BMJ Open Sport & Exercise Medicine

Biomechanical risk factors of lower back pain in cricket fast bowlers using inertial measurement units: a prospective and retrospective investigation

Billy Senington,[1] Raymond Y Lee,[2] Jonathan M Williams [3]

To cite: Senington B, Lee RY, Williams JM. Biomechanical risk factors of lower back pain in cricket fast bowlers using inertial measurement units: a prospective and retrospective investigation. *BMJ Open Sport & Exercise Medicine* 2020;**6**:e000818. doi:10.1136/bmjsem-2020-000818

► Additional material is published online only. To view please visit the journal online (http://dx.doi.org/10.1136/bmjsem-2020-000818).

This article is derived from the thesis http://eprints.bournemouth.ac.uk/31682/1/SENINGTON%2CBilly_Ph.D._2018.pdf archived in the Bournemouth University repository.

Accepted 2 July 2020

[1]School of Biosciences and Medicine, University of Surrey, Guildford, UK
[2]Faculty of Technology, University of Portsmouth, Portsmouth, UK
[3]Department of Rehabilitation and Sport Sciences, Bournemouth University, Bournemouth, UK

Correspondence to
Dr Jonathan M Williams; jwilliams@bournemouth.ac.uk

ABSTRACT

Objectives To investigate spinal kinematics, tibial and sacral impacts during fast bowling, among bowlers with a history of low back pain (LBP) (retrospective) and bowlers who developed LBP in the follow-up season (prospective).

Methods 35 elite male fast bowlers; senior (n=14; age=24.1±4.3 years; height=1.89±0.05 m; weight=89.2±4.6 kg) and junior (n=21; age=16.9±0.7; height=1.81±0.05; weight=73.0±9.2 kg) were recruited from professional county cricket clubs. LBP history was gathered by questionnaire and development of LBP was monitored for the follow-up season. Spinal kinematics, tibial and sacral impacts were captured using inertial measurement units placed over S1, L1, T1 and anteromedial tibia. Bonferroni corrected pairwise comparisons and effect sizes were calculated to investigate differences in retrospective and prospective LBP groups.

Results Approximately 38% of juniors (n=8) and 57% of seniors (n=8) reported a history of LBP. No differences were evident in spinal kinematics or impacts between those with LBP history and those without for seniors and juniors. Large effect sizes suggest greater rotation during wind-up (d=1.3) and faster time-to-peak tibial impacts (d=1.5) in those with no history of LBP. One junior (5%) and four (29%) seniors developed LBP. No differences were evident in spinal kinematics or impacts between those who developed LBP and those who did not for seniors. In seniors, those who developed LBP had lower tibial impacts (d=1.3) and greater lumbar extension (d=1.9) during delivery.

Conclusion Retrospective analysis displayed non-significant differences in kinematics and impacts. It is unclear if these are adaptive or impairments. Prospective analysis demonstrated large effect sizes for lumbar extension during bowling suggesting a target for future coaching interventions.

What does this study add?

- Retrospective analysis showed altered motion sharing with absence of thoracic rotation away from the direction of delivery ('wind-up') for juniors and greater front foot impacts (FFIs) for seniors in those bowlers with a history of low back pain (LBP).
- Prospective analysis showed lower tibial impact variables at FFI but over twice the range of lumbar extension at back foot impact in seniors who developed LBP.
- This is the first time inertial measurement units have been used to investigate fast bowling kinematics, sacral and tibial impacts during live cricket fast bowling and their relationship to LBP.

INTRODUCTION

Fast bowling injuries account for 44% of all injuries within cricket, with 22% of injury-related time-loss a result of lower back injury and pain in the fast bowling population.[1 2] Consequently, lower back injury has received much attention in the cricket literature.[3–5] Prevalence of lumbar spine abnormalities, such as spondylolysis and spondylolisthesis, have been reported as 24%–55% in the adult fast bowling population.[6–8] Junior bowlers' risk has been shown to be even greater with reported prevalence of 64%.[8 9] The fact that these injuries often result in long recovery times (an average of 32 games missed per reported stress fracture) amplifies the need for effective identification and management of risk factors.[10 11]

In the search for modifiable risk factors of low back injury, previous studies have investigated bowling technique.[12–14] Excessive shoulder counter-rotation (SCR) has been highlighted as a risk factor.[13 15] However, this metric is limited to a two-dimensional description of the orientation of the shoulders in the transverse plane, therefore three-dimensional kinematics are not known.[16] More recent studies have explored three-dimensional spinal kinematics using optoelectronic systems.[14 17 18] These studies have highlighted excessive contralateral lateral flexion and axial rotation of the spine as potential risk factors to lower back injury due to high compressive forces on the pars interarticularis.[19] However, only one study has reported a significant relationship between lateral flexion and lower back injury incidence.[17] Furthermore many studies have investigated ground reaction force and low back injury, with reviews concluding, that to date, no relationship has been established.[5]

Despite these preliminary findings linking spinal kinematics during bowling with low back injury risk, almost no attention has been paid to back pain. The relationship between spinal pathology and back pain is far from linear with high prevalence of MRI-determined spinal pathological changes in asymptomatic individuals.[20] Similarly, pathological changes in the lumbar spine have been detected in fast bowlers in the absence of back pain.[21] As pain is often the 'symptom' bowlers report, there is a paucity of literature investigating technique-related risk factors (spinal kinematics and ground reaction force) on back pain. In addition literature reviews do not separate out injury and pain.[4,22] Therefore it is not known whether bowling technique poses a risk factor for low back pain (LBP). If established, such information will enable coaches, medical staff and players to optimise both rehabilitation and preventative strategies, to minimise the risk of developing LBP.

The aim of this study was to explore, for the first time, the spinal kinematics, tibial and sacral impacts during fast bowling in bowlers with a history of LBP (retrospective) and in bowlers who went on to develop back pain in the follow-up season (prospective). In addition, this will be the first study to integrate the use of inertial measurement units (IMUs) to measure biomechanical variables during on the field fast bowling.

METHODS

This study adopted a retrospective and prospective cohort design.

Participants

Fast bowlers were recruited through coaches from professional county cricket clubs. Inclusion criteria included being classified as a fast bowler by a qualified cricket coach, over 3 years playing experience (regular training and match schedule), playing hard ball cricket, free of pain or injury at time of testing and aged between 11 years and 17 years for juniors and 18 years and 40 years for seniors. Sample size was derived from data from Portus *et al*[13] with an alpha of 0.05, beta 0.8, effect size of 2 and allocation ratio of 0.75, yielding a sample size requirement of seven and five per group, however it was not clear how many would develop pain; therefore a small over-recruitment was embedded. All participants (and where necessary parents) provided written, informed consent before participation.

