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Characteristics of elite cricket fast bowlers who do and do not sustain a lumbar bone stress injury: Multifactorial analysis over 4 years

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ABSTRACT

Lumbar bone stress injuries (LBSI) are the highest time-loss injuries among elite adult and adolescent male cricket fast bowlers. Previous research in these cohorts has not identified any consistent stand-alone risk-factors beyond younger age. The purpose of this study was to address gaps in existing research by retrospectively reviewing four-seasons of data from male and female fast bowlers across multiple domains. Data of elite male and female fast bowlers was retrieved from Cricket Australia's online database for the seasons 2016-17 to 2019-20. Bowlers who sustained a LBSI during a season, denoted 'injured' (n = 43: 33 male, 10 female) were compared to bowlers who did not sustain a LBSI in the previous four years, denoted 'non-injured' (n = 28: 18 male, 10 female). Musculoskeletal screening, bowling technique, and bowling frequency were compared between injured and non-injured bowlers using univariate and multivariate analyses. History of any LBSI previously (odds ratio 8.84 [1.08–37.59], p = 0.003), younger age (odds ratio 0.73 [0.61–0.86], p > 0.001), and more days bowled in the previous four weeks (1.19 [1.03–1.38], p = 0.018) explained 45% of LBSI risk in elite fast bowlers. The remaining 55% was not explained by any individual, musculoskeletal, or technique variables across all bowlers. Practitioners should take into consideration any history of LBSI and the age of the bowler when prescribing bowling frequency to reduce the risk of LBSI. An individualised and adaptive approach to fast bowler preparation may also address other factors such as musculoskeletal characteristics or bowling technique if deemed relevant to the individual at the time.

1. Introduction

Lumbar bone stress injuries (LBSI) are the highest time-loss injuries among elite male cricket fast bowlers (Frost & Chalmers, 2014; Goggins et al., 2020; Johnson et al., 2012; Orchard et al., 2016). While LBSI are currently reported to be less common in female cricket players (Jacobs et al., 2021), they have also resulted in considerable time-loss in elite female fast bowlers (Perera et al., 2019). In fast bowlers, bone stress develops in the posterior elements of the lumbar vertebrae when the repetitive and high-force nature of the bowling action exceeds the tissue capacity (Johnson et al., 2012). The balance between the load on the lumbar vertebrae and the tissue capacity is determined by a multitude of factors such as age and musculoskeletal characteristics, bowling technique, and bowling frequency (Johnson et al., 2012).

Younger bowlers, particularly under 22 years, are purported to be at increased risk of LBSI due to a combination of skeletal immaturity and training age capability (Blanch et al., 2015; Cyron & Hutton, 1978; Farfan et al., 1976). Two studies which have investigated musculoskeletal risk factors of LBSI in young male fast bowlers over one season identified a lower medial longitudinal arch of the foot (Foster, 1989); and shorter lumbar extension endurance, poor lumbopelvic stability, and larger knee valgus on single-leg decline squat (Bayne et al., 2016). A recent study investigated LBSI risk factors in a much larger cohort of adolescent male fast bowlers over five seasons and did not corroborate the previously identified risk factors, but did identify

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younger age, taller height, and poorer Star-Excursion Balance Test performance as risk factors (Sims et al., 2021). Research has yet to evaluate musculoskeletal risk factors in adult male and female bowlers, or adolescent female bowlers.

Bowling technique characteristics such as excessive shoulder counter-rotation, thoracolumbar lateral flexion at front foot contact and ball release, and increased flexion of the hip and knee at back foot contact have all been associated with LBSI in young and adult male bowlers (Alway et al., 2020; Bayne et al., 2016; Elliott et al., 1992; Foster et al., 1989; Portus et al., 2004). Similarly, a more extended or extending hip and knee joint during the latter phases of the bowling action has been attributed with bowlers having a greater risk of LBSI; noting these bowlers also experience higher peak forces (Portus et al., 2004) and bowl faster which places them at higher risk of LBSI (Elliott et al., 1992; Foster et al., 1989). While there is some agreement across these studies, the specific contribution of bowling technique to LBSI risk remains unclear.

Acute spikes in bowling frequency have been associated with increased risk of any injury in subsequent weeks in elite male fast bowlers (Orchard et al., 2015b; Orchard et al., 2009). A high bowling frequency (>234 balls) over seven days at any time in the season has been associated with lumbar stress fractures in elite male fast bowlers (Alway et al., 2019a). Conversely, bone stress injuries in elite male fast bowlers have been associated with a high bowling frequency over a few months on a background of low career bowling loads (Orchard et al., 2015a). The number of days between bowling sessions has been shown to be a pertinent aspect of bowling frequency in young male bowlers (Dennis et al., 2005; Kountouris et al., 2019), however this has not been directly investigated in adult male and female bowlers. Further research is needed to understand whether bowling frequency is a stand-alone risk factor for LBSI, directly related to the rate of bone damage exceeding the rate of repair (Robling, 2006), or whether there is an interplay with other factors such as strength and technique.

Collectively, the literature suggests that several factors relating to musculoskeletal characteristics, bowling technique, and bowling frequency may increase the risk of LBSI in fast bowlers. However, beyond younger age, there are no consistent stand-alone risk factors. Instead, the interplay of two or more factors may be more meaningful. For instance, a certain bowling technique factor may only pose an increased risk if coupled with a certain musculoskeletal characteristic. Injury risk may also develop over multiple seasons, so a bowler with certain characteristics may not develop a LBSI in one season but may be injured in the following season. A further gap in the literature is that risk factors for LBSI in female fast bowlers have not been investigated. The purpose of this study was to address gaps in existing research by retrospectively reviewing four cricket seasons of data from elite male and female fast bowlers across multiple domains, comparing bowlers who sustained a LBSI to those who did not sustain any LBSI in the previous four years.

