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Anthropometric and biomechanical factors in elite male and female fast bowlers

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ABSTRACT

Researchers have extensively studied the biomechanics and anthropometrics of fast bowling in men's cricket, but there is still limited research in women's cricket. This study describes and compares the anthropometric qualities and bowling biomechanics between elite male and female fast bowlers. An inertial measurement system was used to collect three-dimensional biomechanical data for 20 elite fast bowlers (13 males and seven females). Kinematic data was captured at one step before back foot contact, back foot contact, front foot contact, ball release to one step after ball release. Anthropometric measurements included body segment lengths, mass, body fat (BF%) and muscle mass (MM%). The student *t*-test and Mann-Whitney *U* test were used for analyses. Hotelling's T2 statistic was calculated to control Type I error during multiple comparisons ($p = 0.045$). Males and females differed in overall height, limb length, BF% and MM%. Females presented with slower ball release speeds ($p = 0.001$). Biomechanically, the females were more front-on when approaching the delivery stride and then initiated pelvis and trunk rotation during the delivery stride, not seen in the males. Females and males have a similar magnitude of trunk side-flexion, but females present with a different strategy than males ($p = 0.038$). Females presented with increased front knee extension at ball release ($p = 0.05$). The findings from this study emphasise the differences between male and female fast bowlers and suggest that the coaching principles used in male fast bowling may not be relevant to female fast bowlers.

1. Introduction

The performance of fast bowlers is mainly linked to their ball release speed, as increasing ball release speed increases the difficulty for batters to score runs or defend their wicket. Hence, fast bowlers and their coaches constantly try to increase ball release speed by addressing bowling kinematics and techniques (Worthington et al., 2013). Research on fast bowling biomechanics and anthropometrics in men's cricket (Wormgoor et al., 2010, Portus et al., 2004, Glazier et al., 2000, Worthington et al., 2013) is widely researched. Still, the same cannot be said for female fast bowling.

Several studies have investigated the relationship between biomechanics and ball release speed in men's cricket (Wormgoor et al., 2010, Portus et al., 2004, Glazier et al., 2000). In the last decade, research on male fast bowling indicates that ball release speed is linked to faster run-up speeds (Kiely et al., 2021; Worthington et al., 2013), reduced time at the back foot contact (BFC) (Kiely et al., 2021), braced front knee during front foot contact (FFC) (Worthington et al., 2013), greater trunk flexion and delayed onset of shoulder counter-rotation (Worthington et al., 2013). Besides kinematic factors in male fast bowlers, anthropometric qualities also play a role in ball release speed. Previous research (Glazier et al., 2000) suggests increased shoulder-to-wrist and total arm length may be associated with increased ball release speed in male fast bowlers. However, recent studies suggest that no single anthropometric characteristic or body somatotype variable influences the ball release speed of male fast bowlers (Salter et al., 2007, Wormgoor et al., 2010).

Bowling biomechanics are found to be different between male and female fast bowlers, and it could be the cause for the slower ball release

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speeds seen among females (Felton et al., 2019). Research on female fast bowling indicates that females generally have shorter run-ups than male fast bowlers, resulting in slower ball release speeds (Savage and Portus, 2002, Lucente et al., 2021). More recently, Felton et al. (2019) discovered that female fast bowlers have slower run-up speeds and less whole-body momentum, resulting in a slower ball release speed and biomechanical differences compared to male fast bowlers. Felton et al. (2019) indicated that female fast bowlers use more thoracic and pelvis rotation to compensate for the loss of whole-body momentum.

Besides bowling biomechanics, anthropometric qualities are also unique for female fast bowlers. According to Savage and Portus (2002), female fast bowlers have slower ball release speeds than their male counterparts due to shorter upper and lower limb lengths and lower muscle strength. Stuelcken et al. (2007) suggested that female fast bowlers had slower ball release speed than males due to the more endomorphic body build than males' mesomorphic body type. Letter et al. (2022) further indicated that ball release speed is affected by lower and upper body strength in female fast bowlers. The findings above suggest that certain factors influencing bowling performance are sex independent, with implications for both male and female fast bowlers.

There is still a significant gap in scientific knowledge around female fast bowlers' biomechanical technique and factors contributing to ball release speed. It is unknown if the knee angle at FFC indicates increased ball release speed for females as it is for males or if shoulder counter-rotation affects the ball release speed in female cricket players. There is limited research investigating if shorter limb lengths or body types are associated with reduced ball release speeds in females compared to males. This study will shed light on the potential anthropometric and biomechanical factors contributing to differences in fast bowling performance between elite male and female cricketers. Understanding these differences could lead to a more individualised approach, including more tailored training programs for both male and female fast bowlers, promoting sex-specific sports advancements. To gain a better insight into biomechanics and anthropometric qualities for female fast bowlers, this study describes and compares the differences between elite male and female fast bowlers in South Africa in terms of these constructs.

2. Methods

2.1. Study design and setting

This was a cross-sectional, quantitative study. Data collection occurred at the respective cricket unions during the 2022/2023 season for elite male and female fast bowlers.

2.2. Participants

Elite male and female fast bowlers were recruited from the elite fast bowling cohort of Cricket South Africa (CSA). Twenty injury-free bowlers, 13 male and seven female fast bowlers, agreed to participate in this study. Ethical approval was granted by CSA's Medical Research Committee permission and the Human Research Ethics Committee (Medical) of the University of the Witwatersrand. Before the start of the study, all participants and guardians of those under the age of 18 provided written consent for using their data in this study.