Injury surveillance

Before the start of the 2015 season, history of LBP or injury was explored using a specifically created questionnaire developed to mirror a physiotherapy assessment, completed with the guidance of the researcher and the club physiotherapist where possible (online supplementary file 1). This provided the foundation for the retrospective analysis.

In addition, bowlers were instructed to keep a record of any LBP or injury during the 2015 season. LBP was defined as any pain affecting the area of the back inferior to the lower ribs, superior to the inferior gluteal folds and medial to the midaxillary line that impacted on their ability to bowl for a minimum of 3 days. This formed the foundation of the prospective analysis.

Instrumentation

Three IMUs (3AMG sensors, THETAmetrix, Portsmouth, Hampshire) housing triaxial accelerometers, magnetometers and gyroscopes were attached to the skin over the T1, L1 and S1 spinous processes using double-sided tape. Fusion of the sensing elements, sampling at 100 Hz, computed drift-free orientation for each sensor. An additional accelerometer (±200 g) (impact sensor, THETAmetrix, Portsmouth, Hampshire), sampling at 750 Hz was attached to the medial aspect of each tibia, re-inforced with elastic wrap.

Procedure

After a self-prescribed warm-up bowlers were instrumented with the sensors and bowled six bowls to familiarise themselves with bowling while instrumented. Following this, participants bowled six balls with maximal effort while data were captured. All bowlers bowled at a right-handed batsman (to provide a constant target) in a standard 'nets' set-up as part of a typical training session on grass wickets.

Data processing

All Eular angle and acceleration data were transferred to Matlab for processing. Spinal kinematics were derived from the relative angles between two sensors calculated from their direction cosine matrices. A direction cosine matrix is a matrix that transforms one reference frame to another, enabling the orientation of the upper sensor to be described relative to the lower. The initial standing position was taken as the frame of reference from which flexion/extension, side-bending and rotation were determined. Motion data were low pass filtered at 5 Hz, to remove high frequency noise determined through residual analysis.

Tibial and sacral impacts were derived from the tibial and sacral acceleration data. The sacral sensor was corrected for sensor tilt using it's orientation to yield anterioposterior, medial-lateral and inferior-superior accelerations. The tibial sensors were not able to be corrected for orientation due to a lack of additional sensing elements, therefore accelerations were described according to the local coordinate system, that is, along the sensor casing. Impact data were low pass filtered at 50 Hz,

Table 1 Mean (SD) tibial and sacral impact characteristics of junior fast bowlers with (n=8) and without (n=13) a history of low back pain (junior retrospective)

	LBP (n=8)		No-LBP (n=13)		P value		Effect size (d)	
Tibial acceleration	**BFI**	**FFI**	**BFI**	**FFI**	**BFI**	**FFI**	**BFI**	**FFI**
Peak Acc x (g)	10.1 (4.6)	28.0 (13.2)	12.0 (4.6)	25.0 (5.4)	0.283	0.557	−0.41	0.33
Peak Acc y (g)	2.5 (1.7)	15.5 (9.2)	2.8 (1.9)	12.0 (6.8)	0.676	0.327	−0.18	0.44
Peak Acc z (g)	13.0 (5.3)	19.1 (8.9)	17.6 (10.7)	16.3 (6.3)	0.209	0.449	−0.50	0.38
Peak resultant Acc (g)	15.4 (5.2)	36.2 (17.5)	19.8 (8.0)	31.3 (7.2)	0.141	0.470	−0.63	0.41
Time-to-peak Acc x (ms)	28.1 (18.1)	16.8 (4.3)	19.6 (6.9)	16.4 (2.7)	0.238	0.982	0.69	0.09
Time-to-peak resultant (ms)	39.8 (11.6)	59.0 (18.8)	50.6 (28.8)	56.5 (8.5)	0.305	0.735	−0.45	0.19
Mean loading rate x ($g.s^{-1}$)	581.1 (396.4)	1848.0 (959.1)	715.2 (288.1)	1621.1 (378.5)	0.423	0.540	−0.40	0.35
Mean resultant loading rate ($g.s^{-1}$)	465.8 (276.8)	897.5 (937.0)	480.8 (232.1)	644.6 (194.4)	0.831	0.668	−0.06	0.43
Normalised peak Acc x ($g.kg^{-1}$)	0.2 (0.1)	0.4 (0.2)	0.2 (0.1)	0.3 (0.1)	0.416	0.474	−0.35	0.40
Normalised resultant Acc ($g.kg^{-1}$)	0.2 (0.1)	0.5 (0.2)	0.3 (0.1)	0.4 (0.1)	0.220	0.479	−0.54	0.40
Sacral acceleration								
Peak vertical Acc (g)	2.5 (0.7)	3.1 (0.6)	2.7 (0.8)	3.2 (0.7)	0.366	0.697	−0.40	−0.17
Peak mediolateral Acc (g)	0.5 (0.1)	0.6 (0.2)	0.7 (0.3)	1.1 (0.7)	0.165	0.028	−0.65	−0.89
Peak anterioposterior Acc (g)	1.5 (0.7)	1.6 (1.0)	1.3 (0.7)	1.4 (0.9)	0.492	0.582	0.32	0.23
Resultant Acc (g)	3.0 (0.8)	3.7 (0.8)	3.2 (0.8)	4.0 (0.8)	0.691	0.456	−0.18	−0.33
Time-to-peak vertical Acc (ms)	70.1 (19.0)	60.6 (16.5)	72.9 (18.5)	64.1 (10.8)	0.749	0.185	−0.15	−0.26
Time-to-peak resultant Acc (ms)	73.6 (22.2)	65.1 (12.8)	75.0 (20.9)	68.2 (13.6)	0.891	0.316	−0.06	−0.16
Mean vertical loading rate ($g.s^{-1}$)	38.7 (8.3)	61.2 (21.5)	46.0 (16.9)	63.7 (17.2)	0.204	0.837	−0.51	−0.10
Normalised peak vertical Acc ($g.kg^{-1}$)	0.04 (0.01)	0.05 (0.01)	0.04 (0.01)	0.05 (0.02)	0.537	0.619	−0.28	−0.22

Acc, acceleration; BFI, back foot impact; FFI, front foot impact; g, units of gravity; kg, kilogram; LBP, low back pain; s, second.

to remove high frequency noise, determined through residual analysis. All sensor data were synchronised.