2. Methods

2.1. Study design

Retrospective cohort study. Ethics approval was attained from the La Trobe University Human Research Ethics Committee (HEC20058). Data were retrieved from Cricket Australia's online database (Athlete Management System, Fair Play Pty Ltd.).

2.2. Participants

177 Australian fast bowlers (107 male, 70 female) participated in elite senior state and national cricket programs over four seasons (2016–17 to 2019–20, season from July to March). A bowler is defined as a 'fast' bowler if they deliver (bowl) the ball at a pace which requires the wicket-keeper to stand back from the stumps to receive the ball (as opposed to slow bowlers where the wicket-keeper stands just behind the stumps).

During the study period, 43 bowlers (33 male, 10 female) who did not have a LBSI at the start of the study period sustained a LBSI and were designated to the 'injured' group. Bowlers who sustained multiple LBSI were included once for their most recent injury. A 'non-injured' group of bowlers (n = 28: 18 male, 10 female) was included for comparison based on the following criteria: i) participated in the 2019-20 season (most recent complete season when this study was conducted), ii) had been in the state or national cricket program since July 2016, iii) had not sustained a LBSI since July 2016, and iv) had no other injury or illness which made them unavailable to train or play for more than four weeks consecutively since July 2016 (potential to confound data).

2.3. Procedures

2.3.1. Injury

A LBSI was defined as a region of bone stress in the posterior elements (pars, pedicle, lamina) of the lumbar vertebrae which was confirmed by magnetic resonance imaging (MRI) (abnormal bone marrow oedema +/- fracture) and required the bowler to stop bowling for a period of time (time-loss injury). A minimum time off was not defined, however the minimum number of days off for injuries which met the injury definition was 23 days. Some injuries were asymptomatic, identified through routine screening at the end of the season and managed with time off bowling – the methods used to describe whether asymptomatic bone stress was considered clinically relevant and required time-off bowling have been previously described (Kountouris et al., 2019; Sims et al., 2019). A recurrent LBSI occurred at the same site as a previous LBSI after successfully returning to match availability as a bowler following the previous injury. Return to match availability was determined by the team doctor and physiotherapist, based upon clinical assessments, imaging, and clinical judgement for each individual bowler. Previous LBSI were described as healed if the fracture (if present) was reported as united and bone marrow oedema resolved on follow-up MRI.

2.3.2. Musculoskeletal screening

Cricket players routinely complete a musculoskeletal screening assessment prior to the start of the cricket season (between June and October). The assessments are standardised and performed by a team physiotherapist. The most recent screening during the study period was selected for non-injured bowlers, and the most recent screening prior to injury was selected for injured bowlers.

In some cases, assessments were not completed annually, hence the most recent season with data available may have been one (injured n = 8) or two (injured n = 1) seasons prior.

Screening assessments included: height, lower limb length (sitting height subtracted from height), weight, ankle dorsiflexion range of motion (Dennis et al., 2008), Star Excursion Balance Test (Hertel et al., 2006), lumbar lateral flexion (Nealon & Cook, 2018), trunk rotation (Johnson & Grindstaff, 2010), Modified Thomas hip extension (Kendall et al., 1993), active knee extension (Dennis et al., 2008), passive hip internal rotation (Nussbaumer et al., 2010), bent knee fall out (Malliaras et al., 2009), Biering-Sorenson test (Biering-Sorensen, 1984), hip abduction and adduction strength (Thorborg et al., 2010), groin squeeze strength (Delahunt et al., 2011), hip flexion and extension strength (Thorborg et al., 2010), lumbopelvic control (Mills et al., 2005), Beighton Hypermobility Scale (Smits-Engelsman et al., 2011), single leg hamstring bridge (Freckleton et al., 2014), single leg decline squat (Bayne et al., 2016), and calf raises (Dennis et al., 2008). Test procedures are detailed in Supplementary Table 1. When a test involved assessing lower limbs separately, the limb side was denoted as either front foot (FF: the foot contralateral to the bowling arm) or back foot (BF: the foot ipsilateral to the bowling arm).

2.3.3. *Bowling technique*

Cricket players routinely complete a three-dimensional (3-D) bowling technique assessment at a time of convenience throughout the year. The assessments are performed in an indoor environment with a full length run up. The most recent screening during the study period was selected for non-injured bowlers, and the most recent screening prior to injury was selected for the injured bowlers. In some cases, assessments were not completed annually, hence the most recent season with data available may have been one (injured n = 6, non-injured n = 4), two (injured n = 7, non-injured n = 4), or three or more (injured n = 1, non-injured n = 4) seasons prior.

A standard protocol was used for biomechanical assessments that included the bowler performing their warm-up and several warm-up deliveries. The assessment consisted of the bowler bowling 18 deliveries, each aimed at a specific region on the pitch: full length (yorker), good length, or bouncer. Ball speed was captured with a radar (Stalker Pro II radar, 34.7 GHZ) mounted in front of the bowler approximately 20 metres from the point of delivery at a height of approximately two metres.

Deliveries were recorded by a 20 camera Vicon Motion Analysis System (Oxford Metrics, Oxford UK) operating at 250 Hz. Sixty-three, 14mm diameter, spherical reflective markers were attached to bony landmarks using adhesive and double-sided tape according to a previously described Vicon plug-in-gait upper body model and lower limb marker set and model (Schache et al., 2006).

Data processing involved selecting six deliveries to three specific regions (two at each region) in addition to the maximum ball speed achieved. Marker trajectories were filtered using a fourth-order low-pass Butterworth filter with cut-off frequency of 10Hz. Back foot flat (BFF) was defined as the lowest point of the calcaneus marker following the foot contacting the ground (Ranson et al., 2008). Front foot contact (FFC) was defined as the first frame the forefoot contacted the ground (Ranson et al., 2008; Worthington et al., 2013), both determined from marker trajectories. A simple method of determining ball release (BR) was calculated from a high-speed camera (Bonita 720c, 125fps) placed perpendicular to the bowling crease and was defined as one frame prior to the first frame that the ball was no longer in contact with the hand (Wells et al., 2015).