2.3. Instrumentation and outcome measures

The researchers gathered 3D biomechanical data using an inertial measurement unit (IMU) and an analysis system. The Xsens (MVN Link Biomech, Xsens Technologies B.V., Enschede, Netherlands) system consists of a full-body human measurement system recording at 240 Hz using biomechanical models and sensor integration algorithms. The Xsens hardware comprises a lycra suit with markers for each of the 17 IMU sensors (Roetenberg et al., 2013). The MVN Analyse software was used to capture biomechanical data, which was subsequently synchronised by an algorithm into corresponding joint and segment angles. A comparison was made between the joint angles in the sagittal plane and non-sagittal torso-related angles obtained from Xsens MVN and those obtained from a 3D marker-based motion capture system. Xsens is a validated biomechanical system (Zhang et al., 2013), and a pilot study was conducted prior to the initiation of the present study.

2.4. Data collection

Anthropometric measurements were taken before the commencement of the biomechanical analysis. First, the anthropometrics measurement was conducted per the calibration requirements of the Xsens system. The metrics represent the overall stature of an individual, comprising the total height, shoulder height, shoulder width, arm span, hip height, hip width, knee height, ankle height, shoe height, and foot length (Suppl. Table S1). The body measurements were then logged into the Xsens software. Secondly, body composition measurements were taken on the Omron (Model OM-BF511) body composition scale (Omron BF306, Omron Healthcare, Inc., Vernon Hills, IL) (Lintsi et al., 2004). Data from the scale comprised various measurements such as mass, body mass index (BMI), body fat percentage, muscle mass percentage, and resting metabolic rate (RMR).

Before conducting the 3D bowling analysis, all participants were directed to engage in a complete warm-up routine similar to a match warm-up. Subsequently, the bowler then put the lycra suit on. The IMUs were connected and calibrated in the N-pose (arms neutral alongside the body) and walking as an activity (Roetenberg et al., 2013). After a successful calibration, the bowlers were instructed to bowl six deliveries at match speed with a 156 g cricket ball for males and a 142 g ball for females. Bowling accuracy was measured using a target behind the wickets as used by Portus et al. (2000). The velocities at which the bowlers released the balls were recorded using a radar gun (Stalker ATS®, Texas, USA) that was situated 180° behind the ball release point. The Xsens software was utilised to capture three-dimensional biomechanical data during the trials.

2.5. Data reduction and statistical analysis

Ninety-eight bowling trials (61 for males and 37 for females) were successfully extracted from the Xsens software. The data analyst calculated the biomechanical angles for all bowling trials according to the definitions and movement planes (Table 1) in MATLAB (v 2022b, MathWorks, Natick, MA). Key segments of each bowling trial were identified for analysis, i.e. one step before back foot contact, back foot contact (BFC), front foot contact (FFC), ball release (BR) and one step after ball release (Fig. 1).

Before-BFC was defined as the time interval of 100 timesteps (100hz) from before BFC and identified the maximum combined acceleration of the front leg in the interval. BFC was identified as occurring four frames (0.017 s) before the peak resultant back tibial acceleration that occurred within 100 frames (0.42 s) prior to front foot contact (Olivier et al., 2023, Lamb et al., 2022). FFC was identified as occurring three frames (0.013 s) before the peak resultant front tibial acceleration that occurred within 300 frames (1.25 s) prior to the overall (for the trial) peak resultant forearm acceleration. BR was identified as occurring at the instant of the peak resultant bowling forearm acceleration that was recorded within 50 frames (0.21 s) after front foot contact (Olivier et al., 2023, Spratford et al., 2015). One step after BR was identified as five frames (0.021 s) occurring before the peak resultant back tibial acceleration that occurred within 125 frames (0.52 s) after ball release (Olivier et al., 2023). The BFC phase was defined as beginning at BFC and ending at FFC. The FFC phase was defined as beginning at FFC and ending at BR. The follow-through phase began at BR and ended at the one step after BR. The total movement was defined as the sum of these three phases. Three-dimensional data time stamps for each segment mentioned above were extracted for further data analysis. Definitions

Table 1
Definitions for biomechanical variables.

Biomechanical variable	Definition	Xsens MVN System movement variable*
Time duration	The measurable length of a phase of the bowling action.	N/A
Trunk side-flexion	The biomechanical variable represents the lateral bending of the trunk. The trunk is the segment between the shoulders (C7 or T1) and L5. Trunk side-flexion to the left was captured as negative degrees, and to the right, it was positive.	Joint Angles ZXY or XZY were used to capture trunk side-flexion. The rotation around the Z-axis (for ZXY) or X-axis (for XZY) represented trunk side-flexion.
Trunk rotation	The axial turning of the trunk relative to the pelvis. The trunk is defined as the segment between the shoulders (C7 or T1) and L5, and this rotation is also referred to as the pelvis-shoulder separation angle.	Joint Angles ZXY or XZY were used to capture trunk rotation. The rotation around the Y-axis (for both ZXY and XZY) represented trunk relative to the pelvis.
Pelvis rotation	The rotational movement of the pelvis relative to the lower back (L5).	Joint Angles ZXY or XZY were used to capture pelvis rotation. The rotation around the Z-axis (for ZXY) or X-axis (for XZY) represented the rotational movement of the pelvis.
Centre of mass	The centre of mass is a point within the pelvis representing the average location of the body's mass.	N/A
Hip flexion and extension	The biomechanical movements of the hip joint that involve a decrease (flexion) or an increase (extension).	Joint Angles ZXY or XZY were used to capture hip flexion and extension. The rotation around the Y-axis (for both ZXY and XZY) represented hip flexion and extension.
Knee flexion and extension	The biomechanical movements of the knee joint that involve a decrease (flexion) or an increase (extension).	Joint Angles ZXY or XZY were used to capture knee flexion and extension. The rotation around the Y-axis (for both ZXY and XZY) represented knee flexion and extension.
Ball release speed	The velocity at which the cricket ball is released during the bowling action.	N/A
Shoulder counter rotation	The transverse clockwise movement (away from the batter) of the shoulder alignment was recorded between back foot and front foot contact.	Joint Angles ZXY or XZY were used to capture shoulder counter rotation. The rotation around the Z-axis (for ZXY) or X-axis (for XZY) represented the transverse movement of the shoulder alignment.