Variables

All kinematics and impact data were reported for the delivery stride. Back foot impact (BFI) was determined by peak back leg tibial acceleration and front foot impact (FFI) was determined by peak vertical sacral acceleration. In addition to LBP, the following biomechanical variables were measured. Spinal orientation at BFI and FFI, spinal range of motion (ROM), SCR and hip-separation angle were calculated as defined in Senington *et al.*[16] Briefly resultant angles between two sensors determined spinal orientation at BFI and FFI, with the differences in peak orientations between BFI and FFI used to determine spinal ROM. SCR was calculated by subtracting T1 orientation at BFI from T1 maximum right rotation and hip-shoulder separation angle calculated by taking the maximum difference in hip and shoulder orientation about the longitudinal axis following BFI.[13] Peak tibia and sacral accelerations along three orthogonal axes were reported, along with resultant acceleration, calculated as the square root of the sum of the squared accelerations. Accelerations normalised to body weight were also reported. The time-to-peak acceleration and loading rate were calculated as the time taken to reach the peak acceleration and then converted to rate of loading in units of gravity per second.

Statistics

Data were assessed for normality (Shapiro-Wilk testing) and independent t-tests or Mann-Whitney U tests were conducted where appropriate to compare means of the relevant data. Bonferroni corrections were applied to minimise the risk of type I error. In addition to significance testing, Cohen's d effect sizes were calculated to provide an estimate of the magnitude or strength of certainty of the observed effect. This work considers a large effect size as ≥0.90.[23]

Table 2 Mean (SD) spinal kinematics of junior fast bowlers with (n=8) and without (n=13) a history of low back pain (junior retrospective)

	BFI				FFI				Range			
Spinal Ori or ROM (°)	**LBP**	**No LBP**	**P value**	**Effect size**	**LBP**	**No LBP**	**P value**	**Effect size**	**LBP**	**No LBP**	**P value**	**Effect size**
SCR	39.7 (8.9)	36.6 (11.3)	0.498	0.29								
HSS	27.0 (7.6)	32.6 (18.0)	0.340	−0.37								
T1 Ori	271.2 (42.8)	270.8 (35.1)	0.979	0.01								
S1 Ori	257.1 (35.9)	277.6 (40.0)	0.140	−0.53								
Lx Flex	−13.1 (21.9)	−14.1 (15.2)	0.919	0.05	19.8 (12.7)	20.9 (7.3)	0.832	−0.11	32.9 (33.3)	34.9 (21.4)	0.883	−0.08
Lx LB	−8.6 (6.4)	−12.5 (12.5)	0.358	0.37	17.1 (7.9)	21.7 (10.2)	0.253	−0.50	25.7 (9.1)	34.2 (18.7)	0.177	−0.54
Lx Rot	−2.9 (3.6)	−5.0 (9.3)	0.804	0.28	11.4 (5.1)	15.7 (9.4)	0.193	−0.53	14.3 (6.3)	20.8 (15.2)	0.195	−0.51
Th Flex	−33.4 (12.1)	−28.6 (17.3)	0.468	−0.30	27.3 (12.4)	29.1 (18.4)	0.800	−0.11	60.7 (20.9)	57.7 (32.4)	0.797	0.11
Th LB	−13.1 (19.6)	−21.2 (15.0)	0.537	0.48	26.2 (9.7)	24.1 (11.3)	0.659	0.19	39.2 (24.1)	45.2 (18.2)	0.554	−0.29
Th Rot	−3.9 (9.8)	−15.5 (8.8)	0.16	**1.27**	16.6 (7.6)	20.5 (17.6)	0.801	−0.27	20.5 (13.3)	36.0 (19.1)	0.041	**−0.90**
TL Flex	−43.0 (26.2)	−37.3 (19.3)	0.606	−0.26	43.3 (17.6)	38.2 (20.1)	0.553	0.26	86.2 (41.3)	75.5 (37.9)	0.429	0.27
TL LB	−21.9 (8.7)	−25.4 (11.7)	0.443	0.33	29.0 (10.2)	29.1 (15.6)	0.988	−0.01	51.0 (17.2)	54.5 (22.6)	0.686	−0.17
TL Rot	−17.6 (7.2)	−14.0 (12.4)	0.413	−0.33	23.4 (10.1)	27.1 (15.5)	0.519	−0.27	41.0 (16.6)	41.1 (22.0)	0.992	0.00

Bold text denotes large effect size (d ≥0.9).
BFI, back foot impact; FFI, front foot impact; Flex, flexion; HSS, hip separation angle; LB, lateral bending; LBP, low back pain; Lx, lumbar spine; Ori, orientation; ROM, range of motion; Rot, rotation; S1, first sacral vertebrae; SCR, shoulder counter rotation; T1, first thoracic vertebrae; Th, thoracic; TL, thoracolumbar.

Table 3 Mean (SD) tibial and sacral impact characteristics of senior fast bowlers with (n=8) and without (n=6) a history of low back pain (senior retrospective)

	LBP		No-LBP		P value		Effect size (d)	
Tibial acceleration	**BFI**	**FFI**	**BFI**	**FFI**	**BFI**	**FFI**	**BFI**	**FFI**
Peak Acc x (g)	13.7 (7.4)	21.8 (10.0)	14.4 (6.5)	28.3 (17.3)	0.843	0.392	–0.11	–0.44
Peak Acc y (g)	6.8 (5.7)	10.1 (8.2)	6.7 (3.8)	11.8 (10.0)	0.982	0.725	0.01	–0.19
Peak Acc z (g)	10.0 (5.2)	29.4 (20.7)	20.3 (7.9)	21.3 (11.5)	0.016	0.402	**–1.49**	0.51
Peak resultant Acc (g)	20.7 (5.4)	37.5 (19.0)	24.9 (8.1)	38.8 (20.7)	0.342	0.911	–0.53	–0.60
Time-to-peak Acc x (ms)	31.6 (2.4)	28.3 (12.0)	27.9 (8.6)	26.9 (15.7)	0.274	0.345	0.55	0.10
Time-to-peak resultant (ms)	65.9 (5.4)	49.6 (10.7)	67.3 (12.7)	67.0 (12.8)	0.796	0.017	–0.13	**–1.45**
Mean loading rate x ($g.s^{-1}$)	486.8 (229.6)	1112.0 (665.9)	600.5 (306.3)	1673.0 (1328.0)	0.443	0.324	–0.41	–0.51
Mean resultant loading rate ($g.s^{-1}$)	347.5 (133.8)	825.9 (453.7)	411.3 (145.8)	736.8 (459.0)	0.413	0.724	–0.45	0.20
Normalised peak Acc x ($g.kg^{-1}$)	0.2 (0.1)	0.2 (0.1)	0.2 (0.1)	0.3 (0.2)	0.722	0.384	–0.20	–0.46
Normalised resultant Acc ($g.kg^{-1}$)	0.2 (0.1)	0.4 (0.2)	0.3 (0.1)	0.4 (0.2)	0.214	0.707	–0.71	–0.20
Sacral acceleration								
Peak vertical Acc (g)	3.1 (0.8)	3.2 (0.4)	2.7 (0.7)	3.3 (0.3)	0.389	0.609	0.49	–0.28
Peak mediolateral Acc (g)	1.5 (1.1)	0.9 (0.4)	1.2 (0.7)	1.2 (0.7)	0.568	0.372	0.35	–0.46
Peak anterioposterior Acc (g)	1.4 (0.9)	1.5 (0.7)	1.7 (0.9)	1.4 (0.6)	0.538	0.902	–0.34	0.07
Resultant Acc (g)	3.5 (1.1)	3.8 (0.6)	3.4 (0.8)	4.0 (0.7)	0.832	0.677	0.12	–0.22
Time-to-peak vertical Acc (ms)	71.7 (26.1)	66.7 (14.4)	67.1 (14.8)	69.0 (14.1)	0.710	0.772	0.23	–0.16
Time-to-peak resultant Acc (ms)	75.2 (25.4)	67.1 (17.6)	70.0 (15.2)	69.8 (17.2)	0.643	0.804	0.25	–0.16
Mean vertical loading rate ($g.s^{-1}$)	50.9 (24.6)	60.1 (16.8)	46.3 (21.4)	54.3 (14.2)	0.718	0.510	0.20	0.38
Normalised peak vertical Acc ($g.kg^{-1}$)	0.03 (0.01)	0.04 (0.01)	0.03 (0.01)	0.04 (0.01)	0.674	0.852	0.23	–0.17