The laboratory coordinate system was defined as the y-axis orientation along the length of the pitch (positive in the direction of travel), the x-axis orientation along the width of the pitch (positive to the right of the bowler in the direction of travel) and the z-axis orientation vertically (positive upwards). For each segment the y-axis was orientated forwards with positive in the direction of travel, the x-axis bisected this with positive towards the bowler's right, and the z-axis orientated along the longitudinal axis. The orientation of each segment in the laboratory co-ordinate system was such that rotation about the x-axis was flexion-extension, about the y-axis was adduction-abduction, and about the z-axis longitudinal rotation. All segment and joint angles were calculated as Cardan angles, using an xyz sequence except for thorax and pelvis segments that were calculated using zyx (Baker, 2001). Anatomical position is 180^o; flexion, contralateral side flexion, rotation and anterior tilt is $<180^o$.

To align this research with previous cricket biomechanics literature the following segments were defined. The shoulder segment was defined by projecting a three-dimensional line between the left and right acromia in the transverse (Ranson et al., 2008). Thorax segment was defined by previously described Vicon plug-in-gait upper body model and pelvis segment marker set and model (Schache et al., 2006). The shoulder and pelvis segments were measured relative to the laboratory co-ordinate system. Shoulder counter-rotation was calculated by subtracting the maximum shoulder angle after BFF from the shoulder angle at the point of BFF about the z-axis or transverse plane (Portus et al., 2004). Hip-shoulder separation angle was calculated by subtracting the shoulder angle from the pelvis angle at BFF about the z-axis or transverse plane (Portus et al., 2004). Lateral flexion was defined as the rotation of the thorax about the pelvis in the y-axis or frontal plane (Bayne et al., 2016). Thoraco-pelvic extension was defined as the rotation of the thorax about the pelvis in the x-axis or sagittal (Alway et al., 2020).

2.3.4. *Bowling frequency*

The number of balls bowled in training and matches was recorded by the bowler in a custom database with mobile application interface (Athlete Management System, Fair Play Pty Ltd.). Bowling frequency (balls and days bowled) was calculated as averages over the previous four-, 12-, and 52-week windows calculated from the end of the respective Australian cricket season (March 31) for non-injured bowlers or from the date of injury diagnosis for injured bowlers.

2.4. *Analysis*

Analysis was completed using SPSS (version 25, IBM, Armonk, NY, USA). Independent samples T-tests were used to compare individual characteristics of male and female bowlers. Independent samples median tests were used to compare bowling frequency variables of male and female bowlers. Limited research on elite female fast bowlers has demonstrated differences in bowling technique compared to elite male fast bowlers (Felton et al., 2019). However, visual inspection of scatterplots revealed no notable increase in variability by combining male and female data across technique data, nor musculoskeletal and bowling frequency data. Therefore, we determined it was reasonable to conduct analyses on grouped male and female data, with further analysis by sex for any variables found to be of potential interest from the grouped analysis. Variability was increased for height, weight, lower limb length (consistent with Stuelcken et al., 2007), and ball speed so these were analysed separately for males and females.

Visual inspection of frequency histograms revealed data was not normally distributed for all variables, however, was acceptable for linear regression. For accuracy and consistency, central tendency is reported as median and interquartile range (IQR) for all variables. Proportions were calculated with a Wilson 95% confidence interval (CI).

To compare injured and non-injured groups, analyses were performed using binary logistic regression (method: enter) with injury as the dependent variable and non-injured bowlers acting as the control. Univariate analyses were conducted on all variables for all bowlers. Results of the univariate analysis informed variables included in multivariate analysis. To reduce the number of Type 1 errors from analysing a large number of variables (n=110), a Bonferroni-corrected p-value of 0.0005 was set as the absolute cut-off for inclusion in the multivariate analysis. However, it is necessary to acknowledge the elite athlete cohort and relatively small sample size which preclude such a small statistical cut-off. Hence, we also applied clinical judgement and previous research to decide on variables which may be significant in practice for inclusion in the multivariate analyses. Linear regression with collinearity diagnostics were used to assess multicollinearity.

3. Results

Most LBSI occurred on the side contralateral to the bowling arm (81% [95% CI 67–90]) and at levels L4 (42% [28–57]) and L5 (33% [20–47]) (Table 1). Twenty-seven bowlers (63% [48–76]) had a history of LBSI either at the same or different location to the LBSI included in this study. Of these, 22 LBSI were recurrent injuries, occurring a median of 161 (79–640) days since returning to match availability following the previous LBSI. Fourteen of the 22 bowlers with recurrent LBSI also had a history of LBSI at a different location. Nine of the 28 non-injured bowlers had a history of LBSI, occurring a median of 1997 (1955–2279) days (approximately 5–6 years) prior to the end of the study capture. The likelihood of LBSI increased by a factor of 3.94 (1.43–10.83) ($p = 0.008$) if bowlers had a history of any LBSI previously.

Individual characteristics of injured bowlers and non-injured bowlers are presented in Table 2. Comparing male and female bowlers, there was no difference in age ($p = 0.219$), however male bowlers were taller, had longer lower limb lengths, and higher weight (all $p < 0.001$). Comparing injured and non-injured bowlers, injured bowlers were younger ($p = 0.007$), with the likelihood of injury reducing by a factor of 0.85 (0.76-0.96) with each year older. Injured bowlers did not statistically differ on any musculoskeletal characteristics (Table 3) or bowling technique (Table 4) variables.

