displayed relatively symmetric SL across all segments (0–4%), despite notable GCT asymmetries. Player Y showed in-creasing outside-foot dominance in C3,

whereas Player Z demonstrated slightly longer outside-foot strides later in the sprint (C3–C4). Collectively, it seems that curvilinear sprinting asymmetry is not necessarily expressed through SL, but rather theorized through how force is applied and managed during stance.

Push-off acceleration

Push-off acceleration highlighted the functional role of the inside foot as the primary propulsive foot during curvilinear sprinting. Player X demonstrated consistently greater inside-foot push-off acceleration (4–12%), with especially large asymmetries in C2 for Player Z (−12%), coinciding with curvilinear initiation. In contrast, Player Y showed smaller asymmetries (1–8%) and even a reversal in C2, suggesting a different force-sharing strategy or possibly a less aggressive entry into the curve. Across all players, push-off asymmetry tended to reduce in later segments, aligning with the transition toward reacceleration in the latter stages of the curved path that has more linearized sprint approach in reaching second base.

Interestingly, across both linear and curvilinear sprinting, Player X generally demonstrated the greatest absolute stride lengths despite being the shortest athlete (166.0 cm), compared with Players Y (178.0 cm) and Z (179.7 cm). This descriptive observation highlights that greater stature does not necessarily correspond to longer strides in these individual cases, with differences in running velocity and sprint mechanics potentially contributing to the observed patterns. However, lower-limb length was not measured and may provide a more specific anthropometric consideration than stature when interpreting absolute stride length.

8.6 Curvilinear sprint transition

As using the same segment-to-segment comparison approach applied to the linear sprint, the curvilinear trial was examined across C1–C4 (see Table 2). This approach provides a clearer indication of how the players adapt to counteract curvilinear demands through each curvilinear segment. The following interpretations are descriptive and should be read as plausible mechanical explanations rather than confirmed causal mechanisms. The description of each curvilinear sprint segment differences is as follows:

- C2–C1—data from these segments reflected how sprint mechanics adjust when entering the curve;
- C3–C2—data from these segments reflected how mechanics changed from curve entry into turn negotiation after rounding first base;
- C4–C3—data from these segments reflected how the base runner adjusts mechanics while exiting the curve and progressing toward second base.

Entering the Curve (C2–C1)

When athletes transition from linear sprinting into the curve:

- Ground contact time (GCT) decreased across all three players. Player X decreased by −33% and −27%, Player Y by −16% and −18%, and Player Z by −2% and −8% for the inside and outside foot, respectively. This may indicate an increase in speed into the curve entry by an increase in rapid force generation;
- Stride length (SL) increased for both inside and outside foot (30–41%) across all players. These increases suggest that athletes maintained or built speed rather than braking on curve entry;
- Push-off acceleration increased markedly, especially in Players X by 22% and 17% and Y by 16% and 23% for the inside and outside foot respectively, and Player Z inside foot by 26%. This reflects greater propulsive demand to initiate curvilinear sprinting. However, Player Z may be redirecting and depending on the inside foot for propulsion entering the curve compared to Players X and Y;

Interpretation: Entry into the curve is characterized by aggressive mechanical adjustments, prioritizing propulsion and high rate of force development to maintain momentum while initiating directional change.

Mid-curve transition (C3–C2)

As base runners reorganize mechanics while fully rounding first base:

- Ground contact time (GCT) increased slightly in Player X (10% and 15%) and Y (12% and 13%), which may indicate that these athletes are slowing down signaling time spent in stance for stabilization and redirection;
- Stride length (SL) generally decreased or plateaued (−0.3% to −3%) for all the players, suggesting a slowing down or maintenance of speed through the curve to accommodate the feet on the way to the left side (i.e., to cover less space when changing direction);
- Push-off acceleration declined across all players (−2% to −11%), although Player Z showed a small outside-foot increase. These changes may suggest a lower propulsive emphasis during mid-curve negotiation;

Interpretation: This phase may represent a period of mechanical stabilization, where reduced push-off acceleration and slightly longer ground contact times could indicate a shift toward path negotiation rather than further propulsion. Furthermore, it is likely a mechanical stabilization period, where reduced push-off acceleration and slightly longer GCT could indicate a shift toward stabilization and curvilinear path negotiation rather than pure propulsion.

Exiting the Curve Toward Second Base (C4–C3)

As base runners transition back toward linear sprinting:

- Ground contact time (GCT) changed slightly during this transition for Player X and Y, while Player Z showed a smaller and more stable response (−3% and 1%). These changes suggest that contact timing became shorter or remained relatively stable during the transition from curve exit toward second base;
- Stride length (SL) increased slightly in all players, with the largest increases in Player Z (9% and 10%) and smaller increases in Players X (4% and 1%) and Y (6% and 1%). This may suggest that Player Z depends greater on running in a more linear path to reaccelerate after curve negotiation compared to Players X and Y;
- Push-off acceleration remains reduced in all players except for Player X outside foot (1%). This may suggest that base runners may not have increased propulsive magnitude during curve exit. Instead, reacceleration toward second base may have been supported by other mechanical adjustments, such as changes in stride timing, foot placement, or force orientation as the sprint path became straighter.

Interpretation: Curve exit is marked by a progressive re-establishment of linear sprint mechanics, with athletes lengthening stride, decreasing stance time, and pre-paring for maximal linear acceleration toward second base.

8.7 Inside- vs. outside-foot asymmetry diagnostics

Foot roles change during curvilinear sprinting, as asymmetry between the inside and outside foot was calculated for each variable. In this context, asymmetry should not automatically be interpreted as dysfunction. Instead, segment-specific asymmetry may reflect a reorganization to curvilinear task demands, particularly when the inside foot assumes greater stabilization demands and the outside foot contributes more to propulsion. The purpose of this analysis is therefore not to classify base runners as symmetrical or asymmetrical in a simplistic sense, but to illustrate how the magnitude and direction of asymmetry may help practitioners interpret foot-specific mechanical strategies across base running segments. Importantly, although group-level data have suggested a predominant outside-foot push-off acceleration pattern during curvilinear sprinting (88), the present case examples indicate that individual base runners may depart from that average pattern, reinforcing the need for case-by-case interpretation of foot-specific mechanical strategies.

Percent asymmetry between inside and outside feet provides insight into the inside- and outside-foot mechanical balance of a base runner during linear and curvilinear sprinting. It reflects how the inside and outside foot contribute to exerting force on the ground to propel the body forward. Positive values indicate greater values for the outside foot, whereas negative values indicate greater values for the inside foot. Larger

percentages therefore represent greater mechanical asymmetry between the two feet during the curvilinear running task. Asymmetry is calculated using the following formula provided by the manufacturer:

$$\text{Asymmetry (\%)} = \frac{(R-L)}{\max(R,L)} \times 100$$

This formula normalizes asymmetry to a higher foot value, allowing for a standardized interpretation of mechanical asymmetry. A value near 0% indicates minimal difference between the inside and outside feet for that specific variable. Larger values indicate greater foot-specific differences, with the direction of the value identifying whether the higher value occurred on the inside or outside foot.

In this calculation, R and L represent the right- and left-foot measurements, respectively. During the curvilinear sprint, the right foot was classified as the outside foot and the left foot as the inside foot, with the same designation retained for the linear comparisons. The denominator represents the greater of the two foot measurements. For example, Player X demonstrated a ground contact time of 125 ms for the inside foot and 98 ms for the outside foot during C1, resulting in an asymmetry of −21.6%. The negative value indicates a greater measurement for the inside foot. This procedure was applied separately to the foot-specific variables within each sprint segment.

In the context of curvilinear base running, percent asymmetry helps identify whether the mechanical demands of rounding a base increase or decrease foot differences. Curvilinear sprinting imposes inside- and outside-foot loading differences; thus, asymmetry values often shift relative to the segment. For example, an asymmetry value of 10% indicates that the inside and outside feet differed by approximately 10% for that specific variable within that segment. No baseball-specific IMU asymmetry threshold has been established; thus, values approaching or exceeding 10% were used only as a practical flag to guide visual inspection and practitioner discussion. This threshold was not treated as a statistical cutoff or diagnostic criterion. Therefore, percent asymmetry provides a variable-specific indicator of foot-to-foot difference during base running. Table 4 describes the asymmetry values observed during curvilinear sprinting and compares them with the matched linear baseline segments. This comparison helps determine whether curvilinear running amplifies, reduces, or reverses the asymmetry already present during linear sprinting for each player.

Table 8.3. Percent asymmetry comparison between inside and outside foot across three different players.

	Player X			Player Y			Player Z		
Seg	Inside Foot	Outside Foot	% Asym	Inside Foot	Outside Foot	% Asym	Inside Foot	Outside Foot	% Asym

Average GCT (ms)									
C1	125	98	−21.6	144	139	−3.47	193	197	1.78
L1	105	98	−6.67	125	121	−3.59	195	186	−4.36
C2	84	72	−14.2	121	114	−6.17	189	182	−3.69
L2	79	77	−2.53	99	99	0.00	183	176	−4.09
C3	92	83	−9.78	135	129	−4.44	199	183	−8.27
L3	75	68	−8.67	99	100	0.50	185	167	−9.46
C4	89	80	−10.1	119	111	−6.69	193	185	−3.89
L4	77	67	−12.3	102	95	−6.86	184	178	−3.25
Average stride length (m)									
C1	2.61	2.62	0.38	2.68	2.68	0.00	2.47	2.41	−2.43
L1	2.77	2.72	−1.81	2.63	2.59	−1.52	2.73	2.65	−2.93
C2	3.68	3.53	−4.08	3.55	3.64	2.47	3.22	3.25	0.92
L2	3.82	3.76	−1.57	3.74	3.55	−5.08	3.35	3.37	0.59
C3	3.63	3.63	0.00	3.43	3.63	5.51	3.17	3.22	1.55
L3	4.09	3.98	−2.69	3.79	3.80	0.26	3.49	3.51	0.57
C4	3.79	3.68	−2.90	3.63	3.66	0.82	3.45	3.55	2.82
L4	4.18	4.04	−3.35	3.75	3.79	1.06	3.56	3.67	3.00
Average push-off acceleration (g)									
C1	20.0	18.4	−8.13	12.2	12.0	−1.40	11.5	10.6	−8.23
L1	19.2	17.9	−7.02	18.8	17.8	−5.26	11.0	12.1	9.34
C2	24.4	21.5	−12.0	14.1	14.8	4.34	14.5	11.4	−21.3
L2	23.6	23.4	−0.72	16.2	15.2	−6.23	14.7	14.4	−2.24
C3	22.3	21.0	−6.01	13.5	13.2	−2.22	13.0	11.9	−8.82
L3	25.3	25.6	1.17	16.1	15.2	−5.34	13.7	14.3	4.00
C4	22.2	21.3	−3.88	12.8	11.8	−8.27	11.3	11.8	4.40
L4	25.6	26.3	2.70	15.1	15.2	0.59	12.7	12.6	−1.41

Note: Seg = segments; Asym = Asymmetry. Absolute asymmetry values ≥ 10% were highlighted to assist visual identification of the segments and variables with more pronounced inside- and outside-foot differences.

Across all three players, curvilinear sprinting segments (C1–C4) consistently altered both the magnitude and direction of asymmetry relative to their matched linear segments (L1–L4). However, the nature of these changes was highly player- and variable-specific. Relative to the baseball-specific reference pattern reported

by Martinez-Rodriguez et al. (84), the present case examples mentioned that the direction and magnitude of asymmetry can vary by base runner, variable, and segment. Overall, curvilinear running did not uniformly increase asymmetry across all variables. Instead, it produced selective amplification, attenuation, or even reversal of asymmetry, depending on the mechanical variable considered and the individual runner.

Ground contact time (GCT)

The asymmetry magnitude of Player X was consistently greater in curvilinear segments than matched linear segments (e.g., C1 −22% vs. L1 −7%), consistent with a stronger stabilization role of the inside foot when rounding the base. Player Y also showed greater inside-foot asymmetry in curvilinear segments (e.g., C2 −6% vs. L1 0%), though to a lesser extent than Player X. Player Z differences between curvilinear and linear segments were modest, suggesting less segment-specific reorganization of GCT. In summary, curvilinear segments generally increased inside-foot dominance (more negative asymmetry) relative to linear segments, particularly in Players X and Y. Player Z showed smaller and more stable asymmetries, with minimal curvilinear–linear divergence.

Interpretation*:* Curvilinear sprinting tends to increase temporal loading on the inside foot, but the magnitude of this adaptation is highly individual.

Stride length

SL changes between matched curvilinear and linear segments rarely exceeded ~3–5%. Some curvilinear segments showed slightly greater asymmetry, but this was inconsistent in both direction and magnitude. In summary, SL asymmetry was small across all conditions, regardless of segment type. Curvilinear sprinting did not systematically amplify asymmetry compared with linear sprinting.

Interpretation: SL appears to be relatively preserved across linear and curvilinear conditions, suggesting that runners modulate other mechanical variables (timing and force application) rather than spatial stride parameters when rounding a base.

Push-off acceleration

Player X often demonstrated larger inside-foot dominance in the curvilinear segments compared with linear segments (e.g., C2 −12% vs. L2 −0.7%). Player Y displayed mixed responses, with both amplification and reduction in asymmetry in curvilinear segments. Player Z exhibited large curvilinear increases in push-off asymmetry magnitude in some cases (e.g., C2−21% vs. L2 −2%). In summary, push-off acceleration showed

greater sensitivity to curvilinear task demands than SL. Contrary to group-level expectations of a dominant outside-foot propulsive strategy, all three players frequently showed increased inside-foot push-off dominance during curvilinear segments.

Interpretation: Rather than a uniform outside-foot propulsion strategy, the data indicated individualized propulsion solutions, with some runners increasing reliance on the inside foot during curvilinear acceleration demands.

8.8 Curvilinear vs. linear diagnostics

In this section the linear and curvilinear same-segment-variables are compared to show how much a specific spatiotemporal variable can change, when linear sprinting and curvilinear base running variables are compared. This comparison helps determine the magnitude to which curvilinear sprinting demands alter linear mechanical characteristics. The percent difference is calculated as follows:

$$\text{Percent difference (\%)} = \frac{\text{Curvilinear} - \text{Linear}}{\text{Linear}} \times 100$$

A value close to 0% indicates that the base runner maintained similar mechanical characteristics in both linear and curvilinear sprinting, which may indicate strong transfer of linear mechanics into curvilinear sprinting. Positive or negative values indicate the degree of mechanical alteration that may be associated with curvilinear demands. These differences highlight how each base runner adapts mechanically when navigating curvilinear direction changes. For example, a 5% value for GCT means the runner exhibited slightly longer GCT during a specific curvilinear segment compared to the same linear segment. Mechanically speaking, the percent difference comparisons provide insight into how the curvilinear demands disrupt or reorganize the base runner's usual linear sprint strategy.

The key spatiotemporal and mechanical variable changes when base runner's same-segment linear and curvilinear sprinting is compared; they are shown as percent differences in Table 8.4. The observations from this table are summarized below.

Table 8.4. Percent difference comparison between linear and curvilinear sprint across three different players.

	Player X				Player Y				Player Z			
Seg	Inside Foot	% Diff	Outside Foot	% Diff	Inside Foot	% Diff	Outside Foot	% Diff	Inside Foot	% Diff	Outside Foot	% Diff
	Average GCT (ms)											
C1	125	17.4	98	0.00	144	13.7	139	13.9	193	−0.77	197	5.48

L1	105		98		125		121		195		186	
C2	84	6.73	72	−6.02	121	20.4	114	14.1	189	3.22	182	3.63
L2	79		77		99		99		183		176	
C3	92	20.4	83	19.1	135	30.3	129	25.3	199	7.54	183	8.84
L3	75		68		99		100		185		167	
C4	89	15.0	80	17.6	119	15.8	111	16.0	193	4.50	185	3.85
L4	77		67		102		95		184		178	
Average stride length (m)												
C1	2.61	−5.95	2.62	−3.75	2.68	1.88	2.68	3.42	2.47	−10.00	2.41	−9.49
L1	2.77		2.72		2.63		2.59		2.73		2.65	
C2	3.68	−3.73	3.53	−6.31	3.55	−5.21	3.64	2.50	3.22	−3.96	3.25	−3.63
L2	3.82		3.76		3.74		3.55		3.35		3.37	
C3	3.63	−11.92	3.63	−9.20	3.43	−9.97	3.63	−4.58	3.17	−9.61	3.22	−8.62
L3	4.09		3.98		3.79		3.80		3.49		3.51	
C4	3.79	−9.79	3.68	−9.33	3.63	−3.25	3.66	−3.49	3.45	−3.14	3.55	−3.32
L4	4.18		4.04		3.75		3.79		3.56		3.67	
Average push-off acceleration (g)												
C1	20.0	4.07	18.4	2.87	12.2	−43.0	12.0	−39.2	11.6	5.06	10.6	−13.3
L1	19.2		17.9		18.8		17.8		11.0		12.1	
C2	24.4	3.50	21.4	−8.56	14.1	−13.7	14.8	−2.87	14.5	−1.43	11.4	−23.1
L2	23.6		23.4		16.2		15.2		14.7		14.4	
C3	22.3	−12.6	21.0	−19.9	13.5	−17.4	13.2	−14.2	13.0	−4.86	11.9	−18.1
L3	25.3		25.6		16.1		15.2		13.7		14.2	
C4	22.2	−14.2	21.3	−20.8	12.8	−16.3	11.8	−25.5	11.3	−12.0	11.8	−6.08
L4	25.6		26.3		15.1		15.2		12.7		12.6	
L4	27.1		30.6		28.0		29.2		22.7		23.0	

Note: Seg = segment; Asym = Asymmetry.

Ground contact time (GCT)

Player X showed positive percent differences ≥10% in four of eight foot-by-segment GCT comparisons, while Player Y showed positive percent differences ≥10% in all eight foot-by-segment GCT comparisons. These findings suggest that curvilinear sprinting was associated with longer stance phases in these players

when compared with their matched linear sprint segments. Player Z showed smaller or inconsistent GCT differences, suggesting a more constrained mechanical strategy that changes less with task demands. Overall, increased GCT reflects the need for greater mediolateral force control and stability during curved running, supporting the premise that curvilinear demands alter linear sprint mechanics.

Stride length (SL)

The largest reductions occurred in C3 and C4, highlighting the cumulative mechanical cost of sustained curve running. Player X had the greatest SL reductions (inside foot: 12%; outside foot: 9%) and may indicate a deliberate trade-off, sacrificing SL to maintain control and speed through the curve. Player Y and Z had smaller relative reductions (C3−L3: ≤10%; approximately ≤ 5% in most segments), again most likely reflecting limited adaptability rather than superior efficiency. These findings align with the expectation that curved running constrains horizontal displacement per step due to centripetal force requirements.

Push-off acceleration

Push-off acceleration had variable percent differences, but the dominant trend was reduction during curvilinear sprinting, particularly in later segments. Player Y and Player Z exhibited large negative differences that may infer a reduced ability to generate propulsive force under curvilinear constraints. Player X had smaller reductions or near-zero differences in early curve segments, suggesting better transfer of linear propulsive mechanics into curved sprinting. This supports the interpretation that higher-level runners are better able to reorganize force application without large performance penalties.

Inside- vs. outside-foot effects

While both feet had meaningful deviations from linear mechanics, outside-foot values often displayed larger percent differences, especially for GCT and push-off acceleration. This supports the biomechanical expectation that the outside leg bears greater load and force-redirection demands during curvilinear running. However, the magnitude of this effect is player-specific, highlighting individual strategies for managing curve running.

8.9 Translating IMU data into applied training decisions

To illustrate how the IMU framework may inform practice, Player Z showed relatively longer GCT, shorter SL, and lower push-off acceleration than Player X and Y, with a marked inside–outside push-off acceleration asymmetry during C2. These patterns may suggest that practitioners should first examine whether general acceleration capacity and SL development are limiting factors, while also considering curve-specific drills that target the approach into first base and reacceleration toward second base. For

example, a potential training emphasis could include short-resisted curvilinear acceleration drills. Dasso et al. (30) linked hip abductor/adductor strength and inside and outside leg hip abductor symmetry with curvilinear sprint performance; therefore, single-leg hip exercises could be considered, in addition to hamstring (121) and calf (44,124) muscle exercises, which are also important for linear and curvilinear tasks. This example is intended to illustrate how IMU-derived segmental data may guide individualized training hypotheses, rather than to prescribe a definitive intervention or infer a direct causal mechanism.

8.10 Conclusion

IMU-derived spatiotemporal variables appear to provide a useful diagnostic framework for examining both linear and curvilinear base running mechanics. The perspective analysis was conducted on three baseball players and is intended solely to demonstrate the interpretive framework rather than establish normative performance benchmarks. Segmenting the home-to-second-base sprint allows practitioners to observe how curvilinear demands may alter foot-specific mechanics relative to linear sprint patterns, while the inclusion of asymmetry and linear-curvilinear difference metrics offers additional insight into how base runners reorganize movement under curve-running demands. The present case examples suggest that inside- and out-side-foot mechanics can assume distinct and segment-dependent roles during base running, but these examples are intended to illustrate an interpretive framework rather than establish normative patterns or direct causal training effects. From an ap-plied perspective, the IMU approach may help practitioners better understand the individual mechanical characteristics associated with acceleration, curve negotiation, and reacceleration in baseball settings.

8.11 Practical applications

IMU foot pod technology may provide practitioners additional information for identifying foot-specific movement patterns associated with changes in base running speed and assist in generating hypotheses about their underlying biomechanical mechanisms. Segment-level comparisons of GCT, SL, and IMU-derived push-off acceleration may reveal individual differences between the inside and outside feet. However, these measurements do not independently determine the braking forces, propulsive ground-reaction forces, or causal mechanisms responsible for speed loss. Percentage asymmetry and linear–curvilinear difference metrics can therefore be used to generate individualized technical and training hypotheses rather than prescribe definitive corrections. Strength and conditioning coaches may use these observations alongside directly measured sprint performance to select and evaluate appropriate training tasks.

Chapter 9: Functional asymmetries in inside-outside foot mechanics when curvilinear sprinting in baseball

This chapter comprises the following published paper in the *A*symmetry journal

Reference: Martinez-Rodriguez JA, Neville J, and Cronin J. Functional asymmetries in inside-outside foot mechanics when curvilinear sprinting in baseball. *Asymmetry* 3, 2026.

9.1 Prelude

Chapters 7 and 8 established that IMU foot pod technologies can provide reliable and practically useful information for assessing baseball base running, moving the thesis from broad velocity-time diagnostics to step-level mechanical interpretation. Building on the rationale developed in Chapters 3 and 4, which identified the distinct curvilinear demands of base running, Chapter 9 used IMU foot pod technology to examine whether inside–outside foot asymmetries are present during linear and curvilinear sprinting in baseball players. This chapter moved from methodological development to a targeted biomechanical investigation by determining whether foot-specific differences were segment-dependent and whether they reflected the functional demands of curve negotiation. In doing so, Chapter 9 provided important information for practitioners about how inside-foot stabilization and outside-foot propulsion may contribute to efficient base running performance and helped establish the mechanical rationale for the training studies that followed.

9.2 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 (20-22,25,95), 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 (18,19,64,65,119,120). 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 (18,19,64,65), typically using a fixed radius that differs substantially from the narrower and self-selected curvilinear path encountered during base running (103,149). 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) (3,18,19,64,65,86), 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 (18,19,64,65). 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 IMU foot pod technology. Martinez-Rodriguez et al. (84), 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), providing a methodological context for the analysis used in this paper. Kinematic measures (time, maximum and average speed and right and left GCT, SL, and total and averaged push-off acceleration) 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 ICCs 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, 13.7–27.4 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 (149). 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 (149). 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 (149), 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 (3,18,19,44,64,65,124). 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 (18,19,64,65). 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 (79) and baseball pitching/throwing (151). 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.

9.3 Methods

9.3.1 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 base running 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).

9.3.2 Subjects

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).

9.3.3 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 Martinez-Rodriguez et al. (84).

Following the warm-up, participants completed two trials of 54.7 m straight-line sprinting, with three minutes of passive rest between trials (84). After ten minutes of recovery (84,103), 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 (84). 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 (103).

9.3.4 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 Martinez-Rodriguez et al. (84). These insoles were fitted inside each participants' shoes before starting the warmup (84). For all sprint trials, participants wore a GNSS receiver to provide positional data for segment identification.

9.3.5 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 analysed:

- 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 analysed:

- Start to 13.7 m: Linear segment 1 (L1)
- 13.7 to 27.4 m: Linear segment 2 (L2)
- 27.4 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 GNSS data and then applied to the IMU-derived trace. Right and left GCT, SL, and average push-off measures were obtained from the Plantiga Cloud. Description for these variables are detailed in Martinez-Rodriguez et al. (84).

9.3.6 Statistical analyses

Outlier and normality analysis were performed using the Kolmogorov-Smirnov test (101). The mean of two trials was calculated for each variable and descriptive results are reported as mean ± standard deviations. Inside–outside foot asymmetry was expressed as a percentage difference using the formula:

$$\text{Asymmetry (\%)} = \frac{(R-L)}{\max(R,L)} \times 100$$

where R and L represent the right- and left-foot measurements, respectively. For curvilinear sprinting, the right foot represented the outside foot, and the left foot represented the inside foot. The same foot classification was retained during linear sprinting to allow comparisons. Positive values indicated greater outside-foot measurements, whereas negative values indicated greater inside-foot measurements. Percentage asymmetry was calculated using the average of the right- and left-foot values for each variable and running segment. Percentage asymmetry was used to describe the magnitude and direction of foot-specific differences.

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) [26]. Within-session reliability of the foot pod derived variables was assessed using trial-to-trial data. Relative reliability was quantified using ICC, while absolute reliability was evaluated using a 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 $p \leq 0.05$.

9.4 Results

Reliability varied across running segments (see Table 9.1). In terms of absolute consistency, CV values between 2.0–5.0% were observed for GCT, SL between 7.1–9.3%, and push-off acceleration between 3.2–8.3%. In terms of relative consistency, ICC ranged from 0.45–0.94 for GCT, 0.60–0.77 for SL, and 0.75–0.95 for push-off 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 GCT. 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 9.1. 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

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

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 (see Table 9.1 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 9.1. With regards to the linear-curvilinear sprint analysis (Table 9.2), 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%) 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 9.1). 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 9.2. 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						
L4:41.1–54.7 m	18.1 ± 3.94	18.8 ± 4.16	3.83	0.00	0.31	22.65	< 0.001	1.34	22.27	< 0.001	1.18

Key: Asym = Asymmetry; Diff = Difference

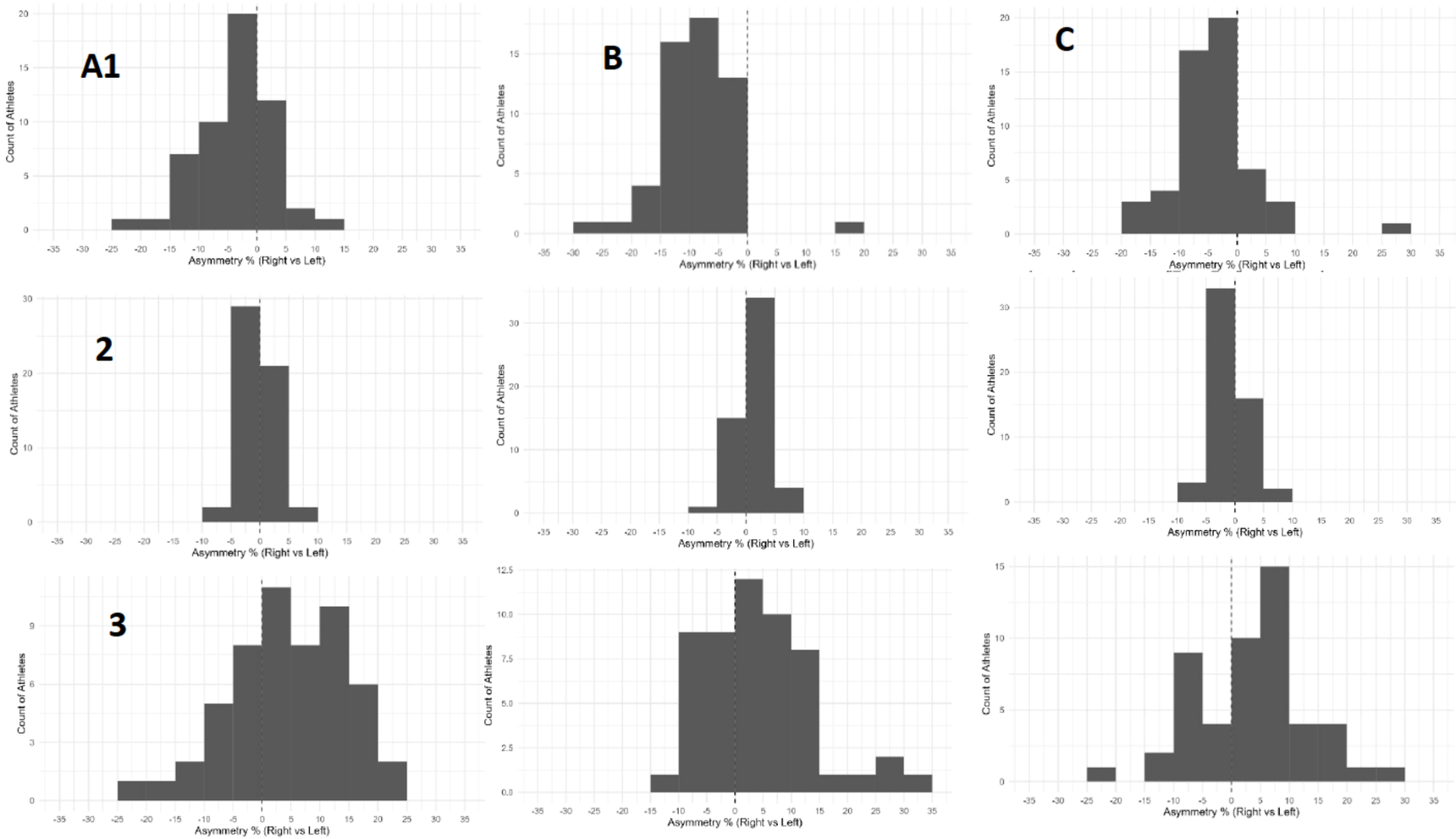


Table 9.3. Distribution of athletes' asymmetry among three segments on the home-to-second base sprint.