Bold text denotes large effect size (d ≥0.9).
Acc, acceleration; BFI, back foot impact; FFI, front foot impact; g, units of gravity; kg, kilogram; LBP, low back pain; s, second.

Patient and public involvement

Patients and/or public were not involved in the design, conduct, reporting or dissemination plans of this research. Athletes were not invited to comment on the study design, interpret the results, or contribute to the writing or editing of this manuscript. Data from participants were provided on request.

RESULTS

Participants

Thirty-five elite male fast bowlers, separated into senior (n=14; mean (SD) age 24.1 (4.3) years; height 1.89 (0.05) m; weight 89.2 (4.6) kg and junior (n=21; age 16.9 (0.7) years; height 1.81 (0.05) m; weight 73.0 (9.2) kg volunteered for this study.

Prevalence and incidence of LBP

A total of 38% (n=8) of juniors reported a history of LBP with the mean age (SD) of first occurrence 15.4 (1.1) years. Only one (5%) junior bowler developed LBP in the follow-up season and this individual had a previous history of LBP.

A total of 57% (n=8) of seniors reported a history of LBP with the mean age (SD) of first occurrence 16.6 (2.6) years. Four (29%) senior bowlers developed LBP in the follow-up season. All bowlers who developed pain had a previous history of LBP.

Retrospective findings among juniors

No differences were observed for any of the impact variables (p>0.003), and no effect sizes were ≥0.9 (table 1).

No differences were observed for any of the kinematics variables (p>0.004) (table 2). Bowlers without a history of LBP displayed larger thoracic rotation away from the direction of delivery at BFI (d=1.3). Range of thoracic rotation between BFI and FFI was larger in bowlers without a history of LBP (d=–0.9).

Retrospective findings among seniors

No differences were observed for any of the impact variables (p>0.003) (table 3). A large effect size observed in the history of LBP group demonstrated less peak acceleration Z (d=–1.5) and faster time-to-peak resultant tibial acceleration at FFI (d=–1.5).

No differences were observed for any of the kinematics variables (p>0.004) (table 4). Large effect sizes were observed where those with a history of LBP demonstrated greater thoracolumbar extension at BFI (d=1.0).

Prospective findings among juniors

As only one junior went on to develop LBP no prospective analysis was possible.

Prospective findings among seniors

No differences were observed for any of the impact variables (p>0.003) (table 5). Effect size analysis showed large

Table 4 Mean (SD) spinal kinematics of senior fast bowlers with (n=8) and without (n=6) a history of low back pain (senior retrospective)

	BFI				FFI				Range			
Spinal ori or ROM (^{O})	LBP	No LBP	P value	Effect size	LBP	No LBP	P value	Effect size	LBP	No LBP	P value	Effect size
SCR	35.7 (11.7)	35.6 (6.5)	1.00	0.01								
HSS	41.2 (30.8)	41.8 (10.7)	0.963	–0.03								
T1 ori	274.6 (34.6)	264.1 (37.9)	0.600	0.29								
S1 Ori	292.3 (10.8)	281.7 (32.6)	0.412	0.41								
Lx Flex	–15.3 (11.0)	–14.7 (8.0)	0.908	–0.07	24.2 (6.7)	21.1 (5.7)	0.345	0.50	39.5 (15.2)	34.3 (11.1)	0.492	0.41
Lx LB	–8.6 (12.2)	–15.8 (5.9)	0.228	0.79	19.6 (5.5)	20.0 (7.1)	0.910	–0.06	28.3 (14.8)	33.0 (7.6)	0.501	–0.42
Lx Rot	–1.5 (11.3)	0.8 (8.2)	0.950	–0.24	14.7 (6.5)	14.4 (6.0)	0.932	0.05	16.2 (14.8)	13.6 (7.2)	0.703	0.24
Th Flex	–26.9 (15.2)	–22.8 (27.3)	0.731	–0.18	40.0 (14.7)	31.7 (11.5)	0.281	0.64	66.8 (27.9)	48.9 (32.3)	0.288	0.59
Th LB	–11.9 (17.6)	–10.5 (11.9)	0.871	–0.10	33.9 (17.5)	26.1 (9.4)	0.356	0.58	45.8 (33.4)	34.0 (16.4)	0.455	0.47
Th Rot	–7.1 (9.8)	–8.9 (13.8)	0.778	0.15	19.7 (11.5)	19.9 (5.9)	0.963	–0.03	26.7 (11.7)	28.8 (17.5)	0.797	–0.13
TL Flex	–40.5 (10.2)	–29.4 (11.3)	0.079	**–1.02**	48.4 (13.0)	45.0 (11.3)	0.625	0.28	88.9 (22.2)	70.8 (19.3)	0.143	0.88
TL LB	–19.2 (23.5)	–20.3 (17.1)	0.923	0.06	36.1 (9.7)	31.1 (9.2)	0.347	0.54	55.3 (24.6)	51.4 (19.0)	0.755	0.18
TL Rot	0.3 (14.7)	–0.3 (24.2)	0.949	0.03	27.1 (7.3)	29.5 (12.6)	0.652	–0.23	26.7 (15.3)	29.9 (20.6)	0.748	–0.17

Bold text denotes large effect size (d ≥0.9).
BFI, back foot impact; FFI, front foot impact; Flex, flexion; HSS, hip separation angle; LB, lateral bending; LBP, low back pain; Lx, lumbar spine; Ori, orientation; ROM, range of motion; Rot, rotation; S1, first sacral vertebrae; SCR, shoulder counter rotation; T1, first thoracic vertebrae; Th, thoracic; TL, thoracolumbar.

