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Review

Baseball pitching biomechanics in relation to pain, injury, and surgery: A systematic review

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ABSTRACT

Objectives: To investigate the relationship between baseball pitching biomechanics and pain, injury, or surgery, in pitchers of all ages and competition levels.
Design: Systematic review.
Methods: This study was registered on Prospero (CRD42019137462). Four online databases (MEDLINE, SPORTDiscus, CINAHL, and Embase) from inception to June 13, 2019 were systematically searched. Risk of bias was assessed through the modified Downs and Black.
Results: 967 titles/abstracts were screened with 11 studies (1376 pitchers) included. Four studies used 3D biomechanical analyses, five studies video analysis, and two studies evaluated EMG activity. Level 1b evidence suggests that injured pitchers had greater elbow valgus torque at late arm cocking (injured: 91.6 N m, non-injured: 74.7 N m, $p = 0.013$) and early trunk rotation was predictive of increased upper extremity surgical risk (Hazard Ratio: 1.69 (95% CI 1.02–2.80)). Level 3b evidence observed pitchers with upper extremity surgical history had greater lateral trunk tilt at release (surgery: 29.3°, controls: 23.4°, $p = 0.035$), and flexor carpi ulnaris EMG activity was decreased (injured: 68% MMT, controls: 103% MMT) in pitchers with elbow injury.
Conclusions: Increased elbow valgus torque and early trunk rotation were injury risk factors, and elbow injured pitchers displayed diminished forearm muscle activity. Due to the low power of many of these studies, and the lack of prospective 3D biomechanical studies, other pitching biomechanical variables cannot be ascertained as injury risk factors. Future studies are needed to prospectively assess pitching injury risk through 3D biomechanical methods.

Practical implications

- Increased elbow valgus torque and improper trunk kinematics may increase pitching injury risk; as a result, further research is needed to determine whether interventions to correct these pitching mechanics will reduce injury rates.
- Coaches and clincians should be aware that surgical history and pain has potenital to alter pitching mechanics, and therefore injury risk.
- Flexor carpi ulnaris EMG activity was decreased in pitchers with an elbow injury, further reseach is needed to determine whether strengthening flexor carpi ulnaris can reduce risk of elbow injury or recurrence of elbow injury in pitchers.

1. Introduction

Baseball injuries are a significant problem and injury incidence continues to rise.[1–4] Baseball injury incidence is as high as 3.6,[3] 4.6,[4] and 5.8[2] injuries per 1000 athlete exposures in professional, high school, and college baseball respectively. Many pitching injuries have been attributed to high volumes of repetitive pitching.[5,6] One way in which repetitive pitching injury risk may be evaluated is through pitching stress.[7–9] Pitching stress is defined as the mus-

Abbreviations: 3D, three dimension; EMG, electromyographic; SLAP, superior labrum anterior to posterior; UCLR, ulnar collateral ligament reconstruction.

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cular and joint load produced during pitching.[10] These muscular and joint loads can be quantified through evaluating the pitching motion,[7,8] which is a complex multifaceted process that integrates the entire body.[11] In order to effectively analyze this complex motion, biomechanical methods have been utilized.[7–9]

Pitching biomechanical analytical methods include three dimensional (3D) kinematics,[7,8] video,[9,11] and electromyographic muscle activity.[12,13] These methods have been used in order to improve pitching motion efficiency, which is modifiable with understanding of pitching biomechanics.[14] Improving pitching motion efficiency has been proposed to reduce pitching stress through improving the kinematic sequence and ultimately reducing kinetic joint forces.[7,8,15,16] This is conducive due to the high joint forces produced during pitching, which can increase ligament load.[8,17,18] For example, youth pitchers with more efficient pitching mechanics produced reduced shoulder internal rotation torque and lower elbow valgus torque in comparison to youth pitchers with less efficient pitching mechanics.[19] In another study, 97% of variation in professional pitcher's elbow valgus torque was explained by four kinematic variables (shoulder abduction at front foot contact, peak shoulder horizontal adduction velocity, elbow angle at peak elbow valgus torque, and maximum shoulder external rotation torque).[16] However, while there is a direct relationship between pitching motion efficiency and joint force,[7,8,15,16] it is unclear whether these factors relate to pitching injury risk.[9,11]

Pain, injury, and surgical history also have the potential to alter pitching mechanics.[12,20,21] Altered pitching mechanics can increase joint force, further exacerbating pain or injury at a specific joint or further down the kinetic chain, potentially increasing re-injury risk.[12,13,22] However, it is unclear how pain, injury, or surgery currently effect the pitching motion, or joint forces compared to healthy pitching controls. Due to this, there is a need to understand the relationship between pitching biomechanics and pitching pain, injury, or surgery.