for each biomechanical plane are listed in Table 1.

All statistical analyses, including means, data distribution (standard deviation (SD)), standard error, and significance, were carried out using SPSSv.28 (SPSS Corporation, USA). The trials for each player were grouped, and a mean for each player (13 males and seven females) was calculated. The means of the trials for each player reduced the standard error during the analyses. The data were assessed for normality using Levene's Test for Equality of Variances to compare means. Hotelling's T^2 statistic was calculated to control Type I error between the two sexes for differences in biomechanics ($p = 0.045$). The student *t*-test was used to analyse the independent variables, and if any parameters violated the normality assumption, the non-parametric Mann-Whitney *U* test was conducted instead. Cohen's d and η^2 classification were used to determine the effect sizes of parametric and non-parametric tests, respectively. The effect sizes were grouped as small effect sizes < 0.2, medium 0.2–0.8, and large > 0.8, indicating the strength of the relationship or the practical significance of the observed effect. The anthropometric values were standardised using z-score normalisation, subtracting the mean and dividing by the standard deviation to transform each value. The distribution has a mean of 0 and a standard deviation of 1.

3. Results

3.1. Participant characteristics

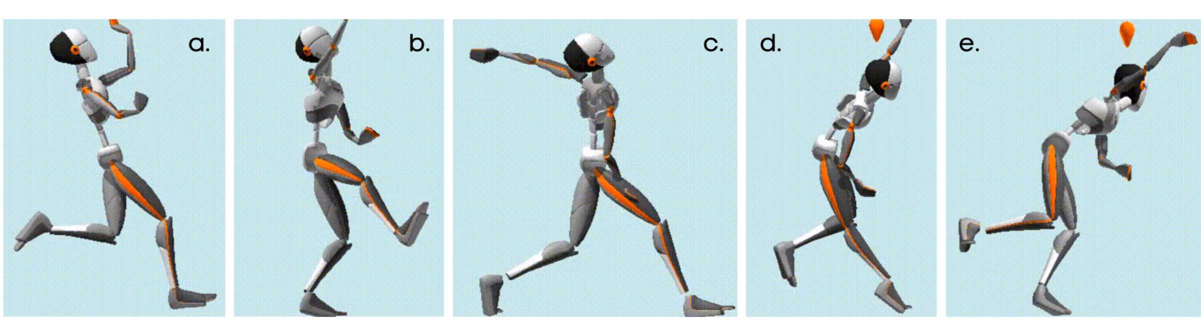
Seven female fast bowlers and 13 male fast bowlers with a mean (SD) age of 22.86 (3.93) years for females and 23.77 (3.68) years for males participated in this study. All 20 participants were right-handed fast bowlers.

3.2. Anthropometric qualities

Anthropometric measurements are indicated in Table 2. Significant differences were found for the following variables: mass, height, BF%, MM% and RMR. Males had increased body measurements with larger effect sizes compared to females.

3.3. Bowling biomechanics

The bowling biomechanics data are indicated in Table 3. Males had increased ball release speed compared to females. Females took more time than males for all phase lengths from one bowling phase to another (Fig. 2A). Before-BFC, female fast bowlers had reduced trunk and pelvis rotation and decreased hip and knee flexion of the front leg (Fig. 2C–H). There were differences at BFC for trunk side-flexion (Fig. 2B) and knee flexion of the back leg (Fig. 2H). At FFC, females had longer phase lengths to ball release than males. Females also had reduced trunk side-flexion and knee flexion of the back leg, while males had increased knee flexion of the front leg. At BR, females presented with reduced knee



a. before back foot contact, b. back foot contact, c. front foot contact, d. ball release, e. one step after ball release

Fig. 1. Each time point of the bowling action (images screenshots from Xsens software) *a. before back foot contact, b. back foot contact, c. front foot contact, d. ball release, e. one step after ball release.*

Table 2
Group means and differences of body measurements and anthropometric qualities for elite male and female fast bowlers.