Table 5 Mean (SD) tibial and sacral impact characteristics of senior fast bowlers that developed LBP (n=4) and those who didn't develop LBP (n=10) (senior prospective)

	LBP		No-LBP		P value		Effect size (d)	
Tibial acceleration	BFI	FFI	BFI	FFI	BFI	FFI	BFI	FFI
Peak Acc x (g)	10.8 (6.3)	17.5 (10.9)	15.4 (6.6)	28.7 (15.0)	0.217	0.162	–0.70	–0.79
Peak Acc y (g)	5.7 (2.7)	3.8 (2.0)	7.1 (5.1)	14.0 (9.0)	0.616	0.006	–0.32	**–1.30**
Peak Acc z (g)	10.7 (6.1)	17.8 (6.0)	18.0 (8.6)	27.6 (18.0)	0.116	0.177	–0.89	–0.61
Peak resultant Acc (g)	19.6 (2.4)	23.7 (9.0)	24.5 (9.0)	44.0 (19.4)	0.139	0.022	–0.62	**–1.16**
Time-to-peak Acc x (ms)	27.1 (6.2)	35.4 (15.8)	30.5 (7.0)	24.3 (12.2)	0.406	0.142	–0.50	0.84
Time-to-peak resultant (ms)	58.4 (12.3)	61.8 (13.8)	70.0 (7.0)	58.6 (15.5)	0.155	0.720	**–1.34**	0.21
Mean loading rate x ($g.s^{-1}$)	459.8 (180.0)	744.2 (678.2)	588.5 (301.9)	1708.1 (1136.0)	0.351	0.081	–0.47	**–0.93**
Mean resultant loading rate ($g.s^{-1}$)	389.3 (119.2)	461.0 (163.7)	381.8 (152.6)	900.5 (459.4)	0.925	0.022	0.05	**–1.08**
Normalised peak Acc x ($g.kg^{-1}$)	0.1 (0.1)	0.2 (0.1)	0.2 (0.1)	0.3 (0.2)	0.240	0.231	–0.69	–0.73
Normalised resultant Acc ($g.kg^{-1}$)	0.2 (0.0)	0.3 (0.1)	0.3 (0.1)	0.5 (0.2)	0.138	0.034	–0.62	**–1.22**
Sacral acceleration								
Peak vertical Acc (g)	2.7 (0.8)	3.0 (0.5)	2.9 (0.7)	3.3 (0.3)	0.721	0.328	–0.24	–0.87
Peak mediolateral Acc (g)	1.6 (0.8)	0.7 (0.5)	1.2 (0.9)	1.2 (0.6)	0.525	0.147	0.37	–0.88
Peak anterioposterior Acc (g)	1.5 (1.2)	1.2 (0.8)	1.6 (0.8)	1.6 (0.6)	0.811	0.437	–0.18	–0.59
Resultant Acc (g)	3.2 (1.3)	3.5 (0.7)	3.5 (0.7)	4.0 (0.6)	0.814	0.219	–0.33	–0.89
Time-to-peak vertical Acc (ms)	88.3 (18.7)	70.8 (13.9)	61.3 (14.5)	66.8 (14.2)	0.054	0.647	**1.73**	0.28
Time-to-peak resultant Acc (ms)	89.8 (16.6)	72.3 (14.6)	64.2 (16.4)	69.0 (11.6)	0.163	0.772	**1.55**	0.25
Mean vertical loading rate ($g.s^{-1}$)	33.2 (9.6)	53.7 (19.0)	54.3 (23.0)	58.0 (14.2)	0.031	0.705	**–1.03**	–0.27
Normalised peak vertical Acc ($g.kg^{-1}$)	0.03 (0.01)	0.04 (0.01)	0.03 (0.01)	0.04 (0.00)	0.574	0.454	–0.33	–0.64

Bold text denotes large effect size (d ≥0.9).
Acc, acceleration; BFI, back foot impact; FFI, front foot impact; g, units of gravity; kg, kilogram; LBP, low back pain; s, second.

effect sizes for higher time-to-peak resultant tibial acceleration in the 'no LBP' group at BFI. At FFI almost all tibial loading variables (peak tibial acceleration y, peak resultant tibial acceleration, mean loading rate acceleration x, mean loading rate resultant and normalised resultant acceleration) were higher (d≥0.9) in the 'no-LBP' group. At the sacrum, time-to-peak vertical acceleration and time-to-peak resultant acceleration were greater at BFI in the 'LBP group' (d>1.6).

No differences were observed for any of the kinematics variables (p>0.004) (table 6). At BFI large effect sizes suggest the no-LBP group displayed less lumbar extension (d=1.9), more lumbar lateral flexion away from the direction of delivery (d=1.0). At FFI the no-LBP group displayed less lumbar extension (d=0.9) and lumbar rotation (d=1.3).

DISCUSSION

The study set out to explore the kinematics and impacts of junior and senior fast bowlers and how these relate to the retrospective and prospective presence of LBP. This study makes a number of novel contributions to the literature.

This study is the first of its kind to integrate IMUs to measure impacts and spinal movement during cricket fast bowling. The literature is dominated by the use of optoelectronic measurement systems and force plates which are high cost and require a dedicated environment for data capture.[24–27] Portable miniature sensors like those used in this study may offer a viable alternative. Indeed the application of sensors for cricket bowling analysis is beginning to find its place in the literature,[28–32] however this is the first time they have been used to explore LBP, spinal kinematics and limb impacts.

The prevalence of LBP in fast bowlers has been reported at 40%–64%[6 8 33–35] which is similar to the 57% and 38% for the seniors and juniors of the current study. Incidence rates were lower at just 29% and 5% for senior and junior bowlers, respectively. This is in line with the 30% incidence of lower back injury in senior bowlers previously reported, however the present study is the first to report the incidence of LBP.[13] All bowlers who developed LBP had a previous history of pain, suggesting this could be a good prognostic indicator. This is in agreement with earlier literature identifying previous back pain as a predictor of future back pain.[36 37]

Previous systematic reviews on bowling-related risk factors have either amalgamated the concepts of injury and pain making the extraction difficult,[38 39] focused on a specific radiographically identifiable injury[3] or focused on non-bowling related risk factors.[22] In those studies investigating pain, the focus was either on muscle morphology[35 40] or progression of radiographical findings;[41] therefore the findings of the current study provide a novel addition.

