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Original Research

Biomechanical Basis of Interval Throwing Programs for Baseball Pitchers: A Systematic Review

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Background

Interval throwing programs are used in rehabilitation of throwing injuries, especially ulnar collateral ligament injuries. Athletes who are rehabilitating begin by throwing on flat ground progressing through increasing distances, number of throws, and intensity of throwing. If the athlete is a baseball pitcher, the flat-ground throwing phase is followed by pitching on a mound at progressively increased effort. The goal is to build back arm strength and capacity with an emphasis on proper mechanics.

Purpose

To determine whether interval throwing progressively builds joint kinetics (specifically, elbow varus torque) to the level required during full-effort baseball pitching. A secondary purpose was to examine the kinematics produced during interval throwing compared to those seen during baseball pitching.

Study Design

Systematic Review

Methods

Following PRISMA guidelines, PubMed, Embase, Web of Science, SPORTDiscus, and Google Scholar were systematically searched for biomechanical studies of flat-ground throwing and partial-effort pitching in baseball between 1987 and 2023. Studies that reported the biomechanics of either flat-ground throwing, or partial-effort pitching were included in this review. The AXIS tool was used to assess study quality.

Results

Thirteen articles met the inclusion criteria. Ten studies were determined to be of moderate quality, while three studies were deemed high quality. Elbow varus torque during partial-effort pitching was less than during full-effort pitching. Elbow varus torque for most flat-ground throws did not exceed full-effort pitching torque. While most studies showed increased elbow varus torque with increased flat-ground throwing distance, the distance at which elbow varus torque matched or exceeded full-effort pitching elbow varus torque was not consistent.
As flat-ground throwing distance increased, shoulder external rotation angle and shoulder internal rotation velocity increased. Arm slot (forearm angle above horizontal) decreased as flat-ground throwing distance increased. For varied effort pitching, shoulder external rotation angle, shoulder internal rotation velocity, elbow extension velocity, and ball velocity increased as effort increased. While the front knee extended slightly from

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foot contact to ball release in full-effort pitching, the front knee flexed slightly during partial-effort pitching.

Conclusions

An interval throwing program progressively builds elbow varus torque up to levels produced in full-effort baseball pitching. While differences exist between interval throwing kinematics and pitching kinematics, the patterns are similar in general.

Level of Evidence

2

INTRODUCTION

Baseball continues to grow in popularity throughout the United States and worldwide. In fact, nearly half a million athletes participate in baseball at the high school level alone.[1] At the collegiate level, there was a 32% increase in participants between 2004 and 2019.[2,3] With the growing number of participants, sport specialization, increased ball velocity during pitching, and the use of weighted balls during training, baseball throwing injuries and required surgeries have risen dramatically.[3-5] Elbow surgeries, such as ulnar collateral ligament surgery ("Tommy John Surgery"), have seen a disproportionate rise with studies reporting two to sixfold increases in performed procedures.[4,6-9] When a baseball player suffers a throwing-related injury, the subsequent rehabilitation process typically involves completing an interval throwing program to return to sport.[10-12]

Interval throwing programs are designed to systematically build strength, flexibility, and endurance to ensure a safe return to play while protecting post-surgical structures.[10,11] The intensity of the throws and the quantity of throws are carefully monitored and gradually increased. An interval throwing program typically begins with an athlete throwing on flat ground (also known as "long-toss"), typically at a distance of 9 or 14 meters (30 or 45 ft), and incrementally progresses until the athlete can throw 37 m (120 ft) without pain.[10,11,13] If the player is a position player, they continue the flat-ground throwing program until they reach 55 m (180 ft).[13] If the player is a pitcher and can throw 37 m without pain, they transition to pitching from the mound at the standard pitching distance of 18.44 meters (60.5 feet). Pitchers begin pitching from the mound at 50% intensity, progress to 75% intensity, and eventually to 100% intensity, provided they do not experience any pain while doing so.[10,13]

There are instructions, assumptions, and implications about throwing biomechanics in the interval program relative to pitching biomechanics.[10,11] Instructions for interval throwing programs emphasize proper throwing biomechanics utilizing coordinated movements of the legs, trunk, and arms.[13,14] Improper biomechanics may decrease performance (i.e. fastball velocity) or increase risk of injury (i.e. joint kinetics).[14,15] Elbow varus torque is a key kinetic parameter as it is related to risk of UCL injury.[16,17] Theoretically, if an athlete attempts to throw at a longer distance or greater effort than for which he is ready, he may alter his kinematics, thereby increasing the kinetics and injury risk to his elbow and shoulder.