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

9.5 Discussion

Of particular interest was whether GCT, SL, 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 statistically significant difference between inside and outside foot for GCT and push-off . 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 (65) 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 (3,18,19,64,65), 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 (149), 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 (18,19,64,65). 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. (149), who reported that minimizing sudden or sharp changes of direction to the left and decreasing the distance covered during Segment 2 reduced the BREr 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 (19,64), 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. (149), 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 push-off . 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), 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), 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, and lower propulsion characteristic due to inward lean (18,19,64,65).

9.6 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 (18,65). 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 (3,18,19,64,65) collected data in a single fixed location (often the apex of the curvilinear sprint), disparate to the average 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.

9.7 Practical applications

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 (149). 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 (15,60,87).

(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 (87). 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 (15,60).

(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 (149). 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, GNSS 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, 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.

Chapter 10: Base running responses to calf-loaded wearable resistance in baseball: A case study comparison of two versus three sessions per week

This chapter is ready for submission.

10.1 Prelude

Chapters 2 to 9 established the need to assess base running as a linear-curvilinear task, showed that wearable technologies can quantify segment-specific and foot-specific performance characteristics, and identified that curvilinear running produces distinct inside–outside foot demands. However, these chapters were primarily diagnostic and did not determine whether targeted training could improve baseball-specific base running efficiency. Chapter 4 established the theoretical rationale for movement-specific curvilinear sprint training and introduced wearable resistance as a potential training modality, discussing external micro-loading, load placement, and associated mechanical demands, while highlighting the limited evidence for its application to baseball-specific curvilinear sprinting. Chapter 9 suggested that the inside and outside feet may require different mechanical capabilities to negotiate the curve effectively, therefore, Chapter 10 examined whether calf-loaded WR, implemented during baseball-specific sprint training, could influence linear sprinting, curvilinear base running, and foot-specific mechanics. A case study design was used to explore individual responses to two training frequencies (2 or 3 times per week), allowing the GNSS and IMU diagnostic frameworks developed in the earlier chapters to be applied to training adaptation and retained performance change.

10.2 Introduction

Base running in baseball is often reduced to linear sprint speed, yet advancing from home to second base requires the base runner to solve a more complex locomotor strategy: accelerate rapidly out of the box, position the body to enter the curve near the first base, negotiate the curve around the base, and then preserve or reaccelerate after the curve toward second base (88,89). This distinction is important because baseball-specific running is performed as a field-based, curvilinear, and segment-dependent locomotor task rather than as a simple linear sprint. During curvilinear sprinting, the base runner generally leans inward, with the inside foot generating greater mediolateral force for absorption and stabilization, using a relatively mobile (oblique push-off axis) foot position (88). In contrast, the outside foot generates greater anteroposterior force to propel the body around the curve using a stiffer (transverse push-off axis) foot position (88). These foot-specific mechanics suggest that linear and curvilinear sprinting require different movement strategies and, consequently, may benefit from different training approaches when advancing one versus multiple bases (88).

Previous training studies designed to improve curvilinear performance have generally involved resisted linear sprint training and curvilinear sprint training. In soccer players, Baena-Raya et al. (8) reported that 8 weeks of resisted (sled towing) sprint training performed two session per week (16 total sessions) improved curvilinear sprint performance under both light and very heavy loading conditions ($p \leq 0.03$; $ES \geq 0.60$). Grazioli et al. (53) similarly reported that the heavy and very heavy sled-towing resisted sprint training performed over 8 weeks, 2 sessions per week in the first week and one session per week for the following seven weeks (9 total sessions), significantly improved 10-m sprint (−1.53 to −4.15%; ES = −0.35 to −0.75; $p = 0.003$) and curve sprint performance (−0.75 to −1.39%; ES = −2.54 to −4.27; $p = 0.004$). More specifically, Solleiro-Duran et al. (143) found that 2 sessions per week of curvilinear sprint training for 6 weeks (11 total sessions) significantly improved curvilinear sprint performance (3.36 – 4.16%; $p = 0.006$). In summary, it appears that curvilinear sprint performance can be improved through both resisted and movement-specific training one-to-two session per week.

Despite previous researchers showing that curvilinear speed can be improved through resisted, unresisted, and movement-specific training, most interventions have yet to target the specific inside–outside foot demands of baseball base running (88). Wearable resistance (WR) is a training method that can provide task limb specific overload while preserving the movement pattern of sprinting. WR can be used centrally, such as with trunk or vest loading, or peripherally, such as with arm or leg loading. Given the literature gap at present, more work is needed to understand the application of WR loading of the lower leg (calf) on curvilinear sprinting adaptation. Theoretically, the location of the loading at the distal region of the leg is expected to result in greater rotational inertia ($I = mr^2$) and if moved quickly even a light load will result in greater kinetic energy given the work-energy relationship i.e. torque x angular displacement = ½ I x angular velocity^2. Given the potential of greater kinetic energy, distal limb loading may increase muscular effort required to accelerate and decelerate the segment during curvilinear sprinting, and requires further testing on limb specific loading of the inside and outside leg during curved running for performance enhancement.

Although WR effects on curvilinear running are unknown, research on the effects of lower limb WR on linear sprinting in youth soccer players has been published. Bustos et al. (15) reported that calf-loaded WR performed at 2 to 3 session per week for 8 weeks integrated into a typical football warm-up improved 10-m (1.64%; $p < 0.05$) and 20-m (1.23%; $p < 0.05$) sprint performance compared with unloaded training (between-group ES = 0.97 - 0.64). Furthermore, Ryan et al. (133) found that 6 weeks (2 sessions per week) of calf-loaded WR during warm up improved 15-m sprint time (−2.14%; ES = −1.55; $p < 0.01$) and the reacceleration phase (9.73%; ES = −1.02; $p = 0.05$) in a COD test in youth netball players. These preliminary insights in linear sprinting signal the possibility of benefit to curvilinear sprint performance with calf loaded WR. The purpose of this study was to compare the individual responses of 2 base runners to the same calf-loaded WR intervention performed at either 2 or 3 sessions per week to identify if training frequency is a factor in optimizing multiple base sprinting and if more exposure to calf WR is efficacious. It was hypothesized that the performance improvements of the athlete training three sessions per week would be greater than the athlete training two sessions per week.

10.3 Methods

10.3.1 Experimental approach to the problem

A single-subject design was implemented in two, male, high school level baseball base runners, one completing the intervention training two session per week (S2wk) and the other three session per week (S3wk) Baseline data was collected across three sessions separated by seven days, then at week 4 mid-training (MID), week 8 post-training (POST), and week 10, two weeks after cessation of training (2POST). Calf-loaded WR was used as the primary training stimulus over the 8-week training intervention. The change in various kinematic measures as well as isometric strength were quantified. The results were statistically analysed via visual analysis and the ± 2 x standard deviation (SD) band method (±2SD) to identify meaningful changes between testing sessions. For each subject, the mean and SD from the 3 baseline sessions were used to define an individual reference band, and MID, POST, and 2POST values falling outside this band were interpreted as substantial deviations from normal baseline variability (118). Reliable GPS-derived variables were retained a priori for further analysis (85).

10.3.2 Subjects

Two trained male high school baseball position players volunteered to participate in this study, S2wk (14 years old, 69.5 kg, 153.2 cm, baseball experience = 11 years, gym experience = 1 year) and S3wk (15 years old, 83.5 kg and 182 cm, baseball experience = 5 years, gym experience = 1 year). Participants were healthy, actively competing and training at a high school baseball academy in Puerto Rico, and had at least five years of baseball experience. Before participating, both base runners received an information sheet, and written assent plus legal guardian consent forms to sign. Participants were informed that they could withdraw from the study at any time. This research was approved by the Auckland University of Technology Ethics Committee (24/267).

10.3.3 Equipment

Portable Fixed Dynamometer. A portable fixed dynamometer (PFD - Hawkin Dynamics, Portland, ME, USA) sampling at 1,200 Hz, was used to measure the maximal isometric strength of the subjects. The PFD used Bluetooth connection to a phone via the Hawkin TruStrength mobile application. The device was attached and secured to a baseplate pulled to the floor by the weight of the participant. An adjustable tether was attached to both the strain gauge device and the hand bar via carabiners (see Figure 10.1).

Figure 10.1. IMTP setup



A 10 Hz multi-constellation GNSS receiver (VX Sport, Wellington, New Zealand) was affixed posteriorly between the scapulae of the subjects in a specialized polyester and elastane vest supplied by the manufacturer. Prior to each testing session, the researcher powered on the GNSS receiver approximately 10 minutes before the first activity to allow for satellite signal recognition (35), and calibration by placing the GNSS unit for 30 seconds at the start of each test, the end of each test, and the first base. The VX Sport GNSS receiver collected data at 10 Hz. The data was uploaded to the VX Sports software, trimmed, and split for analysis.

Foot pod IMU technology. IMU foot pod technology (Plantiga Technologies, Vancouver, Canada) was used to quantify inside-outside leg loading and comprised of a 6-axis IMUs (triaxial accelerometer and triaxial gyroscope) placed in an inner sole and then inserted into the subject's shoes (see Figure 10.2). Each IMU was small (42 × 47 × 3.4 mm), durable, and water and impact resistant. The IMU collected data at a sampling rate of 416 Hz. The innersoles were placed in the participants' shoes prior to the warmup (134). An iPad Air (5th generation; Apple Inc., Cupertino, CA, USA) was used to record each sprint trial from a lateral viewpoint in high-definition format to assist step counting and segment identification. At the end of testing, the data were uploaded to the Plantiga cloud, where the manufacturer software was used to quantify the variables of interest.

Figure 10.2. IMU sensor and insole. IMU = inertial measurement unit.



Wearable Resistance. For the 8-week training study, the subject wore Lila™ Exogen™ calf sleeves (Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) for each training session. For WRT trials, a combination of 100, 200, and 300 g fusiform shaped loads (with Velcro backing) were attached to the compression garments (Figure 10.3) for the required loading as per the training program (see Table 10.2).

Figure 10.3. Proximal wearable resistance assistive (left leg) and resistive (right leg) loading



10.3.4 Procedures

Testing protocol. No familiarization session was provided for linear and curvilinear sprinting because all participants were acclimatized, based on their daily training and routine testing prior to the study. Participants were familiarized for the isometric midthigh pull (IMTP) test. Before the first testing session, participants were randomly allocated to either a S2wk or S3wk training schedule. Testing comprised of; three sessions separated by seven days to establish baseline data for each subject, retesting at week 4 mid-training (MID), week 8 post-training (POST),

and week 10, two weeks after cessation of training (2POST). Testing sessions occurred on the same day and at the same time of day each week to reduce biological confounding factors. The testing order remained constant - isometric mid-thigh pull [IMTP], linear and then curvilinear sprinting. This order was intentionally selected because linear sprinting involved maximal efforts at higher velocities and greater overall mechanical demands; performing this task in a fatigued state could alter sprint mechanics and increase injury risk (96). Although currently beyond the scope of the current study, a parallel study is suggested to be undertaken in future given that the fixed testing order has the potential to introduce fatigue that may systematically influence curvilinear trials. Therefore, despite the rest periods provided, the possibility of accumulated neuromuscular fatigue or potentiation cannot be excluded, and this should be considered when interpreting the findings. No injuries or abnormal training disruptions were reported during the study. Each testing session lasted approximately 40 minutes.

IMTP. The familiarization session was used to coach the IMTP and identify the joint angles, [approximately 125° - 145° at knee, 140° - 150° at hip and upright torso (28)] to which the corresponding bar height and tether length were adjusted, and recorded for consistent testing procedures. . Participants stood on the steel baseplate hip-width apart directly over the PFD. At the start of the IMTP test, each participant completed a standardized warm-up consisting of two pull practices without biofeedback and one pull practice with biofeedback to familiarise themselves with the pretension needed to commence testing. Following the warm-up, participants completed three maximal isometric pulls and were instructed to, "pull hard and as fast as possible." On the screen, the PFD was zeroed to account for any drift, automatic pretension and two-second duration of force application was set for each individual. Trials were separated by 2-minute of rest intervals (28).

Sprinting. For the start of the sprints tests, each subject completed a standardized warm-up consisting of lower-body dynamic movement drills. The warm-up protocol consisted of dynamic stretching, quick back and forward lunges, three linear sprints (80, 90, and 100% of intensity) and three curvilinear sprints (80, 90, and 100% of intensity) (84,85). Following the warm-up, participants completed two trials of 54.7 m straight-line sprinting, with three minutes of passive rest between trials. After ten minutes of rest the subjects performed two trials of the home-to-second base sprint test by running from home to the second base (54.7 m) rounding the first base, decelerating after touching the second base. Each trial was separated by three minutes of rest. The lead-off position (frontal plane starting position) was the starting position for the linear and home-to-second base sprint test. Participants placed the right foot in the middle of the home base and the left foot shoulder-width apart. For the linear sprint test, subjects started from a lead-off shoulder-width position as well. This starting position was the normal position a baseball player uses when preparing to run to second base during a during the offensive phase when a player may elect to steal second base. Subjects 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 (84,85). The two trials for the linear sprint and home-to-second base tests were collected and averaged for further analysis. Instructions for all testing were to use plastic cleats for turf baseball surfaces, and to complete the test as fast as possible without

decelerating before the final point. Table 10.1 illustrates the testing protocol for the four phases during the 8-week training cycle.

Table 10.1. The four-session testing plan, including sets, reps, and time commitment by session and total.

Phases	Tests	Sets of test rep	Rest between sets
Pre-training (pre-intervention)	Isometric mid-thigh pull	3	2 minutes
	Linear sprint	2	3 minutes
	Curvilinear sprint	2	3 minutes
Mid-training (mid-training block)	Isometric mid-thigh pull	3	2 minutes
	Linear sprint	2	3 minutes
	Curvilinear sprint	2	3 minutes
Post-training (end of training block)	Isometric mid-thigh pull	3	2 minutes
	Linear sprint	2	3 minutes
	Curvilinear sprint	2	3 minutes
2 weeks post-training	Isometric mid-thigh pull	3	2 minutes
	Linear sprint	2	3 minutes
	Curvilinear sprint	2	3 minutes

Training procedures. The 8-week WR training intervention is presented in Table 10.2. Training was performed using the Curvilinear Ability Test (CAT) to maintain specificity to the curvilinear and change of direction demands of baseball base running. The CAT setting was selected because it reproduced multidimensional sprint event that included a lead-off start, curvilinear running, and subsequent direction-change actions that are relevant to base-running performance, while also emphasizing segment-specific running demands rather than total time alone (87).

WR was attached to the calf area and alternated between the inside and outside leg and lateral and medial sides in a circumferential fashion across the training cycle. In this study, left lateral placement means that the external load was positioned toward the inside of the curve (inside foot lateral and outside foot medial) and was intended to assist, challenging the stabilization demands associated with curvilinear running. Right lateral placement means that the external load were positioned toward the outside of the curve (inside foot medial and outside foot lateral) and was intended to increase the resistive demand, thereby requiring greater control of limb motion and curve negotiation. This alternating placement strategy was used to overload different mechanical demands of curvilinear sprinting while preserving the movement pattern of base running. Distal placement was anatomically theorized to produce greater overload based on the distance to the axis of rotation, whereas proximal placement was thought to reduce intensity while maintaining movement specificity as the load is brought closer to the axis of rotation. The final one or two repetitions of each training session, depending on the week, were completed unloaded to reduce

acute and longitudinal fatigue. Planned unloading was incorporated into the training program: week 4 served as a testing-offloading week, and proximal placement was again used in weeks 5 and 8 as an intensity-reduction strategy and also to reduce detraining effects that could cause acute workload spiking when resuming distal WR loading. Overall, this periodized scheme was intended to progressively overload curvilinear sprinting while managing fatigue and preserving the quality of movement before subsequent testing.

Table 10.2. Eight-week training plan, including training frequency and WR loading schemes.

Week	CAT Training plan			
	Training frequency per week	Sets x reps x distance	Rest between reps (mins)	Load(g) - placement
1	2 or 3 times	1 x 6 x 20.1 m (curvilinear) 1 x 5 x 32.9 m (curvilinear + 180° COD) (last 2 reps of the training session unloaded) Total distance 285 m	2	200 g, distal left lateral, calf
2	2 or 3 times	1 x 7 x 20.1 m (curvilinear) 1 x 5 x 32.9 m (curvilinear + 180° COD) (last 2 reps of the training session unloaded) Total distance 305.1 m	2	300 g, distal right lateral, calf
3	2 or 3 times	1 x 7 x 20.1 m (curvilinear) 1 x 6 x 32.9 m (curvilinear + 180° COD) (last 2 reps of the training session unloaded) Total distance 338 m	2	400 g, distal left lateral, calf
4	Testing Offloading Week – 1 session only after testing	1 x 7 x 20.1 m (curvilinear) 1 x 6 x 32.9 m (curvilinear + 180° COD) (last 2 reps of the training session unloaded) Total distance 338 m	2	400 g, distal right lateral, calf
5	2 or 3 times	1 x 7 x 20.1 m (curvilinear) 1 x 7 x 32.9 m (curvilinear + 180° COD) (last 2 reps of the training session unloaded) Total distance 370.9 m	2	300 g, proximal left lateral, calf
6	2 or 3 times	1 x 8 x 20.1 m (curvilinear) 1 x 6 x 32.9 m (curvilinear + 180° COD)	2	600 g, distal right lateral, calf

		(last 2 reps of the training session unloaded) Total distance 358.1 m		
7	2 or 3 times	1 x 8 x 20.1 m (curvilinear) 1 x 5 x 32.9 m (curvilinear + 180° COD) (last 1 rep of the training session unloaded) Total distance 325.2 m	2	600 g, distal left lateral, calf
8	2 or 3 times	1 x 8 x 20.1 m (curvilinear) 1 x 4 x 32.9 m (curvilinear + 180° COD) (last 1 rep of the training session unloaded) Total distance 292.4 m	2	600 g, proximal right lateral, calf

10.3.5 Statistical analysis

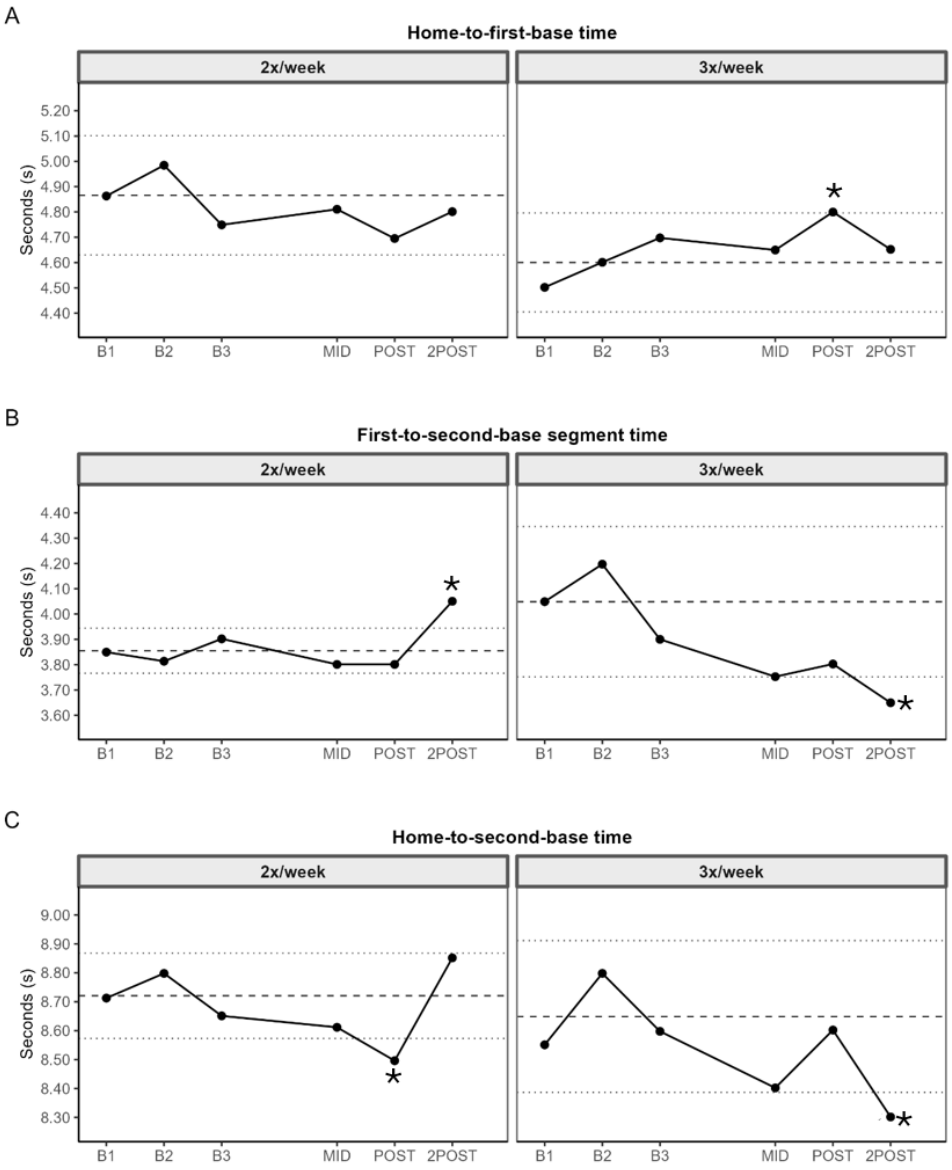
Longitudinal change was quantified using a mixed statistical and visual analysis method (72) to allow for the quantification of large changes in the analysed variables (118). The two band standard deviation (SD) method was used for the purpose of this investigation due to its agreement with the C statistic and split method of trend estimation (118). Within this method, numerical changes were tracked via graphs with meaningful changes quantified by a clear rule. The graphs have two bands that indicate two SD above and below (band) the pre-test mean. The rule was: if the post-baseline data points on the graph fell outside either 2SD bands/threshold, changes were interpreted as meaningful/substantial. Changes were considered more meaningful when consecutive or numerous data points fell outside the SD lines (118). Visual analysis was used to identify trends in the data and was defined as two or more data points trending in the same direction.

10.4 Results

The home-to-first-base (A), first-to-second-base (B), and home-to-second-base (C) times, for both subjects for both subjects throughout the intervention are presented in Figure 10.4. The subjects did not begin from identical performance levels, with baseline mean time differences ranging from 0.07 to 0.27 s. Also, S3wk demonstrated greater baseline variability measures, and therefore, had wider ±2 SD thresholds. Distinct time-course patterns were observed across variables and base runners. S2wk demonstrated faster home-to-second-base sprint times at POST, however, this adaptation was not retained 2POST. Interestingly, S2wk first-to-second-base time at 2POST was the only variable that fell outside the ±2 SD reference band, and was markedly slower than baseline (4.05 s; 5.07%; ES = 4.39). For S3wk, the clearest meaningful improvements were observed at 2POST, with first-to-second-base time improving to 3.65 s (−9.86%; ES = −2.69) and home-to-second-base time improving to 8.30 s (−4.02%; ES = −2.65), whereas home-to-first-base time remained essentially unchanged (4.65 s; 1.13%; ES = 0.53). A

transient performance decrement was observed following the first base time variables at POST and then it recovered at 2POST in S3wk.

Figure 10.4. The home-to-first-base (A), first-to-second-base (B), and home-to-second-base times, for both subjects across the training intervention.

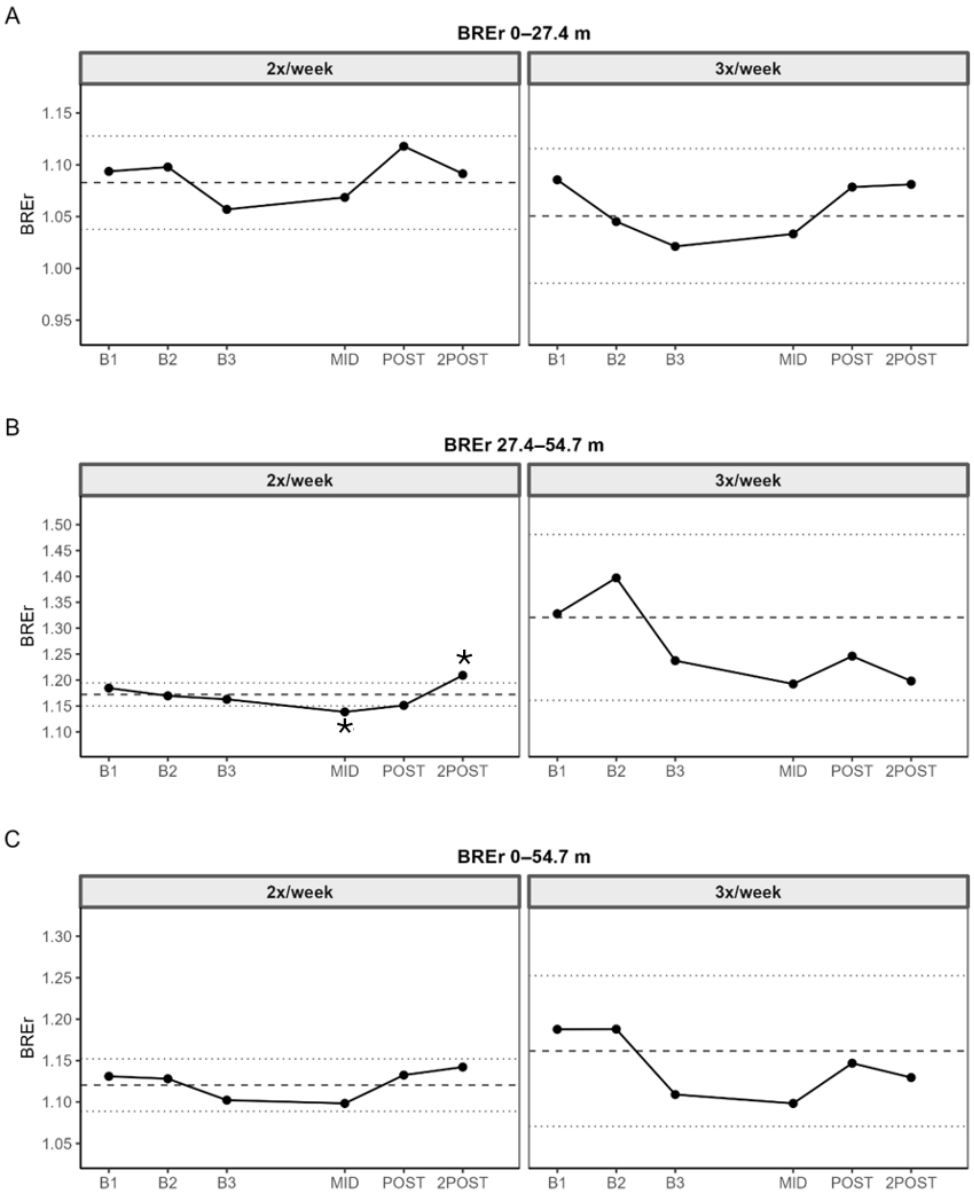


Key: * = greater of less than 2SD; B1 = baseline testing 1; B2 = baseline testing 2; B3 = baseline testing 3; MID = mid-training testing session; POST = post-training testing session; 2POST = 2-week post training testing session

The BREr 0–27.4 m (A), BREr 27.4–54.7 m (B), and BREr 0–54.7 m (C) ratios for both subjects across are presented in Figure 10.5. S2wk less baseline variability and consequently narrower ±2 SD reference bands. S2wk demonstrated the only meaningful change, with BREr 27.4–54.7 m decreasing at MID (1.14; −2.88%; ES = −3.02). This improvement was not retained at 2POST, where BREr increased to 1.21 (3.14%; ES = 3.30). S3wk demonstrated a progressive decrease in BREr 27.4−54.7 m from 1.32 at baseline to 1.19 at MID (−9.72%; ES =

−1.60), then 1.25 at POST (−5.66%; ES = −0.93), and 1.20 at 2POST (−9.23%; ES = 1.53); however, none of these changes were meaningful.

Figure 10.5. BREr 0–27.4 m (A), BREr 27.4–54.7 m (B), and BREr 0–54.7 m (C), for both subjects across the training intervention



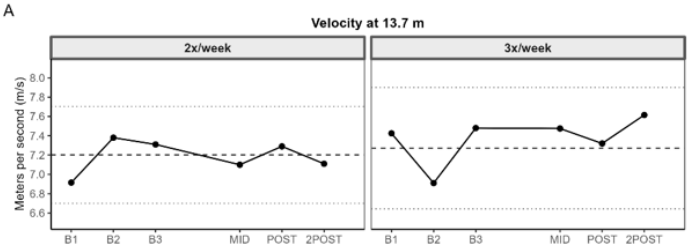
Key: * = greater of less than 2SD; B1 = baseline testing 1; B2 = baseline testing 2; B3 = baseline testing 3; MID = mid-training testing session; POST = post-training testing session; 2POST = 2-week post training testing session

The velocity at 13.7 m (A), peak velocity before first base (B), velocity at first base (C), minimum velocity between peaks (D), peak velocity before second base and after first base (E), velocity at 41.1 m (F), and velocity at second base (G), for both subjects across the training intervention are detailed in Figure 10.6. In terms of baseline performance, the between-subject differences were modest across most variables. Contrasting velocity-response

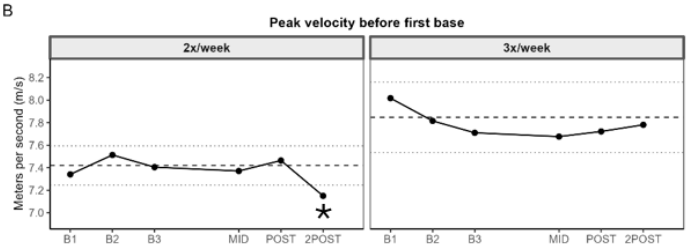
patterns were observed between subjects. S2wk demonstrated a meaningful increase in peak velocity before first base only at 2POST (Figure 6B). Improvement was noted in S3wk after the first base, with peak velocity before second base at MID and POST maintained and then improved to 8.09 $m \cdot s^{-1}$ at 2POST (4.27%; ES = 3.41). An increasing trend was observed in Figure 6G, where S3wk velocity at second base increased from 5.89 $m \cdot s^{-1}$ at baseline to 7.15 $m \cdot s^{-1}$ at MID (21.36%; ES = 1.24), then 7.22 $m \cdot s^{-1}$ at POST (22.55%; ES = 1.31), and 7.51 $m \cdot s^{-1}$ at 2POST (27.47%; ES = 1.59). However, none of these changes were meaningful.