Table 6 Mean (SD) spinal kinematics characteristics of senior fast bowlers that developed LBP (n=4) and those who didn't develop LBP (n=10) (senior prospective)

	BFI				FFI				Range			
Spinal Ori or ROM (°)	**LBP**	**No LBP**	**P value**	**Effect size**	**LBP**	**No LBP**	**P value**	**Effect size**	**LBP**	**No LBP**	**P value**	**Effect size**
SCR	39.3 (11.2)	34.1 (7.6)	0.443	0.60								
HSS	53.2 (29.5)	36.9 (15.5)	0.356	0.82								
T1 Ori	268.8 (32.8)	268.5 (38.3)	0.987	0.01								
S1 Ori	284.7 (19.7)	286.9 (28.3)	0.870	−0.08								
Lx Flex	−24.3 (7.7)	−11.2 (6.5)	0.031	**−1.92**	26.3 (2.6)	20.9 (6.5)	0.047	**0.93**	50.6 (8.5)	30.9 (9.3)	0.008	**2.16**
Lx LB	−6.3 (13.9)	−15.3 (6.3)	0.287	**1.03**	19.3 (5.1)	20.1 (6.8)	0.833	−0.11	25.6 (14.4)	33.1 (9.4)	0.539	−0.69
Lx Rot	−0.3 (11.6)	−0.1 (9.0)	0.830	−0.02	19.3 (7.9)	12.6 (4.1)	0.188	**1.26**	19.6 (13.3)	12.8 (9.5)	0.396	0.65
Th Flex	−16.5 (8.3)	−27.8 (25.5)	0.236	0.50	30.8 (15.3)	37.0 (12.6)	0.509	−0.46	47.3 (20.4)	60.3 (34.3)	0.404	−0.41
Th LB	−7.4 (24.7)	−12.5 (8.4)	0.708	0.36	35.0 (21.6)	27.2 (9.3)	0.534	0.57	42.4 (45.0)	37.7 (14.2)	0.852	0.18
Th Rot	−2.8 (16.1)	−10.2 (9.9)	0.441	0.63	22.0 (13.3)	18.9 (6.2)	0.685	0.36	24.8 (16.6)	29.1 (14.7)	0.667	−0.29
TL Flex	−33.6 (14.8)	−34.4 (11.5)	0.930	0.06	47.3 (17.1)	46.1 (9.9)	0.905	0.10	80.9 (31.0)	77.6 (19.1)	0.854	0.14
TL LB	−20.9 (24.5)	−19.4 (18.2)	0.918	−0.07	33.3 (14.1)	33.2 (7.9)	0.987	0.01	54.2 (23.7)	52.6 (21.4)	0.911	0.07
TL Rot	4.6 (7.0)	−1.9 (23.4)	0.446	0.31	29.9 (4.2)	27.9 (12.2)	0.661	0.18	25.3 (29.8)	29.8 (20.8)	0.582	−0.24

Bold text denotes large effect size (d ≥0.9).
BFI, back foot impact; FFI, front foot impact; Flex, flexion; HSS, hip separation angle; LB, lateral bending; LBP, low back pain; Lx, lumbar spine; Ori, orientation; ROM, range of motion; Rot, rotation; S1, first sacral vertebrae; SCR, shoulder counter rotation; T1, first thoracic vertebrae; Th, thoracic; TL, thoracolumbar.

Overall the results, while not statistically significant, did yield some large effect sizes. Junior bowlers without a history of LBP demonstrated around four times greater thoracic rotation at BFI, right rotation for the right handed bowler. Similarly senior bowlers without a history of LBP demonstrated 11° or 27% less range of thoracolumbar extension at BFI. These kinematics away from the direction of delivery are likely to serve as a 'wind up' mechanism for the generation of bowling pace, similar to the cocking phase in throwing. Using spinal rotation to generate wind-up is seen in other sports such as tennis and golf. However this is the first time separate thoracic and lumbar spinal regions have been investigated providing novel insights into the interplay or so-called 'relative motion' between spinal regions. The concept of relative motion between two neighbouring anatomical regions has been reported previously.[42–44] In golfers, altered relative motion between the hips and lumbar spine was identified in those with LBP, suggesting greater relative contribution from the lumbar spine (and reduced contribution from the hips).[44 45] This finding was mirrored in tennis where ROM, normalised to maximal range, during forehand strokes resulted in a range of rotation values beyond the maximum, in those with LBP during 'wind up'.[43] These suggest the potential for excessive relative contribution of motion from the lumbar spine resulting in high levels of tissue stress due to the utilisation of most or all of the available ROM. The findings of this study illustrate that in juniors the ratio of lumbar rotation to thoracic rotation at BFI was 1:1.3, whereas the equivalent was 1:3.1 for those without a history of LBP.

Prospective analysis was unfortunately limited to seniors due to an absence of the development of LBP in the junior sample. Seniors who developed LBP in the follow-up season had greater sagittal spinal movement during the delivery stride and greater lumbar extension at BFI. Previous studies have identified that SCR was associated with risk of lumbar injury,[15] however the study did not include pain data. The relationship between radiographically diagnosed lumbar injury and pain is questionable, hence this study focused on pain and demonstrated no such relationship. In seniors, the posterior shifting of the shoulders compared with the hips has the potential for generating bowling pace by providing greater range to develop trunk and arm velocity. However, this is likely to place additional stress on the spine due to using more of the available range and positioning the spine closer to end-of-range extension. This is one mechanism for potential high levels of tissue stress.[46 47] Similar findings have been identified in other sporting populations with LBP.[48] It has been shown that positioning of the lumbar spine closer to the end of range was associated with pain in gymnastics, cycling, golf and rowing,[49–52] and altering the position of the lumbar spine to be further from the end of range was associated with pain relief.[52 53]

In addition to these kinematic differences, high effect sizes were discovered demonstrating greater tibial acceleration along the z-axis at BFI in individuals with no history of LBP as well as greater time to peak resultant tibial acceleration in the no history of LBP group at FFI. A previous review of ground reaction force (GRF) studies demonstrated no link between GRF and lumbar injury or pain,[5] therefore these findings are novel. The z-axis is most closely aligned to the mediolateral axis of the limb and suggests either a greater side-on posture or greater acceleration in line with the wicket with an externally rotated limb. The latter would be possible with a front-on bowler who alters the back leg orientation and uses the adduction/abduction plane to beginning to arrest or 'check' the forward momentum. Side on bowling postures are thought to offer less risk of back pain and therefore this may explain this finding in the group without a history of LBP.