Table 1: Injury details and injury history of injured bowlers

	Male (n=33)	Female (n=10)	All (n=43)	All percent (95% CI)
Injured side relative to bowling arm				
Contralateral	27	8	35	81 (67-90)
Ipsilateral	5	1	6	14 (7-27)
Bilateral	1	1	2	5 (1-15)
Injured lumbar vertebrae				
L2	2	0	2	5 (1-15)
L3	3	0	3	7 (2-19)
L4	16	2	18	42 (28-57)
L5	9	5	14	33 (20-47)
Multiple	3	3	6	14 (7-27)
Recurrent injury (n=22)				
Recurrent, previously healed	9	1	10	48 (28-68)
Recurrent, previous did not heal[a]	10	1	11	52 (32-72)
History of other LBSI (n=20)				
Other LBSI, same level	6	1	7	35 (18-57)
Other LBSI, different level	12	1	13	65 (43-82)
Other LBSI, contralateral	6	1	7	35 (18-57)
Other LBSI, ipsilateral	10	1	11	55 (34-74)
Other LBSI, bilateral	2	0	2	10 (3-30)
Other LBSI, healed	12	2	14	70 (48-85)
Other LBSI, did not heal[a]	6	0	6	30 (15-52)

Note: [a]Cases with healing status unknown not included in data. Proportions calculated from total of known cases.

Table 2: Individual characteristics of injured and non-injured bowlers

	Injured bowlers[a]			**Non-injured bowlers[a]**			**Injured Vs All Non-injured[b]**	
Individual characteristics	**All (n=43)**	**Male (n=33)**	**Female (n=10)**	**All (n=28)**	**Male (n=18)**	**Female (n=10)**	**Odds ratio (95% CI)**	***p***
Age (years)	21.5 (19.8-25.4)	22.6 (19.8-25.7)	20.9 (18.1-22.3)	26.4 (22.3-30.0)	27.5 (23.0-30.0)	23.4 (21.6-29.0)	All: 0.85 (0.76-0.96) Male: 0.84 (0.72-0.97) Female: 0.83 (0.66-1.05)	All: 0.007 Male: 0.016 Female: 0.115
Height (cm)	190.5 (184.3-193.0)	192.0 (190.0-195.0)	174.3 (169.1-178.0)	185.2 (175.3-191.3)	187.5 (185.4-195.0)	173.1 (169.0-174.5)	All: 1.04 (0.99-1.09) Male: 1.08 (0.96-1.22) Female: 1.05 (0.89-1.23)	All: 0.146 Male: 0.176 Female: 0.575
Lower limb length (cm)	93.1 (87.9-96.3)	94.5 (93.0-97.4)	85.3 (81.9-86.4)	91.3 (85.9-94.0)	93.0 (91.5-96.0)	85.0 (82.9-86.1)	All: 1.03 (0.94-1.12) Male: 1.02 (0.88-1.18) Female: 1.02 (0.78-1.33)	All: 0.515 Male: 0.768 Female: 0.898
Weight (kg)	86.7 (78.0-92.9)	90.4 (85.5-95.7)	69.5 (66.1-74.0)	84.4 (76.6-92.7)	89.2 (83.3-94.4)	74.8 (66.0-77.0)	All: 1.02 (0.97-1.06) Male: 1.02 (0.94-1.11) Female: 0.97 (0.86-1.09)	All: 0.478 Male: 0.631 Female: 0.555

Note: [a]Descriptive data presented as median (interquartile range). [b]*p*-value compares injured vs all non-injured bowlers for each of the 3 groups: all, male, female.

Table 3: Musculoskeletal characteristics (trunk and lower limb) of injured and non-injured bowlers

	Injured bowlers[a]			**Non-injured bowlers[a]**			**All Injured Vs All Non-Injured**
Musculoskeletal variables	**All (n=41)**	**Male (n=31)**	**Female (n=10)**	**All (n=28)**	**Male (n=18)**	**Female (n=10)**	***p***
Ankle dorsiflexion (FF) (cm)	12 (11-13)	12 (11-14)	11 (11-12)	13 (11-15)	14 (10-16)	13 (12-15)	0.328
Ankle dorsiflexion (BF) (cm)	12 (11-14)	12 (11-14)	12 (12-13)	13 (10-15)	14 (11-17)	11 (9-14)	0.729
Star Excursion Balance Test total (FF) (cm)	106 (101-111)	106 (101-111)	106 (100-107)	107 (98-111)	108 (102-112)	100 (94-105)	0.806
Star Excursion Balance Test total (BF) (cm)	106 (101-112)	107 (102-112)	104 (99-107)	103 (98-111)	109 (98-112)	98 (96-101)	0.286
Lumbar lateral flexion (FF) (cm)	47 (44-50)	48 (46-52)	42 (40-47)	47 (46-50)	47 (47-50)	46 (45-48)	0.493
Lumbar lateral flexion (BF) (cm)	46 (43-50)	47 (44-51)	43 (41-46)	46 (45-48)	47 (45-49)	46 (45-47)	0.939
Trunk rotation (FF) (deg)	72 (70-80)	72 (70-80)	67 (55-75)	72 (65-90)	70 (62-90)	76 (71-84)	0.405
Trunk rotation (BF) (deg)	75 (65-80)	75 (70-80)	65 (64-76)	75 (66-90)	75 (60-90)	75 (71-83)	0.664
Modified Thomas hip extension (FF) (deg)	0 (-3-0)	0 (-1-0)	-1 (-4-0)	-1 (-4-0)	-2 (-3-0)	-1 (-3- -1)	0.515
Modified Thomas hip extension (BF) (deg)	0 (-2-0)	0 (-1-0)	-1 (-2-0)	-1 (-2-0)	0 (-2-0)	-1 (-2- -1)	0.988
Active knee extension (FF) (deg)	70 (63-77)	70 (62-77)	70 (65-76)	72 (66-80)	74 (69-78)	69 (59-80)	0.517
Active knee extension (BF) (deg)	70 (67-79)	70 (65-78)	80 (70-84)	72 (65-79)	72 (65-78)	72 (62-79)	0.724
Passive hip internal rotation in hip flexion (FF) (deg)	30 (26-37)	30 (23-37)	29 (27-36)	34 (28-45)	34 (23-45)	38 (33-45)	0.286
Passive hip internal rotation in hip flexion (BF) (deg)	28 (24-40)	27 (23-40)	37 (27-48)	32 (22-40)	26 (19-40)	34 (28-45)	0.806