Figure 10.6. The velocity at 13.7 m (A), peak velocity before first base (B), velocity at first base (C), minimum velocity between peaks (D), peak velocity before second base and after first base (E), velocity at 41.1 m (F), and velocity at second base (G), for both subjects across the training intervention

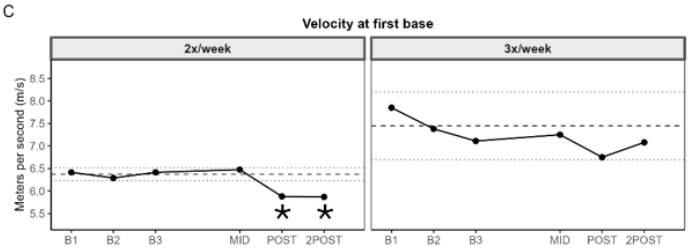
A


Velocity at 13.7 m
2x/week
3x/week
Meters per second (m/s)
8.0
7.8
7.6
7.4
7.2
7.0
6.8
6.6
B1 B2 B3 MID POST 2POST

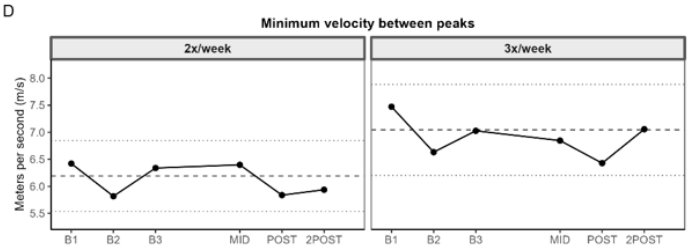
B


Peak velocity before first base
2x/week
3x/week
Meters per second (m/s)
8.2
8.0
7.8
7.6
7.4
7.2
7.0
*
B1 B2 B3 MID POST 2POST

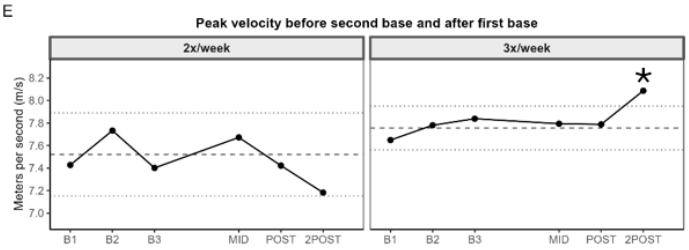
C


Velocity at first base
2x/week
3x/week
Meters per second (m/s)
8.5
8.0
7.5
7.0
6.5
6.0
5.5
* *
B1 B2 B3 MID POST 2POST

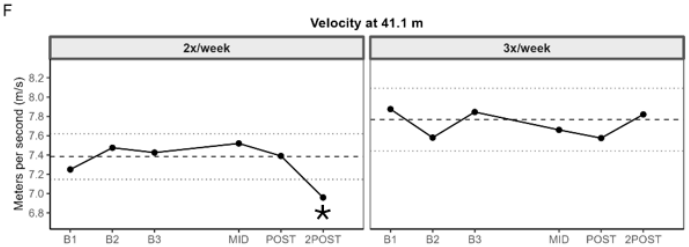
D


Minimum velocity between peaks
2x/week
3x/week
Meters per second (m/s)
8.0
7.5
7.0
6.5
6.0
5.5
B1 B2 B3 MID POST 2POST

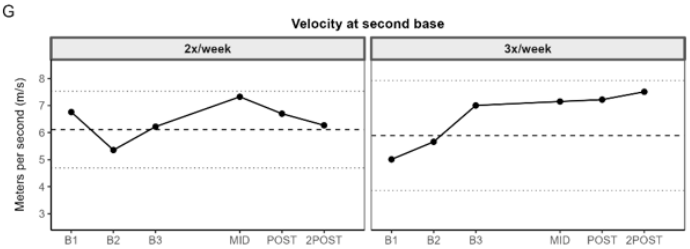
E


Peak velocity before second base and after first base
2x/week
3x/week
Meters per second (m/s)
8.2
8.0
7.8
7.6
7.4
7.2
7.0
*
B1 B2 B3 MID POST 2POST

F


Velocity at 41.1 m
2x/week
3x/week
Meters per second (m/s)
8.2
8.0
7.8
7.6
7.4
7.2
7.0
6.8
*
B1 B2 B3 MID POST 2POST

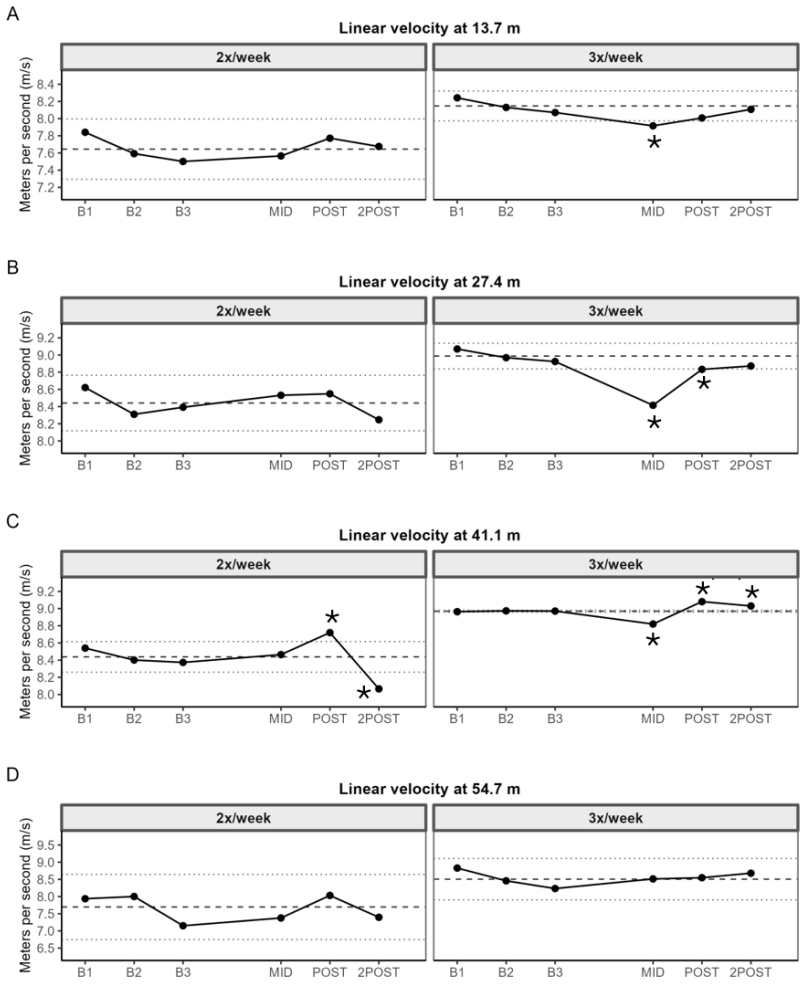
G


Velocity at second base
2x/week
3x/week
Meters per second (m/s)
8
7
6
5
4
3
B1 B2 B3 MID POST 2POST

Key: * = greater of less than 2SD; B1 = baseline testing 1; B2 = baseline testing 2; B3 = baseline testing 3; MID = mid-training testing session; POST = post-training testing session; 2POST = 2-week post training testing session.

The linear velocity at 13.7 m (A), 27.4 m (B), 41.1 m (C), and 54.7 m (D), for both subjects across the training intervention are detailed in Figure 10.7. S3wk was faster than S2wk at all 4 distances, with baseline mean differences ranging from 0.50 to 0.81 $m \cdot s^{-1}$. S3wk had meaningful changes at 41.1m for all three testing sessions because of the very tight baseline band, with POST (9.08 $m \cdot s^{-1}$; 1.24%; ES = 21.32), and 2POST (9.03 $m \cdot s^{-1}$; 0.68%; ES = 11.66) higher than baseline. By contrast, S2wk showed no meaningful change at MID, but had a meaningful increase in velocity at POST (8.72 $m \cdot s^{-1}$; 3.35%; ES = 3.17) and then decrease velocity at 2POST (8.07 $m \cdot s^{-1}$; −4.42%; ES = −4.18). At 54.7 m.

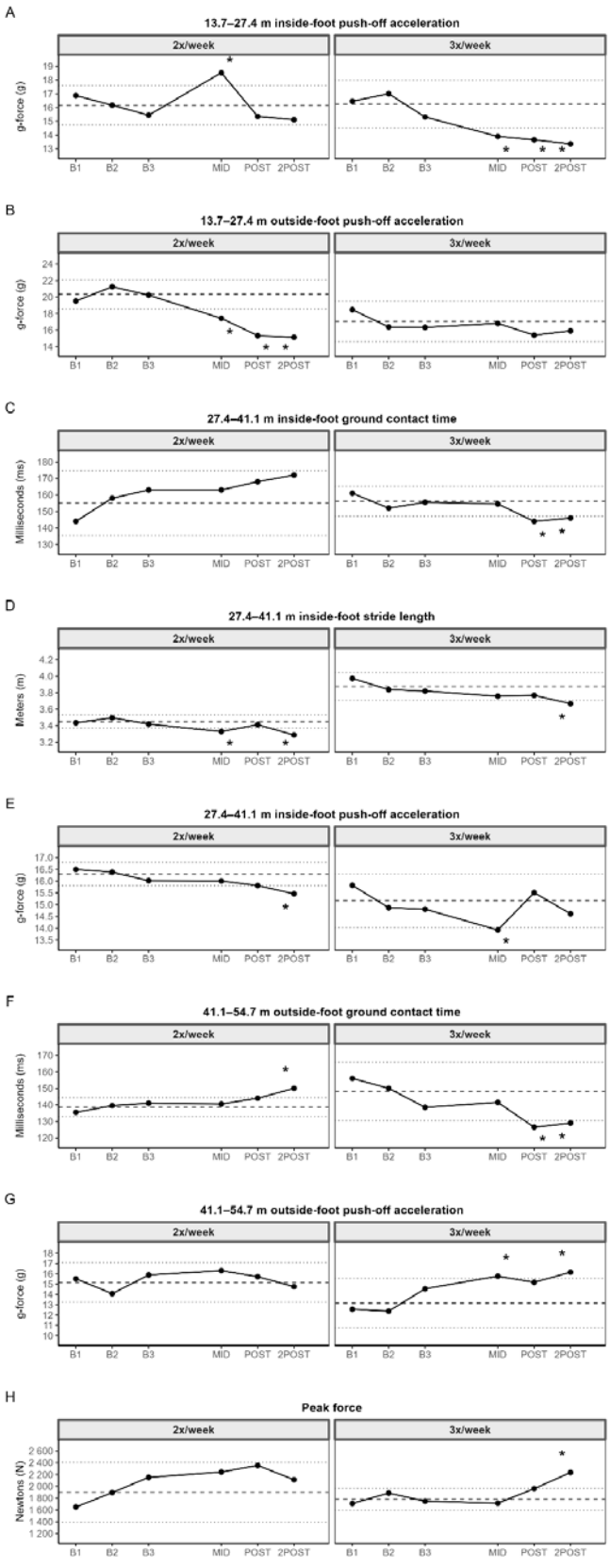
Figure 10.7. Linear velocity at 13.7 m (A), linear velocity at 27.4 m (B), linear velocity at 41.1 m (C), and linear velocity at 54.7 m (D), for both subjects across the training intervention.



Key: * = greater of less than 2SD; B1 = baseline testing 1; B2 = baseline testing 2; B3 = baseline testing 3; MID = mid-training testing session; POST = post-training testing session; 2POST = 2-week post training testing session

Inside-outside foot mechanics across distances and IMTP peak force, for both subjects across testing occasions are detailed in Figure 10.8. Baseline performance was variable between S3wk and S2wk. In the 13.7–27.4 m segment, S2wk demonstrated an opposite foot-specific response compared to S3wk. The inside-foot push-off acceleration increased meaningfully at MID from 16.2 to 18.5 g (14.63%; ES = 3.31), while the S3wk had a meaningful reduction in the inside-foot push-off acceleration from 16.3 g to 13.35 g at across the testing sessions (−14.50 to −17.88%; ES = −2.73 to −3.37). In the 27.4–41.1 m segment, the clearest meaningful change was observed in S3wk, where inside-foot GCT decreased from 156 ms to 146 ms across POST and 2POST (−7.79 to −6.51%; ES = −2.68 to −2.24). In the 41.1–54.7 m segment, meaningful retained pattern were observed in S3wk, with outside-foot GCT decreasing from 148 ms to 127–129 ms at POST and 2POST (−14.62 to −12.94%; ES = −2.44 to −2.16), while outside-foot push-off acceleration increased from 13.2 g to 15.8 g at MID and 16.2 g at 2POST (19.79% to 22.71%; ES = 2.17 to 2.49). Peak force increased meaningfully only in S3wk at 2POST, rising from 1779.89 to 2235.04 N (25.57%; ES = 4.88).

Figure 10.8. Inside-outside foot mechanics across distances and IMTP peak force, for both subjects across testing occasions.



Key: * = greater of less than 2SD; B1 = baseline testing 1; B2 = baseline testing 2; B3 = baseline testing 3; MID = mid-training testing session; POST = post-training testing session; 2POST = 2-week post training testing session

10.5 Discussion

The purpose of this study was to compare the individual responses of two base runners to the same calf-loaded WR intervention performed at either 2 or 3 sessions per week. It was hypothesized that progressive limb loading would transiently suppress performance during the training period, but that once the external load was removed, performance would improve because the athlete would be able to express the adaptation in an unloaded condition.It should be acknowledged that the WR intervention did not positively affect many of the variables of interest in a meaningful manner, and in some instances substantial reductions in performance were observed. Accordingly, the discussion focuses on the variability of the responses, meaningful performance reductions, retained adaptations at 2POST, segment-specific responses, and the potential influence of training frequency. In summary, the clearest retained baseball-specific sprint, mechanical, and force responses were observed in S3wk at 2POST, whereas S2wk showed fewer meaningful positive responses and less evidence of retained adaptation.

Visual analysis identified variable response patters across GPS- and IMU-related variables with two or more data points trending in the same direction demonstrating inconsistency in metric expression, training cycle. It is possible that some of the selected variables were highly sensitive to small fluctuations in fatigue, recovery status, neuromuscular state, or external workload. This is particularly relevant because the intervention was conducted in-season, when the athletes were exposed to competing demands outside the intervention itself, including baseball training, competition, and week-to-week variation in overall workload. Consequently, no training week was identical, making it difficult to isolate the effects of the intervention as would be possible in a tightly controlled laboratory-based design. Nonetheless, this variability also reflects ecological validity, as the intervention was implemented in the type of real sporting environment in which athletes have to train and recover in.

Additionally, WR training resulted in substantial reductions in performance in some GPS-related variables, particularly in S2wk and in several velocity-related measures. In addition, substantial reductions in mechanical profiles were also evident in the foot-pod-related variables. S2wk demonstrated a meaningful reduction in outside-foot push-off acceleration during the 13.7–27.4 m segment. This finding is important because the outside foot contributes substantially to propulsion during curvilinear sprinting (88). Therefore, reduced push-off acceleration may reflect diminished propulsive characteristics during curve negotiation. (88). A temporary reduction in performance is expected when an external distal load is added to a high-velocity task, because the additional resistance increases the muscular work required to accelerate and decelerate the limbs and may acutely perturb the coordination pattern of sprinting. However, once the external load was removed during testing, positive adaptations would be expected to become apparent under unloaded conditions. One theoretical explanation is that S2wk could have experienced enough overload to produce acute suppression of performance, but not enough weekly exposure to produce a stable positive adaptation for performance when unloaded. No meaningful results were retained for S2wk in peak force and 41.1–54.7 m outside-foot GCT. In this context, the lower training frequency may have been insufficient to shift the response from short-term exposure to retained performance enhancement.

A limited number of GPS-derived performance variables improvements were observed at POST, whereas clearer retained responses were evident at 2POST. The 13.7-27.4 m outside-foot push-off acceleration and peak force followed a similar pattern, with the clearest retained mechanical profile appearing in S3wk at 2POST. The absence of many substantial training effects at POST could be explained in two ways: either the WR loading used in this study was ineffective in producing the desired adaptation, or the athletes were tested before fatigue had sufficiently dissipated and before the adaptation could be fully expressed. The latter explanation appears plausible because POST testing occurred approximately five days after the final training session. This interpretation is consistent with the notion that immediate post-testing may underestimate the true magnitude of training adaptation when residual fatigue is still present. A similar pattern has been reported by Morin et al. (105) where they found that after a high-resistance sprint training block, individual peak post-training values were not captured at the 1-week post-test and were more commonly observed at 3-week and 4-week post testing. Given this context, it maybe that a single immediate POST assessment might not be sufficient to identify the true magnitude of adaptation, and that the 2POST testing accounted for the recovery/rest needed for physiological adaptation.

Previous researchers have demonstrated that limb-loaded WR can increase rotational work during sprinting, providing a biomechanical rationale for investigating the effects of distal limb loading on base running performance (33,77). The lack of improvement in home-to-first-base time (1.13%; ES = 0.53), despite meaningful improvements in first-to-second base from 4.05 to 3.65 s (−9.86%; ES = −2.69) and home-to-second-base time from 8.65 to 8.30 s (−4.02%; ES = −2.65), is likely explained by the nature of the mechanical overload provided by calf-loaded WR. Based on the rotational work-energy relationship (torque × angular displacement = $\frac{1}{2}I\omega^2$), the magnitude of muscular rotational work required to move the loaded limb is influenced by its rotational inertia (mass and placement) angular velocity. However, the influence of these variables is not equal because the effects of limb angular velocity increase exponentially. Consequently, faster limb motion produces exponentially greater muscular loading. This provides a plausible explanation for why later phases of base running would be expected to produce a larger effective overload than the lower-velocity earlier phase. The foot pod data support this segment-specific interpretation, as S3wk had the most favourable retained mechanical changes after first base rather than during the home-to-first-base segment. Specifically, S3wk reduced 27.4–41.1 m inside-foot (less time during ground contact for stabilization) and outside-foot GCT (quicker propulsion) while increasing 41.1–54.7 m outside-foot push-off acceleration (higher foot take-off acceleration). In other words, the later segments of the task may have exceeded the threshold load needed to stimulate adaptation, whereas the earlier segment may not have done so to the same extent. This interpretation is strengthened by the linear sprint capacity results, which suggest that S3wk maintained linear sprint capacity at 41.1 and 54.7 m across the training cycle. Therefore, the improvement in peak speed after first base, first-to-second-base time, and the improving trend in BREr 27.4–54.7 m (1.32 to 1.20; −9.29%; ES = −1.53) appear to reflect a better transfer of preserved linear sprint capacity into the baseball-specific curvilinear task rather than a compensatory slowing of linear sprint performance.

An important note is that S2wk experienced the same loading scheme as S3wk. Based on the same work-energy rationale, similar improvements in the later segments might have been expected. Ironically, this was not the case as no substantial retained adaptations were evident in S2wk, which suggests that training frequency may have been an important programming variable when using calf-loaded WR in this baseball-specific context. Previous curvilinear sprint-training studies (8,53,143) have found that training at 2 session per week across 6–8 weeks can improve general curvilinear sprint performance (3–4%; ES = ≥ 0.60; $p < 0.05$), whether the stimulus is curvilinear-specific or based on resisted sprinting. In this study, however, the 2 session per week condition did not appear sufficient to produce the same retained baseball-specific response as the 3 session per week condition. It appears distal calf loading assumed to increase rotational overload within a baseball-specific curvilinear task requires a 3 sessions per week of exposure to accumulate enough specific stimulus for retained adaptation.

10.6 Limitations

Several limitations should be acknowledged when interpreting the findings. First, this study used a single-subject case design involving only 2 baseball base runners; therefore, the findings should be interpreted as individual responses rather than generalized training effects. Second, the intervention was conducted in-season within a real baseball training environment, where weekly workload, competition demands, nutrition, lifestyle, and recovery status could not be fully standardized, and this likely contributed to the variability observed across several variables. Third, despite the rest periods provided, the possibility of accumulated neuromuscular fatigue or potentiation cannot be excluded and should be considered when interpreting the findings. Fourth, the absence of a control group limits causal inference, such that the observed changes cannot be attributed solely to the calf-loaded WR intervention with complete certainty. Fifth, the immediate POST testing session may have underestimated the true training response because it was conducted relatively close to the end of the training block, when residual fatigue may still have been present. Despite these limitations ecological validity of the study creates balance, as the intervention and testing were implemented under realistic baseball training conditions. It is suggested that future study is undertaken with a larger sample size, a control group, more screening to determine recovery status to increase the likelihood of peak performance when engaged in testing protocols.

10.7 Conclusion

Although meaningful improvements were not widespread across all variables, the clearest retained baseball-specific adaptations adaptations were observed in S3wk at 2POST. First-to-second-base and home-to-second-base time improved alongside a higher peak speed after first base and before second base with supportive trends in BREr 27.4–54.7 m and velocity at second base. In terms of the foot pod data, the clearest retained meaningful differences for S3wk compared to S2wk were observed in the 27.4-41.1 m inside-foot GCT, 41.1-54.7 m outside foot GCT and push-off acceleration, as well as substantial peak force improvements were retained at 2POST. It appears that calf-loaded WR sprint training at 3 session per week with baseball-specific curvilinear sprint training may be a potential baseball specific sprint training method, particularly when the goal is to improve performance from first

base to second base. However, because responses differed between the 2 athletes, findings cannot be generalized, and coaches should use repeated monitoring and individualized interpretation rather than assuming that all base runners will respond similarly to the same loading scheme.

10.8 Practical applications

This is the first study to use WR to improve multiple-base running using the CAT, which includes a baseball-specific curvilinear and linear path segments in the same setting, and attaching peripheral loading (distal and proximal; lateral and medial) to increase the rotational work of the limb during curvilinear-specific base running. Strength coaches may consider using resisted CAT sprint training with calf-loaded WR as a baseball-specific method to overload baseball-specific curvilinear mechanics. The CAT provides a practical training setting that combines a lead-off start and baseball-specific curvilinear and linear sprinting, while calf-loaded WR allows peripheral loading to be applied distally or proximally and medially or laterally to increase limb-specific rotational work of the inside and outside leg.

Coaches should be data-informed, monitoring foot pod variables such as inside- and outside-foot GCT and push-off acceleration by segment, because improvements in total time may depend on specific segmental mechanical changes. Based on the findings of this study, 3 sessions per week may be more appropriate than 2 sessions per week to improve home-to-second-base performance, particularly the first-to-second-base segment, the peak speed after first base, and BREr 27.4 to 54.7 m. Due to different responses between athletes, confounding variables may impede recovery prior to testing. It is recommended that strength coaches monitor individual sprint responses across the training cycle, adjust loading, frequency, or recovery when performance suppression is observed to allow for a more accurate depiction of adaption when evaluating maximum sprint efforts.

Chapter 11: Training the Curve: Calf-Loaded Wearable Resistance Sprint Training IMPACT on Base Running Performance in High-School Baseball Players

This chapter is ready for submission.

11.1 Prelude

Chapter 10 provided preliminary evidence that calf-loaded WR may improve selected aspects of curvilinear base running, particularly when training is performed three times per week. However, because Chapter 10 used a two-athlete case-study design, the findings could not be generalised or clearly separated from individual variation, technical learning, and normal training exposure. Chapter 11 therefore extends the findings of Chapter 10 using a randomized controlled design. The purpose of this study was to quantify the effects of an 8-week baseball-specific calf-loaded WR training intervention on base running performance in high-school baseball players compared with the same baseball-specific sprint training performed without WR. IMU foot pod measurements were initially intended to provide additional information about the mechanical changes associated with the intervention. However, the foot pod equipment failed on two separate testing occasions, interrupting data collection and leaving insufficient complete paired observations for valid longitudinal and between-group analyses. Consequently, foot pod outcomes were excluded from Chapter 11, and the study focused on the GPS-derived base running and strength measures for which sufficiently complete data were available.

11.2 Introduction

Base running in baseball is often reduced to linear sprint speed (21,22,26,27,95), yet running multiple bases requires the base runner to negotiate a more complex locomotor situation. They must accelerate, organize entry into the curve phase, negotiate the curve around the first base to maintain velocity, and then reaccelerate toward second base (89). As a result, improving base running performance requires an appreciation of both linear and curvilinear sprint mechanics. With regards to running multiple bases, players shift the weight to the inside leg, creating an inward lean of the body, thus redistributing the force application between the inside and outside feet (88,149). The inside foot is more aligned to stabilization and redirection and the outside foot to forward propulsion (88). Understanding these mechanical differences between linear (single base) and curvilinear (multiple base) sprinting enables coaches to align training methods that optimize adaptation specific to the linear-curvilinear motor qualities for improved performance.

Recent evidence from soccer researchers has shown that various training methods can improve curvilinear sprint performance. Baena-Raya et al. (8) reported that 8 weeks (2 times per week) of light and very heavy resisted sprint training (sled towing) improved curve sprint performance ($p \leq 0.03$; ES ≥ 0.60), with very heavy loading group

also improving change-of-direction performance ($p \leq 0.001$; ES ≥ 0.80). It seems that resisted sprint training that provides a linear force overload can improve curvilinear performance. Solleiro-Duran et al. (143) reported that curvilinear specific-movement training also influences adaptation to curvilinear performance. After 6 weeks of training, the curvilinear sprint training group improved ($p < 0.01$) curvilinear sprint performance on both the good (d = -1.05; fastest time recorded) and weak (d = -0.90; slowest time recorded) sides, as compared to the linear sprint training group. From this work, it appears that curvilinear sprint performance can be improved through both linear resisted overload and movement-specific training, with the greater effects noted when the training stimulus reflected the curve of the targeted task. However, these findings come from soccer-specific trajectories rather than baseball base running, where the athlete must accelerate, organize entry into the curve around first base to maintain velocity, and then reaccelerate toward second base. Experimental evidence for baseball-specific base running training remains unexplored.

Training interventions that provide resisted overload to the base runner while preserving the curvilinear movement pattern in running multiple bases may better optimize base running adaptation. WR would seem ideally suited to provide such overload for freedom of movement and overload of the runner. WR is a training method that uses micro-loads (50-300 gm) attached to compression garments to create movement specific overload. WR has commonly been applied to the trunk or limbs to increase movement demands without altering sprint mechanics (15,60,78,133). Because distal loading increases rotational inertia ($I = mr^2$), the lower limb must perform greater mechanical work while preserving the natural sprinting movement pattern (33,77). Additionally, each limb can be overloaded independently in the medial-lateral and anterior-posterior planes of motion. This is especially relevant to baseball-specific curvilinear running given the inside-outside foot mechanics associated with running multiple bases (88).

Bustos et al. (15) found that 8 weeks of calf-loaded WR integrated into the warm-up had a moderate-to-large improvement in 10- ($d = -0.97$) and 20-m ($d = -0.64$) sprint performance compared to an unloaded training group ($p < 0.05$) of youth soccer players. To our knowledge only one group of researchers have investigated the implementation of WR in base running, however, this was in an unpublished case study design experimental approach (90). They compared the effects of an 8-week calf-loaded WR training intervention in an applied baseball setting, with one subject who trained two times per week and another who trained three times per week. The main findings were that post intervention that the subject training three times per week recorded faster first-to-second-base time (4.05 vs. 3.65 s; −9.86%; ES = −2.69) and a faster home-to-second-base time (8.65 vs. 8.30 s; −4.02%; ES = −2.65), these results falling outside the ± 2 SD baseline thresholds for relevant difference.

Due to evidence of loaded sprint training improving curved sprint performance, combined with the large effects in a recent case study, a gap in the literature exists using a randomized control design to study the effects of WR on running multiple bases in baseball. Therefore, the purpose of this study was to quantify the effect of an 8-week baseball-specific calf-loaded WR training intervention on base running performance in high-school baseball

players. It was hypothesized that WR training group (WRT) would produce greater improvements in baseball-specific curvilinear sprint performance than identical sprint training performed without WR.

11.3 Methods

11.3.1 Experimental approach to the problem

The effects of an 8-week calf-loaded WR training intervention on baseball base running performance were analysed using a randomized controlled trial design. Performance was assessed at four time points: pre-training (BASE), mid-training (MID; week 4), post-training (POST; end of the 8-week training cycle), and 2 weeks post-training (2POST; 2 weeks after cessation). Twenty-five male high-school baseball players were matched for home-to-second-base ability and randomly allocated to either a WR training group (WRT; n = 13) or an unloaded control group (CON; n = 12). The WRT and CON groups participated in the same on-field and off-field academy training activities. In addition, both groups completed the same lower-body dynamic warm-up before the curvilinear and linear sprint training, which comprised of running the curvilinear ability test (CAT) as the training intervention (87). The only difference was that the WRT group wore compression garments with 200–600 g distributed on each calf during the field-based sprint training 3 times per week.