Currently it is not known how pitching biomechanics relate to injury risk. Identifying modifiable risk factors is important to attenuate injuries.[22] Clarifying the relationship between pitching biomechanics and injury may allow scientists, clinicians, and coaches to more effectively identify pitchers at risk of injury. Further, identifying how pitching pain, injury, or surgery alters pitching biomechanics can inform targeted interventions to reduce injury and re-injury risk. Therefore, the purpose of this systematic review was to investigate the relationship between baseball pitching biomechanics and pain, injury, or surgery, in pitchers of all ages and competition levels.

2. Methods

2.1. Study design

This systematic review was conducted and reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).[23] This review was prospectively registered with The International Prospective Register of Systematic Reviews (PROSPERO) (CRD42019137462).

2.2. Search strategy

A systematic computerized search of the literature, with the assistance of a medical librarian, was performed using four online databases (MEDLINE, SPORTDiscus, CINAHL, and Embase) from database inception to June 13, 2019. This search was conducted using controlled vocabulary (e.g., Medical Subject Headings) and key words in the title and abstract relating to baseball pitching (e.g. "baseball" or "pitcher") AND biomechanics (e.g. "biomechani*" or "kinematics" or "kinetics") AND injury or pain (e.g. "injur*" or pain or "shoulder injuries" or "collateral ligament*", "tear*" or "lesion*"). A literature hand search was performed following the initial search to screen for any additional eligible studies. Studies were tracked in EndNote (Version 9, Clarivate Analytics). For full search strategy, please refer to Appendix 1 (Supplementary material).

2.3. Eligibility criteria

To be eligible for inclusion in this review, articles had to meet the following criteria:

- Assessed pitching biomechanics through 3D biomechanical analysis, video, or electromyographic (EMG) analyses in baseball pitchers of any age and competition level.
- Evaluated the relationship or association between pitching biomechanics and pain, injury or surgery in any region of the body.
- Biomechanical comparisons were made between injured versus non injured pitchers, pitchers with pain versus no pain, or pitchers that had surgery versus pitchers who did not.
- Full text written in English.
- Published in a peer review journal.
- Study methodological design was prospective, retrospective, randomized controlled trial, or cross-sectional.

Exclusion criteria consisted of:

- Case-reports, conference abstracts, dissertations, editorials, letters to the editor, commentaries, or literature reviews.
- Cadaveric studies.
- Animal studies.

2.4. Study selection

Two authors (G.B., G.M.) independently assessed studies identified by the search criteria for applicability to inclusion/exclusion criteria. If the title and abstract did not provide sufficient information to determine whether eligibility criteria were met, the study was included for subsequent independent full-text review. In case of disagreement regarding full-text eligibility between the two authors, a third reviewer (K.N.) was asked to resolve the discrepancy.

2.5. Quality assessment

Two authors (G.B., G.M.) independently conducted a quality assessment of each included study. The Oxford Centre for Evidence-Based Medicine level of evidence were employed to grade methodological study design.[24] Level 1a studies are defined as systematic reviews of randomized control trials, level 1b studies are prospective cohorts or randomized control trials, level 2a studies are systematic reviews of cohort studies, level 2b studies are retrospective cohorts, level 2c studies are ecological studies, level 3a studies are systematic reviews of case control studies, level 3b are case control studies, and level 4 studies are case series.[24] The modified Downs and Black scale[25] was used to assess risk of bias. The modified Downs and Black scale is derived from the original Downs and Black scale.[26] The modified Downs and Black scale has been adjusted due to the original scale utilized questions pertaining to surveys, which is not applicable to this systematic review.[25] The modified version assessed reporting, internal validity, and external validity, and power.[25] The modified Downs and Black scale has been shown to be a reliable tool for quality assessment of case-control and cohort studies.[27] Using this scale ranging from 0 to 15, studies scoring ≥12 are regarded as high quality, those scoring 10

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or 11 are regarded as moderate quality, and those scoring ≤9 are deemed low quality.[25]

2.6. Data extraction

Data from each included study were extracted independently by two authors (G.B., G.M.). Any disagreements in data extraction were discussed and resolved. Data elements recorded included anthropomorphic data, competition level, pitch and innings counts, pitch velocity, pitch type, biomechanical assessment methodology (i.e. video, 3D analysis), kinematic and kinetic data, muscle EMG activity, injury incidence/rate/risk, pain, or surgical history.

2.7. Statistical analyses

Due to the nonuniformity of the data in the included studies, the results were summarized in a descriptive manner. Data were stratified by biomechanical methodological approach and by competition level.

3. Results

3.1. Study selection

The online database searches identified 967 titles and 541 titles remained after duplicate removal. Following the screening process, a total of eleven studies,[9,12,13,20,21,28–33] were included in the systematic review (Fig. 1).