Variables	Female Mean (SD)	Male Mean (SD)	Mean Difference (SE)	Normalisation		P-value	Effect sizes
				Female Mean (SD)	Male Mean (SD)		
Age (years)	22.86 (3.93)	23.77 (3.68)	0.91 (1.77)	−0.62 (3.93)	0.48 (0.75)	0.612	0.24
Mass (kg)	67.30 (11.37)	81.82 (11.21)	14.52 (5.28)	−0.91 (0.83)	0.92 (0.76)	0.013	1.29
Height (m)	165.50 (9.04)	184.77 (7.58)	19.27 (3.80)	−1.64 (0.73)	1.62 (0.68)	0.481	2.38
BMI (kg/m^2)	24.97 (2.49)	24.45 (2.47)	0.52 (1.16)	0.26 (0.77)	−0.26 (0.77)	0.661	0.21
Body fat %	35.46 (5.70)	19.36 (7.26)	16.10 (3.18)	1.15 (0.86)	−1.15 (1.00)	<0.001	2.37
Muscle mass %	26.41 (1.97)	39.84 (4.20)	13.42 (1.69)	−1.38 (0.89)	1.38 (0.95)	<0.001	3.72
RMR (kcal)	1381.86 (154.55)	1804.54 (137.20)	422.68 (67.14)	−1.50 (0.91)	1.50 (0.85)	<0.001	2.95
Shoulder height (mm)	141.71 (8.83)	158.46 (6.17)	16.75 (3.36)	−1.61 (0.83)	1.61 (0.80)	<0.001	2.34
Shoulder width (mm)	38.57 (1.27)	41.54 (2.73)	2.97 (1.10)	−1.54 (0.85)	1.54 (0.89)	0.015	1.27
Arm span (mm)	167.64 (8.29)	187.77 (5.31)	20.13 (3.03)	−1.55 (0.84)	1.55 (0.87)	<0.001	2.99
Hip height (mm)	87.64 (6.39)	101.46 (5.30)	13.82 (2.67)	−1.63 (0.83)	1.63 (0.87)	<0.001	2.43
Hip width (mm)	23.86 (1.35)	28.15 (2.44)	4.30 (1.00)	−1.70 (0.85)	1.70 (0.87)	<0.001	2.01
Knee height (mm)	46.07 (3.52)	52.46 (3.67)	6.39 (1.70)	−1.39 (0.84)	1.39 (0.85)	<0.001	1.77
Ankle height (mm)	7.43 (2.76)	11.62 (1.33)	4.19 (0.90)	−1.07 (0.86)	1.07 (0.86)	<0.001^b	0.68*
Shoe height (mm)	2.93 (0.19)	3.23 (0.44)	0.30 (0.18)	−1.54 (0.76)	1.54 (0.91)	0.08^b	0.16*
Foot length (mm)	27.86 (1.57)	29.38 (1.04)	1.53 (0.58)	−1.59 (0.87)	1.59 (0.87)	0.018	1.23

^{a}t-test, ^{b}Mann-Whitney U test. Effect sizes were calculated by Cohen's d (parametric) and *η^2 (non-parametric).

flexion of the front leg compared to males (Fig. 2G). At one step after BR, females showed increased trunk and pelvis rotation compared to males. Females had increased hip flexion and decreased knee flexion of the front leg compared to males (Fig. 2E&G).

4. Discussion

This study aimed to describe and compare the anthropometric qualities and bowling biomechanics of female fast bowlers, highlighting distinctions from male counterparts to emphasise the need for a unique approach when working with female players. The unique biomechanical and anthropometric discrepancies can be further investigated to guide coaches to implement individualised training techniques for female fast bowlers, as the coaching strategies used for male fast bowlers cannot be replicated for females.

The anthropometric variables between males and females displayed several key observations. Notably, the variables related to body composition, such as BF%, MM% and RMR, show substantial differences between the two sexes. Females exhibited higher body fat percentages and lower muscle mass percentages compared to males. Additionally, the RMR is significantly lower in females. Furthermore, height-related variables, such as shoulder height, arm span, hip height, and knee height, all demonstrate considerable distinctions, with males consistently displaying larger measurements. These findings underscore the importance of considering sex-specific variations in anthropometric characteristics and suggest potential areas for targeted interventions or further investigation. Although these differences between males and females are not unique to cricketers (Santos et al., 2014), they may influence the ball release speed attained during the bowling action. Previous researchers discovered strong correlations between arm length and overall body mass, leading to increased ball release speed in men's cricket (Glazier et al., 2000, Pyne et al., 2006). Analyses of body compositions in this study indicated high BF% and low MM% for female fast bowlers. These findings are similar to previous research on elite fast bowlers, where females were more endomorphic and less mesomorphic than males (Stuelcken et al., 2007). Savage and Portus (2002) suggested that female bowlers have reduced muscle strength and shorter upper limbs, which could be linked to slower ball release speeds compared to males. Future research should investigate if the differences in anthropometric measurements, such as arm span, hip height and overall height, BF% and MM%, could be a factor for the biomechanical differences we observe in female fast bowlers.

The female fast bowling biomechanics in this study vary from the male fast bowlers. Female fast bowlers presented with longer phase lengths from before-BFC to one step after BR, which indicates reduced linear momentum for female fast bowlers as they progress through the delivery stride. Another finding at before-BFC indicated that females presented with reduced hip flexion of the back leg, which could be linked to the reduced linear momentum generated in their bowling action. Notably, males, leveraging increased hip flexion of the back leg, stride forward to BFC with more linear momentum. In contrast, females in this study demonstrate slower ball release speeds (101.30 ± 5.63 km/h) than their male counterparts. This divergence challenges conventional expectations, as previous research has often suggested that female fast bowlers adopt techniques resembling those of their male counterparts. Contrary to this expectation, our findings align with Savage and Portus (2002), who found that female fast bowlers have slower run-ups than males and findings by Felton et al. (2019) that females have less linear momentum as they approach the delivery stride. Thus, our findings are similar to previous research suggesting that female fast bowlers have reduced linear momentum during the delivery stride and reduced ball release speeds compared to male fast bowlers (Felton et al., 2019).