11.3.2 Subjects

Twenty-five male high-school baseball position players aged 14–18 years volunteered to participate in this study (mean ± SD: age = 15.8 ± 1.19 years; body mass = 72.8 ± 15.2 kg; height = 174.9 ± 7.74 cm). Subjects were matched on the primary allocation variable, home-to-second-base time, and then randomly allocated to the WR training (WRT) group (n = 12) or control (CON) group (n = 13). All 13 WRT subjects were available for the BASE, MID, and POST testing sessions and were included in the BASE-MID and BASE-POST analyses. However, three WRT subjects were unavailable for the 2POST follow-up assessment because of pain associated with baseball or physical activities performed outside the study protocol. These cases were not considered study-related adverse events and were not attributed to the calf-loaded WRT intervention. Therefore, the POST-2POST analysis included 9 WRT subjects and 13 CON subjects. Subjects were included if they were actively training and competing in the academy, free from injury or medical conditions affecting performance, and able to complete the training program with ≥ 80% attendance. All subjects provided written assent, and their legal guardians provided written consent before participation. All procedures were reviewed and approved by the Auckland University of Technology's Research Ethics Committee (24/267), in accordance with the Declaration of Helsinki. No injuries were reported as part of the training program.

11.3.3 Equipment

Portable Fixed Dynamometer. A portable fixed dynamometer (PFD - Hawkin Dynamics, Portland, ME, USA) was used to measure the maximal isometric mid-thigh pull (IMTP) strength of the subjects (Figure 10.1). The PFD was

a wireless load cell that sampled at 1200 Hz and used Bluetooth connection to a phone via the Hawkin TruStrength mobile application. The device was attached and secured to a baseplate pulled to the floor by the weight of the subject. An adjustable tether was attached to both the strain gauge device and the hand bar via carabiners.

Global Navigation Satellite System device. GNSS wearable technology (VX Sport, Wellington, New Zealand) was affixed posteriorly between the scapulae of the subjects in a polyester and elastane vest supplied by the manufacturer (Figure 5.1). Prior to each testing session, the researcher powered on the GNSS receiver approximately 10 minutes before the first activity to allow for satellite signal recognition (35), and calibration by placing the GNSS unit for 30 seconds at the start of each test, the end of each test, and the first base. The VX Sport GNSS receiver collected data at 10 Hz. The data was uploaded to the VX Sports software, trimmed, and split for analysis.

Wearable Resistance. The subject wore Lila™ Exogen™ calf sleeves (Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) for each training session. For WRT trials, a combination of 100, 200, and 300 g fusiform shaped loads (with Velcro backing) were attached to the compression garments (Figure 10.3) for the required loading as per the training program.

11.3.4 Procedures

Testing procedures. No familiarization session was provided for the linear and curvilinear sprinting because all subjects were well-familiarized, based on their daily training and routine testing. However, subjects were familiarized with the IMTP test. Testing was conducted at baseline, after 4 weeks of training (MID), after 8 weeks of training (POST), and then 2 weeks post the last testing (2POST). Testing was conducted at the same time of day and on the same baseball turf field. Testing was distributed across adjacent days to accommodate the academy schedule. The subjects wore breathable clothing and baseball cleats for each testing and training session.

Curvilinear and linear sprint. The standardized lower body warm up consisted of general dynamic movements, quick back and forwards, lunges, and three linear sprints and three curvilinear sprints (84,85). After the standardized warm up, the subjects performed two trials, separated by three minutes of rest of the linear sprint test and the home to second base sprint base. Subjects performed the linear sprint test starting from a lead-off shoulder-width position and then decelerating after passing through the final cones at the 54.7 mark. For the home-to-second base sprint test, the subjects rounded the first base, decelerating after going through the second base. The starting position for the home-to-second base sprint test was a lead-off position, placing the right foot in the middle of the home base and the left foot shoulder-width. This starting position was the normal position a baseball player uses when prepared to run during the offensive phase. Subjects 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 (84,85). The two trials for the linear sprint and home-to-second base tests were collected and averaged for further analysis. Three minutes of passive rest between trials were provided to limit fatigue, performance fluctuations and decrease the

risk of injury (87,103). Instructions for all testing were to complete the test as fast as possible without decelerating before the final point.

IMTP. The familiarization session was used to instruct the subjects on the movement and determine the bar height and corresponding tether length. Subjects stood on the steel baseplate hip-width apart. The bar was then positioned mid-thigh with the arm straight down and the tip of the fingers touching the upper part of the bar using a double overhand grip. The tether was adjusted, and the tether length number was assigned to the subjects for the repeated testing sessions. The tether was adjusted, so that the subject assumed a posture of approximately 125° - 145° at knee, 140° - 150° at hip and upright torso (28). At the start of the IMTP test, each subject completed a standardized warm-up consisting of two pull practices without biofeedback and one pull practice with biofeedback to familiarise themselves with the pretension needed to commence testing. Following the warm-up, subjects completed three maximal isometric pulls where the instructions were to pull the bar as hard and as fast as possible. On the screen, the PFD was zeroed to account for any drift, automatic pretension, and two-second duration of force application was set for each individual. Trials were separated by 3-minute of rest intervals to minimise fatigue. The average of three trials were used for analysis. Table 10.1 presents the testing protocol across the four phases of the 8-week training cycle.

Training procedures. Both the CON and WRT groups took part in the same training sessions comprising the same activities during an 8-week in-season training block. The CAT was used for the training intervention to simulate the linear and curvilinear demands of baseball base running, with the only difference being that the WRT group completed these activities while wearing calf-loaded WR (87). The CAT format was chosen because it included a lead-off start, curved sprinting, and direction-change actions that closely reflect base running performance. This setup also allowed the intervention to target segment-specific running demands rather than focusing only on total sprint time (87). For the WRT group, WR was integrated into the warm-up before starting the on-field sprint training intervention section. The 8-week WR training intervention is summarized in Table 11.1.

Table 11.1. Eight-week WR training plan.

Week	Training plan			
	Training frequency per week	Sets x reps x distance	Rest between reps (mins)	Load(g) - placement
1	3 times	1 x 6 x 20.1 m (curvilinear) 1 x 5 x 32.9 m (curvilinear + 180° COD) (last 2 reps of the training session unloaded) Total distance 285 m	2	200 g, distal left lateral, calf
2	3 times	1 x 7 x 20.1 m (curvilinear) 1 x 5 x 32.9 m (curvilinear + 180° COD)	2	300 g, distal right lateral, calf

		(last 2 reps of the training session unloaded) Total distance 305.1 m		
3	3 times	1 x 7 x 20.1 m (curvilinear) 1 x 6 x 32.9 m (curvilinear + 180° COD) (last 2 reps of the training session unloaded) Total distance 338 m	2	400 g, distal left lateral, calf
4	Testing Offloading Week – 1 session only after testing	1 x 7 x 20.1 m (curvilinear) 1 x 6 x 32.9 m (curvilinear + 180° COD) (last 2 reps of the training session unloaded) Total distance 338 m	2	400 g, distal right lateral, calf
5	3 times	1 x 7 x 20.1 m (curvilinear) 1 x 7 x 32.9 m (curvilinear + 180° COD) (last 2 reps of the training session unloaded) Total distance 370.9 m	2	300 g, proximal left lateral, calf
6	3 times	1 x 8 x 20.1 m (curvilinear) 1 x 6 x 32.9 m (curvilinear + 180° COD) (last 2 reps of the training session unloaded) Total distance 358.1 m	2	600 g, distal right lateral, calf
7	3 times	1 x 8 x 20.1 m (curvilinear) 1 x 5 x 32.9 m (curvilinear + 180° COD) (last 1 rep of the training session unloaded) Total distance 325.2 m	2	600 g, distal left lateral, calf
8	3 times	1 x 8 x 20.1 m (curvilinear) 1 x 4 x 32.9 m (curvilinear + 180° COD) (last 1 rep of the training session unloaded) Total distance 292.4 m	2	600 g, proximal right lateral, calf

WR (200-600 g) was affixed to the calf and systematically alternated between the inside and outside foot, as well as between medial and lateral calf placements, throughout the training cycle. For clarity, left-lateral placement refers to the external load positioned toward the inside of the curve, with the load placed laterally on the inside foot and medially on the outside foot. This configuration was intended to provide assistive stimulus while challenging the stabilization demands of curvilinear running. Right-lateral placement refers to the external load being positioned toward the outside of the curve, with the load placed medially on the inside foot and laterally on the outside foot. This configuration was designed to increase the resistive demand and require greater control of limb motion while negotiating the curve.

This alternating loading strategy was used to expose subjects to different mechanical demands of curvilinear sprinting while maintaining the movement pattern of baseball base running. Load placement also progressed between proximal and distal positions on the calf. Distal placement was used to increase the overload stimulus, whereas proximal placement was used to reduce training intensity while preserving movement specificity. Depending on the training week, the final one or two repetitions of each session were completed without WR to help reduce acute fatigue and manage cumulative training load. Planned unloading was also included within the program: week 4 functioned as a testing and unloading week, and proximal calf placement was reintroduced during weeks 6 to 8 as an intensity-management strategy. Overall, this periodized approach was designed to progressively overload curvilinear sprinting while controlling fatigue and maintaining high-quality movement before subsequent testing sessions.

11.3.5 Data analysis

Portable fixed dynamometer. The three IMTP trials were averaged to calculate an individual mean for each force-time variable (15). Peak force, peak rate of force development (RFD), and net force at 50, 100, 150, 200, and 250 ms were calculated for each trial. Peak force was defined as the highest instantaneous vertical ground reaction force produced during the pull. Peak RFD was calculated using an 8-tap finite impulse response (FIR) filter. This filter is a non-recursive digital filter with no feedback loop, making it inherently stable. Because RFD calculation requires differentiation of the force-time signal, which can increase noise, the FIR filter was applied to reduce noise while preserving the true peak value. The 8-tap FIR filter used a rolling average of eight data points to identify peak RFD during the contraction period. This filtering approach was selected because it provided the most appropriate balance between noise reduction and peak-signal preservation when compared with 4-tap, 12-tap, and 16-tap FIR filters. Net force at 50, 100, 150, 200, and 250 ms was defined as the instantaneous net vertical ground reaction force produced at each corresponding time point during the trial. All force-time measures were obtained from the Hawkin Dynamics mobile application. Peak force had high between-session reliability (CV = 4.6-7.9%; ICC = 0.94-0.98), whereas peak RFD and early-time force generation measures did not demonstrate consistently acceptable reliability (CV > 10%; ICC < 0.80); therefore, only peak force was emphasized in the longitudinal interpretation (123)

Linear and curvilinear sprint – GNSS. Multi-constellation GNSS receiver calibration data were processed by identifying trial-specific calibration periods, extracting positional coordinates for home plate, first base, second base, and the start and end calibration points, and calculating the mean and standard deviation for each calibration location. These values were stored and used as reference points for subsequent analysis. Each sprint trial was processed iteratively using time-series and velocity GNSS data. Trial start was identified as the first sample in which the runner's velocity exceeded 0.152 $m \cdot s^{-1}$, and trial end was identified as the first sample after maximum velocity in which velocity decreased below 0.152 $m \cdot s^{-1}$. The five samples immediately preceding the start threshold were averaged to determine the starting location for each trial. All GNSS receiver coordinates were then aligned to a predefined home-plate reference point obtained from Google Maps to standardize spatial orientation across trials.

GNSS samples were matched to predefined base locations, and two midpoint locations were calculated: the midpoint between home plate and first base, and the midpoint between first base and second base. Raw velocity data were smoothed using a zero-phase fourth-order Butterworth low-pass filter with a cutoff frequency of 0.5 Hz and numerically integrated to calculate cumulative distance. Distance thresholds of 13.7, 27.4, 41.1, and 54.7 m were used to extract split times, temporal markers, and velocity-based outcomes. For the linear sprint, time and instantaneous velocity were collected at 13.7, 27.4, 41.1, and 54.7 m. Peak velocity and the 27.4–54.7 m split time were also retained. These segments represented early acceleration, transitional acceleration, peak-velocity expression, and velocity maintenance across the 54.7-m sprint. The 27.4–54.7 m split was defined as the time required to complete the second half of the linear sprint. Based on a previous between-session GNSS reliability results the following GNSS-derived variables were used for primary analysis: curvilinear time to 13.7 m, time to 41.1 m, time to second base, first-to-second-base time, velocity at 13.7 m, velocity at 41.1 m, velocity at second base, peak velocity before first base, peak velocity before second base and after first base, peak total curvilinear speed, minimum speed between peaks, linear times at 27.4, 41.1, and 54.7 m, linear velocities at 13.7, 27.4, 41.1, and 54.7 m, and peak total linear speed.

BRE variables were calculated to determine how effectively subjects preserved linear sprint capacity during curvilinear base running by expressing curvilinear sprint time relative to the equivalent linear sprint segment time (12). Base running efficiency from 0 to 27.4 m was calculated as the ratio of home-to-first-base curvilinear time to the corresponding 0–27.4 m linear sprint time. This value reflected the subject's ability to maintain speed during the early phase of increasing curvilinear demand. Base running efficiency from 27.4 to 54.7 m was calculated as the ratio of first-to-second-base curvilinear time to the equivalent 27.4–54.7 m linear sprint time. This value reflected the subject's ability to preserve velocity after negotiating the curve. Overall base running efficiency from 0 to 54.7 m was calculated as total home to second base curvilinear time divided by total 54.7-m linear sprint time. Values closer to 1.00 indicated greater efficiency, suggesting that subjects maintained curvilinear sprint performance closer to their linear sprint capacity. Values farther from 1.00 indicated a greater performance loss during curvilinear running (12,13).

Curvilinear sprint variables were used to describe the home to second base task. Time to 13.7 m represented the time from home plate to the first 13.7 m of the curvilinear path toward first base. Time to peak velocity before first base represented the time required to reach peak velocity between home plate and first base. Time to first base was defined as the total time from home plate to first base. Time to minimum velocity between peaks represented the time required to reach the lowest velocity between the first and second velocity peaks. Time to 41.1 m was defined as the time from home plate to the 41.1-m point toward second base. Time to peak velocity after first base and before second base represented the time required to reach peak velocity between first and second base. Time to second base was defined as the total time from home plate to second base.

Velocity variables included peak velocity before first base, velocity at first base, minimum velocity between peaks, peak velocity after first base and before second base, and velocity at second base. Peak velocity before first base

was defined as the highest velocity reached between home plate and first base. Velocity at first base was the instantaneous velocity recorded at first base. Minimum velocity between peaks was the lowest velocity observed between the first and second velocity peaks. Peak velocity after first base and before second base was the highest velocity reached between first and second base. Velocity at second base was the instantaneous velocity recorded at second base. A detailed description of the linear and curvilinear sprint variables has been previously reported by Martínez-Rodríguez et al. (8). For the GNSS-derived outcomes used in this study, all directly measured linear and curvilinear time and velocity variables demonstrated acceptable absolute reliability (CV < 10%). Linear speed at 13.7, 27.4, 41.1, and 54.7 m showed CVs of 1.5-3.7% and ICCs of 0.85-0.98, whereas the curvilinear time and speed variables reported in the present analysis showed CVs of 1.6-8.4% and ICCs of 0.56-0.97, indicating low within-subject measurement error but moderate-to-large ICC for some event-specific measures (8).

11.3.6 Statistical analysis

Statistical analyses were conducted in R using RStudio version 2023.06.0+421 (Posit Software, PBC, Boston, MA, USA). For the GPS-derived variables, the normality of the raw observations was assessed separately for each variable, group, and session using the Shapiro–Wilk test. Group-by-session cells exhibiting a non-normal distribution were screened for extreme outliers. Observations were considered extreme when they exceeded the outer 3 × interquartile range (IQR) boundaries or had an absolute robust z-score greater than 3.5. Only observations meeting at least one of these extreme-outlier criteria were removed, after which normality was reassessed. A variable was classified as nonparametric when at least one group-by-session cell remained non-normally distributed following quality-control procedures. Normally distributed variables are presented as mean ± standard deviation, whereas non-normally distributed variables are presented as median [IQR].

Baseline group differences were examined before the training-response analysis using Welch independent-samples t-tests for normally distributed variables and Wilcoxon rank-sum tests for non-normally distributed variables. After raw-value screening and extreme outlier removal, no retained GNSS-derived and IMTP variable differed significantly between WRT and CON at baseline.

Home-to-second-base time was designated a priori as the primary outcome. Training responses were evaluated using three prespecified contrasts: BASE–MID, BASE–POST, and BASE–2POST. These contrasts were selected apriori to assess early adaptation during the intervention, adaptation following the complete 8-week intervention, and the extent to which changes from baseline were retained following 2 weeks of training cessation, respectively (132,138).

For each outcome and planned contrast, participant-level raw change scores were calculated by subtracting the value at the initial session from the value at the subsequent session. Thus, change scores were calculated as MID minus BASE, POST minus BASE, and 2POST minus BASE. Within-group changes were evaluated using paired-samples t-tests for normally distributed variables and Wilcoxon signed-rank tests for non-normally distributed variables. Between-group differences in change were evaluated using Welch independent-samples t-tests on the

raw change scores for normally distributed variables and Wilcoxon rank-sum tests on the raw change scores for non-normally distributed variables. The WRT-minus-CON difference in change for each planned contrast was interpreted as the contrast-specific group × session effect (132).

The three planned contrasts for the primary outcome were evaluated using nominal, two-sided p-values. All other retained GPS-derived time, speed, and velocity variables were considered secondary outcomes. To control the family-wise Type I error rate, p-values for these secondary outcomes were adjusted using the Holm sequential procedure. Within-group secondary analyses were adjusted separately for WRT and CON because these analyses represented descriptive changes within each group. Both unadjusted and Holm-adjusted p-values were retained, with statistical conclusions for the secondary outcomes based on the Holm-adjusted values.

For normally distributed variables, within-group effect sizes were calculated as Cohen's d, in which the mean change was standardized using the average variability across the two sessions. Between-group effect sizes were calculated as Cohen's (d) for the difference between WRT and CON raw change scores. For non-normally distributed variables, paired rank-biserial correlations were calculated for within-group changes, and independent-samples rank-biserial correlations were calculated for between-group differences in change. The absolute magnitudes of standardized effect sizes were classified as large (≥1.20), moderate (0.60–1.19), small (0.20–0.59), or trivial (<0.20) (3,10). For nonparametric analyses, matched-pairs rank-biserial correlations were calculated for within-group comparisons, and rank-biserial correlations on change scores were calculated for between-group comparisons.

Rank-biserial correlation coefficients (r_{rb}) were selected a priori as the standardized effect-size measures corresponding to the rank-based Wilcoxon analyses. Although conventionally termed correlations, they were used here as effect-size estimates rather than as measures of association between two continuous variables. Two forms of rank-biserial effect size were used to match the comparison design: a matched-pairs coefficient for within-group repeated-measures contrasts and an independent-samples coefficient for between-group comparisons of change scores. For within-group Wilcoxon signed-rank contrasts, the matched-pairs rank-biserial coefficient ($r_{rb,paired}$) quantified the direction and consistency of paired changes. For between-group Wilcoxon rank-sum comparisons of change scores, the independent-samples rank-biserial coefficient ($r_{rb,ind}$), equivalent to Cliff's delta subject to the sign convention used, quantified the extent to which change scores in one group tended to exceed those in the other group. Both coefficients range from −1 to +1, with the sign interpreted according to whether an increase or decrease represented improved performance. Effect-size estimates were interpreted alongside statistical significance to provide context regarding the potential practical relevance of the observed changes. Absolute magnitudes were classified as large (≥0.43), moderate (0.28–0.42), small (0.11–0.27), or trivial (<0.11), consistent with the Vargha and Delaney classification (43).

Because this was an applied training study with a relatively small sample, effect sizes were interpreted. The absence of statistical significance was not interpreted as definitive evidence of no effect. The following practically relevant

interpretation of moderate-to-large effects (|ES| > 0.60; $|r_{rb}| > 0.28$) was considered meaningful. Statistical significance was accepted at ($p < 0.05$); for outcomes included in the Holm family, significance was determined using the Holm-adjusted p-value.

11.4 Results

The home-to-second-base sprint outcomes are presented in Table 11.2, linear sprint outcomes in Table 11.3 and the IMTP results in Table 11.4.

BASE to MID intervention phase

The BASE–MID contrast was examined to characterize early adaptation during the first four weeks of training. The following section summarizes outcomes that were statistically significant and/or practically relevant across the curvilinear, linear, and IMTP tests. Four practically relevant curvilinear changes were noted in the CON group, which included; reductions in BREr 0–27.4 m (−3.69%; d=-0.87, p=0.001), BREr 27.4–54.7 m (−3.76%; d=-0.76), and BREr 0–54.7 m −1.60%; $r_{rb,paired}$ = -0.34), together with an increase in velocity at second base (13.08%; $r_{rb,paired}$ = 0.94) and a reduction in time to first base (−3.43%; d=-0.60). These findings indicate that the early CON response was primarily characterized by improved BREr and a faster home to first base performance and greater velocity at second base. In terms of linear and IMTP changes during the BASE to MID phase, no within-group adaptations were found to be statistically significant or practically relevant.

Three practically relevant curvilinear changes were noted in the WRT group during this phase, which included: reductions in BREr 0–27.4 m (−3.68%; d=-0.78) and BREr 0–54.7 m (−2.80%; $rr_{rb,paired}$ = -0.77, p=0.021), together with an increase in velocity at second base (17.07%; $r_{rb,paired}$ = 0.62). Collectively, the early WRT response was characterized by improved BREr in each segment and increased velocity at second base. In terms of linear adaptations, a practically relevant increase in linear speed at 13.7 m (0.96%; $r_{rb,paired}$ = 0.36) was noted, however, no other relevant linear or IMTP changes from BASE to MID were observed.

With regards to the BASE–MID between-group comparisons, no statistically significant or practically relevant effect exceeded the prespecified thresholds.

BASE to POST-Intervention Phase

The BASE–POST contrast was examined to characterize adaptation following the 8-week training intervention. Five curvilinear adaptations exceeded the predefined threshold for practical relevance with respect to the BASE–POST curvilinear adaptations in the CON condition. Curvilinear speed at 41.1 m increased by 6.49% (d=0.80), peak velocity after first base and before second base increased by 5.20% (d=0.66), and velocity at second base increased by 15.45% ($r_{rb,paired}$ = 0.85). In addition, BREr 0–54.7 m decreased by 1.61% ($r_{rb,paired}$ = -0.47), and first-to-second-base time decreased by 4.42% (d=-0.68). Practically relevant linear changes entailed a 1.71% increase in linear speed at 13.7 m ($r_{rb,paired}$ = 0.43) and a 21.73% (d=0.79, p<0.001) in IMTP peak force were detected.

Three distinct segmented adaptation were observed, characterized by early improvements in curvilinear efficiency, broader adaptation following 8 weeks of training, and the clearest performance benefits after the 2-week post-training period with WRT. Improvements in three outcomes associated with the first-to-second-base path were noted such as increased curvilinear speed at 41.1 m of 6.05% (d=0.76), peak velocity after first base and before second base of 7.18% (d=0.93), and velocity at second base of 16.26% ($r_{rb,paired}$ = 0.62). Improvements in five outcomes associated with the home-to-first-base path: time to first base decreased by 3.40% (d=-0.65), time to 13.7 m decreased by 4.76% (d=-0.62), BREr 0–27.4 m decreased by 3.36% (d=-0.73), velocity at 13.7 m increased by 3.83% (d=0.74), and peak velocity before first base increased by 4.46% (d=0.80). Lastly, improvements in two outcomes associated with the home-to-second-base path: reduction by 2.72% in BREr 0–54.7 m ($r_{rb,paired}$ = -0.54), increased in peak curvilinear speed by 4.33% (d=0.72). As for the linear adaptation, none were deemed practically relevant, whereas peak force increased by 18.42% (d=0.97, p=0.003).

Practically relevant between-group (WRT–CON) curvilinear differences were noted for BREr 0–27.4 m, (−3.32%; $d = -0.63$) and curvilinear speed at 13.7 m, 3.67% ($d = 0.76$) favouring WRT. Regarding linear sprint adaptation, practically relevant between-group effects favored CON for linear time to 13.7 m and 27.4 m. The WRT–CON differences in change ranged from 1.99% to 2.45%, with effect sizes ranging from $d = 0.74$ to 0.79. No significant or practically relevant findings were found in BASE–POST IMTP between-group comparisons.

BASE to 2-week Post-Intervention Phase

The BASE–2POST comparisons were examined to determine adaptation retention after 2-week of training cessation. Five practically relevant curvilinear changes were observed in the CON group, which included: curvilinear speed at 41.1 m increased by 5.88% (d=0.72); peak velocity after first base and before second base increased by 5.41% (d=0.71); velocity at second base increased by 11.84% (r=0.45); BREr 0–54.7 m decreased by 1.91% ($r_{rb,paired}$ = -0.36); and, BREr 27.4–54.7 m decreased by 3.01% (d=-0.65). As for practically relevant linear adaptations only one was noted, a1.80% increase in linear speed at 13.7 m ($r_{rb,paired}$ = 0.51). IMTP peak force increased by 23.80% (d=0.86, p<0.001).

Nine practically relevant within-group WRT changes were noted in this phase and included: 1) improvements in four outcomes associated with the first-to-second-base path - curvilinear speed at 41.1 m increased by 5.51% (d=0.62), peak velocity after first base and before second base increased by 8.08% (d=1.07), velocity at second base increased by 18.80% ($r_{rb,paired}$ = 0.75); 2) improvements in two outcomes associated with the home-to-first-base path - time to first base decreased by 4.12% (d=-0.76) and peak velocity before first base increased by 4.11% (d=0.69); 3) improvements in three outcomes associated with the home-to-second-base path - BREr 0–54.7 m decreased by 1.60% ($r_{rb,paired}$ = -0.49), home-to-second-base time decreased by 3.57% (d=-0.64, p=0.022), and peak curvilinear speed increased by 4.99% (d=0.84); and, 4) minimum velocity between peaks also increased by 8.26% (d=0.68). Regarding the linear adaptations, a practically relevant 2.20% increase in linear speed at 13.7 m ($r_{rb,paired}$ = 0.64) was observed in the WRT group, as well as an increase in IMTP peak force by 24.12% (d=1.08, p=0.005).

With regards to the between group curvilinear changes, practically relevant improvements in time to 13.7 m (−3.87%; d=-0.61), and minimum velocity between peaks, (9.25%; d=0.67) were observed for WRT. As for the linear variables, linear time to 54.7 m, (−1.79%; d=-0.62), linear speed at 41.1 and 54.7 m (2.51%; d=0.74), and 5.12% (d=0.71) respectively, were noted for WRT that were practically relevant between-group improvements. No between-group IMTP comparison exceeded the criterion for practical relevance. The similar improvements in peak force observed in both groups suggest that differences in sprint adaptation were unlikely to be explained solely by changes in maximal lower-body strength.

Table 11.2. Retained curvilinear GNSS variables across BASE, MID, POST, and 2POST, including within-group % change (ES) and between-group differences in change.