3.2. Study characteristics

A total of 1376 pitchers were included in this study, in which all were males.[9,12,13,20,21,28–33] Ten (91%) studies were performed in the United States,[9,12,13,21,28–33] and one (9%) study was performed in Taiwan.[20] The median age was 21.4 (range 11–28) years old, median mass was 75.5 (range 41.1–96.4) kilograms, and the median height was 161 centimeters (range 142–189). Seven (50%) studies investigated professional adult baseball pitchers,[9,28–33] three (21%) studies investigated collegiate pitchers,[12,13,21] and four (29%) studies investigated youth pitchers.[9,20,29,33] Three (27%) studies evaluated both professional and collegiate pitchers.[12,13,21] Four (36%) studies used 3D biomechanical analyses,[12,20,21,32,33] five (45%) studies used video analysis,[9,28–31] and two (18%) studies evaluated EMG activity (Table 1).[13,29]

3.3. Study quality assessment

Of the eleven studies reviewed, three studies were level 1b,[9,28,30] one was level 2b,[31] and seven were level 3b.[12,13,20,21,29,32,33] The median modified Downs and Black score was 11, with study quality ranging from 9 to 12 (Table 2). Four studies were scored as high quality,[21,30,31,32] four studies were of moderate quality,[9,12,28,29] and three studies were of low quality.[13,20,33] Nine out of eleven studies did not perform a power analysis,[9,12,13,20,28,29,30,31,33] ten out of eleven studies did not describe the potentiality of selection bias,[9,13,20,21,28,29,30,31,32,33] and seven out of eleven did not blind study assessors.[12,13,20,21,28]

3.4. Kinetics

3.4.1. Professional pitchers

Four studies investigated pitching kinetics.[21,28,32,33] Three studies[21,28,32] evaluated kinetics in both healthy and injured (i.e. a history of injury or a new injury in prospective studies) professional pitchers, and one study assessed kinetics in youth pitchers with or without shoulder pain.[33] One was a prospective study (level 1b), which evaluated pitchers at the beginning of the 1998 spring training using video analysis, and were followed for the course of three seasons (injured = 9, non-injured = 14).[28] Injury was defined as time spent on the Major League Baseball Injured List (IL).[28] A prospective study observed differences between pitchers who incurred an injury and those who remained injury free, for shoulder external rotation torque at late arm cocking (non-injured: mean 71.9 N m, injured: mean 89.8 N m, $p = 0.0018$) and elbow valgus torque at late arm cocking (non-injured: mean 74.7 N m, injured: mean 91.6 N m, $p = 0.013$).[28] No differences were observed for maximum shoulder external rotation torque, maximum elbow valgus torque, shoulder external rotation torque, elbow valgus torque at front foot contact, shoulder external rotation torque, or elbow valgus torque at release.[28] The other professional baseball investigations were case control studies (level 3b) using 3D biomechanical analyses that compared pitchers with a history of superior labrum anterior to posterior (SLAP) tear to controls without a history of SLAP tear (SLAP = 13, controls = 52),[21] and compared pitchers with a history of ulnar collateral ligament reconstruction (UCLR) to controls with no history of UCLR (UCLR = 39, controls = 38).[32] No differences were observed for maximum shoulder internal rotation torque,[21,32] maximum shoulder horizontal adduction torque,[32] maximum proximal shoulder force,[32] maximum elbow valgus torque,[32] maximum elbow flexion torque.[21] The youth baseball investigation (level 3B) used 3D biomechanical analyses to compare pitchers with current shoulder pain (n = 7) and no current shoulder pain (n = 12).[33] For every 1 N increase in peak proximal shoulder force, there was a 4.6% increase in likelihood of shoulder pain, with 84.2% of model variance explained by proximal shoulder force. Only one other kinetic variable was assessed, with peak anterior shoulder force not demonstrating a significant relationship to shoulder pain.[33]

3.5. Kinematics

3.5.1. Professional pitchers

One case control study (level 3b) investigated professional baseball kinematics using 3D analyses, comparing pitchers with a history of UCLR to controls without a history of UCLR (UCLR = 39, controls = 38).[32] No statistical differences were observed for any kinematic variables, which included maximum shoulder external rotation, maximum shoulder horizontal adduction, maximum shoulder internal rotation velocity, maximum elbow flexion, maximum elbow extension velocity, stride length, trunk forward tilt, shoulder external rotation at front foot contact, abduction at foot contact, abduction at ball release, or lateral trunk tilt at ball release.[32]