Table 3 continued: Musculoskeletal characteristics (trunk and lower limb) of injured and non-injured bowlers

	Injured bowlers[a]			**Non-injured bowlers[a]**			**All Injured Vs All Non-Injured**
Musculoskeletal variables	**All (n=41)**	**Male (n=31)**	**Female (n=10)**	**All (n=28)**	**Male (n=18)**	**Female (n=10)**	***p***
Bent knee fall out (FF) (cm)	15 (15-19)	15 (14-19)	15 (15-18)	14 (11-17)	16 (14-17)	14 (10-15)	0.205
Bent knee fall out (BF) (cm)	15 (14-18)	15 (14-18)	15 (12-16)	14 (10-16)	14 (12-17)	13 (10-13)	0.153
Biering-Sorenson test (sec)	150 (120-180)	150 (129-180)	106 (97-125)	135 (119-180)	159 (105-180)	134 (122-158)	0.550
Hip abduction strength (FF) (N)	211 (174-253)	228 (211-266)	165 (143-169)	202 (169-231)	226 (204-237)	149 (149-171)	0.545
Hip abduction strength (BF) (N)	214 (185-246)	231 (206-255)	167 (158-171)	209 (183-237)	220 (200-244)	184 (140-187)	0.650
Hip adduction strength (FF) (N)	216 (184-249)	237 (210-268)	147 (134-154)	193 (158-231)	230 (203-262)	149 (138-176)	0.732
Hip adduction strength (BF) (N)	220 (180-244)	231 (215-261)	138 (132-156)	201 (158-239)	239 (202-259)	154 (149-158)	0.866
Groin squeeze strength (N)	312 (245-387)	352 (292-394)	233 (222-240)	279 (221-355)	334 (268-413)	224 (217-245)	0.406
Hip flexion strength (FF) (N)	383 (317-431)	409 (369-440)	269 (255-294)	367 (325-437)	418 (356-448)	323 (292-360)	0.985 Female: 0.100
Hip flexion strength (BF) (N)	378 (324-442)	418 (375-451)	264 (255-303)	365 (326-431)	400 (356-454)	325 (292-352)	0.464 Female: 0.140
Hip extension strength (FF) (N)	347 (290-391)	360 (321-405)	270 (235-333)	369 (305-406)	378 (334-415)	352 (277-379)	0.271 Female: 0.097
Hip extension strength (BF) (N)	343 (318-400)	388 (336-404)	290 (251-328)	369 (316-405)	375 (325-409)	352 (316-392)	0.568 Female: 0.095
Lumbopelvic control grade	4 (2-5)	4 (3-5)	2 (1-4)	3 (2-4)	4 (2-5)	2 (2-3)	0.411
Beighton Hypermobility Scale	0 (0-2)	0 (0-2)	0 (0-2)	1 (0-5)	0 (0-2)	3 (0-6)	0.068 Male: 0.440 Female: 0.119
Single leg hamstring bridge total (FF)	30 (22-30)	30 (24-30)	21 (17-30)	25 (21-30)	30 (25-30)	18 (13-21)	0.262
Single leg hamstring bridge total (BF)	30 (20-30)	30 (24-30)	21 (20-28)	24 (19-30)	20 (24-30)	18 (13-21)	0.168
Single leg decline squat (FF) (0-2)	2 (1-2)	2 (1-2)	2 (1-2)	2 (1-2)	2 (1-2)	2 (1-2)	0.516
Single leg decline squat (BF) (0-2)	2 (1-2)	2 (1-2)	2 (1-2)	1 (1-2)	1 (1-2)	1 (1-2)	0.407
Calf raises total (FF)	23 (20-25)	24 (20-25)	23 (22-26)	25 (21-25)	25 (25-25)	19 (17-25)	0.502
Calf raises total (BF)	25 (20-25)	24 (20-25)	25 (21-26)	25 (22-25)	25 (25-25)	22 (19-25)	0.293

Note: [a]Data presented as median (interquartile range). Abbreviations: BF = back foot, FF = front foot, N = newton.