This study identified that females initiated more trunk and pelvis rotation during their bowling action. Females initially presented with reduced pelvis and trunk rotation compared to males at the point of before-BFC, indicating a front-on approach for females as they approach the delivery stride. The females then presented with more trunk and pelvis rotation at the phase length from BFC to FFC. It is also interesting to note that the females' phase lengths from BFC to FFC were longer than males. The additional time available can be used to generate rotation in the trunk and pelvis. No significant increase in trunk or pelvis rotation or trunk side-flexion was observed during FFC to BR. During BR to one step after BR females presented with increased rotation of the trunk and pelvis compared to males. This could be because of the transverse momentum generated from BFC to FFC. The transverse momentum pushes the females into further rotation after the delivery stride, similar to a wind-up and wind-down effect. Felton et al. (2019) suggested that females have less linear momentum when arriving at the crease and compensate by using large rotator muscles to generate momentum. Similar to these findings, the females in our study could use the increased rotational strategies to increase transverse momentum during their delivery stride.

There were notable biomechanical differences between male and female fast bowlers at the front leg. Males presented with increased hip flexion of the front leg at BFC and decreased hip flexion at BR (Fig. 2E) compared to females. This finding suggests that males use more hip extension of the front leg from BFC to BR, indicating that males rely on the flexion to extension movement of the front hip compared to females

Table 3
Group means and standard deviation of biomechanical variables for elite male and female fast bowlers.

Variables	One step before BFC				BFC				FFC			
	Female Mean (SD)	Male Mean (SD)	P-value	Effect sizes	Female Mean (SD)	Male Mean (SD)	P-value	Effect sizes	Female Mean (SD)	Male Mean (SD)	P-value	Effect sizes
Time duration (ms)	75.17 (10.15)	71.13 (15.80)	0.551[a]	0.20	40.78 (4.60)	39.42 (7.33)	0.664[a]	0.28	58.90 (20.98)	46.59 (22.60)	0.250[a]	0.56
Trunk side-flex (°)	−1.8 (4.19)	−0.41 (3.26)	0.420[a]	0.39	4.04 (2.21)	0.31 (4.88)	0.073[a]	0.89	−3.44 (3.83)	−7.71 (4.16)	0.038[a]	1.05
Trunk rotation (°)	17.92 (8.06)	22.30 (6.68)	0.209[a]	0.61	13.40 (8.51)	15.14 (6.39)	0.612[a]	0.24	21.84 (6.41)	19.88 (9.11)	0.621[a]	0.24
Pelvis rotation (°)	8.11 (3.60)	10.08 (2.99)	0.205[a]	0.62	6.00 (3.92)	6.80 (2.84)	0.604[a]	0.25	9.98 (2.89)	9.10 (4.11)	0.658[a]	0.21
COM (m)	1.02 (0.47)	1.11 (0.17)	0.208[a]	0.61	0.98 (0.05)	1.12 (0.04)	<0.001[a]	3.11	0.84 (0.04)	0.97 (0.08)	0.001[a]	1.80
Hip flex/ext (FL) (°)	1.21 (8.77)	3.68 (15.21)	0.699[a]	0.18	49.77 (12.93)	56.40 (7.52)	0.160[a]	0.69	50.04 (5.70)	52.41 (7.44)	0.474[a]	0.34
Hip flex/ext (BL)(°)	41.96 (15.59)	54.49 (15.09)	0.097[a]	0.82	16.25 (6.40)	15.78 (6.40)	0.879[a]	0.07	−2.41 (2.79)	−1.62 (6.19)	0.754[a]	0.15
Knee flex (FL) (°)	31.82 (6.92)	39.16 (14.83)	0.501[b]	0.02*	51.32 (6.68)	49.01 (13.01)	0.722[a]	0.17	17.76 (6.64)	14.70 (7.94)	0.398[a]	0.41
Knee flex (BL) (°)	114.24 (18.06)	106.01 (17.32)	0.331[a]	0.47	32.64 (8.78)	21.76 (13.39)	0.070[a]	0.90	49.16 (6.76)	55.67 (7.58)	0.074[a]	0.89