Several authors have reported the biomechanics of throws used in interval throwing programs, such as flat-ground throws and/or partial-effort pitching.[12,18-27] However, there have been no systematic reviews examining the biomechanics that occur during interval throwing programs The purpose of this review was to determine whether interval throwing progressively builds joint kinetics (specifically, elbow varus torque) to the level required during full-effort baseball pitching. A secondary purpose was to examine the kinematics produced during interval throwing compared to those seen during baseball pitching. Results from this review will provide an analysis of how well the throwing biomechanics in interval throwing programs achieve their intended purpose for the rehabilitation of baseball pitchers.

METHODS

This systematic review was completed according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta Analyses) guidelines.[28] An electronic, manual search of literature published between 1987 and 2023 was conducted by searching PubMed (which included Medline), Embase, Web of Science, and SPORTDiscus using search terms relating to upper extremity rehabilitation and interval throwing programs in baseball (Appendix A). The same search terms were used for all databases.

Two investigators (T.D. and B.L.) independently screened the resulting article titles and abstracts to identify records to be considered for full text review. In the case of disagreement, articles were discussed until a consensus was reached or the senior author (G.F.) was consulted for resolution. Next, the two investigators (T.D. and B.L.) independently screened the full text articles for inclusion in the systematic review; the senior author (G.F.) was once again consulted in case of disagreement. Eligible articles were included in this review if they were published in the prior 35 years, peer-reviewed, and included biomechanical data of baseball throws used in interval throwing programs, specifically flat-ground throwing and/or partial-effort pitching from the mound. Exclusion criteria were review articles, case reports, commentaries, technical notes, or studies that only evaluated subjects who were not baseball players. The references cited within the identified studies were also screened to discern additional articles that were not identified in the literature search. A supplementary search of "interval throwing program biomechanics" was performed on

Google Scholar in which the first 100 search results were screened to identify any articles that may have been missed by the databases search. The entire search process in accordance with PRISMA guidelines. Additional data were requested and received via personal communication with the authors of one study.[22]

QUALITY ASSESSMENT

Two authors (T.D. and B.L.) used the AXIS tool[29] to assess the quality of each included study. The AXIS tool uses 20 Yes-No questions that assess the aims, methods, results, and conclusions reported in each study.[29] A score greater than or equal to 75% is considered high quality. A score of 60% - 70% is considered moderate quality. A score below 60% is considered low quality.

RESULTS

The search of PubMed, Embase, Web of Science, and SPORTDiscus revealed 2985 articles (Figure 1). After removing duplicates, 1105 articles remained.

The supplementary search on Google Scholar revealed one additional journal article and one additional conference abstract that qualified for inclusion. After reviewing titles and abstracts, 85 articles remained for full-text review. Of the 85 articles, 73 were excluded, with 12 articles qualifying for inclusion. After reviewing the references of the 12 included articles, one additional record was identified that qualified for inclusion.[18] In total, 11 journal articles and two conference abstracts qualified for inclusion in this review. Ten studies (77%) were determined to be of moderate quality, while three studies (23%) were deemed high quality (Table 1). No studies were scored as low quality. The mean AXIS score was 14±0.8 (70±4%) which indicates moderate quality for the 13 studies included.[29] Table 2 provides details of all included studies.

Of the 13 studies, six[12,18,20,24,27,30] used optical motion capture while the other seven utilized inertial measurement unit (IMU) sensors.[19,21-23,25,26,31] The majority of studies in this review investigated either high school pitchers, college pitchers, or a mix of both. Three studies investigated only high school pitchers[22,23,27]; three studies investigated only college pitchers[12,18,25]; five studies had a mix of high school and college pitchers[19,21,26,30,31]; and one study had a mix of college, club (i.e., recreational), and one minor league pitcher[20]; and the final study investigated professional pitchers.[24] It should be noted that Leafblad et al.[21] and Melugin et al.[26] used the same group of subjects for their studies but investigated different aspects of interval throwing programs.