Two studies investigated professional baseball pitching kinematics using video analyses.[30,31] One prospective study (level 1b) evaluated the presence of the inverted w position (i.e. the hyper abduction and internal rotation of both throwing and non-throwing shoulders at front foot contact) or early trunk rotation (i.e. trunk rotation prior to front foot contact) as a risk factor for upper extremity surgery throughout one season in 250 pitchers.[32] A total of 38% (93/248) of professional pitchers were observed to pitch with an inverted w position, with 30% of inverted w pitchers (28/93) undergoing an upper extremity surgery in one season, compared to 27% (42/155) of pitchers that did not pitch with the inverted w position. Pitching with an inverted w position was not associated with greater upper extremity surgical risk (Hazard Ratio: 1.30 (95% CI 0.79–2.14)).[30] A total of 46% (111/243) of pitchers were observed to pitch with early trunk rotation, with 33% of early trunk rotation pitchers (37/111) undergoing an upper extremity surgery in one season, compared to 23% (30/132) of pitchers who did not pitch with early trunk rotation. Early trunk rotation was observed to have greater surgical risk (Hazard Ratio: 1.69 (95% CI 1.02–2.80)).[30]

Table 1
Study characteristics.

Study	Methodological Study design	Number of participants	Age (years)	Mass (Kg)	Height (cm)	Pitch velocity (m/s)	Competition level	Biomechanical assessment method	Outcome	Key findings
Anz et al.[28]	Level 1 Prospective	23	Injured: 25.9 (20–30) Non-injured: 27.1 (23–30)	Injured: 92.3 (79.5–107.3) Non-injured: 87.4 (72.7–102.3)	Injured: 189 (185–196) Non-injured: 189 (180–201)	NR	Professional	Video	Upper Extremity Injury	Increased elbow valgus torque related to elbow injury
Chalmers et al.[12]	Level 3 Case-control	18	SLAP: 28.0 ± 4.2 Bicep tenodesis: 22.4 ± 2.1 Controls: 21.4 ± 1.7	NR	NR	SLAP: 27 ± 2 Bicep tenodesis: 27 ± 2 Controls: 30 ± 2	Professional and collegiate	3D and EMG	History of upper extremity surgery	Pitchers with previous SLAP demonstrated increased trunk rotation
Chalmers et al.[29]	Level 3 Case-control	420	History of injury: 16.1 ± 2.4 Controls: 14.3 ± 2.4	History of injury: 75.5 ± 13.6 Controls: 63.6 ± 17.7	History of injury: 180 ± 9 Controls: 169 ± 14	NR	Youth	Video	History of upper extremity injury	Pitch velocity, height, and pitching for multiple team was related to injury
Douoguih et al.[30]	Level 1 Prospective	250	27 ± 4	NR	NR	NR	Professional	Video	Upper extremity surgery	Early trunk rotation was related to increased throwing arm surgery risk
Fleisig et al.[32]	Level 3 Case-control	77	History of UCLR: 23.4 ± 1.9 Controls: 21.4 ± 2.0	History of UCLR: 95.1 ± 10.3 Controls: 96.3 ± 11.4	History of UCLR: 188 ± 6 Controls: 191 ± 5	History of UCLT: 37.9 ± 1.7 Controls: 38.3 ± 1.4	Professional	3D	History of UCLR	Professional pitchers with a history of UCLR had no biomechanical differences compared to pitchers with no history of UCLR
Hamilton et al.[13]	Level 3 Case-control	36	NR	NR	NR	NR	Professional and collegiate	EMG	Elbow injury	Flexor carpi radialis muscle had reduced activity in UCL injured pitchers compared to non UCL injured pitchers
Huang et al.[20]	Level 3 Case-control	15	Elbow pain: 11.3 ± 0.6 Controls: 11.1 ± 1.0	Elbow pain: 44.0 ± 1.3 Controls: 41.4 ± 10.3	Elbow pain: 149 ± 9 Controls: 147 ± 9	Elbow pain: 24.8 ± 2.7 Controls: 23.0 ± 2.7	Youth	3D	Elbow pain	History of elbow pain pitchers had increased lateral trunk tilt compared to no history of elbow pain pitchers
Keeleyand Oliver[33]	Level 3 Case-control	19	All participants: 11.2 ± 1.7	All participants: 41.1 ± 6.3	All participants: 142.6 ± 9	NR	Youth	3D	Shoulder pain	Pitchers with shoulder pain demonstrated increased proximal shoulder force compared to pitchers without shoulder pain
Laughlin et al.[21]	Level 3 Case-control	13	SLAP: 23.2 ± 3.5 Controls: 20.9 ± 2.0	SLAP: 93.6 ± 10.8 Controls: 90.4 ± 3.5	SLAP: 188 ± 6 Controls: 188 ± 7	SLAP: 35.7 ± 2.0 Controls: 35.8 ± 2.0	Professional and collegiate	3D	History of SLAP	Pitchers with a history of SLAP demonstrated decreased shoulder horizontal abduction, shoulder external rotation, and forward trunk tilt compared to pitchers with no history of SLAP.
Lyman et al.[9]	Level 1 Prospective	476	12 (9–14)	48	152	NR	Youth	Video	Upper extremity pain	There were no biomechanical differences between injured and healthy pitchers
Sutter et al.[31]	Level 2 Retrospective	449	NR	NR	NR	NR	Professional	Video	Upper extremity injury or surgery	Injury risk was reduced by overall delivery score

3D = three dimensional, EMG = electromyographic, SLAP = superior labrum anterior posterior, UCLR = ulnar collateral ligament reconstruction, NR = not reported.
Means are reported as mean ± standard deviation or as mean (range).