Variables	BR				One step after BR			
	Female Mean (SD)	Male Mean (SD)	P-value	Effect sizes	Female Mean (SD)	Male Mean (SD)	P-value	Effect sizes
Time duration (ms)					98.69 (12.54)	102.68 (22.12)	0.613[a]	0.21
Trunk side-flexion (°)	−2.62 (14.34)	−2.62 (11.72)	1.000[a]	0.00	12.67 (7.84)	13.54 (5.88)	0.782[a]	0.13
Trunk rotation (°)	22.04 (12.12)	18.95 (10.58)	0.560[a]	0.28	28.93 (4.99)	21.18 (9.69)	0.104[b]	0.14*
Pelvis rotation (°)	10.26 (5.45)	8.74 (4.93)	0.533[a]	0.30	13.52 (2.53)	9.94 (4.56)	0.037[a]	0.89
COM (m)	0.87 (0.06)	1.00 (0.08)	0.002[a]	1.70	0.85 (0.06)	0.99 (0.08)	0.002[a]	1.71
Hip flex/ext (FL) (°)	45.55 (15.37)	40.92 (10.37)	0.431[a]	0.38	30.40 (5.82)	14.86 (13.19)	0.008[b]	0.37*
Hip flex/ext (BL) (°)	52.51 (15.13)	51.82 (14.88)	0.878[a]	0.07	66.67 (5.44)	59.75 (16.75)	0.192[a]	0.49
Knee flexion (FL) (°)	13.09 (11.71)	16.13 (19.49)	0.050[a]	0.27	21.61 (13.97)	42.09 (16.1)	0.011[a]	1.33
Knee flexion (BL) (°)	50.36 (20.11)	65.89 (27.19)	0.166[a]	0.62	35.26 (5.50)	39.32 (13.17)	0.451[a]	0.36
Ball release speed (km/h)	101.30 (5.63)	131.90 (5.11)	<0.001[a]	5.78				
Shoulder counter rotation (°)	21.46 (15.57)	12.25 (9.16)	0.191[b]	0.09*				

Back foot contact (BFC), front foot contact (FFC), ball release (BR), front leg (FL), back leg (BL), flexion (flex), extension (ext).
[a]t-test, [b]Mann-Whitney U test. Effect sizes were calculated by Cohen's d (parametric) and $^*\eta^2$ *(non-parametric).*

who maintain somewhat of a similar magnitude of hip flexion from BFC to BR. Felton et al. (2019) also noted a difference in timing in hip extension between male and female fast bowlers but at the back leg. Further research is warranted to investigate if the magnitude of hip flexion/extension is a performance factor for female fast bowling, as this differs from the action we see in males. Another difference was noted at the knee joint of the front leg. Females presented with decreased knee flexion from FFC to BR compared to males, who presented with increased knee flexion from FFC to BR. Females also presented with reduced front knee flexion (more extended knee) at BR compared to males. It could be suggested that the females in our study used a knee extension technique at the front leg from FFC to BR (Fig. 2E), in contrast to males who used a hip extension technique of the front leg from BFC to BR (Fig. 2G). A straighter knee throughout the front foot contact phase is associated with faster ball release speeds (Worthington et al., 2013). However, Olivier et al. (2016) found that bowlers can potentially enhance their BR speed and remain injury-free over a season by maintaining a flexed knee throughout the bowling action. Future studies should investigate the knee angles of the front leg at FFC and BR and the association with ball release speed and knee injury risk in female fast bowlers.

A noteworthy finding of this study was the disparity in trunk side-flexion between males and females (see Fig. 2B). Females presented with left trunk side-flexion compared to a neutral (upright) trunk position of the males at before-BFC. Females then transition to side-flexion to the right, whereas males maintain a neutral (upright) trunk at BFC. Males and females present with increased trunk side-flexion towards the left at FFC. Interestingly, the magnitude of left trunk side-flexion from BFC to FFC was similar for both sexes. However, males exhibited an augmented total magnitude of right side trunk flexion at FFC due to their neutral (upright) trunk position at BFC, in contrast to females who initially presented with left side trunk flexion at BFC. This technique could be beneficial for the females as previous research indicated that female fast bowlers had proportionally longer trunk lengths than male fast bowlers (Stuelcken et al., 2007) and could be an anthropometrical and biomechanical advantage for the females to use right to left trunk