FLAT-GROUND THROWING KINETICS

Ten of the 13 studies investigated kinetics of flat-ground throwing. Nine of these investigated varying distances, while Melugin et al.[26] looked at varied efforts at 37 meters. Fleisig et al.[30] only evaluated the biomechanics of flat-ground throwing at 18 meters as part of an investigation into the biomechanics of weighted ball throwing. As shown in Figure 2, most included articles demonstrated that elbow varus torque increased as distance increased for most studies, while Slenker et al.[20] and Wight et al.[25] found different trends. Slenker et al.[20] reported greater torque during 18m and 27m throws without a crow hop compared to their 37m and 55m throws with crow hop. Wight et al.[25] found no differences in elbow varus torque across throws of 27, 37, 46, and 55 meters.

FLAT-GROUND THROWING KINEMATICS

Eight studies investigated the kinematics of flat-ground throws as commonly used in an interval throwing program,[12,21-25,30,31] while Melugin et al.[26] investigated kinematics of varied effort flat-ground throwing. Kinematics of flat-ground throwing and full-effort pitching from a mound are presented in Table 3. Stride length was consistently shorter during flat-ground throws in comparison to full-effort pitching.[12,24,30] Values for foot position at foot contact were also lower during flat-ground throwing, suggesting that pitchers step more to the closed side when pitching than during flat-ground throwing.[12,30] Additionally, upper trunk tilt was greater (more "uphill") in flat-ground throwing than in pitching.[12,30]

All seven studies that recorded maximum shoulder external rotation across multiple flat-ground throwing distances showed that maximum shoulder external rotation increased as flat-ground throwing distance increased.[12,21-25,31] Similarly, all seven studies also found increasing shoulder internal rotation velocities (or "arm speed" for studies that used an IMU) as flat-ground throwing distance increased.[12,21-25,31] At ball release, shoulder abduction and lateral trunk tilt maintained consistent values around 90 degrees and 25 degrees, respectively, for flat-ground throws and pitching from the mound.[12,30] Arm slot (i.e., the forearm and horizontal plane at the time of ball release) decreased as flat-ground throwing distance increased for each study that used an IMU sensor.[21,23,31]

PARTIAL-EFFORT PITCHING KINETICS

Four studies investigated kinetics of pitching at increasing effort.[18-20,27] All four studies had pitchers pitch at varying perceived efforts, either throwing at 50%, 75%, and 100% intensity[18,19] or 60%, 80%, and 100% intensity.[20] Fiegen et al.,[27] Fleisig et al.,[18] Lizzio et al.,[19] and Slenker et al.[20] all found that elbow varus torque increased as pitching effort increased (Figure 3). Pitching at 50% and 60% effort produced less elbow varus torque than pitching at 75% and 80% effort, and all partial-effort pitching produced less elbow varus torque than full-effort pitching.[18-20,27]

PARTIAL-EFFORT PITCHING KINEMATICS

Fleisig et al. investigated the kinematics of pitching at increased effort.[18] As shown in Table 4, they found no significant differences in stride length during partial-effort pitches. However, lead knee flexion at front foot contact was significantly less during 50% and 75% effort pitches.