Variable	Group	BASE	MID	POST	2POST	Within-group			Between-group		
						BASE–MID %Δ (ES)	BASE–POST %Δ (ES)	BASE–2POST %Δ (ES)	BASE–MID %Δ (ES)	BASE–POST %Δ (ES)	BASE–2POST %Δ (ES)
Parametric variables											
Time from home to second base	CON	9.15 ± 0.64	8.99 ± 0.52	8.84 ± 0.48	8.94 ± 0.47	-1.47 (-0.28)	-3.19 (-0.55)*	-2.47 (-0.43)			
	WRT	8.83 ± 0.70	8.58 ± 0.67	8.54 ± 0.22	8.62 ± 0.36	-2.81 (-0.37)**	-2.86 (-0.56)	-3.57 (-0.64)*	-1.34 (-0.18)	0.33 (0.03)	-1.10 (-0.22)
First-to-second-base time	CON	4.24 ± 0.34	4.26 ± 0.46	4.04 ± 0.25	4.09 ± 0.29	0.97 (0.03)	-4.42 (-0.68)	-3.41 (-0.48)			
	WRT	3.98 ± 0.47	3.90 ± 0.38	3.87 ± 0.11	3.94 ± 0.25	-1.51 (-0.18)	-1.45 (-0.31)	-2.26 (-0.33)	-2.48 (-0.20)	2.97 (0.24)	1.14 (0.11)
Time to first base	CON	4.91 ± 0.33	4.74 ± 0.26	4.81 ± 0.28	4.85 ± 0.23	-3.43 (-0.60)	-2.03 (-0.35)	-1.57 (-0.31)			
	WRT	4.86 ± 0.36	4.68 ± 0.31	4.67 ± 0.18	4.68 ± 0.21	-3.45 (-0.52)	-3.40 (-0.65)	-4.12 (-0.76)	-0.02 (0.00)	-1.37 (-0.26)	-2.55 (-0.42)
Time to 13.7 m	CON	2.72 ± 0.15	2.64 ± 0.12	2.70 ± 0.18	2.70 ± 0.15	-2.59 (-0.55)	-0.70 (-0.13)	-0.53 (-0.11)			
	WRT	2.78 ± 0.34	2.66 ± 0.18	2.62 ± 0.12	2.65 ± 0.14	-3.51 (-0.41)	-4.76 (-0.62)	-4.40 (-0.54)	-0.92 (-0.24)	-4.06 (-0.59)	-3.87 (-0.61)
Time to 41.1 m	CON	7.16 ± 0.45	6.99 ± 0.35	7.00 ± 0.37	7.04 ± 0.37	-2.19 (-0.42)	-2.08 (-0.39)	-1.73 (-0.32)			
	WRT	6.91 ± 0.55	6.79 ± 0.51	6.76 ± 0.21	6.80 ± 0.31	-1.75 (-0.24)	-1.77 (-0.37)	-2.58 (-0.47)	0.44 (0.13)	0.32 (0.02)	-0.85 (-0.19)
BREr 0–27.4 m	CON	1.06 ± 0.04	1.02 ± 0.05	1.05 ± 0.04	1.05 ± 0.04	-3.69 (-0.87)**	-0.05 (-0.03)	-0.82 (-0.25)			
	WRT	1.07 ± 0.06	1.03 ± 0.04	1.03 ± 0.04	1.04 ± 0.05	-3.68 (-0.78)	-3.36 (-0.73)	-2.63 (-0.53)	0.01 (-0.06)	-3.32 (-0.63)	-1.81 (-0.33)
BREr 27.4–54.7 m	CON	1.20 ± 0.08	1.16 ± 0.04	1.16 ± 0.07	1.16 ± 0.03	-3.76 (-0.76)	-3.29 (-0.58)	-3.01 (-0.65)			
	WRT	1.17 ± 0.10	1.15 ± 0.05	1.15 ± 0.06	1.18 ± 0.03	-1.15 (-0.23)	-1.15 (-0.27)	0.33 (-0.06)	2.62 (0.40)	2.15 (0.19)	3.34 (0.37)
Speed at 13.7 m	CON	7.01 ± 0.38	6.99 ± 0.41	7.02 ± 0.34	7.06 ± 0.32	-0.31 (-0.07)	0.17 (0.02)	1.32 (0.24)			
	WRT	6.98 ± 0.34	7.13 ± 0.39	7.23 ± 0.35	7.11 ± 0.47	2.24 (0.40)	3.83 (0.74)	2.03 (0.33)	2.55 (0.49)	3.67 (0.76)	0.71 (0.12)
Speed at first base	CON	6.60 ± 0.55	6.45 ± 0.69	6.68 ± 0.58	6.47 ± 0.64	-1.68 (-0.24)	1.45 (0.15)	-0.73 (-0.13)			
	WRT	6.81 ± 0.50	6.85 ± 0.68	6.85 ± 0.43	7.04 ± 0.62	1.34 (0.08)	1.04 (0.08)	4.22 (0.40)	3.02 (0.22)	-0.41 (-0.09)	4.95 (0.40)
Speed at 41.1 m	CON	6.75 ± 0.58	7.37 ± 1.63	7.16 ± 0.45	7.08 ± 0.38	4.29 (0.50)	6.49 (0.80)	5.88 (0.72)			
	WRT	6.99 ± 0.61	7.19 ± 0.63	7.36 ± 0.33	7.24 ± 0.48	3.34 (0.33)	6.05 (0.76)	5.51 (0.62)	-0.95 (-0.09)	-0.45 (-0.08)	-0.37 (-0.03)
Peak speed before first base	CON	7.26 ± 0.48	7.25 ± 0.39	7.38 ± 0.37	7.36 ± 0.34	0.18 (-0.01)	1.90 (0.30)	2.29 (0.37)	2.33 (0.37)	2.56 (0.46)	1.82 (0.29)

	WRT	7.28 ± 0.46	7.44 ± 0.43	7.58 ± 0.27	7.52 ± 0.35	2.51 (0.37)	4.46 (0.80)	4.11 (0.69)			
Peak speed before second base	CON	6.97 ± 0.56	7.18 ± 0.44	7.31 ± 0.49	7.27 ± 0.41	3.49 (0.41)	5.20 (0.66)	5.41 (0.71)			
and after first base	WRT	7.18 ± 0.63	7.53 ± 0.56	7.64 ± 0.30	7.56 ± 0.42	5.40 (0.60)	7.18 (0.93)	8.08 (1.07)	1.92 (0.24)	1.98 (0.21)	2.67 (0.36)
Total peak speed	CON	7.27 ± 0.48	7.38 ± 0.41	7.46 ± 0.40	7.43 ± 0.34	1.70 (0.24)	2.75 (0.43)	3.14 (0.52)			
	WRT	7.40 ± 0.49	7.60 ± 0.49	7.69 ± 0.30	7.65 ± 0.38	2.81 (0.39)	4.33 (0.72)	4.99 (0.84)	1.11 (0.18)	1.58 (0.22)	1.84 (0.31)
Minimum speed between peaks	CON	6.28 ± 0.63	6.40 ± 0.46	6.26 ± 0.59	6.17 ± 0.67	2.46 (0.21)	0.03 (-0.04)	-1.00 (-0.15)			
	WRT	6.28 ± 0.65	6.48 ± 0.78	6.55 ± 0.46	6.62 ± 0.64	4.26 (0.27)	5.48 (0.48)	8.26 (0.68)	1.80 (0.10)	5.45 (0.44)	9.25 (0.67)

Non-parametric variables

Variable	Group	BASE median [IQR]	MID median [IQR]	POST median [IQR]	2POST median [IQR]	BASE–MID %Δ($r_{rb,paired}$)	BASE–POST %Δ($r_{rb,paired}$)	BASE–2POST %Δ($r_{rb,paired}$)	BASE–MID WRT–CON %Δ($r_{rb,ind}$)	BASE–POST WRT–CON %Δ($r_{rb,ind}$)	BASE–2POST WRT–CON %Δ($r_{rb,ind}$)
BREr 0–54.7 m	CON	1.11 [1.09, 1.17]	1.09 [1.07, 1.11]	1.09 [1.07, 1.13]	1.10 [1.07, 1.11]	-1.60 (-0.34)	-1.61 (-0.47)	-1.91 (-0.36)	-1.20 (-0.05)	-1.11 (-0.12)	0.30 (-0.08)
	WRT	1.12 [1.09, 1.15]	1.08 [1.05, 1.11]	1.07 [1.06, 1.09]	1.10 [1.08, 1.12]	-2.80 (-0.80)*	-2.72 (-0.54)	-1.60 (-0.50)			
Speed at second base	CON	6.55 [5.81, 6.74]	6.74 [6.51, 7.00]	6.85 [6.71, 6.92]	6.57 [6.24, 7.04]	13.08 (0.94)	15.45 (0.85)	11.84 (0.46)	3.99 (0.06)	0.80 (0.07)	6.96 (0.24)
	WRT	5.87 [5.29, 7.09]	7.11 [6.67, 7.31]	7.07 [6.88, 7.28]	6.99 [6.41, 7.33]	17.07 (0.62)	16.26 (0.62)	18.80 (0.75)			

Note. Session descriptives are reported as mean ± SD for parametric variables and median [IQR] for nonparametric variables. Within-group entries are presented as percentage change with effect size, expressed as Cohen's d_{av} for parametric variables and matched-pairs rank-biserial correlation ($r_{rb,paired}$) for nonparametric variables. Between-group entries are presented as the WRT–CON difference in percentage change with effect size, expressed as Cohen's d on change scores for parametric variables and independent-samples rank-biserial correlation ($r_{rb,ind}$) for nonparametric variables. Significance symbols indicate the contrast-specific p value: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$. BASE = baseline; MID = 4 weeks; POST = end of the 8-week training cycle; 2POST = 2 weeks post-training.

Table 11.3. Retained linear GNSS variables across BASE, MID, POST, and 2POST, including within-group % change (ES) and between-group differences in change.

Variable	Group	BASE	MID	POST	2POST	Within-group			Between-group		
						BASE–MID %Δ (ES)	BASE–POST %Δ (ES)	BASE–2POST %Δ (ES)	BASE–MID %Δ (ES)	BASE–POST %Δ (ES)	BASE–2POST %Δ (ES)
Parametric variables											
Linear time to 13.7 m	CON	2.83 ± 0.12	2.85 ± 0.12	2.78 ± 0.10	2.85 ± 0.13	0.56 (0.12)	-1.88 (-0.48)	0.65 (0.14)	0.59 (0.18)	2.45 (0.79)	-1.56 (-0.49)
	WRT	2.79 ± 0.16	2.82 ± 0.19	2.80 ± 0.14	2.78 ± 0.15	1.15 (0.18)	0.56 (0.09)	-0.91 (-0.18)			
Linear time to 27.4 m	CON	4.65 ± 0.22	4.67 ± 0.20	4.56 ± 0.19	4.63 ± 0.22	0.33 (0.06)	-1.98 (-0.46)	-0.74 (-0.16)	-0.18 (-0.06)	1.99 (0.74)	-1.08 (-0.48)
	WRT	4.54 ± 0.26	4.55 ± 0.28	4.54 ± 0.20	4.50 ± 0.22	0.15 (0.02)	0.02 (-0.02)	-1.82 (-0.36)			
Linear time to 41.1 m	CON	6.42 ± 0.35	6.42 ± 0.30	6.31 ± 0.30	6.39 ± 0.32	0.09 (0.00)	-1.73 (-0.36)	-0.89 (-0.18)	0.20 (0.07)	1.66 (0.56)	-1.20 (-0.50)
	WRT	6.23 ± 0.40	6.24 ± 0.37	6.22 ± 0.29	6.15 ± 0.33	0.29 (0.04)	-0.06 (-0.03)	-2.09 (-0.37)			
Linear time to 54.7 m	CON	8.20 ± 0.50	8.19 ± 0.41	8.05 ± 0.42	8.17 ± 0.44	-0.02 (-0.02)	-1.69 (-0.31)	-0.75 (-0.14)	-0.41 (-0.10)	1.25 (0.39)	-1.79 (-0.62)
	WRT	7.96 ± 0.51	7.92 ± 0.50	7.92 ± 0.40	7.83 ± 0.42	-0.43 (-0.08)	-0.44 (-0.10)	-2.54 (-0.45)			
Linear speed at 27.4 m	CON	7.74 ± 0.55	7.80 ± 0.42	7.88 ± 0.47	7.91 ± 0.48	0.86 (0.11)	1.94 (0.27)	2.89 (0.41)	-0.64 (-0.16)	-1.32 (-0.30)	-0.32 (-0.07)
	WRT	8.15 ± 0.62	8.15 ± 0.48	8.18 ± 0.43	8.25 ± 0.51	0.22 (0.01)	0.62 (0.06)	2.58 (0.34)			
Linear speed at 41.1 m	CON	7.83 ± 0.54	7.85 ± 0.51	7.92 ± 0.51	7.90 ± 0.49	0.33 (0.04)	1.33 (0.18)	1.34 (0.18)	1.42 (0.40)	0.25 (0.05)	2.51 (0.74)
	WRT	8.13 ± 0.62	8.26 ± 0.55	8.24 ± 0.50	8.34 ± 0.52	1.76 (0.23)	1.58 (0.20)	3.84 (0.52)			
Linear speed at 54.7 m	CON	7.31 ± 0.73	7.47 ± 0.60	7.45 ± 0.68	7.24 ± 0.68	2.80 (0.25)	2.25 (0.21)	-0.05 (-0.04)	2.51 (0.32)	-0.47 (-0.11)	5.12 (0.71)
	WRT	7.49 ± 0.85	7.84 ± 0.70	7.58 ± 0.70	7.69 ± 0.63	5.31 (0.45)	1.79 (0.12)	5.07 (0.43)			
Linear peak speed	CON	7.92 ± 0.56	7.97 ± 0.47	8.08 ± 0.48	8.00 ± 0.48	0.83 (0.10)	2.15 (0.31)	1.64 (0.22)	0.63 (0.19)	-0.64 (-0.17)	1.81 (0.59)
	WRT	8.24 ± 0.60	8.35 ± 0.52	8.35 ± 0.47	8.43 ± 0.50	1.46 (0.20)	1.51 (0.20)	3.44 (0.49)			

Non-parametric variables											
Variable	**Group**	**BASE median [IQR]**	**MID median [IQR]**	**POST median [IQR]**	**2POST median [IQR]**	**BASE–MID %Δ($r_{rb,paired}$)**	**BASE–POST %Δ($r_{rb,paired}$)**	**BASE–2POST %Δ($r_{rb,paired}$)**	**BASE–MID WRT–CON %Δ($r_{rb,ind}$)**	**BASE–POST WRT–CON %Δ($r_{rb,ind}$)**	**BASE–2POST WRT–CON %Δ($r_{rb,ind}$)**
Linear speed at 13.7 m	CON	7.44 [7.01, 7.58]	7.22 [7.03, 7.32]	7.40 [7.19, 7.57]	7.31 [7.13, 7.56]	-0.02 (-0.06)	1.71 (0.43)	1.80 (0.51)	0.98 (0.14)	-1.19 (0.26)	0.40 (0.07)
	WRT	7.38 [7.26, 7.78]	7.49 [7.33, 7.86]	7.44 [7.34, 7.57]	7.48 [7.33, 7.71]	0.96 (0.36)	0.52 (0.00)	2.20 (0.64)			

Note. Session descriptives are reported as mean ± SD for parametric variables and median [IQR] for nonparametric variables. Within-group entries are presented as percentage change with effect size, expressed as Cohen's d_{av} for parametric variables and matched-pairs rank-biserial correlation ($r_{rb,paired}$) for nonparametric variables. Between-group entries are presented as the WRT–CON difference in percentage change with effect size, expressed as Cohen's d on change scores for parametric variables and independent-samples rank-biserial correlation ($r_{rb,ind}$) for nonparametric variables. Significance symbols indicate the contrast-specific p value: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$. BASE = baseline; MID = 4 weeks; POST = end of the 8-week training cycle; 2POST = 2 weeks post-training.

Table 11.4. Retained IMTP variables across BASE, MID, POST, and 2POST, including within-group % change (ES) and between-group differences in change.

Variable	Group	BASE	MID	POST	2POST	Within-group			Between-group		
						BASE–MID %Δ (ES)	BASE–POST %Δ (ES)	BASE–2POST %Δ (ES)	BASE–MID %Δ (ES)	BASE–POST %Δ (ES)	BASE–2POST %Δ (ES)
Parametric variables											
Peak force	CON	1687.60±408.90	1826.34±427.21	2042.18±490.63	2131.02±531.56	11.62 (0.47)***	21.73 (0.79)***	23.80 (0.86)***	-1.07 (-0.05)	-3.32 (-0.18)	0.33 (-0.02)
	WRT	1777.40±299.96	1957.19±355.01	2083.51±332.58	2175.70±418.87	10.55 (0.55)*	18.42 (0.97)**	24.12 (1.08)**			

Note. Session descriptives are reported as mean ± SD for parametric variables and median [IQR] for nonparametric variables. Within-group entries are presented as percentage change with effect size, expressed as Cohen's d_{av} for parametric variables. Between-group entries are presented as the WRT–CON difference in percentage change with effect size, expressed as Cohen's d on change scores for parametric variables. Significance symbols indicate the contrast-specific p value: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$. BASE = baseline; MID = 4 weeks; POST = end of the 8-week training cycle; 2POST = 2 weeks post-training.

11.5 Discussion

This was the first controlled experimental study to investigate the effects of baseball-specific sprint training performed with calf-loaded WR on base running performance in high-school baseball players. The hypothesis that WRT would produce consistently greater adaptations than the same training performed without WR was not supported by statistically significant between-group differences. Nevertheless, the distribution of practically relevant effects indicated a progressive and phase-specific WRT response, the main findings summarized herewith: 1) BASE-MID. During the first 4 weeks, reductions in BREr over 0–27.4 m and 0–54.7 m and increases in velocity at second base were observed in both groups, with no practically relevant between-group GNSS effects. This pattern suggests that the principal early adaptation was an improved ability to express linear sprint capacity during the curvilinear base running task, together with greater velocity at second base. 2) BASE-POST. Following the complete 8-week intervention, broader curvilinear adaptation was noted in the WRT as compared to the CON group, with 10 practically relevant changes compared with 5, respectively. The WRT response encompassed faster home-to-first base path performance, lower BREr 0-27.4 m and 0-54.7 m, greater curvilinear velocity at 13.7 and 41.1 m, higher peak velocities before and after first base, greater velocity at second base, and increased total peak curvilinear velocity. Between-group improvements favoured WRT for BREr 0–27.4 m and curvilinear velocity at 13.7 m, whereas the linear sprint-times at 13.7 and 27.4 m were better in the CON group. 3) BASE-2POST. The clearest WRT response was observed at 2POST, where a statistically significant and practically relevant 3.57% improvement in home-to-second-base time ($d = –0.64$, $p = 0.022$), together with an 8.26% increase in minimum velocity between peaks ($d = 0.68$) was observed for the WRT group. Although the corresponding between-group effect for home-to-second-base time was not practically relevant, the between-group changes in minimum velocity favored WRT by 9.25% ($d = 0.67$), consistent with improved preservation of velocity while negotiating the curve. Additional BASE–2POST effects favored WRT for curvilinear time to 13.7 m and later linear sprint performance. Both groups demonstrated practically relevant increases in peak force at POST and 2POST, but no IMTP between-group effect exceeded the practical-relevance threshold. Collectively, these findings suggest that calf-loaded WR did not produce statistically significant differences in between-group performance; however, WRT was found to have a greater number of practically relevant adaptations as compared to the active CON group. The pattern progressed from early improvements in BREr to broader curvilinear velocity adaptations after 8 weeks and, at 2POST, improved home-to-second-base performance and greater velocity preservation through the curve negotiation around the first base.

During the first 4 weeks, both groups demonstrated practically relevant reductions in BREr 0–27.4 m and 0–54.7 m and increases in velocity at second base. Because BREr expresses curvilinear sprint time

relative to the equivalent linear sprint time, the lower BREr values indicate that the players completed the curved base running task with less time lost relative to their linear sprint capacity (89). These shared changes suggest that quick repeated exposure to the baseball-specific sprint task initially improved efficiency during the home-to-second-base path allowing greater velocity improvements when reaching second base. This interpretation is consistent with Filter et al. (44) that curved sprinting presents specific mechanical and neuromuscular demands for the inside and outside limbs and the repeated curvilinear sprint training produces trajectory-specific improvements that help to improve curvilinear performance. For example, Solleiro-Duran et al. (143) found that curvilinear sprint training produced greater improvements ($d = \sim1.00$; $p < 0.05$) in curve-sprint performance. The absence of practically relevant BASE–MID between-group effects indicates that the shared baseball-specific training stimulus was probably the principal contributor to these early adaptations. Importantly, three of the four practically relevant curvilinear outcomes observed at MID were shared by WRT and CON. This suggests that, baseball-specific sprint training alone may have been sufficient to elicit the initial improvements, with no clear additional benefit from calf-loaded WR during the first 4 weeks.

Following the 8-week intervention (BASE-POST), broader curvilinear adaptations were noted in the WRT group as compared to the CON, with 10 practically relevant changes compared with 5, respectively. The WRT response included five adaptations associated with the home-to-first-base path, three velocity adaptations associated with the first-to-second-base path, and two home-to-second-base adaptations related to velocity and BREr. This broader response to WRT is consistent with Bustos et al. (15) who used the same 200–600-g calf-loading range with 16-18 year-old soccer players and found greater improvements in 10- and 20-m linear sprint performance ($d = 0.64-0.97$; $p < 0.05$) after 8 weeks of WR training than after unloaded training (2). Although that study evaluated linear rather than baseball-specific curvilinear sprinting, it supports the possibility that 8 weeks of repeated distal loading is required before the calf-loaded sprint effects become evident. The present findings are also consistent with evidence that resisted and trajectory-specific sprint training can transfer to curvilinear performance. Baena-Raya et al. (8) reported improvements in curve-sprint performance to the left side ($d > 0.75$; $p < 0.05$) following 8 weeks of resisted (light and very heavy) linear sprint training. Therefore, the broader WRT response may reflect the combined effects of movement-specific curvilinear practice and accumulated external overload. A plausible explanation is that positioning the external load on the calf increased the rotational inertia of the limb, with more distal placements creating a greater rotational demand during rapid limb motion (33). Repeated exposure to this additional rotational demand may have contributed to the broader curvilinear response observed in WRT, potentially providing a movement-specific overload during the baseball-specific sprint training. Moreover, the between-group effect was mixed: BREr 0–27.4 m and curvilinear velocity at 13.7 m favored WRT, suggesting that the clearest WR-related pattern at POST occurred during the early portion of the base running path. This

early path outcome improvement may be due to the repeated exposure of the first 13.7 m segment of the CAT (87). However, linear times at 13.7 and 27.4 m favored CON. The unloaded condition may have permitted earlier expression of linear acceleration adaptations, while the calf-loaded condition was associated with a broader curvilinear response, specifically with performance in the first 13.7 m of the home-to-second-base sprint.

The most important WRT findings were observed at 2POST. A statistically and practically relevant 3.57% reduction in home-to-second-base time (d = -0.64, p = 0.022) was noted in the WRT group, representing the only planned contrast in which the primary outcome met both statistical and practical criteria. WRT also increased minimum velocity between peaks by 8.26% (d = 0.68), and the corresponding between-group difference favoured WRT by 9.25% (d = 0.67). Minimum velocity between peaks represents the lowest velocity expressed between the two curvilinear velocity peaks, during the portion of the task associated with negotiating the curve around the first base. Consequently, the higher minimum velocity suggests improved velocity preservation while negotiating the curve around first base. This interpretation is further supported by the POST–2POST response in velocity at first base, which increased by 3.90% in the WRT group ($d = 0.48$) but decreased by 2.59% in the CON ($d = -0.30$), producing a practically relevant between-group effect favoring WRT of 6.49% ($d = 0.81$) (see Supplementary Table 11.1). In addition, the practically relevant improvements established at POST in peak velocity before first base and peak velocity after first base and before second base remained relevant at BASE-2POST, despite a decrease in velocity from POST to 2POST. At 2POST, these velocities remained 4.11% ($d = 0.69$) and 8.08% ($d = 1.07$) above BASE, respectively. Collectively, the faster home-to-second-base time, higher minimum velocity between peaks, favorable POST–2POST change in velocity at first base, and continued elevation of the velocity peaks surrounding first base suggest that WRT improved whole-task performance through a more favorable preservation and expression of velocity across the curve transition, rather than through an improvement isolated to a single segment. The WRT relevant and statistically significant changes in three important outcomes at 2POST may reflect a delayed expression of adaptations accumulated during the loaded training period. Morin et al. (105) reported that, following a high-resistance sprint-training block, athletes' highest post-training values were not captured at the 1-week assessment and were more commonly observed during weeks 2 to 4 after training cessation. In this context, a single immediate POST assessment may not fully capture the magnitude or timing of adaptation. The WRT important outcome changes observed at 2POST may therefore reflect a later expression of adaptation accumulated during the intervention as fatigue dissipated and recovery progressed. Additional between-group effects favoured WRT for curvilinear time to 13.7 m, linear time to 54.7 m, and linear velocity at 41.1 and 54.7 m (d = -0.61 – -0.74). Peak force increased in both groups at 2POST (23.80%–24.12%; d = 0.86–1.08).

Therefore, the use of WR may help to preserve linear sprint performance while improving home-to-second-base sprint ability.

The improved home-to-second-base time observed in WRT at 2POST, accompanied by the increase in minimum velocity between peaks, suggests a more favorable maintenance of velocity while negotiating the curve around first base. From a biomechanical perspective, maintaining velocity during curvilinear sprinting requires the production of sufficient inward-directed force to redirect the centre of mass while preserving the propulsive impulse necessary for forward progression (19,64). These simultaneous demands become increasingly challenging at higher running velocities because the required centripetal acceleration increases with the square of velocity for a given curve radius (i.e., $a_c = v^2/r$). Consequently, the greater minimum velocity observed in WRT may reflect an improved ability to accommodate the mechanical demands of curve negotiation, potentially through more effective coordination of inward redirection and forward propulsion. Such an interpretation is consistent with the asymmetrical characteristics and lower-limb kinematic adjustments associated with curve sprinting, where differences in step characteristics and hip and ankle motion influence the ability to maintain running velocity through high demanding segments (18,19,64,65,88). The additional rotational inertia imposed by calf-loaded WR may have provided a movement-specific overload during repeated limb flying and support phases potentially contributing to adaptations in the coordination of lower-limb movements to decrease the stride frequency during curvilinear sprinting (33,77). However, these proposed adaptations remain hypothetical because ground reaction forces, lower-limb kinematics, and running-path curvature were not directly quantified. Therefore, the greater velocity maintenance observed in WRT may also reflect differences in approach velocity, running trajectory, or movement coordination rather than changes in force application alone. Furthermore, the absence of statistically significant between-group superiority in home-to-second-base time prevents these potential mechanisms from being interpreted as confirmed WR-specific adaptations.

Several limitations should be considered when interpreting the findings of this study. First, the present study was conducted within a single baseball academy, which may limit generalizability to other age groups, competitive levels, or training environments. Second, the sample size was further condensed as three WRT participants were unavailable for the 2POST assessment, reducing the precision of the 2POST estimates and the statistical power to detect between-group differences. The reasons for unavailability were due to two of the participants experiencing pain after a tournament outside of their baseball academy commitments and the other was injured unrelated to the study. Third, the intervention was conducted in-season within an applied baseball academy environment. Although both groups completed the same academy activities and baseball-specific sprint-training program, weekly baseball workloads, competition demands, physical activity outside the study, nutrition, sleep, and recovery status could not be fully standardized. These uncontrolled factors may have contributed to the variability

in results. At the same time, conducting the intervention under normal baseball-training conditions strengthens the ecological validity and practical applicability of the findings. Fourth, several of the GPS-derived variables described related components of the same home-to-second-base task and should not be considered statistically or biomechanically independent. Consequently, the greater number of practically relevant outcomes in WRT should be interpreted as a pattern of adaptation rather than as multiple independent demonstrations of treatment superiority. Fifth, lower-limb kinetics, muscle activation, and foot-related sprint kinematics were not measured. Therefore, it is unclear whether calf-loaded WR altered ground reaction force distribution and inside and outside foot function helped to preserve velocity around first base. The findings should therefore be delimited to high-school baseball players completing the specific 8-week CAT program with 200–600-g calf loads used in this study. Future researchers should include larger samples, repeated follow-up assessments, standardized monitoring of workload and recovery status, and biomechanical measures capable of identifying how different WR loads and placements influence curve-running mechanics and home-to-second-base performance.

11.6 Summary

The findings of this study indicate that baseball-specific curvilinear sprint training can produce improvements in selected measures of base running performance. During the initial four weeks, both groups improved BREr, suggesting that repeated exposure to the specific initial acceleration, curve negotiation, and reacceleration demands of the CAT may have contributed to improved task execution. It seems that incorporating fundamental curvilinear running demands into a structured training program may improve the ability to express sprint capacity during baseball-specific base running.

Following eight weeks, the WRT group demonstrated a broader pattern of practically relevant changes in curvilinear performance. At 2POST, the WRT group also achieved a statistically and practically relevant within-group improvement in home-to-second-base time, accompanied by increased minimum velocity between curvilinear velocity peaks. From a biomechanical perspective, this pattern may reflect an improvement in velocity regulation while negotiating the curve around first base, where athletes must overcome the most demanding segment while maintaining forward progression. Therefore, preserving velocity through this mechanically demanding portion of the running path may be particularly important for improving overall base running performance. However, improvements in approach velocity, running trajectory, and movement coordination could also contribute to these outcomes.

The additional rotational inertia associated with calf-loaded WR may have provided a movement-specific overload affecting coordination and force production due to general strength improvement and greater lower-limb repositioning during sprinting. Repeated exposure to these demands may have

contributed to adaptations in the task-specific application of force during curvilinear running. However, the absence of a meaningful between-group difference in peak force improvements indicates that greater maximal strength development alone cannot explain the WRT-favoring pattern observed in selected curvilinear velocity outcomes. Instead, these responses may reflect an interaction between improvements in general force capacity and adaptations in the task-specific expression of that capacity during curve negotiation. Nevertheless, the proposed mechanisms involving coordination, limb repositioning, and dynamic force application remain hypothetical because lower-limb kinematics, ground-reaction forces, and muscle activation were not directly measured.

In summary, it appears that calf-loaded WR may influence selected aspects of curvilinear base running performance through movement-specific adaptations that complement improvements in general strength. However, the absence of statistically significant between-group superiority, together with the reduced sample size at 2POST, warrants cautious interpretation.

11.7 Practical applications

Based on the findings of this study, the following practical considerations may help guide baseball-specific sprint training. The CAT provided the primary movement-specific training stimulus because both groups repeatedly practiced the lead-off start, acceleration toward first base, curve negotiation, and reacceleration toward second base. Coaches can therefore use repeated linear and curvilinear sprinting within a baseball-specific pathway to improve BREr and velocity expression without external loading. The shared BASE–MID adaptations and absence of practically relevant between-group effects indicate that unloaded baseball-specific sprint training may be sufficient to produce initial improvements during the first four weeks through baseball-specific sprint training using the CAT for four straight weeks. Nevertheless, calf-loaded WR may be most appropriate when the training objective is to improve specific home-to-second base characteristics. For example, early-path acceleration, velocity expression before and after the first base, and the ability to maintain velocity while negotiating the curve. Coaches should therefore assess more than total sprint time. Peak velocity before first base, peak velocity after first base and before second base, and minimum velocity between peaks can help identify where adaptations occur along the base running pathway.

Home-to-second-base time remains the most important, applied outcome because it represents performance across the complete baseball-specific base running task. Practitioners should assess this outcome alongside the maintenance of velocity between peaks when negotiating the curve, peak velocity before and after the first base, and velocity at first base. Home-to-second-base time determines whether whole-task performance improved, minimum velocity between peaks reflects the ability to maintain velocity through the lowest-velocity portion of the curve, peak velocity before and after the first base are the peak velocity reached before and after the first base, and velocity at first base

characterizes the base runner's velocity at the curve transition around the first base. The 2POST assessment may reveal whether the velocity profile across the base running path is maintained, reduced, or more fully expressed after removal of the load. Evaluating these variables together allows practitioners to determine whether improvements occurred through faster acceleration, improved curve negotiation, or better velocity maintenance after first base.

Although 200–600 g represents a light absolute load, placement on the calf increases the rotational demand imposed on the limb. Consequently, coaches should not treat calf-loaded WR as a negligible stimulus. Load magnitude, placement, sprint volume, and exposure frequency should be progressed conservatively. Practitioners should monitor movement quality, fatigue, discomfort, and individual responses and should include fatigue-management strategies such as unloaded repetitions, reduced-volume weeks, or less-distal load placement. The present intervention alternated calf placement, progressed loading, incorporated unloaded repetitions, and included planned reductions in training stress.

The optimal WR prescription for baseball base running remains unknown. The findings of this study are related specifically to calf loads of 200–600 g used during the CAT and should not be generalized to other loading configurations. Future studies should compare results between calf, thigh, and trunk loading; proximal and distal placement; medial and lateral placement; and symmetrical and asymmetrical loading strategies to further advance insights into curvilinear speed development in base runners.