Table 4: Bowling technique of injured and non-injured bowlers

	Injured bowlers[a]			**Non-injured bowlers[a]**			**All Injured Vs All Non-Injured**
Technique variables	**All (n=25)**	**Male (n=21)**	**Female (n=4)**	**All (n=18)**	**Male (n=13)**	**Female (n=5)**	***p***
Pelvis rotation (BFF) (deg)	235 (227-245)	235 (227-245)	235 (131-240)	231 (223-244)	230 (223-243)	243 (226-254)	0.613
Shoulder rotation (BFF) (deg)	219 (209-234)	214 (209-228)	235 (230-239)	219 (203-228)	221 (202-231)	210 (208-221)	0.535
Shoulder counter rotation (deg)	32 (22-41)	32 (26-46)	27 (19-34)	36 (23-45)	31 (23-47)	42 (32-42)	0.791
Lateral flexion (FFC) (deg)	172 (167-180)	171 (167-178)	184 (174-189)	176 (167-180)	175 (167-181)	180 (172-183)	0.810
Lateral flexion (BR) (deg)	149 (140-153)	146 (140-153)	155 (144-162)	146 (140-153)	146 (140-149)	152 (140-153)	0.951
Lateral flexion minimum (deg)	143 (136-148)	143 (137-146)	160 (142-162)	143 (136-150)	142 (136-147)	152 (137-153)	0.815
Hip/shoulder separation (BFF) (deg)	15 (7-24)	18 (13-25)	1 (-3-5)	18 (6-23)	18 (7-23)	N/A	0.752
Thoraco-pelvic extension (BFF) (deg)	174 (165-180)	172 (164-177)	178 (175-182)	172 (163-185)	171 (162-185)	172 (168-178)	0.703
Thoraco-pelvic extension (FFC) (deg)	190 (178-193)	187 (178-193)	192 (170-193)	185 (175-192)	181 (174-189)	194 (188-195)	0.156
Back knee angle (BFF) (deg)	135 (127-144)	135 (125-143)	139 (131-148)	139 (129-145)	139 (125-145)	137 (135-144)	0.860
Back knee angle minimum (deg)	116 (110-124)	122 (110-128)	111 (110-113)	117 (105-130)	119 (104-131)	N/A	0.533
Front knee angle (FFC) (deg)	169 (162-173)	167 (162-172)	175 (172-176)	167 (157-175)	166 (157-170)	176 (173-176)	0.240
Front knee angle (BR) (deg)	163 (131-178)	163 (131-172)	174 (159-182)	164 (144-178)	165 (136-177)	164 (163-173)	0.749
Front knee angle minimum (deg)	154 (132-163)	150 (132-163)	162 (146-172)	157 (134-164)	152 (130-165)	N/A	0.695
Ball speed maximum (km/h)	125 (116-132)	128 (124-132)	104 (101-105)	123 (109-127)	126 (122-128)	104 (99-108)	0.204 Male: 0.318 Female: 0.859

Note: [a]Data presented as median (interquartile range). Abbreviations: BFF = back foot flat, FFC = front foot contact, BR = ball release.

Table 5: Bowling frequency preceding injury of injured bowlers and end of season for non-injured bowlers

	Injured bowlers[a]			**Non-injured bowlers**[a]			**All Injured Vs All Non-Injured**[b]
Bowling frequency variables	**All (n=43)**	**Male (n=33)**	**Female (n-10)**	**All (n=28)**	**Male (n=18)**	**Female (n=10)**	***p***
Total balls previous 4 weeks	343 (219-457)	389 (234-503)	282 (54-357)	288 (143-550)	390 (302-591)	48 (0-156)	All: 0.992 Male: 0.119 Female: 0.039
Total days previous 4 weeks	10 (7-12)	10 (7-12)	9 (2-11)	5 (4-9)	9 (5-10)	2 (0-5)	All: 0.028 Male: 0.570 Female: 0.026
Total balls previous 12 weeks	1059 (700-1332)	1080 (702-1344)	846 (588-1144)	1220 (827-1673)	1543 (1212-1821)	755 (581-873)	All: 0.084 Male: 0.007 Female: 0.341
Total days previous 12 weeks	28 (19-35)	27 (23-35)	31 (19-35)	29 (22-33)	32 (28-37)	20 (18-25)	All: 0.860 Male: 0.092 Female: 0.074
Total balls previous 52 weeks	3542 (3170-4284)	3632 (3232-4358)	3384 (2678-3742)	4507 (3290-5849)	5383 (4945-5946)	3021 (2630-3419)	All: 0.024 Male: 0.001 Female: 0.477
Total days previous 52 weeks	97 (86-113)	96 (85-107)	106 (90-118)	106 (93-120)	115 (103-125)	95 (83-103)	All: 0.106 Male: 0.012 Female: 0.255

Note: [a]Data presented as median (interquartile range). [b]*p*-value compares all injured Vs all non-injured bowlers for each of the 3 groups: all, male, female.

Bowling frequency variables are presented in Table 5. Comparing male and female bowlers, male bowlers bowled more balls over the previous four ($p = 0.005$), 12 ($p = 0.005$), and 52 weeks ($p = 0.021$). There was no difference in the number of days bowled over the previous four ($p = 0.067$), 12 ($p = 0.342$), and 52 weeks ($p = 0.473$). Injured bowlers tended to bowl more days in the previous four weeks ($p = 0.028$), and less balls in the previous 52 weeks ($p = 0.024$). When separated by sex, injured female bowlers bowled more balls ($p = 0.039$) and days ($p = 0.026$) in the previous four weeks. Injured male bowlers bowled less balls in the previous 12 weeks ($p = 0.007$), and less balls ($p = 0.001$) and less days ($p = 0012$) in the previous 52 weeks. Due to the strong multicollinearity between bowling frequency variables, total days bowled in the previous four weeks was selected as the only bowling frequency variable to include in the multivariate analyses based upon previous research in a similar cohort (Kountouris et al., 2019).

Age, history of any LBSI previously, and total days bowled in the previous four weeks were included in multivariate analyses based upon lower p-values and previous research (summarised in the introduction). The best model included all three variables (Chi-square = 28.9, $p < 0.001$). Younger age (odds ratio 0.73 [0.61–0.86], $p < 0.001$), history of any LBSI previously (8.84 [2.08–37.59], $p = 0.003$), and more days bowled in the previous four weeks (1.19 [1.03–1.38], $p = 0.018$) were associated with an increased likelihood of injury. The model explained 45% of the variance (Nagelkerke R square) and correctly classified 79% of cases.