Table 1. AXIS study assessment

Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Positive Responses	Score	Quality
Carr et al.	Y	Y	N	Y	Y	D	N	Y	Y	Y	Y	Y	D	N	Y	Y	Y	Y	D	D	14	70%	Moderate
Cross et al.	Y	Y	N	Y	Y	D	N	Y	Y	Y	D	Y	D	N	Y	Y	Y	N	D	Y	12	60%	Moderate
Dowling et al.	Y	Y	N	Y	Y	D	N	Y	Y	Y	Y	Y	D	N	Y	Y	Y	Y	Y	Y	14	70%	Moderate
Fiegen et al.	Y	Y	N	Y	Y	D	N	Y	Y	Y	Y	Y	D	N	Y	Y	Y	Y	D	Y	14	70%	Moderate
Fleisig et al., 1996	Y	Y	N	Y	Y	D	N	Y	Y	Y	Y	Y	D	N	Y	Y	Y	N	D	Y	13	65%	Moderate
Fleisig et al., 2011	Y	Y	N	Y	Y	D	N	Y	Y	Y	Y	Y	D	N	Y	Y	Y	Y	N	Y	15	75%	High
Fleisig et al., 2017	Y	Y	N	Y	Y	D	N	Y	Y	Y	Y	Y	D	N	Y	Y	Y	Y	N	Y	15	75%	High
Leafblad et al.	Y	Y	N	Y	Y	D	N	Y	Y	Y	Y	Y	D	N	Y	Y	Y	Y	D	Y	14	70%	Moderate
Lizzio et al., 2020	Y	Y	N	Y	Y	D	N	Y	Y	Y	Y	Y	D	N	Y	Y	Y	Y	D	Y	14	70%	Moderate
Lizzio et al., 2021	Y	Y	N	Y	Y	D	N	Y	Y	Y	Y	Y	D	N	Y	Y	Y	Y	D	Y	14	70%	Moderate
Melugin et al.	Y	Y	N	Y	Y	D	N	Y	Y	Y	Y	Y	D	N	Y	Y	Y	Y	D	Y	14	70%	Moderate
Slenker et al.	Y	Y	N	Y	Y	D	N	Y	Y	Y	Y	Y	D	N	Y	Y	Y	Y	N	Y	15	75%	High
Wight et al.	Y	Y	N	Y	Y	D	N	Y	Y	Y	Y	Y	D	N	Y	Y	Y	N	N	Y	14	70	Moderate

Y = yes, N = no, and D = do not know. For each question, 1 point is awarded depending on the answer. A yes is one point for all questions except 13 and 19. A no is one point only on questions 13 and 19. A do not know is 0 points. A score of 75% or greater is considered high quality. A score of 60% - 70% is considered moderate. A score below 60% is considered low quality.

AXIS questions[29] :

1. Were the aims/objectives of the study clear?
2. Was the study design appropriate for the stated aim(s)?
3. Was the sample size justified?
4. Was the target/reference population clearly defined? (Is it clear who the research was about?)
5. Was the sample frame taken from an appropriate population base so that it closely represented the target/reference population under investigation?
6. Was the selection process likely to select subjects/participants that were representative of the target/reference population under investigation?
7. Were measures undertaken to address and categorise non-responders?
8. Were the risk factor and outcome variables measured appropriate to the aims of the study?
9. Were the risk factor and outcome variables measured correctly using instruments/measurements that had been trialed, piloted or published previously?
10. Is it clear what was used to determined statistical significance and/or precision estimates? (e.g., p values, CIs)
11. Were the methods (including statistical methods) sufficiently described to enable them to be repeated?
12. Were the basic data adequately described?
13. Does the response rate raise concerns about non-response bias?
14. If appropriate, was information about non-responders described?
15. Were the results internally consistent?
16. Were the results for the analyses described in the methods, presented?
17. Were the authors' discussions and conclusions justified by the results?
18. Were the limitations of the study discussed?
19.Were there any funding sources or conflicts of interest that may affect the authors' interpretation of the results?
20. Was ethical approval or consent of participants attained?