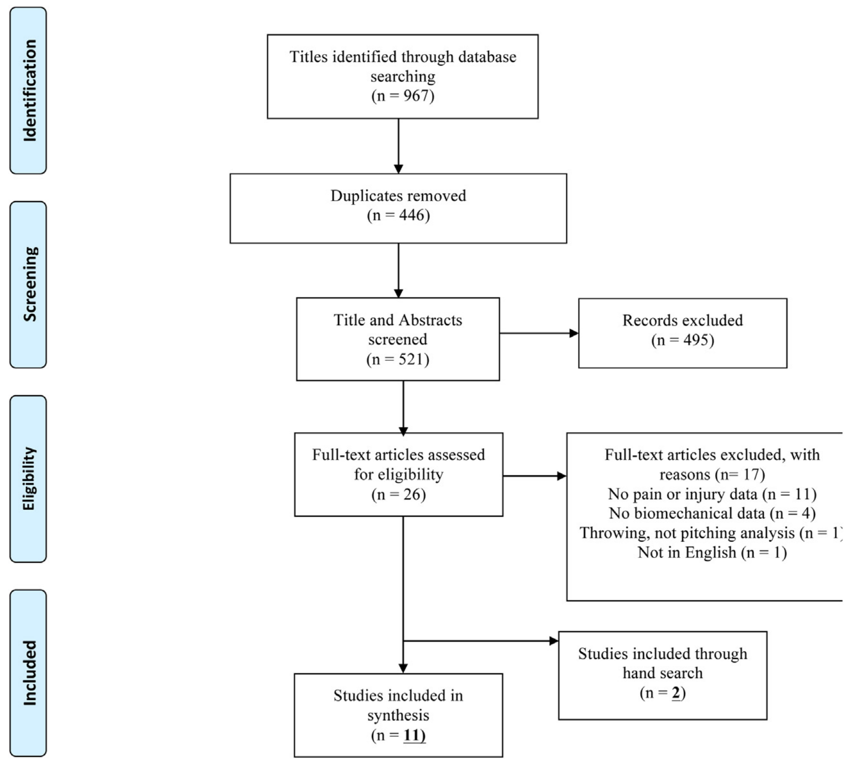

Fig. 1. Flow diagram demonstrating the systematic review of the literature for the relationship between baseball pitching biomechanics and pain, injury, or surgery.

Table 2
Included studies risk of bias.

Study	Modified Downs and Black items															Sum total
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
Anz et al.[28]	1	1	1	0	1	1	1	0	1	1	1	1	1	0	0	11
Chalmers et al.[12]	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	10
Chalmers et al.[29]	1	1	1	0	1	1	1	1	1	1	1	1	0	0	0	11
Douoguih et al.[30]	1	1	1	0	1	1	1	1	1	1	1	1	1	0	0	12
Fleisig et al.[32]	1	1	1	0	1	1	1	0	1	1	1	1	0	1	1	12
Hamilton et al.[13]	1	1	1	0	1	1	1	0	1	1	1	0	0	0	0	9
Huang et al.[20]	1	1	1	0	1	1	1	0	1	1	1	0	0	0	0	9
Keeley et al.[33]	1	1	1	0	1	1	1	0	1	1	1	0	0	0	0	9
Laughlin et al.[21]	1	1	1	0	1	1	1	0	1	1	1	1	0	1	1	12
Lyman et al.[9]	1	1	1	0	1	1	1	1	0	1	1	1	1	0	0	11
Sutter et al.[31]	1	1	1	0	1	1	1	1	1	1	1	1	1	0	0	12
Item total	10/10	10/10	10/10	1/9	10/10	10/10	9/10	4/10	9/10	10/10	10/10	8/10	4/10	2/10	2/10	