4. Discussion

Lumbar bone stress injuries are a concern for fast bowlers, with the cost of injury including significant time off bowling (Frost & Chalmers, 2014; Orchard et al., 2016) and risk of subsequent injury (Cheung et al., 2018; Kountouris et al., 2018). Several risk factors have been purported in the literature (Alway et al., 2019a; Alway et al., 2020; Bayne et al., 2016; Dennis et al., 2005; Elliott et al., 1992; Foster et al., 1989; Kountouris et al., 2019; Orchard et al., 2015a; Portus et al., 2004), however their relative importance is unclear. This study addressed some limitations of previous research by conducting multifactorial analysis for a relatively large cohort of elite male and female fast bowlers over a four-year period to further understand the contribution of purported risk factors to LBSI.

History of any LBSI previously was the strongest factor associated with LBSI in elite fast bowlers, increasing the likelihood of injury by a factor of 3.94 (1.43–10.83) when considered independently, and 8.84 (2.08–37.59) when considered alongside age and total days bowled in the previous four weeks. This is the first time an association between previous and subsequent LBSI has been reported in cricket players. Systematic reviews of risk factors of non-contact injury in adolescent fast bowlers (Forrest et al., 2017) and lower back pain in fast bowlers (Morton et al., 2014) did not include previous stress fracture or bone stress injury. A history of stress fracture has been associated with increased risk of subsequent stress fracture in adolescent female athletes (Nose-Ogura et al., 2019) and runners (Wright et al., 2015), likely related to persistence of factors which contributed to the earlier injury contributing to the subsequent injury (Beck & Drysdale, 2021). An additional factor resulting from the previous injury is that the bone mineral density may be lower at the previously injured site (Beck & Drysdale, 2021). Initial research in this area in elite fast bowlers suggests that bone mineral density of lumbar vertebrae may be lower for bowlers with a history of stress fracture, however further research is needed to elucidate whether this may be a cause or consequence of injury (Alway et al., 2019b). Resumption of bowling once there is no visible fracture line and bone marrow oedema has resolved (Singh et al., 2021) may be premature if bone mineral density has not been sufficiently restored.

Younger age was a strong factor associated with LBSI, with injured bowlers on average five years younger than non-injured bowlers (21.5 [19.8–25.4] vs 26.4 [22.3–20.0], $p = 0.007$). This finding was irrespective of sex and is consistent with previous research which has found fast bowlers under 22 years of age are at three to four times the risk of a bone stress injury, most commonly involving the lumbar spine (Alway et al., 2019a; Blanch et al., 2015). Similarly, across other sports, younger athletes and those less skeletally mature have consistently been found to be at greater risk of LBSI (Blanch et al., 2015; Cyron & Hutton, 1978; Fournier et al., 1997; Fredrickson et al., 1984; Kim & Green, 2011; Micheli & Wood, 1995). These findings align with the theory of bone maturation, whereby peak bone mineral density of the lumbar spine does not occur until approximately 23 years of age in males (Xue et al., 2020), with increases of up to 10% in bone mineral content occurring after linear growth has ended (McCormack et al., 2017). Bone mineral density has been shown to positively adapt to the specific stresses of fast bowling (Alway et al., 2019b; Keylock et al., 2021). Therefore, it is important to consider other factors alongside age which may contribute to bone adaptation or maladaptation with fast bowling.

Bowling technique and musculoskeletal variables did not reveal any strong, consistent risk factors for LBSI. This may in-part be attributed to a lack of precision in the measurement of lumbar motion using the current 3-D bowling biomechanical model. Recent refinements in the modelling of bowling technique separate lateral flexion between the thoracolumbar and lumbopelvic regions, with injured bowlers displaying larger lateral flexion (non-significant, medium effect) at the lumbopelvic junction (Alway et al., 2020). Musculoskeletal screening assessments are not well supported as indicators of injury risk (Bahr, 2016), like biomechanics screenings, they typically only provide a snapshot in time of a movement quality, range or muscle strength, often at a considerable time frame before an individual is injured. They also do not take into account the effect of fatigue on muscle strength and movement control. Although screening tests may not be good predictors of injury, they may still be useful in combination with biomechanical screening to provide individualised interpretation. For example, identifying ranges of available motion or muscle strength that may impact on a bowler’s ability to efficiently transfer the momentum generated from their run up through the delivery stride and into the ball.

Bowling frequency analyses showed different patterns between male and female, injured and non-injured bowlers. Injured female bowlers had a higher bowling frequency in the previous four weeks compared to their non-injured counterparts. Conversely, injured male bowlers tended to have a lower bowling frequency in the previous 12- and 52-weeks compared to their non-injured counterparts. These findings are inconsistent with previous research which has shown a higher bowling frequency in the 12 weeks preceding injury to be associated with LBSI in adolescent male fast bowlers (Kountouris et al., 2019; Sims et al., 2021) and adult male professional fast bowlers (Alway et al., 2019a; Orchard et al., 2015a). The findings of this study must be interpreted with caution, considering the potential inaccuracies of bowler-reported data and the inherent disparity between bowling frequencies taken from the day of injury diagnosis for injured bowlers and from the end of the season for non-injured bowlers. It is also important to note that bone stress develops over time and the date of diagnosis is not at a consistent stage of bone stress (Kountouris et al., 2018). For some bowlers this may mean that low level symptoms that did not trigger investigation and diagnosis may have led to modified bowling loads prior to diagnosis. An additional consideration is that non-injured bowlers were older and hence may have progressed to higher bowling loads.

The stringent criteria for the control group were intended to provide a true representation of 'non-injured' or 'resilient' bowlers. As such, it was not possible to match each individual injured bowler with a sex- and age-matched control which would have strengthened statistical analyses. Due to the relatively small number of female bowlers included in the study, comparison between injured and non-injured female bowlers is statistically underpowered. With ongoing monitoring, it will be possible to conduct follow-up research with a larger dataset to further understand the risk factors in female bowlers.