Table 2. Description of Included Studies

Authors	Subjects	Technology	Flat-Ground Throwing Distance (m)	Pitching from mound (18.44m)	Variables Reported
Carr et al., 2022[22]	7 high school pitchers	Inertial measurement unit	27m, 37m, 46m, 55m	Full-effort	Elbow varus torque Arm speed
Cross et al., 2019[24]	19 professional pitchers	Optical marker tracking	18m, 37m, 55m, 73m, 91m	Full-effort	Full-body kinematics Elbow and shoulder kinetics
Dowling et al., 2018[23]	95 high school pitchers	Inertial measurement unit	9m, 18m, 27m, 37m, 46m	N/A	Elbow varus torque Arm slot Arm speed Maximum shoulder external rotation
Fiegen et al., 2023[27]	10 high school pitchers	Optical marker tracking	N/A	50% effort, 75% effort, & full-effort	Elbow varus torque
Fleisig et al., 1996[18]	27 college pitchers	Optical marker tracking	N/A	50% effort, 75% effort, & full-effort	Full-body kinematics Elbow and shoulder kinetics
Fleisig et al., 2011[12]	17 collegiate pitchers	Optical marker tracking	37m, 55m, full-effort	Full-effort	Full-body kinematics Elbow and shoulder kinetics
Fleisig et al., 2017[30]	18 high school pitchers and 7 college pitchers	Optical marker tracking	18.44m	Full-effort	Full-body kinematics Elbow and shoulder kinetics
Leafblad et al., 2019[21]	28 high school and 32 collegiate pitchers	Inertial measurement unit	27m, 37m, 46m, 55m	Full-effort	Elbow varus torque Arm slot Arm speed Maximum shoulder external rotation Ball velocity
Lizzio et al., 2020[19]	26 high school and 11 collegiate pitchers	Inertial measurement unit	N/A	50% effort, 75% effort, & full-effort	Elbow varus torque
Lizzio et al., 2021[31]	20 high school and collegiate pitchers (split not identified)	Inertial measurement unit	9m, 14m, 18m, 27m, 37m, 46m, 55m	N/A	Elbow varus torque Arm slot Arm speed Shoulder rotation Ball velocity
Melugin et al., 2019[26]	28 high school and 32 collegiate pitchers	Inertial measurement unit	37m	N/A	Elbow varus torque Arm slot Arm speed Shoulder rotation Ball velocity
Slenker et al., 2014[20]	25 collegiate, 3 club league, and 1 Minor League pitchers	Optical marker tracking	18m, 27m, 37m, 55m	60% effort, 80% effort, & full-effort	Elbow and shoulder kinetics Ball velocity
Wight et al., 2019[25]	19 college pitchers	Inertial measurement unit	27m, 37m, 46m, 55m	Full-effort	Elbow varus torque Arm cocking angle

Table 3. Flat-ground throwing kinematic data. Full effort pitching kinematic data provided for comparison.

Foot Contact	9m	14m	18m	27m	37m	46m	Pitch (18.44m)
Stride length (% subject's height)							
Cross et al., 2019			**59 ± 10**		**66 ± 9**		76 ± 8
Fleisig et al., 2011					79 ± 6		80 ± 4
Fleisig et al., 2017			**80 ± 6**				84 ± 6
Foot position (cm to the "closed" side)							
Fleisig et al., 2011					**16 ± 14**		25 ± 12
Fleisig et al., 2017			**13 ± 13**				21 ± 15
Upper trunk tilt							
Fleisig et al., 2011					**13 ± 9**		6 ± 7
Fleisig et al., 2017			10 ± 6				7 ± 9
Lead knee flexion							
Fleisig et al., 2011					46 ± 8		47 ± 9
Fleisig et al., 2017			**42 ± 9**				46 ± 10
Maximum Values							
Shoulder external rotation							
Cross et al., 2019			148 ± 8		156 ± 8		160 ± 12
Dowling et al., 2018	147 ± 7		155 ± 5	161 ± 4	165 ± 4	167 ± 5	
Fleisig et al., 2011					174 ± 10		174 ± 10
Fleisig et al., 2017			175 ± 11				174 ± 12
Leafblad et al., 2019				162 ± 10	167 ± 9	170 ± 9	161 ± 11
Lizzio et al., 2021[a]	137	146	150	155	161	166	
Wight et al., 2019				159 ± 10	164 ± 9	**167 ± 8**	157 ± 11
Elbow flexion							
Cross et al., 2019			92 ± 8		93 ± 7		89 ± 5
Fleisig et al., 2011					103 ± 10		101 ± 11
Fleisig et al., 2017			109 ± 12				109 ± 12
Shoulder internal rotation velocity or Arm speed (deg/s)							