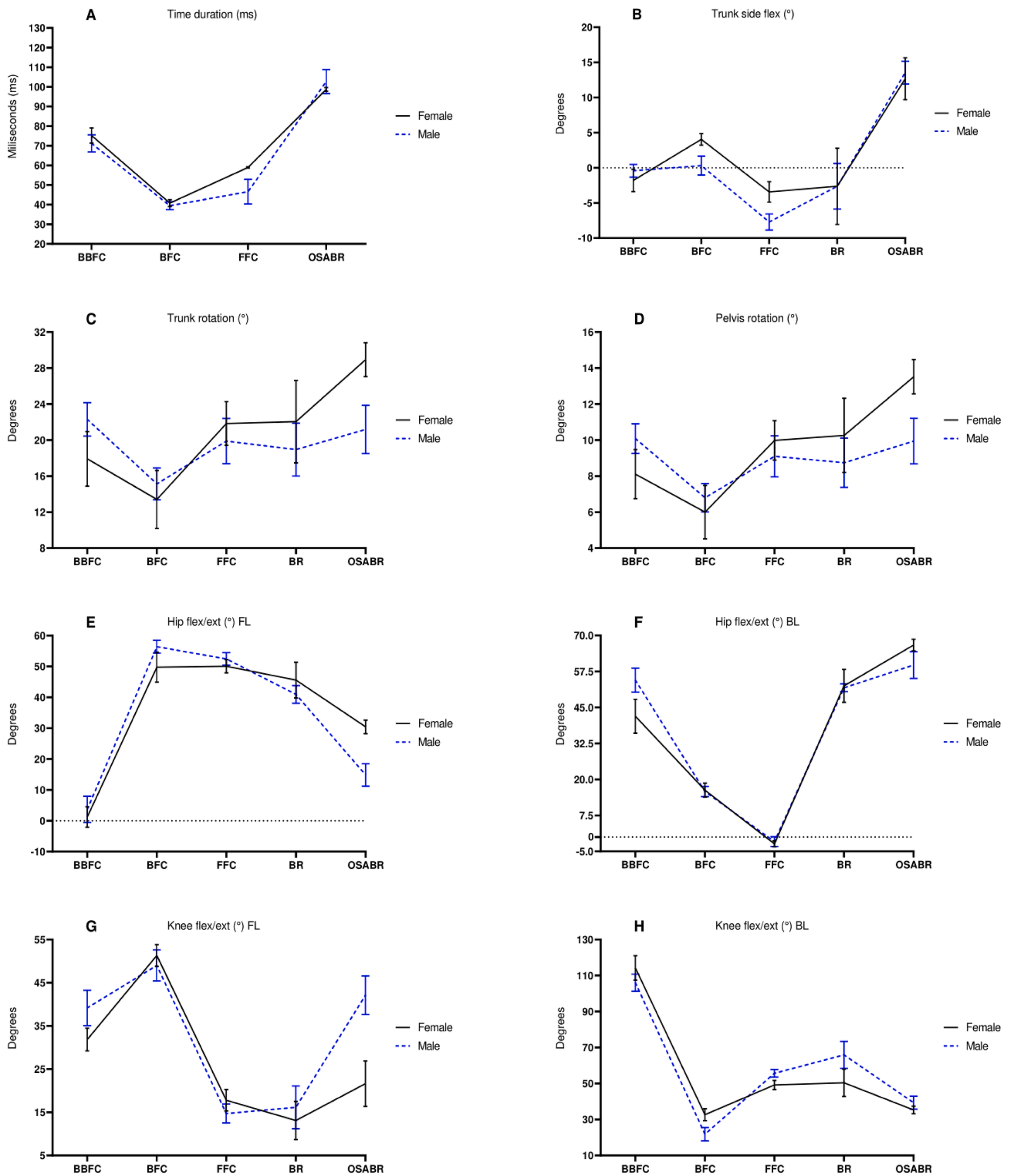


Fig. 2. Line graphs of biomechanical comparisons between elite male and female fast bowlers. *Before back foot contact (BBFC), back foot contact (BFC), front foot contact (FFC), ball release (BR), one step after ball release (OSABR), front leg (FL), back leg (BL), flexion (flex), extension (ext).*

side-flexion to generate momentum during the delivery stride. The rate of lower back injuries among female fast bowlers is lower than that of males (Jacobs et al., 2022). Further research should explore whether the initial right trunk flexion at BFC could be a contributing factor to the reduced occurrence of lower back injuries in females. Lower back injury rates in female fast bowlers are less than for males and future research should investigate if the initial right trunk flexion at BFC could be advantageous and a factor in why females have reduced lower back injuries. Future research should investigate a larger sample size of female fast bowlers to investigate their trunk side-flexion strategy, whether this is an increased ball release speed strategy in females, and the effect on injury risk in fast bowlers.

Females in this study presented with higher shoulder counter-rotation than males. The high degrees of shoulder counter-rotation could aid in the transverse momentum generated during the delivery stride. Felton et al. (2019) suggested that female fast bowlers rotate, using the shoulder, trunk, and pelvis during their bowling stride, similar to a throwing technique. This rotational bowling technique could benefit females by generating more momentum to increase ball release speed, but the high shoulder injury rates in female fast bowlers are a concern (Jacobs et al., 2022). Future research should investigate the trade-off between the high degrees of shoulder counter-rotation for bowling performance and the increased risk of shoulder injury associated with this technique. Coaches and clinicians working with female fast bowlers should focus on strengthening the shoulder muscles for improved performance and injury prevention.

A limitation of this study is the small population of elite female fast bowlers, however, still a big sample compared to the entire population. Future research should investigate a larger cohort of elite female fast bowlers, the relationship between musculoskeletal, anthropometrics and bowling biomechanics, and how these factors could influence ball release speed and injury risks. Our study lacks detailed analysis on bowlers' specific techniques (side-on, front-on, or mixed), which could impact observed biomechanical measures. Future research should address technique variations for a comprehensive interpretation of results.

A strength of this study is the use of IMU, as the players could be exposed to an outdoor pitch and environment, which aided the ecological validity as it was closer to match and training circumstances than testing them in laboratories on a different surface. Also, reporting the before-BFC and one step after BR is a strength of this study, as the fast bowling action should be assessed holistically, not just the phase length from BFC to BR. Future studies should include before-BFC as part of their bowling analyses. This segment predicts the setup of kinematics at the BFC, and the phase length from before-BFC to BFC is an essential technique coaches reinforce in their bowlers during coaching sessions.

5. Conclusion

This study suggests that female fast bowlers have unique anthropometry and bowling biomechanics. Female fast bowlers spend more time in the phase lengths of the delivery stride, specifically from BFC to FFC. Females have increased pelvis and trunk rotation from BFC to FFC and BR to one step after BR and increased total shoulder counter-rotation. A novel finding of this study is that females use a different trunk side-flexion strategy compared to males from before-BFC to FFC. Further, the extended time of the phase length through the delivery stride enables the female bowlers to use muscles working in the transverse plane to generate extra rotational momentum to increase ball release speed. Coaches should be aware of these strategies when altering bowling biomechanics of female fast bowlers. The current extrapolation of coaching strategies adopted from male fast bowling may not be relevant for females.

Ethical statement.