Ultimately, injury is an outcome of a complex system with multiple interacting layers of individual and ecological factors (Hulme & Finch, 2015). Collapsing the complex system down to a handful of routinely monitored variables, as in this study, has inherent limitations. A further limitation is the use of statistics evaluating a linear relationship, when the relationship between factors and injury is likely non-linear (Bittencourt et al., 2016). Future research with a larger, international dataset may lend to more complex analyses to identify patterns of factors which increase injury risk. Another direction for future research is to focus more specifically on the bone structure and tissue capacity of the lumbar vertebrae.

The overarching finding of this study is that history of any LBSI previously, younger age, and higher bowling frequency in the previous four weeks explain approximately 45% of LBSI risk in elite fast bowlers. The remaining 55% is not explained by any individual, musculoskeletal, or technique variables across all bowlers. All variables logically contribute to injury risk, yet their interaction is likely unique and changes over time. A primary goal for injury prevention should be to reduce the risk of a bowler sustaining a LBSI by taking into consideration any history of LBSI and the age of the bowler when prescribing bowling frequency. This will require coaches, parents, and young bowlers to work together to monitor and manage bowling frequency to an appropriate level for the developing vertebrae, gradually increasing bowling frequency as the musculoskeletal system develops and adapts to the specific demands of bowling. Bowling frequency cannot be universally prescribed; however this study and previous research suggests 1–3 days between bowling days allows the tissue to recover from the stress of bowling (Dennis et al., 2005; Kountouris et al., 2018; Orchard et al., 2015a). An individualised and adaptive approach to fast bowler preparation may also address other factors such as musculoskeletal characteristics or bowling technique if deemed relevant to the individual at the time. An additional tool in the management of more elite fast bowlers, if feasible, is to incorporate routine imaging to detect pre-symptomatic bone stress and indicate the need for de-loading of the tissue to prevent progression to a more severe LBSI (Kountouris et al., 2018; Kountouris et al., 2019; Sims et al., 2019).

Conflict of Interest

The authors declare no conflict of interests.

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Supplementary Table 1: Musculoskeletal screening tests

Musculoskeletal test	**Procedure**
Ankle dorsiflexion	Foot positioned on tape measure with zero mark at the wall. Athlete lunges forward, keeping heel on ground, until knee touches the wall (Dennis et al., 2008).
Star Excursion Balance Test	Modified procedure as described by Hertel et al. (2006) measuring distance reached by one limb in the anterior, postero-medial and postero-lateral directions while maintaining single leg balance on the contra-lateral limb.
Lumbar lateral flexion	Athlete stands side on to wall with lateral hip in contact with wall and shoulder nearest wall abducted/elbow flexed. Athlete laterally flexes away from wall and distance to floor from fingertips is measured (Nealon & Cook, 2018).
Trunk rotation	Athlete sitting with stick held across front of shoulders. Trunk rotation measured with goniometer arms aligned with stick and starting position (modified from Johnson & Grindstaff, 2010)
Modified Thomas hip extension	Athlete supine on plinth with knees hanging free, flexes contralateral hip to chest and inclinometer used to measure the range of hip extension on ipsilateral hip (modified from Kendall et al., 1993).
Active knee extension	Athlete supine on bed maintains ipsilateral hip in 90 degrees hip flex with contralateral resting on bed. Athlete extends ipsilateral knee to end range and measured with inclinometer (Dennis et al., 2008).
Passive hip internal rotation in hip flexion	Athlete supine with hip flexed to 90 degrees. Range of internal rotation measured with long arm goniometer (Nussbaumer et al., 2010).
Bent knee fall out	Athlete supine with hips flexed to 45 degrees. Both hips passively abducted and externally rotated keeping feet together. Distance from fibular head to bed measured with tape measure (Malliaras et al., 2009).
Biering-Sorenson test	Athlete lies prone with trunk off edge of bed and lower body secured. Length of time trunk can be maintained horizontal is measured (Biering-Sorensen, 1984).
Hip abduction and adduction strength	Athlete supine on plinth. Hip abduction and adduction resisted and measured with handheld dynamometer (Thorborg et al., 2010).
Groin squeeze strength	Athlete lies supine on the bed in the crook lying position (hips flexed to 45°, knees flexed to 90°). Maximum adduction/squeeze effort measured with handheld dynamometer (Delahunt et al., 2011).
Hip flexion and extension strength	Athlete lies prone (hip extension) or sits on edge of plinth (hip flexion) and manual resistance applied and measured with hand held dynamometer (Thorborg et al., 2010).
Lumbopelvic control	Athlete lies supine with knees bent to 45 degrees and posteriorly tilts pelvis to lightly flatten lumbar spine onto bed. Progressive leg loading is then performed to the point where the athlete is unable to maintain the lumbar spine in contact with the bed (modified from (Mills et al., 2005)).
Beighton Hypermobility Scale	A series of limb and trunk movements evaluated for excessive mobility as previously described (Smits-Engelsman et al., 2011).
Single leg hamstring bridge	Athlete lies supine with foot on 60 cm high step with knee flexed to approximately 20 degrees. Contralateral hip is maintained in 90 degrees hip flexion and the number of hamstring bridges is recorded (Freckleton et al., 2014).
Single leg decline squat	Athlete stands on one leg on a decline board with arms folded across chest and the non-weight bearing knee in 90 degrees flexion with the hip in neutral. The athlete performs a single leg squat to 90 degrees of knee flexion. From an anterior view the examiner makes a subjective evaluation of the amount of femoral adduction and rates it either normal or excessive. From a posterior view the examiner makes a subjective judgement on whether the athlete maintains the trunk and pelvis in a level position (normal) or if there is excessive motion of these regions (modified from Bayne et al., 2016).
Calf raises	Athlete performs repeated single leg heel raises at a frequency of 25 raises per minute to a maximum of 25 repetitions (modified from Dennis et al., 2008)