Foot Contact	9m	14m	18m	27m	37m	46m	Pitch (18.44m)
Carr et al., 2022[b]				3920 ± 1068[a]	4141 ± 757[a]	4482 ± 949[a]	4533 ± 864[a]
Cross et al., 2019			3420 ± 416		3854 ± 460		4462 ± 439
Dowling et al., 2018	2731 ± 563		4066 ± 480	4622 ± 328	4909 ± 332	5044 ± 416	
Fleisig et al., 2011					7590 ± 1214		7640 ± 1173
Fleisig et al., 2017			6705 ± 869				6594 ± 743
Leafblad et al., 2019				5203 ± 736	5302 ± 633	5357 ± 510	5527 ± 554
Lizzio et al., 2021[a]	346	527	661	753	796	839	
Wight et al., 2019				5461 ± 713	5483 ± 658	5490 ± 506	5589 ± 557
Elbow extension velocity (deg/s)							
Cross et al., 2019			1501 ± 211		1711 ± 231		2043 ± 2109
Fleisig et al., 2011					2492 ± 204		2480 ± 255
Fleisig et al., 2017			2317 ± 240				2305 ± 221
Ball Release							
Forward trunk tilt							
Fleisig et al., 2011					**27 ± 8**		34 ± 8
Fleisig et al., 2017			32 ± 6				33 ± 7
Lateral trunk tilt							
Fleisig et al., 2011					24 ± 8		25 ± 8
Fleisig et al., 2017			24 ± 9				25 ± 8
Shoulder abduction							
Cross et al., 2019			91 ± 7		92 ± 7		92 ± 7
Fleisig et al., 2011					89 ± 9		88 ± 7
Fleisig et al., 2017			91 ± 9				91 ± 10
Arm slot							
Dowling et al., 2018	55 ± 6		50 ± 5	48 ± 5	46 ± 6	44 ± 7	
Leafblad et al., 2019				50 ± 13	48 ± 13	48 ± 14	51 ± 15
Lizzio et al., 2021	64	60	53	51	49	46	
Lead knee flexion							

Foot Contact	9m	14m	18m	27m	37m	46m	Pitch (18.44m)
Fleisig et al., 2011					36 ± 12		37 ± 13
Fleisig et al., 2017			36 ± 13				36 ± 14

Data are presented in degrees as mean ± standard deviation and rounded to the nearest whole number unless otherwise noted. A bold value denotes that the study's flat-ground throwing value was statistically significantly different from the study's pitching value. Statistical significance was $p < 0.05$ unless otherwise noted.

a) Data are from throws with a crow hop. Data reported as least squares means.

b) Data received via personal communication with the study's authors.