Ethical approval and permission to conduct this study were obtained from Cricket South Africa's Medical Research Committee, the respective cricket unions' managers, and the Human Research Ethics Committee (Medical) of the University of the Witwatersrand (M220447).

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CRediT authorship contribution statement

Jolandi Jacobs: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Benita Olivier:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Corlia Brandt:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Nathanael Boulle:** Writing – review & editing, Writing – original draft, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2024.112157.

References

Felton, P.J., Lister, S.L., Worthington, P.J., King, M.A., 2019. Comparison of biomechanical characteristics between male and female elite fast bowlers. J. Sports Sci. 37, 665–670.

Glazier, P.S., Paradisis, G.P., Cooper, S.M., 2000. Anthropometric and kinematic influences on release speed in men's fast-medium bowling. J. Sports Sci. 18, 1013–1021.

Jacobs, J., Olivier, B., Dawood, M., Perera, N.K.P., 2022. Prevalence and incidence of injuries among female cricket players: a systematic review and meta-analysis. JBI Evid Synth 20, 1741–1790.

Kiely, N., Pickering Rodriguez, L., Watsford, M., Reddin, T., Hardy, S., Duffield, R., 2021. The influence of technique and physical capacity on ball release speed in cricket fast-bowling. J. Sports Sci. 39, 2361–2369.

Lamb, M.O., McErlain-Naylor, S.A., Felton, P.J., Brooke-Wavell, K., King, M.A., 2022. Surface measured accelerations during cricket fast-bowling. ISBS Proc. Arch 40, 359.

Letter, R.T., Dwyer, D.B., Drinkwater, E.J., Feros, S.A., 2022. The physical differences between faster and slower elite male and female pace bowlers. Int. J. Sports Physiol. Perform. 1, 1–7.

Lintsi, M., Kaarma, H., Kull, I., 2004. Comparison of hand-to-hand bioimpedance and anthropometry equations versus dual-energy X-ray absorptiometry for the assessment of body fat percentage in 17–18-year-old conscripts. Clin. Physiol. Funct. Imaging 24, 85–90.

Lucente, A., Saw, A., Sims, K., Saw, R., Kountouris, A., Crowther, R., 2021. Characteristics of elite cricket fast bowlers who do and do not sustain a lumbar bone stress injury: multifactorial analysis over 4 years. J. Sci. Med. Sport 24, S29–S30.

Olivier, B., Stewart, A.V., Green, A., McKinon, W., 2016. Cricket pace bowling: the trade-off between optimising knee angle for performance advantages v. injury prevention. S Afr J. Sports Med. 27, 76–81.

Olivier, B., Boulle, N., Jacobs, J., Obiora, O.L., Macmillan, C., Liebenberg, J., McErlain-Naylor, S., 2023. Kinematic differences between left-and right-handed cricket fast bowlers during the bowling action. S Afr J. Sports Med. 35.

Portus, M., Mason, B.R., Elliott, B.C., Pfitzner, M.C., Done, R.P., 2004. Technique factors related to ball release speed and trunk injuries in high performance cricket fast bowlers. Sports Biomech. 3, 263–284.

Portus, M.R., Sinclair, P.J., Burke, S.T., Moore, D.J.A., Farhart, P.J., 2000. Cricket fast bowling performance and technique and the influence of selected physical factors during an 8-over spell. J. Sports Sci. 18, 999–1011.

Pyne, D.B., Duthie, G.M., Saunders, P.U., Petersen, C.A., Portus, M.R., 2006. Anthropometric and strength correlates of fast bowling speed in junior and senior cricketers. J. Strength Cond. Res. 20, 620–626.

Roetenberg, D., Luinge, H., Slycke, P., 2013. Xsens MVN: Full 6DOF Human Motion Tracking Using Miniature Inertial Sensors. Xsens Motion Technologies BV, Technical Report.

Salter, C.W., Sinclair, P.J., Portus, M.R., 2007. The associations between fast bowling technique and ball release speed: a pilot study of the within-bowler and between-bowler approaches. J. Sports Sci. 25, 1279–1285.

Santos, D.A., Dawson, J.A., Matias, C.N., Rocha, P.M., Minderico, C.S., Allison, D.B., Sardinha, L.B., Silva, A.M., 2014. Reference values for body composition and anthropometric measurements in athletes. PLoS One 9, e97846.

Savage, T., Portus, M., 2002. A kinematic analysis of fast bowling techniques used by elite female cricketers. In: Proceedings of the 4th Australasian Biomechanics Conference, pp. 178–179.

Spratford, W., Portus, M., Wixted, A., Leadbetter, R., James, D.A., 2015. Peak outward acceleration and ball release in cricket. J. Sports Sci. 33, 754–760.

Stuelcken, M., Pyne, D., Sinclair, P., 2007. Anthropometric characteristics of elite cricket fast bowlers. J. Sports Sci. 25, 1587–1597.

Wormgoor, S., Harden, L., McKinon, W., 2010. Anthropometric, biomechanical, and isokinetic strength predictors of ball release speed in high-performance cricket fast bowlers. J. Sports Sci. 28, 957–965.

Worthington, P.J., King, M.A., Ranson, C.A., 2013. Relationships between fast bowling technique and ball release speed in cricket. J. Appl. Biomech. 29, 78–84.

Zhang, J.-T., Novak, A.C., Brouwer, B., Li, Q., 2013. Concurrent validation of Xsens MVN measurement of lower limb joint angular kinematics. Physiol. Meas. 34, N63.