Modified Downs and Black items.
1) Is the hypothesis/aim/objective of the study clearly described?
2) Are the characteristics of the patients included in the study clearly described?
3) Is the patient sample representative of patients treated in routine clinical practice?
4) Is there information on possibility of selection bias present in study?
5) Was a comparison group identified and clearly defined?
6) Are the main outcomes to be measured clearly described in the Introduction or Methods section?
7) Were the main outcome measures used accurate (valid and reliable)?
8) Was an attempt made to blind those measuring the main outcomes of the intervention?
9) Are the main findings of the study clearly described?
10) Does the study provide estimates of the random variability in the data for the main outcomes?
11) Were the statistical tests used to assess the main outcomes appropriate?
12) Are the distributions of principal confounders in each group of subjects to be compared clearly described?
(e.g. age, sex, height, weight, activity level, sporting activity, player position, dominance, duration symptoms)
13) Was there adequate adjustment for confounding in the analyses from which the main findings were drawn?
14) Was a sample size calculation reported?
15) Did the study have sufficient power to detect a clinically important effect where the probability value for a difference 1being due to chance is less than 5%?

Additionally, a retrospective cohort study (level 2b) investigated six delivery mechanics categories (mass and momentum, arm swing, posture, position at foot strike, arm path, and finish) and their relation to upper extremity injury risk in 449 pitchers.[31] More optimal mass and momentum (risk ratio: 0.84, $p = 0.007$), more optimal arm swing (risk ratio: 0.88, $p = 0.032$), and more optimal body position at foot strike (risk ratio: 0.77, $p < 0.001$) were related to decreased upper extremity injury risk. No other delivery categories (posture, arm path, and finish) were related to upper extremity injury risk.[31]

3.5.2. Professional and collegiate pitchers

Two case control studies (level 3b) investigated both professional and collegiate pitching kinematics using 3D biomechanical analyses, but did not delineate between competition levels.[12,21] Kinematic pitching variables were compared between pitchers that had returned to sport following SLAP surgery (n = 6), pitchers that had returned to sport following bicep tenodesis surgery (n = 5), and professional or collegiate pitching controls that did not have a history of upper extremity surgery (n = 7) in one study[12] and a comparison between pitchers that had returned to sport following SLAP surgery (n = 13) and professional or collegiate healthy pitching controls that did not have a history of upper extremity surgery (n = 52) in the other study.[21] Trunk rotation orientation at foot strike (SLAP: mean 15°, bicep tenodesis: mean 35°, control: mean 25°, p = 0.028)[12] and forward trunk tilt (SLAP: mean 30.2, control mean 34.4, p = 0.048)[21] were different between pitchers with a history of SLAP or bicep tenodesis and controls. Studies reported contrasting findings regarding maximal shoulder external rotation (Chalmers et al.[31] SLAP: mean 127°, bicep tenodesis: mean 134°, control: mean 147°; Laughlin et al. SLAP: mean 168.3°, control: mean 178.3°, p = 0.016),[12,21] and maximal shoulder abduction (Chalmers et al.[12] SLAP: mean 108°, bicep tenodesis: mean 117°, control: 111°; Laughlin et al.21 SLAP: mean 108°, control: mean 111°, p = 0.013)[22,31] regarding differences between pitchers with a history of SLAP or bicep tenodesis and controls.[12,21]

Kinematic variables with no statistical difference between groups included maximal shoulder external rotation[12] maximal shoulder abduction,[12] maximal shoulder horizontal adduction,[21] maximal elbow flexion[12,21] maximal lateral trunk tilt,[12] stride length,[12,21] and knee flexion at release.[12]

3.5.3. Youth pitchers

One case control study (level 3b) evaluated 30 youth pitchers with medial elbow pain (n = 15) compared to pain-free pitching controls (n = 15) for pitching kinematics using 3D biomechanical analyses.[20] Differences were observed between pitchers with and without medial elbow pain at maximum elbow flexion (medial elbow pain: mean 91.2°, controls: mean 101.3°, p < 0.001), lateral trunk tilt at release (medial elbow pain: mean 29.3°, controls: mean 23.4°, p = 0.035), torso rotation velocity (medial elbow pain: mean 1,065.8°/s, controls: mean 931.1°/s, p < 0.0001), and maximum pelvis rotation velocity (medial elbow pain: mean 727.7°/s, controls: mean 622.1°/s, p = 0.001).[20] No differences were observed between youth pitchers with and without medial elbow pain pitchers for maximal shoulder external rotation, shoulder abduction at front foot contact or late cocking, and lateral trunk tilt at late cocking.[20]

Two studies evaluated youth pitching kinematics using video analyses.[9,29] One prospective study (level 1b) of 476 pitchers did not observe any differences in pitching kinematics between youth pitchers that reported shoulder and elbow pain and those that did not report pain, although specific kinematic data was not reported.[9] One case-control study (level 3b) of 420 (history of upper extremity injury: n = 126, controls: n = 294) pitchers observed no statistical differences between pitchers with a history of upper extremity injury and pitchers controls with no history of upper extremity injury.[29]