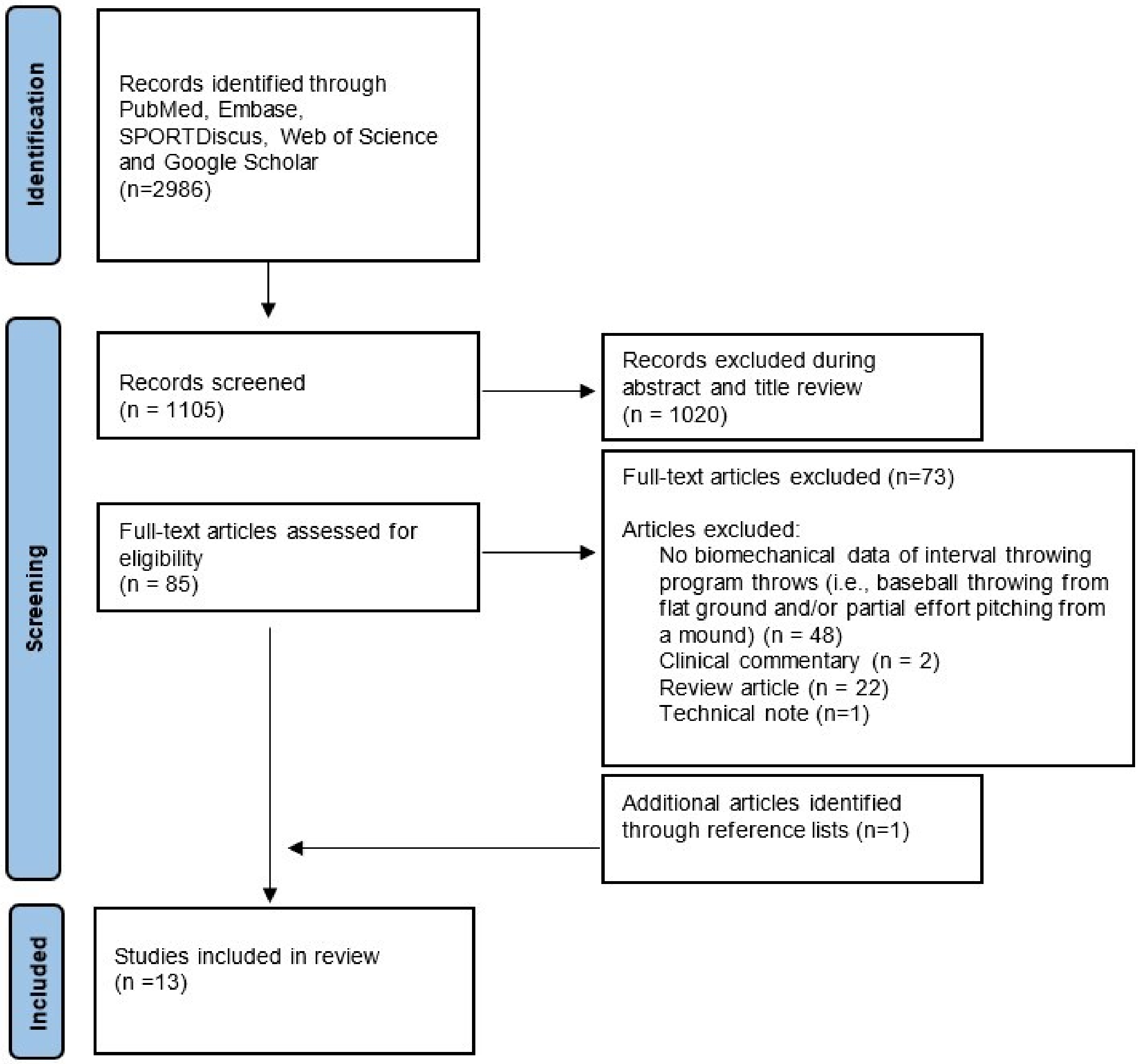

Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta Analyses) flow diagram representing the inclusion strategy for the systematic review.

These authors also found significantly less shoulder external rotation, internal rotation velocities, and elbow extension velocities during partial-effort pitching. At ball release, knee flexion was significantly greater compared to knee flexion during full-effort pitching, thus suggesting that pitchers do not achieve as much knee extension during partial-effort pitching. In fact, during partial-effort pitching, pitchers increased their knee flexion between foot contact and ball release.

DISCUSSION

To determine if an interval throwing program progressively builds joint kinetics up to the level required during full-effort pitching, elbow varus torque values were normalized to the values produced in full-effort pitching (Figure 4). The distance at which flat-ground throwing elbow varus torque equals or exceeds maximum pitching torque varied between studies. Both Fleisig et al.[30] and Slenker et al.[20] found that 18-meter throws had greater elbow varus torque compared to full-effort pitching from the mound. Wight et al.[25] found that throws of 27, 37, 46, and 55 meters all had greater elbow varus torque than pitching. Carr et al.[22] and Leafblad et al.[21] found that elbow varus torque during 55-meter throws was nearly equal to full-effort pitching elbow varus torque, while Fleisig et al.[12] found that elbow varus torque during 55-meter throws was greater than elbow varus torque during full-effort pitching. Interestingly, Cross et al.[24] found that elbow varus torque did not exceed full-effort pitching torque until 91-meter throws. Thus, while flat-ground throwing progressively builds elbow kinetic demands, it is unclear when flat-ground throwing kinetics surpass full-effort pitching kinetics. Caution should be exercised when performing these throws, especially when a pitcher reaches their final flat-ground throwing distance of 37 meters.