Chapter 12: Summary and future research direction

12.1 Summary

The overarching question that guided this thesis was, "Can BRE be improved in baseball players?" To answer this question, three specific research questions were developed.

- What is the current status of the literature on linear and curvilinear base running in baseball?
- Can GNSS and IMU foot pod technologies provide reliable and practically useful information for assessing linear and curvilinear base running performance and mechanical demands?
- Can calf-loaded wearable resistance, integrated into baseball-specific training, improve linear sprinting, curvilinear base running, and BRE?

Section 1: Where are we?

The aim of Section 1 was to answer these research questions:

- What is the current status of the literature and public database evidence on linear and curvilinear base running performance?

In this section, three chapters were used to understand the current state of linear and curvilinear baseball base running research and to identify the gaps and limitations that guided the thesis. Chapter 2 used publicly available Major League Baseball data to determine current base running key performance indicators and examine the relationships between linear sprint measures and baseball-specific outcomes. The main findings were that players who stole the most bases generally demonstrated the highest linear speeds, suggesting that linear sprint ability is important for single-base actions. However, the same pattern was not observed in players who ran two bases (doubles), indicating that multiple-base running likely requires additional qualities beyond linear sprint speed. These findings supported the need to assess and train baseball players for both linear and curvilinear sprint ability rather than assuming that improvements in linear speed automatically transfer to curvilinear base running.

Chapter 3 introduced the CAT as a curvilinear-specific assessment designed to integrate curvilinear sprinting and COD speed characteristics, which were observed in baseball base running. Traditional assessments such as the pro-agility test and 505 test provided useful information, but they did not fully represent the curvilinear demands of base running. Therefore, the CAT was proposed as a more specific field assessment for evaluating the movement demands associated with running between two bases (curvilinear). This chapter helped establish the need for assessment methods that reflected the shoulder-width lead-off start, curve negotiation, and directional changes that occur in baseball base running.

Chapter 4 reviewed the mechanical and training considerations associated with curvilinear running from a linear-curvilinear perspective. The main finding was that baseball-specific research on curvilinear sprinting remains limited, with much of the available information derived from track, soccer, and softball studies. Nevertheless, the evidence suggested that curvilinear running requires distinct inside- and outside-leg roles, with the inside leg contributing more to absorption, stabilization, and redirection, while the outside leg contributes more to propulsion and forward progression around the curve. This chapter also highlighted that training for base running should not only target general sprint speed, but should also address foot-ankle mechanics, inward lean, limb-specific force application, and curvilinear movement coordination. Collectively, Section 1 established the rationale for considering base running as a multidimensional skill involving linear speed and curvilinear tasks and identified the gaps in the literature related to baseball curvilinear mechanical descriptions, assessment, and training.

Section 2: Can technology improve base running diagnostics?

The aim of Section 2 was to answer these research questions:

- Can GNSS and IMU foot pod technologies provide reliable and practically useful information for assessing linear and curvilinear base running performance and mechanical demands?

In this section, five chapters were used to examine the reliability and diagnostic value of wearable technologies for assessing base running performance. Chapter 5 examined the between-session reliability of GNSS technology for quantifying linear and curvilinear base running performance. The chapter addressed a key applied problem: although timing gates and stopwatches are commonly used in baseball testing, these technologies provide limited information about how speed is developed, maintained, or lost across specific segments of a sprint. GNSS technology was therefore investigated as a field-based method for capturing time, velocity, and distance measures during a 54.7 m linear sprint and a home-to-second-base curvilinear sprint. The use of GPS-derived variables for repeated monitoring in applied baseball environments was found of high utility, particularly when interpreting meaningful changes in base running performance.

Chapter 6 extended this work by presenting a GPS-based framework for analysing and interpreting BRE. Rather than relying only on total sprint time, this chapter proposed segment-specific velocity–time diagnostics to examine how athletes accelerate, negotiate the curve around first base, and reaccelerate toward second base. The chapter also introduced the base running efficiency ratio, which compared curvilinear sprint performance with linear sprint capacity. This provided a practical method for determining how effectively a base runner preserves linear sprint ability when exposed to the curvilinear demand. The main contribution of this chapter was the development of a practical framework for interpreting individual base running analysis strategies.

Chapter 7 investigated the between-session reliability of IMU foot pod technology for quantifying linear and curvilinear base running mechanics. The main findings were that most variables demonstrated acceptable reliability, with low CVs and good-to-excellent ICCs across many measures. This suggested that IMU foot pod technology can be used to quantify variables such as GCT, SL, push-off acceleration, impact acceleration, and speed during linear and curvilinear base running tasks. Importantly, this chapter showed that foot pod technology can provide information that timing gates and stopwatches cannot provide, particularly regarding step-by-step inside–outside foot mechanics and the spatiotemporal characteristics underpinning sprint performance.

Chapter 8 provided a methodological case approach for interpreting IMU foot pod data in applied baseball settings. This chapter provided a template as to how practitioners could use foot-specific variables to understand how base runners maintain, reorganise, or lose mechanical efficiency across base running segments. GCT, SL, push-off acceleration, and impact acceleration were used to interpret individual mechanical strategies during linear and curvilinear sprinting. The main finding was that IMU data can help practitioners identify whether speed loss may be related to insufficient propulsion, longer GCT, or ineffective redistribution of mechanical roles between feet.

Chapters 6 and 8 were developed as perspective articles to offer new interpretations, challenge conventional analytical approaches, and propose a theoretical approach based on scientific evidence. The three-player examples were used to illustrate potential applications of these frameworks for interpreting GNSS-derived performance characteristics and IMU-derived foot-specific measurements during linear and curvilinear base running.

Chapter 9 examined functional asymmetries in inside–outside foot mechanics during curvilinear sprinting in baseball. The main findings were that asymmetries were found segment-dependent and differed between linear and curvilinear sprinting. Curvilinear sprinting produced distinct inside–outside foot demands, particularly in later segments where stabilization and curve-negotiation requirements were greater. These findings supported the idea that asymmetry during base running should not automatically be interpreted as a deficit but rather considered in relation to the specific task demands of curvilinear sprinting. Collectively, Section 2 demonstrated that IMU foot pod technology could provide reliable and practically useful diagnostic information beyond total sprint time, allowing practitioners to better understand base running segment-specific performance and foot-specific movement strategies.

Section 3: Can curvilinear training improve base running efficiency?

The aim of Section 3 was to answer these research questions:

- Can calf-loaded WR improve baseball-specific curvilinear base running performance?
- Do individual base runners respond differently to different frequency schemes using WR training?

- Does WR training method improve curvilinear base running outcomes?

In this section, two chapters were used to examine the effects of calf-loaded wearable resistance on linear sprinting, curvilinear base running, and base running efficiency.

Chapter 10 used a case study design to examine individual responses to two WR training frequencies. The main finding was that the base runner who trained three sessions per week had the clearest retained curvilinear response at the 2-week post-training testing session. This base runner reached peak speed before first base earlier, covered a shorter distance while entering the curve, improved first-to-second-base segment time, and improved total home-to-second-base time. However, no clear retained improvement in linear sprint time was observed. This suggested that the intervention may have improved how the 3/WK base runner organised the curvilinear sprint, particularly the approach into and exit from the curve. This chapter adopted an exploratory case-study approach involving two athletes to examine individual responses to different frequencies of calf-loaded WR training. Accordingly, its findings provide preliminary insights into individual training responses rather than evidence of the superiority of one training frequency over another.

Chapter 11 extended this work using a parallel-group training design comparing an experimental wearable resistance group with an unloaded control group across an 8-week training cycle. The main findings were that calf-loaded wearable resistance produced selective rather than global adaptations. The clearest wearable resistance-specific responses were observed in time to peak velocity before first base, early base running efficiency, and selected late-phase linear sprint outcomes. However, the control group improved first-to-second-base segment time more than the experimental group, and strength improvements were observed across both groups. These findings indicate that wearable resistance can provide a movement-specific overload within baseball training, but that adaptations are not uniform across all sprint, strength, or curvilinear outcomes.

Collectively, Section 3 showed that calf-loaded WR may improve selected aspects of base running performance. However, the results also demonstrated that base running adaptations are individual, segment-specific, and dependent on how athletes reorganise movement across the home-to-second-base sprint. Therefore, practitioners should avoid interpreting base running performance only through total time or linear sprint outcomes and should instead consider how each athlete accelerates, negotiates the curve, and reaccelerates toward second base.

Overall, this thesis demonstrates that baseball base running should be assessed and trained as a linear-curvilinear performance task rather than as a purely linear sprinting task. The findings demonstrate that linear speed is important for single-base running, but multiple-base running requires additional curvilinear, technical, and foot-specific qualities. GNSS and IMU foot pod technologies provide reliable and practically useful methods for examining these qualities in applied settings, while calf-loaded WR

may offer a field-based method for overloading baseball-specific curvilinear running. Together, the chapters in this thesis establish a framework for assessing, interpreting, and training BRE in baseball players.

12.2 Practical Applications

The practical applications of this thesis for improving base running assessment, diagnostics, and training became clearer through each chapter and remained a central focus throughout. While the final section of the thesis brings the research together into applied recommendations, the following practical applications are drawn from Chapters 2 to 11.

Chapter 2

1. Linear sprint speed remains an important quality for baseball players, particularly for single-base actions such as stealing bases and running from home to first base.
2. Practitioners should avoid assuming that faster linear sprint performance automatically transfers to superior multiple-base running performance, as players with higher linear speed were not necessarily those who ran two bases (doubles) most effectively.
3. Baseball base running assessment batteries should include both linear and curvilinear running tasks so that coaches can distinguish between linear sprint capacity and curvilinear base running ability.

Chapter 3

1. The CAT provides practitioners with a more baseball- and softball-specific assessment than the traditional pro-agility and 505 tests.
2. Practitioners should analyse by segment rather than the total test time when evaluating curvilinear sprinting. Segment times may provide better information about whether a base runner's limitation is related to acceleration, curve negotiation, or reacceleration.
3. Base running assessments should include a shoulder-width lead-off stance and curvilinear running, as these better reflect the movement demands of running between and around bases.
4. The CAT may be used to identify specific technical or physical deficiencies that can guide drill selection, speed development, and individualised base running training.

Chapter 4

1. Curvilinear sprinting should be trained as a distinct physical and technical quality rather than treated as linear sprinting performed on a curve.
2. Practitioners should consider the different roles of the inside and outside legs during curvilinear running. The inside leg may require greater emphasis on braking, absorption, and mediolateral

control, whereas the outside leg may require greater emphasis on stiffness, propulsion, and forward force application.

3. Training prescriptions should include exercises targeting the foot–ankle complex, hip stabilisers, posterior chain (i.e. the calf muscles), and adductors because these structures contribute to curve negotiation, body lean control, and force transfer during base running.
4. Baseball players should be exposed to both gym-based strength exercises and on-field curvilinear sprint drills so that physical capacities can be expressed within sport-specific movement patterns.

Chapter 5

1. GNSS technology can be used by practitioners to monitor linear and curvilinear base running performance in applied field settings when testing procedures are standardised.
2. GPS-derived time, velocity, and distance variables provide more information than timing gates or stopwatches because they allow practitioners to examine how speed is developed, maintained, or lost across different base running phases.
3. Practitioners should be cautious when interpreting small changes in GPS-derived variables and should consider reliability data, typical error, and smallest worthwhile change before making training decisions.
4. GNSS assessment may be especially useful for monitoring home-to-second-base performance because it allows coaches to evaluate the approach to first base, speed maintenance or loss through the curve, and reacceleration toward second base.

Chapter 6

1. Splitting the home-to-second-base sprint into segments allows practitioners to identify speed maintenance or loss through the curve.
2. The BREr can be used to compare curvilinear base running performance against a base runner's linear sprint capacity, helping practitioners determine how effectively linear speed is expressed during curvilinear running.
3. GPS-derived velocity–time profiles may help identify individual running strategies, including different path selection, excessive speed loss around first base, or poor reacceleration after the curve.
4. Rather than relying only on total home-to-second-base time, practitioners should examine segment-specific variables to determine whether the base runner's main limitation occurs before first base, around first base, or after first base.

Chapter 7

1. IMU foot pod technology can be used to reliably quantify spatiotemporal variables during linear and curvilinear base running, including GCT, SL, push-off acceleration, and impact acceleration.
2. Practitioners can use IMU-derived variables to gain deeper insight into the mechanical factors that underpin base running performance, particularly when total time alone does not explain how the base runner is improving speed during the sprint.
3. Foot pod data may help coaches identify whether a base runner's limitation is related to excessive GCT, short SL, reduced propulsion, increased breaking, or asymmetrical foot mechanics.
4. These diagnostics can inform exercise prescription, drill selection, fatigue monitoring, workload assignment, and individualised technical coaching.

Chapter 8

1. IMU foot pod analysis provides a practical framework for interpreting how base runners maintain, reorganise, or lose mechanical patterns across successive base running segments.
2. Practitioners should compare linear and curvilinear sprint mechanics to determine how base running linear sprint strategy changes when negotiating the curve around first base.
3. Segment-specific IMU data can help determine whether speed loss is primarily associated with excessive braking, insufficient propulsion, longer GCT, shorter SL, or ineffective redistribution of mechanical roles between the inside and outside feet.

Chapter 9

1. Curvilinear base running should be viewed as a sequence of segment-specific mechanical adjustments rather than a single continuous sprint.
2. Inside–outside foot asymmetries during curvilinear running should not automatically be interpreted as deficits. Instead, they should be considered in relation to the task demands of curvilinear running.
3. Practitioners should focus on the middle and later segments of home-to-second-base sprint, where curvilinear demands and inside–outside foot asymmetries appear to be greatest.
4. Training should target both inside-foot stability and braking control, and outside-foot propulsion and force transfer, to improve curve negotiation and overall BRE.

Chapter 10

1. Coaches may consider using calf-loaded WR 3 times per week for 8 weeks when the objective is to improve baseball-specific curvilinear performance, while monitoring home-to-second-base time and first-to-second-base segment time as the primary performance outcomes.
2. These outcomes should be interpreted alongside time to peak speed before first base, 13.7–27.4-m distance covered while entering the curve, and BREr, because the approach into first base appears to influence performance from first base to second base.
3. Foot-specific variables such as GCT, SL, push-off acceleration, and impact acceleration, together with peak force, may help determine whether a favorable response was produced by improved curve entry, more effective performance from first base to second base, or greater transfer of preserved linear sprint capacity with greater curvilinear performance (i.e., BRE).
4. Practitioners should use repeated baseline testing and individual monitoring, as responses to calf-loaded WR may vary between base runners even when the same training frequency is used.

Chapter 11

1. Coaches may begin with four weeks of unloaded baseball-specific sprint training, performed three times per week using the CAT, to develop the lead-off start, acceleration toward first base, curve negotiation, and reacceleration toward second base.
2. Calf-loaded WR should be considered an additional overload and implemented when the training objective is to improve specific home-to-second base characteristics. When used, the tested 200–600 g loading range should be progressed gradually across eight weeks while retaining unloaded repetitions to preserve movement quality.
3. Home-to-second-base time should serve as the primary performance measure. Minimum velocity between peaks, velocity at first base, and peak velocity before and after first base can be monitored to determine whether changes result from improved acceleration, curve negotiation, or velocity maintenance after first base.
4. Practitioners should assess performance immediately after training and approximately two weeks after load removal, while monitoring fatigue, discomfort, movement quality, and individual responses throughout the intervention. Load magnitude, placement, sprint volume, or training frequency should be reduced when performance suppression or technical deterioration is observed.

12.3 Limitations

While this thesis provides new insights into the assessment, interpretation, and training of linear and curvilinear BRE, several limitations should be acknowledged.

- In-game-based running effort and body mass considerations (Chapter 2): Although Statcast incorporates selection criteria designed to emphasize competitive running situations, the available data does not independently verify that players performed at 100% maximal voluntary effort during every recorded play. Running performance may also be influenced by tactical decisions, game circumstances, fatigue, and the demands of individual plays. Consequently, these measurements should be interpreted as observations of competitive running performance rather than independently verified maximal sprinting capacity.
- An additional consideration is that body mass was not incorporated into the analysis. From a biomechanical perspective, body mass influences the absolute centripetal force required to negotiate a curved path at a given velocity and radius. These considerations should be acknowledged when interpreting the findings.
- Population specificity: Most experimental chapters involved young male high-school baseball players from a baseball academy setting. Therefore, the findings may not generalise directly to collegiate athletes or professional players. This is particularly important because maturation, strength levels, training age, technical proficiency, and competitive level may influence both linear and curvilinear sprint mechanics.
- Limited baseball-specific curvilinear literature: A recurring limitation throughout the thesis was the limited availability of baseball-specific curvilinear sprinting research. Much of the mechanical rationale for curvilinear running had to be informed by studies in track, soccer, and softball, despite clear differences in running paths and sport-specific movement demands. As such, some applied interpretations were necessarily extrapolated from related but non-identical sporting tasks.
- Intervention limitations: The training studies provide initial evidence for calf-loaded WR as a baseball-specific training adjunct, but the findings should be interpreted cautiously. The case study included only two athletes, while the group-based study used a sample of high-school baseball players from an academy. Concurrent academy training, maturation, technical learning, normal seasonal games, outside-the-school games, and personalized training may have contributed to changes in sprint, strength, and base running outcomes. Additionally, the WR intervention focused on calf loading from 200–600 g, so the findings cannot be generalised to other loading magnitudes, placements, garments, or periodisation strategies.
- Foot pod data availability: On two testing occasions during the experimental study (Chapter 11), technical malfunctions with the IMU foot pod system resulted in incomplete data collection and an insufficient number of valid observations for further analyses. Consequently, the number of participants with paired linear and curvilinear running data with GNSS data was reduced at several testing time points, which may have limited statistical power and the completeness of the longitudinal and between-group comparisons.

The limitations of this thesis highlight the need for caution when generalising findings beyond the specific populations and base running tasks studied. Nevertheless, these limitations also provide clear opportunities for future research to further develop baseball-specific base running diagnostics and training methods.

12.4 Future research directions

- Broader participant samples: Future researchers should include softball players, collegiate players, professional players. This would allow researchers to determine whether BRE, segment-specific velocity profiles, and inside–outside foot mechanics differ according to maturation, strength level, skill level, and sport.
- Training intervention studies: Future researchers should compare different WR loads, placements, frequencies, and intervention durations to determine optimal programming strategies. The current thesis focused on calf-loaded WR using 200–600 g loads. Furthermore, researchers should investigate whether different load magnitudes, proximal versus distal placements, medial versus lateral placements, and assistive versus resistive orientations produce different adaptations in curve entry, curve negotiation, reacceleration, and total home-to-second-base performance.
- Transfer to game performance: Future researchers should determine whether improvements in base running diagnostics transfer to meaningful baseball outcomes. These may include successful stolen bases, extra-base advancement, run scoring, first-to-third success, home-to-second performance under game constraints, and decision-making efficiency when reacting to fielders, coaches, or ball trajectory.

Overall, future research should continue to move baseball base running assessment beyond total time and linear sprint speed alone. The next phase of work should broaden population-specific data and determine whether targeted WR curvilinear training interventions improve both field-based diagnostics and baseball game outcomes.

12.5 Conclusion

This thesis provides original research that expands the understanding of how linear and curvilinear base running analysis can enhance diagnostic insight into baseball performance. From the findings it appears that base running should not be considered solely a linear sprinting task, as multiple-base running is influenced by acceleration capacity, curve negotiation, path selection, segment-specific velocity regulation, inside–outside foot mechanics, and the ability to reaccelerate after negotiating the curve. The integration of GNSS and IMU foot pod technologies provided reliable and practically useful methods for evaluating base running performance beyond total time alone, while the training studies showed that calf-loaded WR can be incorporated into baseball-specific sprint training as a movement-

specific overload strategy, although adaptations were selective, individualised, and segment-specific. Future research should expand normative data across ages, and playing levels, and examine whether targeted curvilinear training interventions transfer to game-based outcomes such as stolen-base success, extra-base advancement, and run scoring.

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Appendix 1. Ethical approval for Chapter 5-9



Auckland University of Technology Ethics Committee (AUTEC)

31 May 2024

John Cronin
Faculty of Health and Environmental Sciences

Dear John

Re Ethics Application: **24/69 The reliability of high-frequency GPS and IMU technology for base running assessment**

Thank you for your responses to AUTEC's conditions.

Your ethics application has been approved for three years until 31 May 2027.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC.
2. All public facing documents must have the AUTEC approval number and be of a high standard of spelling and grammar. Dates on the Information Sheet(s) and Consent Form(s) must be consistent.
3. Any amendments to the project must be approved by AUTEC prior to being implemented.
4. A progress report is due annually on the anniversary of the approval date.
5. A final report is due at the expiration of the approval period, or, upon completion of project.
6. Any serious or adverse events must be reported to AUTEC, this includes unforeseen issues that might affect continued ethical acceptability of the project.
7. AUTEC grants ethical approval only. You are responsible for obtaining management permission for access from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

The application number and title need to be referenced on all correspondence related to this project.

All forms are available online http://www.aut.ac.nz/research/researchethics

For any enquiries, please contact ethics@aut.ac.nz
(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: jose.martinez.rodriguez@autuni.ac.nz

Auckland University of Technology, D-88, Private Bag 92006, Auckland 1142, New Zealand.
T: +64 9 921 9999 ext. 8316: E: ethics@aut.ac.nz: www.aut.ac.nz/researchethics

Appendix 2. Ethical approval for Chapter 8 and 9



Auckland University of Technology Ethics Committee (AUTEC)

14 February 2025

John Cronin
Faculty of Health and Environmental Sciences

Dear John

Re Ethics Application: **24/267 The effect of wearable resistance training on base running efficiency in baseball players**

Thank you for your responses to AUTEC's conditions.

Your ethics application has been approved for three years until 14 February 2028.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC.
2. All public facing documents must have the AUTEC approval number and be of a high standard of spelling and grammar. Dates on the Information Sheet(s) and Consent Form(s) must be consistent.
3. Any amendments to the project must be approved by AUTEC prior to being implemented.
4. A progress report is due annually on the anniversary of the approval date.
5. A final report is due at the expiration of the approval period, or, upon completion of project.
6. Any serious or adverse events must be reported to AUTEC, this includes unforeseen issues that might affect continued ethical acceptability of the project.
7. AUTEC grants ethical approval only. You are responsible for obtaining management permission for access from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

The application number and title need to be referenced on all correspondence related to this project.

All forms are available online http://www.aut.ac.nz/research/researchethics

For any enquiries, please contact the Secretariat at ethics@aut.ac.nz
(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: jose.martinez.rodriguez@autuni.ac.nz; Jonathon Neville

Auckland University of Technology, D-88, Private Bag 92006, Auckland 1142, New Zealand.
T: +64 9 921 9999 ext. 8316: E: ethics@aut.ac.nz; www.aut.ac.nz/researchethics

Appendix 3. Supplementary material

Supplementary Table 4.1. Description of baseball and softball base running training articles of research groups.

Study and Participant Characteristics						**Within-Group Results**				**Between-Group Results**
Author	**Groups**	**Subjects (sex, age [yrs])**	**Sport (level)**	**Training Intervention**	**Assessment**	**Pre (mean ± SD)**	**Post (mean ± SD)**	**% Difference**	**ES**	**ES**
Ramchandra (58)	Training group (n = 20) CG (n = 20)	n = 40 (male, age not specified)	Softball (trained)	Resistance and plyometric training Duration: 6 weeks Frequency: Not specified Load: Not specified Volume: 40 – 60 min of training Exercises: Deadlift, pull-up, push-ups, shuttle run, run and jump, jump and row, pull with holding, medicine ball throw, grip, and handball holding	Assessment: AAHPER Softball Test – base running test (50 yds dash) (3) Tool: Not specified	**Training group** 41.667 ± 3.309 **CG** 44.733 ± 3.751	**Training group** 44.267 ± 2.789* **CG** 41.267 ± 3.262	**Training group** 6.24 **CG** -7.75	**Not specified**	**Not specified**
Fathoni and Rachman (24)	Sprint training group (n = 14) Shuttle run group (n = 14) Excluded (14)	n = 42 (male, 16.88 ± 1.31 yrs)	Softball (trained)	Sprint vs. shuttle run training Duration: Not specified Frequency: Not specified Load: Not specified Volume: Not specified Exercises: Not specified	Assessment: Home to first base sprint (62) Tool: Stopwatch	**Not specified**	**Not specified**	**Not specified**	**Not specified**	**Not specified.** ($p < 0.05$)

García-Ponce-de-León et al. (29)	One group training	n = 18 (male, age not specified)	Baseball (highly trained)	<u>Resistance and plyometric training to improve H1 performance</u> Duration: 20 weeks Frequency: Not specified Exercises: Vertical and rotatory jumps with unilateral and alternating legs – 10 -20 reps; 6 sets Bilateral and unilateral frontal and lateral jump over hurdles - Bodyweight; 10 to 20 reps; 8 sets Frontal jump over hurdles with ladder drills – 5 to 7 reps; 2 to 3 sets. Ladder drills	Assessment: Home-to-first base sprint time Tool: Stopwatch	**H1** 4.42 (s) 6.22 ($m*s^{-1}$)	**H1** 4.14 (s) 6.65 ($m*s^{-1}$)*	**H1** 6.33 6.91	**Not specified**	**N/A**
Garcia Ponce de León et al. (30)	One group	training n = 10	Baseball (highly trained)	<u>Plyometric training to improve H1 performance</u> Duration: 20 weeks Frequency: Not specified Exercises: Smith machine leg press – ≥ 85% 1RM; 4 to 6 reps; 3 to 5 sets Box and hurdle jump - Bodyweight; 10 to 20 reps; 5 to 15 sets Squat jumps – 30 to 50% 1RM; 2 to 4 reps; 3 to 6 sets. Ladder drills	Assessment: Home to first base sprint time Tool: stopwatch	**Not specified**	**Not specified**	**H1** -4.40	**Not specified**	**N/A**

McEvoy and Newton (44)	Training group (n = 9) CG (n = 9)	n = 18 (male, 24 ± 4 yrs)	Baseball (Elite)	<u>Plyometric training</u> Duration: 10 weeks (15 training sessions) Frequency: 3 sessions every 2 weeks Load: Not specified Volume: 3 sets; 6 to 8 reps Exercises: bench throws and jump squats	Assessment: Home to first base sprint time Tool: Photoelectric beam	**Home to first base speed** **Training group** 6.13 ± 0.26 (m*s^{-1}) **CG** 6.22 ± 0.26 (m*s^{-1})	**Home to first base speed** **Training group** 6.68 ± 0.30 (m*s^{-1})*† **CG** 6.60 ± 0.30 (m*s^{-1})*	**Home to first base speed** **Training group** 9.0 ± 3.0 **CG** 6.1 ± 2.7	Not reported	Not reported
Coleman and Dupler (16)	One group	n = 10 (male, 27.67 ± 4.45 yrs)	Baseball (Elite)	<u>Non-structured running program ~ 15 min before each game and post-game strength training program</u> Duration: 10 weeks (15 training sessions) Frequency: 3 to 5 times per week Load: Bodyweight Volume: 20 to 30 meters sprints (each player was allowed to determine the intensity, distance, reps, and sets) Exercises: Linear sprints	Assessment: Home to first base sprint time Tool: Stopwatch	**H1** April 4.33 ± 0.16 (s) 6.34 ± 0.20 (m*s^{-1})	**H1** September 4.33 ± 0.15 (s) 6.34 ± 0.20 (m*s^{-1})	**H1** 0.00 0.00	Not reported	Not reported

Supplementary Table 4.2. Studies that have studied the effect of different exercise training methods on curvilinear sprint ability

Study and Participant Characteristics											
Author	Groups	Subjects (sex, age yrs)	Sport (level)	Training Intervention	Assessment and Technology	Pre (mean ± SD)	Post (mean ± SD)	% Difference	Within-Group Results ES	Between-Group Results ES	Quality score (0-20)
Altmann et al. (4)	LST (n = 6) CST (n = 7) CG (n = 8)	n = 21 (male, 25.1 ± 4.8 yrs)	Soccer (trained)	<u>Linear vs curvilinear sprint training</u> Duration: 6 weeks (12 sessions) Frequency: 2 times per week Load: Bodyweight sprint Volume: 17 m; 6 – 8 reps; 80 – 200 m per training session	CS wide CS medium CS narrow (penalty arc [17m]) CS wide CS medium CS narrow CS wide CS medium CS narrow The average of the left and right sides was used for analysis Technology: timing gates	LST 2.78 ± 0.13 s 2.87 ± 0.14 s 2.99 ± 0.13 s CST 2.79 ± 0.15 s 2.86 ± 0.13 s 3.02 ± 0.19 s CG 2.98 ± 0.13 s 2.98 ± 0.13 s 3.01 ± 0.11 s	LST 2.86 ± 0.20 s 2.84 ± 0.19 s 2.87 ± 0.20 s CST 2.91 ± 0.12 s 2.88 ± 0.13 s 2.95 ± 0.14 s CG 2.89 ± 0.14 s 2.94 ± 0.14 s 2.98 ± 0.13 s	LST 2.88 -1.05 -4.03 CST 4.30 0.70 -2.32 CG -4.01 -2.32 -1.00	LST *d* = 0.47 *d* = -0.19 *d* = -0.76 CST *d* = 0.88 *d* = 0.14 *d* = -0.38 CG *d* = -0.61 *d* = -0.41 *d* = -0.25	Not reported	9
Baena-Raya et al. (8)	Resisted LST (light) (n = 10) Resisted LST (very heavy) (n = 10). CG (n = 18)	n = 38 (male, 17.5 ± 1.7 yrs)	Soccer (highly trained)	<u>Resisted linear sprint training</u> Duration: 8 weeks (16 sessions) Frequency: 2 times per week Load: sled towing load resulting in 25 (light) and 75% (very heavy) of decrement in sprint velocity Volume: 10 m per set for very heavy group and 20 m for light group; 5 sets	Curvilinear sprint: Left side (penalty arc [17m]) Technology: Dual timing gates (3 pairs)	Very heavy group: CS left (0 - 8.5m) 1.57 ± 0.13 s CS left (0 - 17m) 2.68 ± 0.18 s Light group: CS left (0 - 8.5m) 1.52 ± 0.08 s CS left (0 - 17m) 2.64 ± 0.10 s CG: CS left (0 - 8.5m) 1.59 ± 0.10 s CS left (0 - 17m)	Very heavy group: CS left (0 - 8.5m) 1.42 ± 0.08 s* CS left (0 - 17m) 2.55 ± 0.10 s* Light group: CS left (0 - 8.5m) 1.43 ± 0.08 s* CS left (0 - 17m) 2.56 ± 0.10 s* CG: CS left (0 - 8.5m) 1.60 ± 0.10 s CS left (0 - 17m)	Very heavy group: CS left (0 - 8.5m) -9.80 CS left (0 - 17m) -4.21 Light group: CS left (0 - 8.5m) -5.90 CS left (0 - 17m) -2.82 CG: CS left (0 - 8.5m) 0.68 CS left (0 - 17m)	Very heavy group: CS left (0 - 8.5m) *d* = 1.39* CS left (0 - 17m) *d* = 0.89 Light group: CS left (0 - 8.5m) *d* = 1.06* CS left (0 - 17m) *d* = 0.76 CG: CS left (0 - 8.5m) *d* = -0.10 CS left (0 - 17m)	Very heavy group – Control group: CS left (0 - 8.5m) *d* = 1.15# CS left (0 - 17m) *d* = 0.76# Light group – Control group: CS left (0 - 8.5m) *d* = 1.49# CS left (0 - 17m) *d* = 0.89# Very heavy group – Light group:	20