Strengths and limitations

This is the first study to employ a number of IMUs to monitor spinal kinematics and impact during on the field cricket fast bowling. Such devices could offer a non-invasive and non-intrusive solution to monitoring of bowling over time, enabling coaches, clinicians and players to benefit from bowling-related biomechanics data. Additionally this study is the first of its kind to focus specifically on pain rather than low back injury, therefore offering new insights into the relationship between biomechanics and pain.

The current study was limited in its period of follow-up to just one season. It is not clear if additional incidence would have been determined over more than one season. Additionally the sample in this study investigated young adult fast bowlers, therefore it is not clear if similar results would be obtained from older senior bowlers.

CONCLUSION

This study is the first of its kind to use IMUs to investigate bowling kinematics and lower limb impacts, relating these to LBP history and also to the development of LBP in the follow-up season. This was explored in both junior and senior fast bowlers. Retrospective analysis demonstrated lower mediolateral sacral acceleration (juniors at FFI) and lower time-to-peak resultant tibial acceleration (seniors at FFI) in those with a history of LBP. Bowlers without a history of LBP used greater thoracic rotation away from the direction of delivery. Such a mechanism perhaps serves as an effective wind-up strategy generating pace without the need for excessive motion in the lumbar spine in the direction of delivery. Senior bowlers who demonstrated greater thoracolumbar and lumbar extension either had a history of LBP or went on to develop LBP. Such lumbar extension may place high tissue stress on the lumbar spine. The findings of this study contribute significantly to the understanding of kinematics and impacts which relate to LBP rather than spinal pathology. Coaches and clinicians may use this information in the construction of coaching or rehabilitation programmes or indeed apply the method to monitor bowlers' biomechanics.

Acknowledgements The authors thank the players, coaches and parents who contributed to this study.

Contributors RYL, JMW, BS contributed to the development of the research questions and study design. BS collected the data. JMW developed data processing algorithms. RYL, JMW, BS contributed to the understanding of the findings. JMW developed the first draft and subsequent drafts with significant inputs from BS and RYL. All authors reviewed and approved the final manuscript.

Funding The authors have not declared a specific grant for this research from any funding agency in the public, commercial or not-for-profit sectors.

Competing interests JMW has consulted for THETAmetrix from whom the sensors were acquired.

Patient consent for publication Not required.

Ethics approval Ethical approval was granted by Bournemouth University Ethics committee.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available on reasonable request from BS, b.senington@surrey.ac.uk.