3.6. Electromyographic activity

3.6.1. Professional and collegiate pitchers

Two studies[12,13] investigated muscle EMG activity during pitching. One case control study[12] (level 3b) compared shoulder EMG activity in 18 professional and collegiate pitchers that had returned to sport following SLAP (n = 6), returned to sport following bicep tenodesis surgery (n = 5), and professional or collegiate pitching controls that did not have a history of upper extremity surgery (n = 7). Peak muscular contraction timing within and between pitcher variability was similar in all groups.[12] Further, peak muscular activity was similar between all groups for all muscles.[12] The other case control study13 (level 3b) investigated forearm EMG activity in 36 professional or collegiate pitchers with elbow ulnar collateral ligament injury (n = 23) and professional or collegiate pitching controls without an upper extremity injury (n = 13). There were statistically decreased EMG activity between pitchers with elbow ulnar collateral ligament injury and controls for flexor carpi ulnaris (UCL injury: mean 68% MMT, controls: mean 103% MMT) at all throwing motion phases. Pitchers with elbow ulnar collateral ligament injury also had less EMG activity compared to controls for extensor carpi radialis longus (UCL injury: mean 35% MMT, controls: mean 55% MMT) during the early cocking phase; but, not for other phases of the pitching delivery.[13] No differences in EMG activity were observed between pitchers with elbow ulnar collateral ligament insufficiency and controls at any phases of the pitching cycle for flexor carpi radialis, flexor digitorum superficialis, pronator teres, extensor carpi radialis brevis, extensor digitorum, and supinator muscles.[13]

4. Discussion

Pitching biomechanical testing evaluates pitching mechanic efficiency and joint load in order to ascertain pitching injury risk and inform pitching motion interventions.[7,8,15] The purpose of this systematic review was to investigate the relationship between baseball pitching biomechanics and pain, injury, or surgery at all ages and competition levels. Only three level 1b prospective studies9, 28, 30 were included in this review, with all three studies employing video biomechanical assessment. Of the three level 1b studies21, 28, 32 that evaluated pitching kinetics, elbow valgus torque was greater in injured pitchers compared to non-injured pitchers.28 One level 3b study observed that peak proximal shoulder force was related to shoulder pain in youth pitchers.[37] Level 1b evidence suggests that early trunk rotation was predictive of increased upper extremity surgical risk,30 and level 3b evidence found that three kinematic variables (trunk rotation velocity, pelvis rotation velocity, and trunk tilt at the late cocking phase) were found to be greater in pitchers with a history of upper extremity surgery or current pain compared to pitchers without a history of upper extremity surgery or current pain.12, 20, 21 Two level 3b studies12, 13 evaluated muscular EMG during pitching, and only flexor carpi ulnaris activity was reduced in pitchers with elbow injury compared to pitchers without elbow injured controls.13

Four studies[11,21,32,33] investigated pitching kinetics in relation to injury. In a level 1b prospective study (n = 23), only one variable was observed to be different between groups, whereby pitchers who sustained an injury throughout the course of 3 seasons demonstrated increased elbow valgus torque at baseline testing, compared to those who remained injury free.[11] Pitching places a high stress on the medial elbow, with forces recorded up to 115 N m.[16,34,35] The ulnar collateral ligament has been observed to resist up to 33% of elbow valgus torque when the elbow is flexed at 90°,[36] which is similar to the elbow position during the late cocking phase.[7] A cadaveric study observed that the ulnar collateral ligament fails at 32.1 (SD 9.6) N m,[37] demonstrating that pitching forces routinely exceed ulnar collateral ligament stress capabilities. Potential pitching biomechanical solutions to reduce elbow valgus load include decreasing shoulder abduction at front foot contact,[15,16] increasing elbow flexion at front foot contact,[15,16,38] and increasing shoulder external rotation torque.[16,38] It should be noted that pitching from the mound at shorter distances has not been attributed to decreased elbow kinetics.[39] Pitching biomechanical interventions should focus on decreasing overall elbow joint load. Although further research is needed (as it was only investigated in one study) these findings suggest this has potential to reduce pitching elbow injury risk.