						2.71 ± 0.13 s	2.71 ± 0.14 s	0.08	*d* = 0.00	CS left (0 - 8.5m) *d* = 0.12 CS left (0 - 17m) *d* = 0.33	
Grazioli et al. (53)	Resisted LST (moderate) (n = 10) Resisted LST (very heavy) (n = 11)	n = 21(male, 25.9 ± 5.4 yrs)	Soccer (highly trained)	<u>Resisted linear sprint training</u> Duration: 8 weeks (9 sessions) Frequency: 1 - 2 times per week Load: sled towing load resulting in 15 (moderate) and 50% (heavy) of decrement in sprint velocity Volume: 10 m per set for the very heavy group and 20 m for the light group; 3 sets of 5 reps Note: Typical soccer training routine included one session per week of 1 – 2 sets of 8 to 12 reps of resistance training	Curvilinear sprint: (penalty arc [17m]) The average of the left and right sides was used for analysis Technology: Dual timing gates (2 pairs)	Heavy group: CS (0 – 17 m) 2.75 ± 0.08 s Moderate group: CS (0 – 17 m) 2.83 ± 0.10 s	Heavy group: CS (0 – 17 m) 2.63 ± 0.18 s* Moderate group: CS (0 – 17 m) 2.75± 0.13 s*	Heavy group: CS (0 – 17 m) -4.27 Moderate group: CS (0 – 17 m) -2.54	Heavy group: CS (0 – 17 m *d* = -1.39* Moderate group: CS (0 – 17 m *d* = -0.75*	Pretraining CS (0 – 17 m) *d* = 0.87 Posttraining CS (0 – 17 m) *d* = 0.79	17
Nimphius et al. (116)	One training group	n = 10 (female, 18.1 ± 1.6 yrs)	Softball (highly trained)	<u>Resistance and speed training</u> Duration: 14 weeks (36 sessions) Resistance training - 12 sessions) Frequency: 2 -3 times per week Load: Jump squats - ~ 30% 1RM squat Lifts - 80–100% 1RM Exercises Strength phase: Power clean – 3 sets; 4 reps Squat – 3 sets; 5 to 8 reps Split squat – 2 sets; 6 to 8 reps Deadlift – 2 to 3 sets; 5 to 8 reps Power phase: Hang clean – 3 sets; 4 reps Jump squat – 3 sets; 4 to 6 reps Squat – 2 sets; 5 to 8 reps	Home to second base sprint performance Technology: Dual-beam timing gates (3 pairs)	Home to second base 6.52 ± 0.42 (s)	Home to second base 6.30 ± 0.34 s	Home to second base -2.88	Home to second base *d* = -0.53*	N/A	12

Pereira et al. (122)	Sand training group (n = 9) Grass training group (n = 9) Due to incomplete training sessions: Sand training group (n = 7) Grass training group (n = 8)	n = 18 (male, 18.5 ± 0.6 yrs) Due to incomplete training sessions: n = 15	Soccer (highly trained)	<u>Linear sprint-90° COD-plyometric training performed on grass vs. sand surfaces</u> Duration: 8 weeks (12 sessions) Frequency: 2 times per week Load: Sprint and plyometric training: Bodyweight Volume: Plyometric = 3 – 4 sets; 4 – 6 reps Sprint training = 2 – 6 sets; 1 x 10 - 15 m Note: There were 8 resistance training sessions, 28 technical and tactical training sessions, and 5 friendly matches Exercises: Plyometric: Bilateral hurdle jump Unilateral horizontal jump Vertical drop jumps Horizontal drop jumps Sprint training: Linear sprint 90˚ COD sprint	Curvilinear sprint: Left side (penalty arc [17m]) Technology: Dual beam timing gates (2 pairs)	Sand training group: CS velocity (left side): 6.29 $m*s^{-1}$ Grass training group: CS velocity 6.23 $m*s^{-1}$	Sand training group: CS velocity (left side): 6.49 $m*s^{-1}$ Grass training group CS velocity 6.40 $m*s^{-1}$	Sand training group: CS velocity (left side): 3.18 Grass training group: CS velocity 2.73	Sand training group: CS velocity (left side): 1.46* Grass training group: CS velocity 0.98*	No between group interaction was noted for CS left velocity ($p = 0.756$)	15

Solleiro-Duran et al. (143)	LST (n = 9) CST (n = 10)	n=19 male LST: 15.6 ± 0.5 yrs CST: 15.9 ± 0.3 yrs	Soccer (highly trained)	<u>Linear vs. curvilinear sprint training</u> Duration: 6 weeks (11 sessions) Frequency: 2 times per week Load: Bodyweight sprint Volume: 17 m; 6 – 3 reps; 1 – 4 sets; 102 – 204 m per training session	Curvilinear sprint (penalty arc [17m]): Technology: timing gates	LST CS Good side: 2.82 ± 0.13 s CS Weak side: 2.90 ± 0.15 s CST CS Good side: 2.84 ± 0.10 s CS Weak side: 2.87 ± 0.10 s	LST CS Good side: 2.83 ± 0.19 s CS Weak side: 2.90 ± 0.17 s CST CS Good side: 2.73 ± 0.11 s* CS Weak side: 2.78 ± 0.10 s*	LST CS Good side: 0.02 CS Weak side: 0.13 CST CS Good side: -4.16 CS Weak side: -3.36	LST CS Good side d = 0.05 CS Weak side d = 0.00 CST CS Good side: d = -1.05* CS Weak side: d = -0.90*	 CS Good side: η_p^2 = 0.390 # CS Weak side: η_p^2 = 0.390 #	18

Note: 1RM = One-repetition maximum; CG = Control group; CS = Curvilinear sprint; CST = Curvilinear sprint training; ES = Effect size; LST = Linear sprint training.

* = statistically significant ($p < 0.05$) difference from pre to post-test

= statistically significant ($p < 0.05$) difference between groups

Supplementary Table 4.3. Full methodological quality reports for curvilinear training studies.

Items	Altmann et al. (4)	Baena-Raya et al. (8)	Grazioli et al. (53)	Nimphius et al. (116)	Pereira et al. (122)	Solleiro-Duran et al. (143)
Inclusion criteria were clearly stated;	0	2	1	1	1	2
Subjects were randomly allocated to groups	2	2	2	0	1	2
Intervention was clearly defined;	2	2	2	2	2	2
Groups were tested for similarity at baseline;	0	2	2	2	2	2
Use of a control group	2	2	0	0	0	0
Outcome variables were clearly defined;	2	2	2	2	2	2
Assessments were practically useful;	1	2	2	2	2	2
Duration of intervention practically useful	0	2	2	2	2	2
Between-group statistical analysis appropriate	0	2	2	0	2	2
Point measure of variability	0	2	2	1	1	2
Sum of scores	9	20	17	12	15	18

Supplementary Table 4.4. Measurement of reliability for specific curvilinear data analyses

Study	Curvilinear assessment	Reliability			
Altmann et al. (4)	The mean of both sides:	Not reported			
	CS wide				
	CS medium				
	CS narrow				
Baena-Raya et al. (8)		ICC		CV %	
		Pre	Post	Pre	Post
	CS Left side – 8.5 m	0.98	0.99	0.80	0.71
	CS Left side – 17 m	0.99	0.99	0.46	0.48
Grazioli et al. (53)		ICC		CV %	
		Pre	Post	Pre	Post
	CS – 17 m Moderate-load group	0.87	0.84	3.19	2.37
	CS – 17 m Heavy-load group	0.85	0.82	2.05	1.66
Nimphius et al. (116)	Home to second base time	Not reported			
Pereira et al. (122)	CS Left side – 17 m	ICC = 0.86			
		CV % = < 5%			
Solleiro-Duran et al. (143)		ICC		CV %	
		Pre	Post	Pre	Post
	CS Good side	0.94	0.91	1.08	1.71
	CS Weak side	0.94	0.96	1.03	1.95

Note: CS = Curvilinear sprint; ICC = intra-class correlation; CV = coefficient of variation

Supplementary Table 5.1. Smallest worthwhile change between-session data during home to second base sprint.

Smallest Worthwhile Change	
Session 2-1	Session 3-2
Home-to-Second Base Sprint	
0.038	0.032
0.058	0.052
0.064	0.06
0.144	0.076
0.106	0.09
0.132	0.074
0.152	0.132
0.122	0.094
0.11	0.09
0.108	0.104
0.136	0.118
0.132	0.11
0.132	0.12
0.148	0.108
0.154	0.20
0.102	0.10
0.06	0.064
0.148	0.124
0.088	0.086

Supplementary Table 5.2. Smallest worthwhile change between-session data during linear sprint.

Smallest Worthwhile Change	
Session	Session
2-1	3-2
54.7 m Linear Sprint	
0.038	0.038
0.064	0.062
0.086	0.092
0.12	0.126
0.10	0.106
0.138	0.12
0.132	0.14
0.154	0.174

Supplementary Table 11.1. Retained curvilinear GNSS variables across POST and 2POST, including within-group % change (ES) and between-group differences in change. Secondary time/velocity p-values are Holm-adjusted.

Variable	Group	POST	2POST	Within-group POST–2POST %Δ (ES)	Between-group POST–2POST WRT–CON %Δ (ES)
Parametric variables					
Home-to-second-base time (s)	CON	8.84 ± 0.48	8.94 ± 0.47	1.14 (0.19)	-0.12 (-0.02)
	WRT	8.54 ± 0.22	8.62 ± 0.36	1.03 (0.29)	
First-to-second-base time (s)	CON	4.04 ± 0.25	4.09 ± 0.29	1.64 (0.23)	0.39 (0.08)
	WRT	3.87 ± 0.11	3.94 ± 0.25	2.03 (0.41)	
Time to first base (s)	CON	4.81 ± 0.28	4.85 ± 0.23	0.77 (0.12)	-0.54 (-0.13)
	WRT	4.67 ± 0.18	4.68 ± 0.21	0.23 (0.04)	
Curvilinear time to 13.7 m (s)	CON	2.70 ± 0.18	2.70 ± 0.15	0.02 (-0.02)	1.42 (0.32)
	WRT	2.62 ± 0.12	2.65 ± 0.14	1.44 (0.25)	
Curvilinear time to 41.1 m (s)	CON	7.00 ± 0.37	7.04 ± 0.37	0.69 (0.11)	0.04 (0.03)
	WRT	6.76 ± 0.21	6.80 ± 0.31	0.73 (0.18)	
BREr 0-27.4 m	CON	1.05 ± 0.04	1.05 ± 0.04	-0.47 (-0.16)	1.79 (0.41)
	WRT	1.03 ± 0.04	1.04 ± 0.05	1.33 (0.29)	
BREr 27.4-54.7 m	CON	1.16 ± 0.07	1.16 ± 0.03	0.72 (0.10)	2.09 (0.41)
	WRT	1.15 ± 0.06	1.18 ± 0.03	2.82 (0.59)	
Curvilinear velocity at 13.7 m ($m \cdot s^{-1}$)	CON	7.02 ± 0.34	7.06 ± 0.32	0.75 (0.13)	-1.74 (-0.34)
	WRT	7.23 ± 0.35	7.11 ± 0.47	-0.99 (-0.17)	
Velocity at first base ($m \cdot s^{-1}$)	CON	6.68 ± 0.58	6.47 ± 0.64	-2.59 (-0.30)	6.49 (0.81)
	WRT	6.85 ± 0.43	7.03 ± 0.62	3.90 (0.48)	
Curvilinear velocity at 41.1 m ($m \cdot s^{-1}$)	CON	7.16 ± 0.45	7.07 ± 0.37	-1.27 (-0.25)	-0.82 (-0.13)
	WRT	7.36 ± 0.33	7.24 ± 0.48	-2.09 (-0.36)	
Peak velocity before first base ($m \cdot s^{-1}$)	CON	7.38 ± 0.37	7.36 ± 0.34	-0.21 (-0.06)	-0.85 (-0.25)
	WRT	7.57 ± 0.27	7.52 ± 0.35	-1.07 (-0.25)	
	CON	7.32 ± 0.49	7.27 ± 0.41	-0.52 (-0.11)	-0.63 (-0.12)

Peak velocity after first base and before second base (m·s⁻¹)	WRT	7.64 ± 0.30	7.56 ± 0.42	-1.14 (-0.23)	
Peak curvilinear velocity (m·s⁻¹)	CON	7.46 ± 0.40	7.43 ± 0.34	-0.27 (-0.07)	-0.63 (-0.17)
	WRT	7.69 ± 0.30	7.65 ± 0.38	-0.90 (-0.20)	
Minimum velocity between peaks (m·s⁻¹)	CON	6.26 ± 0.59	6.17 ± 0.67	-1.38 (-0.15)	3.11 (0.31)
	WRT	6.55 ± 0.47	6.62 ± 0.64	1.73 (0.15)	

Non-parametric variables

Variable	Group	POST median [IQR]	2POST median [IQR]	POST–2POST %Δ ($r_{rb,paired}$)	POST–2POST WRT–CON %Δ ($r_{rb,ind}$)
BREr 0-54.7 m	CON	1.09 [1.07, 1.13]	1.10 [1.07, 1.11]	0.05 (0.05)	1.96 (0.17)
	WRT	1.07 [1.06, 1.09]	1.10 [1.08, 1.12]	2.00 (0.78)*	
Velocity at second base (m·s⁻¹)	CON	6.85 [6.71, 6.92]	6.57 [6.24, 7.04]	-2.60 (-0.36)	-0.36 (0.12)
	WRT	7.07 [6.88, 7.28]	6.99 [6.41, 7.33]	-2.96 (0.02)	

Note. POST–2POST analyses included 12 CON and 10 WRT participants. Session descriptives are reported as mean ± SD for parametric variables and median [IQR] for nonparametric variables. Within-group entries are presented as percentage change with effect size, expressed as Cohen's d_{av} for parametric variables and matched-pairs rank-biserial correlation ($r_{rb,paired}$) for nonparametric variables. Between-group entries are presented as the WRT–CON difference in percentage change with effect size, expressed as Cohen's $d$on change scores for parametric variables and independent-samples rank-biserial correlation ($r_{rb,ind}$) for nonparametric variables. Secondary time/velocity p-values are Holm-adjusted; home-to-second-base time is reported using the nominal p-value. Significance symbols indicate the contrast-specific p value: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$. POST = end of the 8-week training cycle; 2POST = 2 weeks post-training.

Appendix 4. Consent and assent forms to participate in Chapters 5-7



Consent Form

Project title: Determining the reliability of GPS and foot-pod technology for measuring base running

Project Supervisor: John B. Cronin

Researcher: José Antonio Martínez-Rodríguez

- O I have read and understood the information provided about this research project in the Information Sheet dated 4 April 2024.
- O I understand that all original documents will be scanned and saved to One Drive and the paper copies shredded.
- O I have had an opportunity to ask questions and to have them answered.
- O I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.
- O I understand that if I withdraw from the study then I will be offered the choice between having any data or tissue that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.
- O I agree to take part in this research.
- O I wish to receive a summary of the research findings (please tick one): YesO NoO
- O I wish to receive a copy of my individual results (please tick one): YesO NoO

Parent's signature: .....

Parent's name: .....

Participant's Contact Details (if appropriate):

.....

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.....

.....

Date:

Approved by the Auckland University of Technology Ethics Committee on 31 May 2024, AUTEC Reference number 24/69

Note: The Participant should retain a copy of this form.

Assent Form

Project title: Determining the reliability of GPS and foot-pod technology for measuring base running

Project Supervisor: John B. Cronin

Researcher: José Antonio Martínez-Rodríguez

- ○ I have read and understood the sheet telling me what will happen in this study and why it is important.
- ○ I have been able to ask questions and to have them answered.
- ○ I understand that data will be collected during the testing and used for analysis.
- ○ I understand that I can stop being part of this study whenever I want and that it is perfectly ok for me to do this.
- ○ If I stop being part of the study, I understand that then I will be offered the choice between having any information that other people can know is about me removed or letting the researcher keep using it. I also understand that sometimes, if the results of the research have been written, some information about me may not be able to be removed.
- ○ I agree to take part in this research.
- ○ I wish to receive a copy of my individual results (please tick one): Yes○ No○

Participant's signature: .....

Participant's name: .....

Participant Contact Details (if appropriate):

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Date:

Approved by the Auckland University of Technology Ethics Committee on 31 May 24 AUTEC Reference number 24/69

Note: The Participant should retain a copy of this form.

Appendix 5. Consent and assent forms to participate in training study



Consent Form

Project title: The effect of wearable resistance training on base running efficiency in baseball players

Project Supervisor: John B. Cronin

Researcher: José Antonio Martínez-Rodríguez

- ○ I have read and understood the information provided about this research project in the Information Sheet dated August 2024.
- ○ I have had an opportunity to ask questions and to have them answered.
- ○ I understand that data will be collected during the testing and used for analysis.
- ○ I understand that taking part in this study is voluntary (my choice) and that I may withdraw my child/children and/or myself from the study at any time without being disadvantaged in any way.
- ○ I understand that if I withdraw my child/children and/or myself from the study then I will be offered the choice between having any data that is identifiable as belonging to my child/children and/or myself removed or allowing it to continue to be used. However, once the findings have been produced, removal of our data may not be possible.
- ○ I agree to my child/children taking part in this research.
- ○ I understand that my child is able to refuse to give assent to take part in this research.
- ○ I wish to receive a summary of the research findings (please tick one): Yes○ No○

Child/children's name/s: .....

.....

Parent/Guardian's signature: .....

Parent/Guardian's name: .....

Parent/Guardian's Contact Details (if appropriate):

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Date:

Approved by the Auckland University of Technology Ethics Committee on 14 February 2025, AUTEC Reference number 24/267

Note: The Participant should retain a copy of this form.

Assent Form

Project title:

The effect of wearable resistance training on base running efficiency in baseball players

Project Supervisor: John B. Cronin

Researcher: José Antonio Martínez-Rodríguez

- ○ I have read and understood the sheet telling me what will happen in this study and why it is important.
- ○ I am a male high school baseball position player between the ages of 14 and 18 years free of injury
- ○ I have been able to ask questions and to have them answered.
- ○ I understand that data will be collected during the testing and used for analysis.
- ○ I understand that I can stop being part of this study whenever I want and that it is perfectly ok for me to do this.
- ○ If I stop being part of the study, I understand that then I will be offered the choice between having any information that other people can know is about me removed or letting the researcher keep using it. I also understand that sometimes, if the results of the research have been written, some information about me may not be able to be removed.
- ○ I agree to take part in this research.
- ○ I wish to receive a copy of my individual results (please tick one): Yes○ No○

Participant's signature: .....

Participant's name: .....

Participant Contact Details (if appropriate):

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Date:

Approved by the Auckland University of Technology Ethics Committee on 14 February 2025, AUTEC Reference number 24/267

Note: The Participant should retain a copy of this form.

Appendix 6. Participant informational sheet for chapters 5–7

Date Information Sheet Produced:

2nd April 2024

Project Title

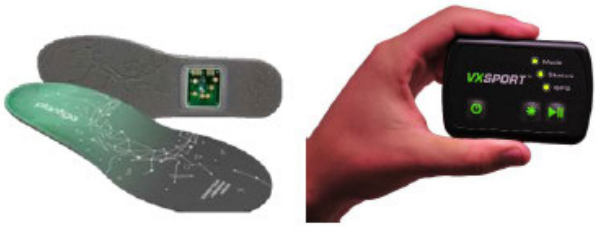
Determining the reliability of GPS and foot-pod technology for measuring base running

I'm José A. Martínez-Rodríguez, a professional affiliated with Zonactiva Kids. I am a doctoral student at Auckland University of Technology, New Zealand, conducting a research project titled "Determining the reliability of GPS and foot-pod technology for measuring base running." I invite you to take part in this study, aiming to determine the reliability of GPS and foot-pod technology for measuring base running.

The baseline and testing assessments involve these specific tests:

- Straight Line Speed Test over 60 yards
- Curvilinear Abilities Test (CAT) – a change of direction test with cones
- Base Running Test – sprinting from home plate to second base

The study involves attending four sections, one for familiarization and three for testing. Testing sessions are spaced seven days apart. After being familiarized, athletes are expected to provide maximum effort. Specialized technology will track your movement. One is a GPS sensor (https://www.vxsport.com/) worn on your upper back inside a vest and placed by the primary researcher, José A. Martínez-Rodríguez, that captures your location and evaluates the speed and how speed changes (see pictures). The second technology is an inertial insole (https://plantiga.com/), which looks at motion characteristics and other measures involving the foot with the ground and displacement of the body (see picture).



Your participation is voluntary, requires both your signature and the signature of a legal guardian, such as a parent. You may withdraw at any time before completing the data collection. To be eligible, you must be free of injury and actively participating in training and competition. However, you are not eligible if you are not participating in training and competition, history of injury that would affect running performance, and if you have a relationship with the primary researcher, José A. Martínez-Rodríguez.

Data collected will be deidentified and used for research publications and academic presentations. All data will be de-identified, meaning no one will know your identity other than the researchers, and all data will be safely stored with privacy measures for data storage.

The assessments have no cost associated and due to scheduling, we kindly ask that you provide us with your decision to enter the study in two weeks from receipt of this invitation. You may also remove yourself from the study at any time without any penalty whatsoever.

For further information, please contact Dr. John B. Cronin or me, who is my primary PhD advisor.

Thank you for considering this opportunity.

What is the purpose of this research?

The purpose of this research is to determine the reliability of GPS and foot-pod technology for measuring base running (e.g., CAT, base running, and straight-line sprint). The reliability of each device will be determined across three testing sessions separated by seven days. The findings of this research will be presented through a doctoral thesis for the primary researcher, José, as well as conference presentations and academic publications.

How was I identified and why am I being invited to participate in this research?

You were identified for this project because you are a high school male baseball player aged 14-18, free of injury, and participating in full training and competition at the time of testing. Since you meet these criteria, we would like to invite you to participate in the research. You came to receive the information sheet because you saw the flyer advertisement or after the meeting with you, staff, and parents, you were interested in more detailed information about the project for your consideration.

How do I agree to participate in this research?

If you agree to voluntarily participate in this study, please complete and sign the attached consent form. This form will be collected in person prior to testing.

Your participation in this research is voluntary, and you can withdraw from the study at any time. If you choose to withdraw from the study, you will be offered the choice of having any data belonging to you removed from the study. However, removal of any data will not be possible once the findings have been published. All data will be protected by a special code to identify you rather than any names to protect your identity.

What will happen in this research?

- The research will take place at the baseball park of your baseball academy for three consecutive days of the week separated by seven days, starting July 1st.
- You will provide age, position, batting side, height, and body weight.
- You will be familiarised with all tests (CAT, maximum straight-line sprinting, and base running) prior to full speed.
- Testing is approximately 55 minutes for each session (3), approximately 13 minutes per testing section plus warm-up.

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- Three minutes of passive rest between trials and 10 minutes of passive rest between tests to limit performance fluctuations resulting from fatigue and decrease the risk of injury.
- You will have 7 days rest between testing sessions.
- 5-min warm-up jogging, 8-minute dynamic stretching of lower limbs and at least four practices runs at submaximal to maximal effort i.e.. 50, 75, 85, 100% effort.
- Two trials will be collected, which will be averaged and analysed
- You will use metal or plastic cleats for grass/dirt and turf baseball surfaces.
- Each testing session is comprised of:

Section 1: Maximum Linear Sprint (60 yards [i.e., same distance from home to second base])

You will start when you are ready and will run at full speed on 60-yard in a straight line, using metal or plastic cleats for grass/dirt and turf baseball surfaces.

Section 2: Curvilinear Ability Test Procedures

You will initiate a movement with a drop/jab step with the right foot followed by a cross-over step, running towards cone number two in a curvilinear movement. You then touch cone number two with the right hand and quickly perform a change of direction towards cone number three, touch it with the left hand, and finally perform a change of direction and sprint past cone number four. The opposite hand should not touch the ground while the player touches the cone.

Section 3: Base Running Sprint

From a position similar to the CAT's starting position, you will start when ready and run at full speed from home to the second base, rounding the first base, as you do when running multiple bases during the game.

What are the discomforts and risks?

This testing will involve the same amount of discomfort and risk typically experienced in normal sprinting; therefore, no discomfort or risks are associated with it. Potential risks are rare, but muscle strains, ligament sprains, and joint injuries are possible. The research team will ensure that any potential risks associated with your research participation are minimized.

How will these discomforts and risks be alleviated?

Researchers in this study will safeguard the athlete at all costs, ensuring that the athletes are familiarised prior to testing sessions and that scheduling of testing sessions will be at the discretion of the athletes' coaching staff to ensure that recovery is ample to be able to put forth maximum effort for testing. In this manner, testing will not occur before or after competitive games and will not be conducted after practices. However, testing can be scheduled before practices to minimize fatigue risks. Athletes will not be tested in wet conditions, and prior to setting the sprint course, the researcher will extensively evaluate the location where testing will occur to remove potential hazards from the testing environment.

What are the benefits?

Your benefit from receiving detailed information about their sprinting ability in short linear and curvilinear testing, straight-line speed, and base running performance. This information can help assist coaches in designing more specific programming to work on. A measure called base running efficiency will be measured, which looks at speed in a straight line in relation to base running speed characteristics. The calculation

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indicating speed differences will inform players if they need more base running than straight-line speed training to optimize their scoring chances.

What compensation is available for injury or negligence?

It is not anticipated that this research would cause any discomfort beyond those described above; however, should you sustain an injury because of the research, you should contact the research project supervisor, Dr. John Cronin. Your injury will be assessed, and you will be referred for relevant medical assessment and, if needed, treatment. There is no monetary compensation for this research. You are undertaking this study voluntarily and understand the associated risks.

How will my privacy be protected?

- The data from the project is confidential and will be coded and held in secured storage device under the responsibility of the principal investigator of the study in accordance with the requirements of the New Zealand Privacy Act (2020). This includes password protection for accessing the data.
- All references to you will be by code number; the publications will only contain an average of the group's results. Identification information will be stored on a separate file and Onedrive from that containing the actual data. Only the investigators will have access to computerised data obtained from you to maintain confidentiality.
- The results from this research, including the de-identified test results (i.e., without your associated name and personal details), will be stored indefinitely in the Sport Performance Research Institute New Zealand research database.
- The de-identified findings of this project will be published as a dissertation thesis that is required for the lead researcher in earning his doctoral degree, while findings will be presented in scientific journals and at conferences. Your identifiable test results will only be made available to yourself, and should you choose, you may share your data with your sports coaches, manager, or any other individual you feel is part of your performance team.

What are the costs of participating in this research?

There are no costs associated with this research. Participating in this research will not cost you. The testing sessions will be performed prior to your regular training sessions, and scheduling for testing sessions will be determined by your coaching staff. Testing is approximately 55 minutes for each testing session (3), approximately 13 minutes per testing section plus warm-up. The total time cost will be 165 minutes for the three sessions plus familiarisation session.

What opportunity do I have to consider this invitation?

- Due to in-season scheduling, you have up to 2 weeks to consider participation from the time of receiving this informational document. Please reach out to the lead researcher below for any questions you may have about anything mentioned in this information sheet.
- As mentioned, this research is completely voluntary, and you are healthy and injury-free, 14 to 18 years of age.
- You may withdraw from the study at any time without any adverse consequences of any kind.
- You may request a copy of your results at any time, and you can also request a report of the research outcomes at the completion of the study.

Approved by the Auckland University of Technology Ethics Committee on *31 May 2024,* AUTEC Reference number *24/69*.

Appendix 7. Participant information sheet for chapters 8 and 9

Date Information Sheet Produced:

August 2024

Project Title

The effect of wearable resistance training on base running efficiency in baseball players

An invitation

My name is José A. Martínez-Rodríguez, a professional affiliated with Zonactiva Kids. I am a PhD student at Auckland University of Technology (AUT), New Zealand, conducting a research project titled "The effect of wearable resistance training on base running efficiency in baseball players" I invite you to take part in this study, aiming to determine the long-term effects of external loading to the calf using a new sport technology called Exogen™ exoskeleton (see photo below) on base running efficiency. Your participation in this study would be greatly valued but is entirely voluntary. If you choose to participate in this study, you may withdraw at any time, prior to the completion of the data collection. To be eligible to participate in this study, you must be: 1) a male position player between the ages of 14 – 18 years; 2) healthy and free of injury that would affect jumping and running performance; and 3) currently participating in training and competition at a high school level Exclusion criteria for your participation in this study include if you are under the age of 14 or over the age of 18, if you have a relationship with the primary researcher, a history of injury that would affect jumping and running performance, if you are not actively participating in training and competition, or if you are in the pitcher position



Information gained from this research will be presented in a way so that your name and personal details remain confidential (i.e., deidentified averaged data). The results of the study will be provided in the form of journal or thesis publications and/or conference presentations. Your legal guardian consent and your assent to participate in this research will be indicated by your signing and dating the accompanying consent and assent form. Your legal guardian signing the consent and you signing the assent form indicates that your legal guardian and you have read and understood this information sheet, freely give your legal guardian consent and your assent to participate, and that there has been no coercion or inducement to participate.