ORCID iD

Jonathan M Williams http://orcid.org/0000-0001-8331-3181

REFERENCES

1 Stretch R. The incidence and nature of injuries in first-league and provincial cricketers. *S Afr Med J* 1992;1992:339–42.
2 Orchard J, James T, Alcott E. Injuries in Australian cricket at first class level 1995/1996 to 2000/2001 * commentary. *Br J Sports Med* 2002;36:270–4.
3 Johnson M, Ferreira M, Hush J. Lumbar vertebral stress injuries in fast bowlers: a review of prevalence and risk factors. *Phys Ther Sport* 2012;13:45–52.
4 Morton S, Barton CJ, Rice S, *et al*. Risk factors and successful interventions for cricket-related low back pain: a systematic review. *Br J Sports Med* 2013;0:1–8.
5 Senington B, Lee RY, Williams JM. Ground reaction force, spinal kinematics and their relationship to lower back pain and injury in cricket fast bowling: a review. *J Back Musculo Rehabil* 2018;31:671–83.
6 Elliott BC, Hardcastle PH, Burnett AE, *et al*. The influence of fast bowling and physical factors on radiologic features in high performance young fast bowlers. *Res Sports Med* 1992;3:113–30.
7 Engstrom CM, Walker DG. Pars interarticularis stress lesions in the lumbar spine of cricket fast bowlers. *Med Sci Sports Exerc* 2007;39:28–33.
8 Hardcastle P, Annear P, Foster DH, *et al*. Spinal abnormalities in young fast bowlers. *J Bone Joint Surg Br* 1992;74:421–5.
9 Hardcastle PH. Repair of spondylolysis in young fast bowlers. *J Bone Joint Surg Br* 1993;75:398–402.
10 Orchard J, James T, Alcott E, *et al*. Injuries in Australian cricket at first class level 1995/1996 to 2000/2001. *Br J Sports Med* 2002;36:270–4.
11 Alway P, Brooke-Wavell K, Langley B, *et al*. Incidence and prevalence of lumbar stress fracture in English County cricket fast bowlers, association with bowling workload and seasonal variation. *BMJ Open Sport Exerc Med* 2019;5:e000529.
12 Crewe H, Campbell A, Elliott B, *et al*. Lumbo-pelvic loading during fast bowling in adolescent cricketers: the influence of bowling speed and technique. *J Sports Sci* 2013;31:1082–90.
13 Portus M, Mason BR, Elliott BC, *et al*. Technique factors related to ball release speed and trunk injuries in high performance cricket fast bowlers. *Sports Biomech* 2004;3:263–84.
14 Stuelcken MC, Ferdinands RED, Sinclair PJ. Three-dimensional trunk kinematics and low back pain in elite female fast bowlers. *J Appl Biomech* 2010;26:52–61.
15 Foster D, John D, Elliott B, *et al*. Back injuries to fast bowlers in cricket: a prospective study. *Br J Sports Med* 1989;23:150–4.
16 Senington B, Lee RY, Williams JM. Are shoulder counter rotation and hip shoulder separation angle representative metrics of three-dimensional spinal kinematics in cricket fast bowling? *J Sports Sci* 2018;36:1763–7.
17 Bayne H, Elliott B, Campbell A, *et al*. Lumbar load in adolescent fast bowlers: a prospective injury study. *J Sci Med Sport* 2016;19:117–22.
18 Ferdinands RED, Kersting U, Marshall RN. Three-dimensional lumbar segment kinetics of fast bowling in cricket. *J Biomech* 2009;42:1616–21.
19 Glazier PS. Is the 'crunch factor' an important consideration in the aetiology of lumbar spine pathology in cricket fast bowlers? *Sports Med* 2010;40:809–15.
20 Brinjikji W, Luetmer PH, Comstock B, *et al*. Systematic literature review of imaging features of spinal degeneration in asymptomatic populations. *AJNR Am J Neuroradiol* 2015;36:811–6.
21 Ranson CA, Kerslake RW, Burnett AF, *et al*. Magnetic resonance imaging of the lumbar spine in asymptomatic professional fast bowlers in cricket. *J Bone Joint Surg Br* 2005;87:1111–6.
22 Olivier B, Gray J. Musculoskeletal predictors of non-contact injury in cricketers - Few and far between? A longitudinal cohort study. *Phys Ther Sport* 2018;34:208–15.
23 Chen H, Cohen P, Chen S. How big is a big odds ratio? Interpreting the magnitudes of odds ratios in epidemiological studies. *Commun Stat Simul Comput* 2010;39:860–4.
24 Middleton KJ, Mills PM, Elliott BC, *et al*. The association between lower limb biomechanics and ball release speed in cricket fast bowlers: a comparison of high-performance and amateur competitors. *Sports Biomech* 2016;15:357–69.
25 Zhang Y, Ma Y, Liu G. Lumbar spinal loading during bowling in cricket: a kinetic analysis using a musculoskeletal modelling approach. *J Sports Sci* 2016;34:1030–5.
26 Ranson C, King M, Burnett A, *et al*. The effect of coaching intervention on elite fast bowling technique over a two year period. *Sports Biomech* 2009;8:261–74.
27 Ranson CA, Burnett AF, King M, *et al*. The relationship between bowling action classification and three-dimensional lower trunk motion in fast bowlers in cricket. *J Sports Sci* 2008;26:267–76.
28 Callaghan SJ, Lockie RG, Andrews WA, *et al*. The relationship between inertial measurement unit-derived 'force signatures' and ground reaction forces during cricket pace bowling. *Sports Biomech* 2018:1–15.
29 Senington B, Lee RY, Williams JM. Are shoulder counter rotation and hip shoulder separation angle representative metrics of three-dimensional spinal kinematics in cricket fast bowling? *J Sports Sci* 2018b;36:1763–7.
30 Wells D, Alderson J, Camomilla V, *et al*. Elbow joint kinematics during cricket bowling using magneto-inertial sensors: a feasibility study. *J Sports Sci* 2019;37:515–24.
31 McGrath JW, Neville J, Stewart T, *et al*. Cricket fast bowling detection in a training setting using an inertial measurement unit and machine learning. *J Sports Sci* 2019;37:1220–6.
32 Jowitt HK, Durussel J, Brandon R, *et al*. Auto detecting deliveries in elite cricket fast bowlers using microsensors and machine learning. *J Sports Sci* 2020;38:767–72.
33 Burnett AF, Khangure MS, Elliott BC, *et al*. Thoracolumbar disc degeneration in young fast bowlers in cricket: a follow-up study. *Clin Biomech* 1996;11:305–10.
34 Dennis RJ, Finch CF, Farhart PJ. Is bowling workload a risk factor for injury to Australian junior cricket fast bowlers? *Br J Sports Med* 2005;39:843–6.
35 Kountouris A, Portus M, Cook J. Quadratus lumborum asymmetry and lumbar spine injury in cricket fast bowlers. *J Sci Med Sport* 2012;15:393–7.
36 Smedley J, Egger P, Cooper C, *et al*. Prospective cohort study of predictors of incident low back pain in nurses. *BMJ* 1997;314:1225.
37 Morton S, Barton CJ, Rice S, *et al*. Risk factors and successful interventions for cricket-related low back pain: a systematic review. *Br J Sports Med* 2014;48:685–91.
38 Forrest MRL, Hebert JJ, Scott BR, *et al*. Risk factors for non-contact injury in adolescent cricket PACE bowlers: a systematic review. *Sports Med* 2017;47:2603–19.
39 Johnson M, Ferreira M, Hush J. Lumbar vertebral stress injuries in fast bowlers: a review of prevalence and risk factors. *Phys Ther Sport* 2012;13:45–52.
40 Engstrom CM, Walker DG, Kippers V, *et al*. Quadratus lumborum asymmetry and L4 pars injury in fast bowlers: a prospective Mr study. *Med Sci Sports Exerc* 2007;39:910–7.
41 Ranson CA, Burnett AF, Kerslake RW. Injuries to the lower back in elite fast bowlers. acute stress changes on MRI predict stress fracture. *JBJSurg* 2010;92-B:1664–8.

42 Alqhtani RS, Jones MD, Theobald PS, *et al*. Investigating the contribution of the upper and lower lumbar spine, relative to hip motion, in everyday tasks. *Man Ther* 2016;21:268–73.
43 Campbell A, Straker L, Whiteside D, *et al*. Lumbar mechanics in tennis groundstrokes: differences in elite adolescent players with and without low back pain. *J Appl Biomech* 2016;32:32–9.
44 Grimshaw PN, Burden AM. Case report: reduction of low back pain in a professional golfer. *Medicine & Science in Sports & Exercise* 2000;32:1667–73.
45 Vad VB, Bhat AL, Basrai D, *et al*. Low back pain in professional golfers: the role of associated hip and low back range-of-motion deficits. *Am J Sports Med* 2004;32:494–7.
46 Adams MA, Dolan P, Hutton WC. The lumbar spine in backward bending. *Spine* 1988;13:1019–26.
47 Green TP, Allvey JC, Adams MA. Spondylolysis. bending of the inferior articular processes of lumbar vertebrae during simulated spinal movements. *Spine* 1994;19:2683–91.
48 Sonvico L, Spencer SM, Fawcett L, *et al*. Investigation of optimal lumbar spine posture during a simulated landing task in elite gymnasts. *Int J Sports Phys Ther* 2019;14:65–73.
49 Ohlén G, Wredmark T, Spangfort E. Spinal sagittal configuration and mobility related to low-back pain in the female gymnast. *Spine* 1989;14:847–50.
50 Burnett AF, Cornelius MW, Dankaerts W, *et al*. Spinal kinematics and trunk muscle activity in cyclists: a comparison between healthy controls and non-specific chronic low back pain subjects-a pilot investigation. *Man Ther* 2004;9:211–9.
51 Lindsay D, Horton J. Comparison of spine motion in elite golfers with and without low back pain. *J Sports Sci* 2002;20:599–605.
52 Ng L, Cañeiro JP, Campbell A, *et al*. Cognitive functional approach to manage low back pain in male adolescent rowers: a randomised controlled trial. *Br J Sports Med* 2015;49:1125–31.
53 Perich D, Burnett A, O'Sullivan P, *et al*. Low back pain in adolescent female rowers: a multi-dimensional intervention study. *Knee Surg Sports Traumatol Arthrosc* 2011;19:20–9.