Level 3b evidence (n = 36) discerned that flexor carpi ulnaris muscular activity was reduced in pitchers with elbow ulnar collateral ligament injury at all phases of the pitching cycle compared to non-injured pitching controls.[13] The flexor carpi ulnaris originates at the medial elbow condyle,[40] and is integral in resisting elbow valgus torque.[35] Diminished forearm flexor strength and fatigue have been shown to increase elbow instability during pitching.[41] Elbow instability increases ulnar collateral ligament strain,[42,43] which can increase elbow injury risk.[44] Potential solutions for addressing reduced forearm flexor strength include strengthening the forearm flexor pronator muscle mass,[45] and increasing forearm and elbow endurance, specifically the flexor carpi ulnaris.[41]

Level 1b evidence (n = 250) found that early trunk rotation was associated with an increased risk of upper extremity surgery, and level 3b evidence (n = 36) found that trunk and pelvis rotation velocity, and trunk tilt were significantly greater in pitchers with a history of upper extremity injury or current elbow pain compared to pitching controls.[12,20,21,30] The trunk has a critical role in the transfer of force between the lower and upper extremities throughout pitching.[46] During the pitching motion, the pelvis initiates a counter clockwise motion prior to trunk rotation. This is followed by a concentric oblique muscular contraction that decelerates the pelvis while simultaneously accelerating the upper trunk during the late arm cocking phase.[47] Early trunk rotation kinematic sequencing is related to increased arm drag, which increases overall upper extremity torque.[15,30,48] Further, increased trunk and pelvis rotation velocity may be attributed to early trunk rotation,[15,48] which has also been associated with higher shoulder torque and pitching velocity.[48,49] Increased lateral trunk tilt at ball release is also linked with greater pitching velocity and shoulder and elbow torque.[50] These trunk and pelvic pitching kinematic discrepancies highlight the effect proximal to distal kinematic sequencing and increased rotation velocity and joint orientation has on upper extremity joint loads. Due to this, particular attention should be focused on identifying pitchers with early trunk rotation and/or increased trunk rotation or tilt, and targeting these deficiencies may have important implications for reducing injury risk.

Only three studies used prospective cohort designs (level 1b),[9,11,30] while one study utilized a retrospective cohort design (level 2b), and the other seven studies employed case control (level 3b)[12,13,20,21,29,32,33] methodologies.[31] Further, the three prospective studies utilized video analysis, with none of these studies assessing biomechanical variables as a continuous measurement.[9,11,30] High speed video pitching analysis has decreased precision,[51] and impaired ability to assess kinetics.[52] Further, these studies categorized continuous data,[9,11,30] which leads to biased inferences, and a decreased ability to compare data to other models.[53] Three dimensional analysis is considered the gold standard biomechanical assessment; however, 3D analysis has not been employed in a prospective study in baseball pitchers. The majority of 3D pitching biomechanical studies are cross-sectional and do not compare healthy and injured pitchers. This decreases the clinical applicability of these findings. Additionally, the overall study methodological quality was moderate, with scores ranging from 9–12.[9,12,13,20,21,28–33] Only two studies[21,32] performed an *a priori* sample size calculation, which had a sufficient sample size, potentially demonstrating that the literature lacks power to accurately assess pitching biomechanical injury risk and differences between injured and non-injured pitchers. This study performed a systematic review using standardized repeatable methodology.[23] Study results were delineated by competition level and biomechanical methods employed, increasing the precision in result reporting. This study only included studies written in English, possibly decreasing the overall study pool. Due to the heterogeneity of the data, and the multitude of biomechanical models employed, study findings could not be pooled, decreasing the interpretability of the results.

4.1. Future research

This systematic review has highlighted research gaps and future research directions. There are currently no prospective injury risk studies incorporating 3D pitching biomechanical assessments. Pitching 3D biomechanical assessment is gaining popularity and access in all competition levels.[54] However, without prospective injury risk studies, there is decreased precision in using these data to ascertain individual pitching injury risk. Deciphering the degree in which elbow valgus torque, shoulder distraction and proximal force, pelvis and trunk kinematic sequencing, pelvis and trunk velocity, and lateral trunk tilt relate to injury risk through 3D biomechanical evaluation, will create improved clinical context for 3D biomechanical pitching analyses. Seven studies[12,13,20,21,29,32,33] assessed differences between pitchers with pain, injury, or a history upper extremity surgery compared to pitchers without pain/injury/surgery. Future studies are needed to examine how changes to post injury and/or pain pitching biomechanics relate to re-injury. Only two studies investigated pitching EMG muscular activity.[12,13] Investigating muscular activity when a pitcher is fatigued, and with different pitch types, may help decipher the role pitching fatigue plays in injury mechanisms and joint stress.[41,55]

5. Conclusion

In summary, the overall methodological quality of the literature was moderate. One study with level 1b evidence suggests that increased elbow valgus torque and improper trunk kinematic sequencing may increase pitching upper extremity injury risk. Three studies with level 3b evidence observed that pitchers with a history of surgery or current pain demonstrated increased trunk and pelvis rotation velocity, and increased lateral trunk tilt compared to pitchers without a history of surgery or current pain, suggesting that surgical history and current pain may alter proximal pitching kinematics. Further, one study with level 3b evidence found that the flexor carpi ulnaris may be important to resisting elbow valgus torque.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jsams.2020.06.015.

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