For further information, please contact Dr. John B. Cronin or me, who is my primary PhD advisor and mentor.

Thank you for considering this opportunity.

What is the purpose of this research?

The purpose of this research is to understand whether wearing the Exogen™ calf improves base running efficiency (i.e., home to second base, and straight-line sprint), change of direction (e.g., CAT), jumping, and lower-body strength. Exogen™ exoskeletons include calf sleeves, which are small (approximately 19 cm long) loads of 200 - 600g and can be attached with Velcro. This research will measure the effects of training with wearable resistance attached to the calf on linear and curvilinear movements. Curvilinear Ability Test, home to second base, and straight-line sprint test will be measured using Plantiga insole foot pods and VX Sport GPS (see pictures below), jumps will be measured using Plantiga insole foot pods, while strength will be measured using TruStrength Tech (see picture below). The findings of this research will be used for the thesis of the primary researcher, Jose, conference presentation(s), and academic publication(s).



The description of tests that will take place are all described as followed:

Base Running Sprint –maximal sprint from home to second base.

Straight-line Sprint Test (60 yards) - the same distance as the home to second base test.

Cyclic Jumps – 20 consecutive countermovement jumps.

Single-leg Jump for Distance Test - five (5) consecutive countermovement jumps on one leg whilst trying to maximize distance while controlling the landing.

Single-leg Jumps for Distance Test - one countermovement jumps on one leg whilst trying to maximize distance while controlling the landing.

Isometric Mid-Thigh Pull – one (1) maximal pull of static contraction of the muscles without any visible movement in the hip

How was I identified and why am I being invited to participate in this research?

Approved by the Auckland University of Technology Ethics Committee on *14 February 2025*, *AUTEC Reference number 24/267*

You were identified for this project because you are currently training and competing with the Carlos Beltran Baseball Academy and through both the academy and coaches, you have been identified as possible candidates to take part in the research. You are a high school male baseball position player aged 14-18, free of injury, participating in full training and competition at the time of testing, and you have no relationship with the primary researcher. Since you meet these criteria, we invite you to participate in the research. You came to receive the information sheet because you receive an email with the flyer advertisement, informational sheet, and consent and assent form, or after the project presentation with you and the staff, that the primary researcher (Jose) remind all the presents to verify the emails for more detailed information about the project for your consideration.

How do I agree to participate in this research?

If you agree to voluntarily participate in this study, please complete and sign the attached consent form. This form will be collected in person prior to testing. Your participation in this research is voluntary (it is your choice), whether or not you choose to participate will neither advantage nor disadvantage you. You can withdraw from the study at any time. If you choose to withdraw from the study, you will be offered the choice between removing any data that belongs to you or allowing it to continue to be used. However, removing any data will not be possible once the findings have been published. A special code will protect all data to identify you rather than any names to protect your identity.

What will happen in this research?

As part of this study, you will provide current age, height, body weight, batting side, and position.

If you choose to participate in the training study, you will be required to complete four testing sessions, as well as 16 to 24 training sessions (see Tables 1 and 3) in the Carlos Beltran Baseball Academy baseball field during the time of your normal training session.

You will complete a standardized warm-up prior to all testing, and you will have a recovery period of at least two minutes before each maximal effort test. Following the standardized warm-up, you will complete a series of performance tests: home to second base, straight-line sprint, three jump modalities, and a lower-body strength test. Tests will not be more physically demanding than you will already undergo during your regular training sessions. Additionally, if requested, you will have access to your performance data, to help inform your level of performance coming into the baseball season.

Upon completion of the pre-intervention testing session, yet prior to the start of the intervention, you will be matched based on your base running efficiency, and randomly assigned to the control and wearable resistance groups. The control group will do the normal warm-up and training without any additional load, while the calf-loaded groups will do the normal warm-up and training with additional weights on their arms and legs, respectively. See the Table below for the periodized training plan for each experimental group.

Long-term effects of shank-loaded WR on base running performance

The pre-intervention testing session will provide you, the participant, with a briefing on the study procedures, and your characteristics (i.e., age, height, body weight, batting side, and position) will be collected. Depending on the test run interspersed with dynamic lower-body stretching, you will perform a standardized warmup consisting of submaximal jumps, progressive sprints, and COD drills. The four testing sessions (i.e., pre-, mid-, post-, and 2-week post-training) will include the following tests: home to second base, straight-line sprint, cyclic jump, single leg jump for distance, single leg jump RSI test, and isometric mid-thigh pull test

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Table 1. The four-session testing plan, including sets, reps, and time commitment by session and total.

Phases	Testing plan			
	Tests	Sets of test rep	Rest between sets	Total time commitment per week
Pre-training (pre-intervention)	Isometric Mid-Thigh Pull	3	2 minutes	~ 5 minutes
	Jump tests (x3)	2	30 seconds	~ 15 minutes
	Sprint tests (x2)	2	3 minutes	~30 minutes
			Total time commitment	~ 50 minutes
Mid-training (mid-training block)	Isometric Mid-Thigh Pull	3	2 minutes	~ 5 minutes
	Jump tests	2	30 seconds	~ 15 minutes
	Sprint tests	2	3 minutes	~30 minutes
			Total time commitment	~ 50 minutes
Post-training (end of training block)	Isometric Mid-Thigh Pull	3	2 minutes	~ 5 minutes
	Jump tests	2	30 seconds	~ 15 minutes
	Sprint tests	2	3 minutes	~30 minutes
			Total time commitment	~ 50 minutes
2 weeks post-training (2-weeks post-training)	Isometric Mid-Thigh Pull	3	2 minutes	~ 5 minutes
	Jump tests	2	30 seconds	~ 15 minutes
	Sprint tests	2	3 minutes	~30 minutes
			Total time commitment	~ 50 minutes
			Total commitment time for the testing plan, which will take place within your training period	~200 minutes (3.2 hours)

The training intervention will occur during the 8 weeks between pre- and post-intervention testing (see Table 2). All groups will continue with their typical training schedule, which will be accounted for by recording it in training diaries. The control and WR groups will perform their normal standardized baseball warm-up, with a few modifications (see Table 3). However, only those participating in the WR group will perform the warm-ups with WR on the shank.

Table 2. Eight-week COD training plan, including the loading scheme for wearable resistance and the time commitment per week and total.

Week	Training plan				
	Training frequency per week	Sets x reps x distance	Rest between reps (mins)	Total time commitment per week	Load(g) -placement
1	2 – 3 times	1 x 6 x 20.1 m (curvilinear) 1 x 5 x 32.9 m (curvilinear + 180° COD) Total distance 285 m	2 - 3	~ 70 to 105 minutes per week	200 g, posterior, calf
2	2 – 3 times	1 x 7 x 20.1 m (curvilinear) 1 x 5 x 32.9 m (curvilinear + 180° COD) Total distance 305.1 m	2 - 3	~ 74 to 111 minutes per week	200 g, posterior, calf
3	2 – 3 times	1 x 7 x 20.1 m (curvilinear) 1 x 6 x 32.9 m (curvilinear + 180° COD) Total distance 338 m	2 - 3	~80 to 120 minutes per week	400 g, posterior, calf
4*	Testing Offloading Week – 1 session	1 x 7 x 20.1 m (curvilinear) 1 x 6 x 32.9 m (curvilinear + 180° COD) Total distance 338 m	2 - 3	~80 to 120 minutes per week	400 g, posterior, calf

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	only after testing				
5	2 – 3 times	1 x 7 x 20.1 m (curvilinear) 1 x 7 x 32.9 m (curvilinear + 180° COD) Total distance 370.9 m	2 - 3	~ 90 to 135 minutes per week	400 g, posterior, calf
6	2 – 3 times	1 x 8 x 20.1 m (curvilinear) 1 x 6 x 32.9 m (curvilinear + 180° COD) Total distance 358.1 m	2 - 3	~ 90 to 135 minutes per week	600 g, posterior, calf
7	2 – 3 times	1 x 8 x 20.1 m (curvilinear) 1 x 5 x 32.9 m (curvilinear + 180° COD) Total distance 325.2 m	2 - 3	~80 to 120 minutes per week	600 g, posterior, calf
8	2 – 3 times	1 x 8 x 20.1 m (curvilinear) 1 x 4 x 32.9 m (curvilinear + 180° COD) Total distance 292.4 m	2 - 3	~ 74 to 111 minutes per week	600 g, posterior, calf
			Total time commitment	~ 638 to 957 minutes (10.5 to 16 hours)	

Table 3. Warm-up exercises – Baseball base running.

Exercises	Distance	Rep	Rest (seconds)	Notes
Linear running	15 yds	2	30	Run to the cone and back
Running hip out	15 yds	2	30	Run to the first cone (5 yards apart), stop, lift knee forwards and rotate the knee out to the side and put your foot down. Repeat for the other leg on each cone. Run to the next cone and repeat.
Butt kicks	15 yds	2	30	Butt kick to the cone and back
Skip	15 yds	2	30	Skip to the cone and back
Lateral shuffles	15 yds	2	30	Lateral shuffle to the cone and back
Quick forwards and backwards	15 yds	2	60	Quick Forwards and Backwards Sprints. Run to the second cone and back to the first cone. Repeat two cones forward one back for the length of 15 yds and back.
Walking Lunges	15 yds	1	30	Standing with feet hip-width apart and hands on hips. Lunge forward and bend your hips and knees to 90-degrees. Keep hips, knees and foot in a straight line.
Linear sprints	15 yds	3	60	Linear sprint to the last cone, increasing the intensity each set. Start at 80% then go to 90% and 100%.

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Curvilinear sprints	15 yds	3	60	Curvilinear sprint rounding the last cone, increasing the intensity each set. Start at 80% then go to 90% and 100%.

What are the discomforts and risks?

No significant discomforts or risks should be associated with this testing beyond those experienced during normal sport testing and training. However, you will likely experience some shortness of breath and perhaps some lower-body muscular soreness in the 48 hours after each testing session. You will be individually fitted and given the same wearable resistance garments on each occasion. Calf (shank) sleeves can be worn either directly on your skin or over your own tight-fitting garments. The suits will be washed between each use.

How will these discomforts and risks be alleviated?

Researchers in this study will safeguard the athlete at all costs, ensuring that the athletes are familiarised prior to testing sessions and that scheduling of testing and training sessions will be at the discretion of the athletes' coaching staff to ensure that recovery is ample to be able to put forth maximum effort for testing and training. In this manner, testing and training will not occur before or after competitive games and will not be conducted after practices. However, testing can be scheduled before practices and training incorporated into practices to minimize fatigue risks. Athletes will not be tested and trained in wet conditions, and prior to setting the sprint course, the researcher will extensively evaluate the location where testing and training will occur to remove potential hazards from the testing environment.

What are the benefits?

You will benefit from being introduced to a new training method (exercise plan and wearable resistance tool). You will also gain insight into your current performance and be exposed to high-level sports performance technology that you do not have access to on a daily basis. You will receive detailed information about your sprinting ability in short linear and curvilinear testing, straight-line speed, base running performance, different jump modalities, and strength. This information can help assist coaches in designing more specific programming to work on. A measure called base running efficiency will be quantified, which looks at speed in a straight line in relation to base running speed characteristics. The calculation indicating speed differences will inform players if they need more base running than straight-line speed training to optimize their scoring chances.

Secondly, this research will benefit the primary researcher (Jose), as it will be included in his PhD thesis and the final study to answer his principal question, "Can base running efficiency be improved in baseball players?"

Lastly, this research will benefit the baseball community, as it will bring new training plans and tools to Puerto Rican baseball coaches, players, and strength coaches. In Puerto Rico, sport science is not well established, and the continued investigation of improving base running ability through research-level methods is limited.

What compensation is available for injury or negligence?

It is not anticipated that this research would cause any discomfort beyond those described above; however, should you sustain an injury because of the research, you should contact the research project supervisor, Dr. John Cronin. Your injury will be assessed and referred to for relevant medical assessment and, if needed, treatment. There is no monetary compensation for this research. You are undertaking this study voluntarily and understand the associated risks. All

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efforts have been made to ensure a safe testing environment and methodology. There is appropriate first aid equipment/facilities, and staff are trained to manage any adverse events during testing.

How will my privacy be protected?

- The data from the project is confidential and will be coded and held in secured storage device under the responsibility of the principal investigator of the study in accordance with the requirements of the New Zealand Privacy Act (2020). This includes password protection for accessing the data.
- All references to you will be by code number; the publications will only contain an average of the group's results. Identification information will be stored on a separate file and Onedrive from that containing the actual data. Only the investigators will have access to computerized data obtained from you to maintain confidentiality.
- The results from this research, including the de-identified test results (i.e., without your associated name and personal details), will be stored indefinitely in the Sport Performance Research Institute New Zealand research database.
- The de-identified findings of this project will be published as a dissertation thesis that is required for the lead researcher in earning his doctoral degree, while findings will be presented in scientific journals and at conferences. Your identifiable test results will only be made available to yourself, and should you choose, you may share your data with your sports coaches, manager, or any other individual you feel is part of your performance team.

What are the costs of participating in this research?

Participating in this research project will not cost you apart from your time, for which we greatly thank you.

You will be required to wear the Exogen exoskeleton with a specified amount of added weight attached. You will be required to complete four testing sessions, as well as 16 to 24 training sessions (see Tables 1 and 3) in the Carlos Beltran Baseball Academy baseball field during the time of your normal training session

What opportunity do I have to consider this invitation?

- Due to in-season scheduling, you have up to 2 weeks to consider participation from the time of receiving this informational document. Please reach out to the lead researcher below for any questions you may have about anything mentioned in this information sheet.
- As mentioned, this research is completely voluntary, and you are healthy and injury-free, 14 to 18 years of age position players with no relationship with the primary researcher.
- You may withdraw from the study at any time without any adverse consequences of any kind.
- You may request a copy of your results at any time, and you can also request a report of the research outcomes at the completion of the study.

Will I receive feedback on the results of this research?

We will provide a summary of the grouped average results via email. If you wish to receive your individual results, please select so on the consent form.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Professor John Cronin, john.cronin@aut.ac.nz.

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Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, *ethics@aut.ac.nz* , (+649) 921 9999 ext 6038.

Whom do I contact for further information about this research?

Please keep this Information Sheet and a copy of the Assent Form for your future reference. You are also able to contact the research team as follows:

Researcher Contact Details:

José A. Martínez-Rodríguez, jose.martinez.rodriguez@autuni.ac.nz

Project Supervisor Contact Details:

Dr. John Cronin, john.cronin@aut.ac.nz

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Appendix 8. Chapter abstracts

Chapter 2: The need for speed: Linear and curvilinear characteristics in major league baseball players

The main aims of this study were to determine: 1) current values of base running key performance indicators related to home-to-first base running and running multiple bases; 2) how KPIs are related to each other; and 3) the descriptive associations of these measures on stealing and running two bases. Data on 475 players across 30 teams was collated from Baseball Savant, Baseball Reference, and Lahman databases for the 2019 to 2023 Major League Baseball (MLB) season, which involved coding 924 player events. The main findings were: a) the averaged base running speed for this sample of MLB players was 8.35 ± 0.39 m.s-1 (27.41 ± 1.27 ft·s^{-1}); b) home-to-first base time averaged 4.41 ± 0.18 s; c) in the first 13.7 m of the run to first base, base runners had achieved 84% of their maximum 27.4 m speed, which was near maximal given the minimal change in acceleration (fourth segment = 0.39 m·s^{-2}); d) the players who stole the most bases had the highest speeds and accelerations; and, e) higher linear speed and acceleration were not observed amongst players who ran two bases. From this data, it could be inferred that traditional linear running measures are important predictors of running single bases; however, other factors seem important for the curvilinear running two bases. It may be that base runners need to be assessed and trained for linear and curvilinear sprint ability rather than assuming that improvement in linear speed via assessment and training, translates to improved multiple base running.

Chapter 3: Introduction to an advanced change of direction test in baseball and softball: The curvilinear ability test

Baseball and softball base running involve appropriate body position and maximal sprinting that may require curvilinear sprinting and subsequent changes of direction depending on the situational context. Traditionally, the pro-agility test has been used in baseball and softball to evaluate agility performance. When evaluating the specific tests that could be used to record CODS time in base running, it is advised to record not only the total time to complete the test, but to record the time to complete each running segment as this will provide greater information about the CODS strengths and weaknesses for each athlete. Furthermore, it is important to consider whether an additional test integrating curvilinear and CODS characteristics to simulate base running provides further objective data to evaluate base running ability. This article introduces a new field assessment called the CAT that measures both curvilinear and CODS

properties in base running. The CAT is believed to provide greater assessment value versus the pro-agility and 505 agility tests in evaluating base running ability.

Chapter 4: Improving base running in baseball: A linear-curvilinear perspective

Base running substantially contributes to offensive performance and team success. Therefore, improving players' linear and curvilinear base running abilities is critical to win more games and competitions. Performance science investigating the biomechanics of base running is scarce with minimal understanding how to efficiently run multiple bases. As a result, this article explored the following; 1) review the literature identifying the technical demands associated with curvilinear running and how these might differ from linear running; 2) identify in-field technology that may provide greater diagnostic insight into determinants of efficacy for various training methods to optimize base running ability; and, 3) detail training methods currently used for curvilinear sprint training and suggest more effective options. A clear gap has emerged for baseball as existing evidence must be derived from studies on track and soccer athletes. Based on the current state of the literature, it is necessary to evaluate understanding of foot-ankle complex mechanics, muscular output by the lower limbs, and distinct functions of the inside and outside leg providing valuable frameworks for analysing curvilinear running mechanics.

Chapter 5: Between-session reliability of GNSS technology for quantifying linear and curvilinear base running performance

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 GNSS 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 CV of 10%, with the majority (93%) of the CVs under 5%. With regard to relative consistency, 66% of the measures had ICCs greater than 0.74, ranging from 0.76 to 0.98. Comparison of 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.

Chapter 6: New perspectives on analysing and interpreting base running efficiency: A GNSS approach

Base running performance in baseball depends on the ability to efficiently transition between linear and curvilinear sprinting; however, current assessment approaches provide limited insight into how speed is developed, maintained, or lost across these phases. This perspective presents a methodological framework for using GNSS technology to enhance the analysis and interpretation of base running performance through segment-specific velocity and time diagnostics. GNSS data were collected during 54.7 m linear sprints and home-to-second-base curvilinear sprints in three high-school baseball players with differing performance profiles. Sprint paths were divided into standardized linear (L1–L4) and curvilinear (C1–C4) segments, allowing examination of speed changes between successive phases to identify acceleration, maintenance, and deceleration patterns. Comparative case analyses illustrate how athletes differ in their ability to negotiate the curve around first base, reaccelerate toward second base, and maintain speed under increasing curvilinear demands. In addition, a BREr is introduced to quantify how effectively linear sprint capacity is preserved during curvilinear base running, both globally and across early and late phases of the sprint. The three players' data illustrated that GPS-derived velocity–time profiles may provide useful insights into individual running strategies, path selection, and segment-specific performance limitations that are not captured by traditional timing methods. Rather than establishing normative benchmarks, this paper emphasizes the applied value of GNSS technology as a diagnostic tool to potentially inform individualized assessment and monitoring in applied settings related to linear and curvilinear sprint performance in baseball.

Chapter 7: Improving base running diagnostics with foot pod technology: Intersession reliability of linear and curvilinear running performance

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. GCT, SL, and average push-off and

impact were quantified using IMU 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.

Chapter 8: New perspectives on analysing and interpreting base running efficiency: An IMU foot pod methodological case approach

The article presents a practical framework for implementing, collecting, and IMU foot pod data to improve diagnostic understanding of baseball base running mechanics. Linear sprinting is used as a baseline, whereas the home-to-second base sprint trial is used to examine how that capacity is expressed when athletes negotiate curvilinear running demands. The purpose is not to establish generalized performance outcomes, but to illustrate how IMU-derived spatiotemporal variables may be interpreted across successive base running segments in applied settings. Three competitive baseball players were selected from a larger dataset of n = 54 base runners tested using the same protocol with distinct home-to-second-base performance profiles: the fastest case (Player X), an intermediate case (Player Y), and the slowest case (Player Z) were selected based on total home-to-second-base time. The cases were selected purposively to demonstrate the application of the IMU interpretation framework, including GCT, SL, push-off acceleration, and impact acceleration. Particular emphasis is placed on how curvilinear demands alter inside- and outside-foot function, and how segment-to-segment comparisons may help practitioners identify phases in which base runners maintain, reorganize, or lose mechanical efficiency. Compared with broader velocity-based approaches, the IMU framework provides complementary step-level information that may help practitioners generate hypotheses about how base runners organize movement across linear and curvilinear segments. These examples are intended to demonstrate a workflow for applied interpretation rather than to establish causal mechanisms. As a result, IMU foot pod analysis may offer practitioners a

structured and portable method for interpreting curvilinear sprint mechanics, yet these case examples should be understood as descriptive rather than prescriptive.

Chapter 9: Functional asymmetries in inside-outside foot mechanics when curvilinear sprinting in baseball

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. GCT, 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.

Chapter 10: Base running responses to calf-loaded wearable resistance in baseball: A case study comparison of two versus three sessions per week

The purpose of this study was to compare training frequency responses of two male high school base runners to the same calf-loaded wearable resistance (WR) intervention performed either two or three sessions per week. The case study design had three initial testing sessions to define the baseline and three follow-up testing sessions: mid training (MID), post training (POST), and 2-week post training (2POST) testing sessions. Performance changes were interpreted primarily using a baseline mean ± 2 standard-deviation (SD) band approach. For each subject, the mean and SD from the three initial testing sessions were used to define the individual players reference baseline ± 2 SD, and MID, POST, and 2POST values falling outside this band were interpreted as substantial/meaningful deviations from normal baseline variability. The subject training three times per week (S3wk) had meaningful faster first-to-second-base segment time (4.05 s vs. 3.65 s; −9.86%; ES = −2.69), and faster home-to-second-base time (8.65 s vs. 8.30 s; −4.02%; ES = −2.65), relative to baseline at 2POST. In contrast, meaningful responses were observed for the subject training twice per week (S2wk) in some variables at MID and POST, but these

adaptations were not retained at 2POST. Calf-loaded WR performed 3 sessions per week may promote longer lasting adaptations when incorporated into baseball-specific curvilinear sprint training versus 2 sessions per week, yet this interpretation at present is exploratory and must be confirmed adequately powered studies.

Chapter 11: Training the curve: Calf-loaded wearable resistance sprint training altered pattern of adaptation in base running performance in high-school baseball players

The purpose of this study was to quantify the effects of an 8-week baseball-specific sprint-training intervention performed with calf-loaded wearable resistance (WR) on base running performance in high-school baseball players. Twenty-five male high-school position players aged 14–18 years were matched according to home-to-second-base time and allocated to either a WR training group (WRT; n = 12) or an unloaded control group (CON; n = 13). Both groups completed the same field-based linear and curvilinear sprint-training program three times per week for 8 weeks, with WRT wearing 200–600-g calf loads during the intervention activities. Three planned contrasts were examined: baseline to mid-training (BASE–MID), baseline to post-training (BASE–POST), and baseline to 2 weeks post-training (BASE–2POST). Outcomes were interpreted using statistical significance and prespecified thresholds for practical relevance. From BASE to MID, CON demonstrated four and WRT three practically relevant curvilinear changes, improving base running efficiency ratio (BREr) over 0–27.4 m and 0–54.7 m and increased velocity at second base. From BASE to POST, WRT demonstrated 10 practically relevant curvilinear changes compared with five in CON. From BASE to 2POST, WRT improved home-to-second-base time by 3.57% ($d = -0.64$, $p = 0.022$) and increased minimum velocity between peaks by 8.26% ($d = 0.68$); the corresponding between-group effect for minimum velocity favored WRT (WRT–CON = 9.25%; $d = 0.67$). The effect-size distribution indicated a phase-specific WRT response, with the clearest most important applied findings at 2POST comprising improved home-to-second-base performance within WRT and a WRT-favoring effect for preservation of velocity while negotiating the curve.

Appendix 9. Supplementary Statistical Reanalysis of Chapter 2

To account for repeated observations within individual players, a supplementary linear mixed-effects analysis was undertaken using the original retrospective MLB dataset from the 2019–2023 seasons. Ten continuous running outcomes were analysed separately: speed and segmented acceleration at 4.6, 9.1, 13.7, and 27.4 m, home-to-first-base time, and base running sprint speed. Each model included stolen bases, doubles, age, log-transformed plate appearances, season (categorical), and playing position (categorical) as fixed effects, together with a random intercept for player identification number. Stolen bases and doubles were divided by 10 only to express regression coefficients per 10 additional recorded events.

Linear mixed-effects models were fitted using maximum likelihood estimation, assuming normally distributed conditional residuals (Gaussian errors). Regression coefficients (β) represented adjusted associations between seasonal stolen-base and doubles counts and each running-performance outcome, accounting for the remaining fixed-effect covariates and player-specific random intercepts. Although the player-specific random intercept accounted for repeated observations within players, some player–season combinations contributed multiple records, and additional dependence within those combinations was not modelled separately. Statistical inference was based on two-sided Wald tests using the standard normal approximation, with 95% confidence intervals calculated as $\beta \pm 1.96 \times SE$. To account for multiple comparisons across the ten running-performance outcomes, p-values were adjusted separately for the stolen-base and doubles coefficient families using the Benjamini–Hochberg false discovery rate (FDR) procedure. Adjusted p-values were reported as q-values, with statistical significance assessed at $q < 0.05$. Model-based intraclass correlation coefficients (ICCs) were calculated as the ratio of the player-level random-intercept variance to the sum of the player-level and residual variances. Across the ten models, ICCs ranged from 0.65 to 0.90, indicating that 65–90% of the unexplained variation in running performance was attributable to differences between individual players after accounting for the model covariates. This suggests that repeated observations from the same player tended to be more similar than observations from different players, supporting the inclusion of a player-specific random intercept to account for within-player correlation.

Appendix Table 9.1. Linear mixed-effects model estimates of the associations between seasonal stolen-base and doubles counts and running-performance outcomes

Running outcome	Stolen bases (per 10)			Doubles (per 10)		
	β [95% CI]	p	q	β [95% CI]	p	q
Home-to-first time (s)	-0.0396 [-0.0493, -0.0300]	<0.001	<0.001	-0.0110 [-0.0200, -0.0020]	0.016	0.161
Base running speed ($m \cdot s^{-1}$)	+0.0835 [+0.0623, +0.1047]	<0.001	<0.001	+0.0147 [-0.0049, +0.0343]	0.141	0.235
4.6 m Speed ($m \cdot s^{-1}$)	+0.0346 [+0.0253, +0.0439]	<0.001	<0.001	+0.0011 [-0.0093, +0.0115]	0.831	0.835
9.1 m Speed ($m \cdot s^{-1}$)	+0.0438 [+0.0334, +0.0542]	<0.001	<0.001	+0.0050 [-0.0057, +0.0157]	0.361	0.451
13.7 m Speed ($m \cdot s^{-1}$)	+0.0492 [+0.0379, +0.0606]	<0.001	<0.001	+0.0072 [-0.0038, +0.0183]	0.201	0.287
27.4 m Speed ($m \cdot s^{-1}$)	+0.0591 [+0.0455, +0.0726]	<0.001	<0.001	+0.0133 [+0.0008, +0.0258]	0.037	0.186
0–4.6 m Acceleration ($m \cdot s^{-2}$)	+0.0630 [+0.0463, +0.0797]	<0.001	<0.001	+0.0020 [-0.0166, +0.0206]	0.835	0.835
4.6–9.1 m Acceleration ($m \cdot s^{-2}$)	+0.0347 [+0.0268, +0.0426]	<0.001	<0.001	+0.0068 [-0.0012, +0.0147]	0.094	0.235
9.1–13.7 m Acceleration ($m \cdot s^{-2}$)	+0.0291 [+0.0224, +0.0359]	<0.001	<0.001	+0.0055 [-0.0013, +0.0123]	0.114	0.235
22.8–27.4 m Acceleration ($m \cdot s^{-2}$)	+0.0221 [+0.0136, +0.0307]	<0.001	<0.001	+0.0071 [-0.0023, +0.0165]	0.139	0.235

Note. β denotes an adjusted fixed-effect estimate per 10 additional stolen bases or doubles; CI, 95% Wald confidence interval; p, unadjusted two-sided Wald p-value; q, Benjamini–Hochberg FDR-adjusted p-value over 10 outcomes within each predictor family.

Appendix 9.1 Results

Greater stolen base totals were significantly associated ($q < 0.001$) with higher base running speed, shorter home-to-first-base time, and faster segment-specific speed and acceleration measures. However, no significant association ($q > 0.05$) were identified between doubles and base running speed, home-to-first-base time, and segment-specific speed and acceleration measures.

Appendix 9.2 Conclusion

The adjusted linear mixed-effects analyses support the descriptive findings that stolen-base totals were more consistently associated with linear sprint speed and acceleration than doubles totals. Although all stolen-base associations remained statistically significant after adjustment for multiple comparisons, the associations involving doubles did not. However, these findings should not be interpreted as evidence that linear sprint ability is unrelated to doubles. Doubles are influenced by several factors beyond linear running performance, including batting ability, ball placement, and game-related opportunities, while curvilinear running ability may also contribute to successful advancement between bases. Consequently, the findings highlight the importance of considering both linear and curvilinear sprint characteristics when investigating baseball base running performance.

THE END

“I FINALLY REST, AND WATCH THE SUNRISE ON A GRATEFUL UNIVERSE”