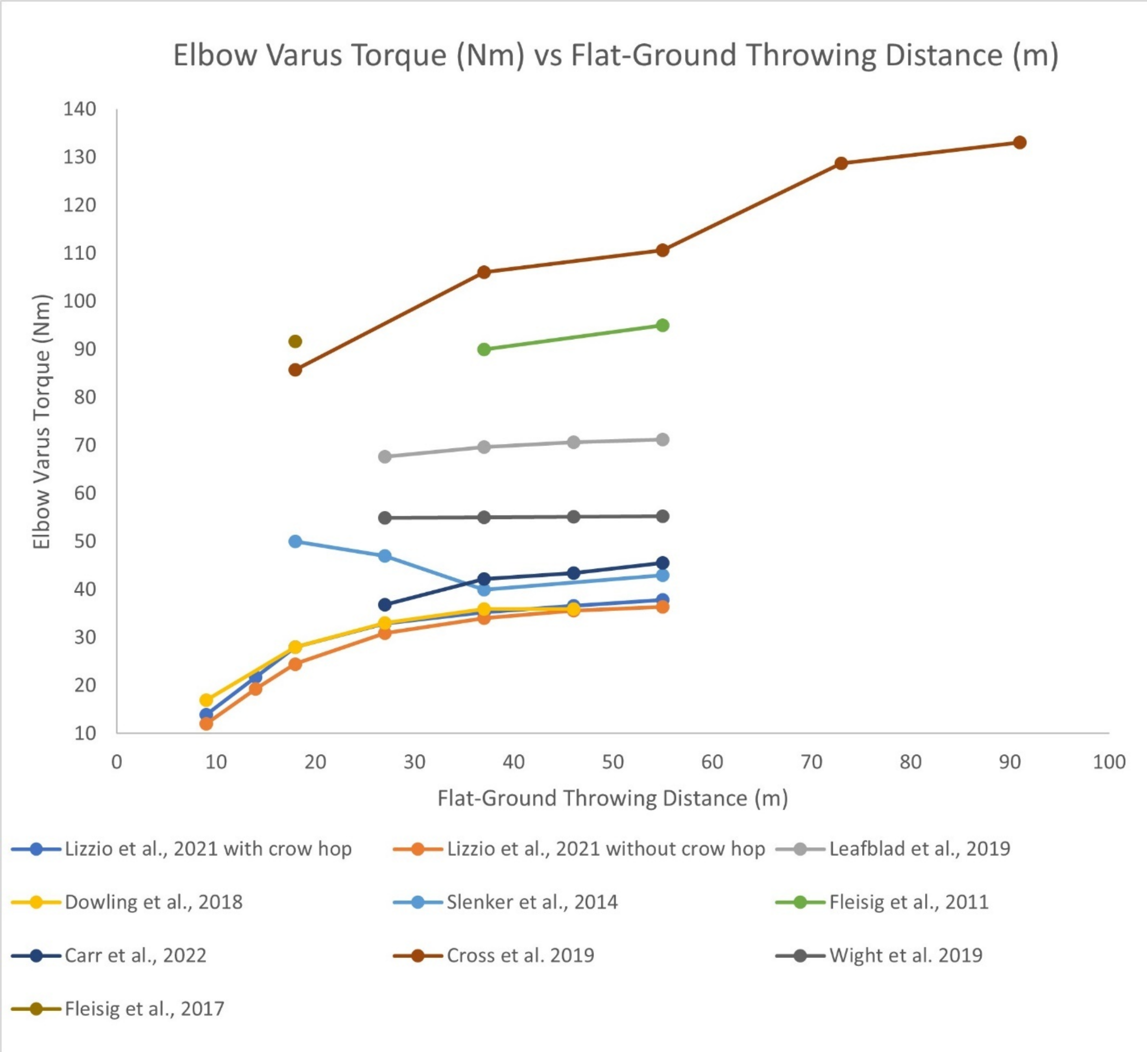

Figure 2. Elbow varus torque (Nm) versus flat-ground throwing distance (m).

Note: both graphs have the same y-axis. On the y-axis, 100% represents full-effort pitching elbow varus torque. For reference, pitching distance is 18.44 meters.

Elbow varus torque during partial-effort pitching did not exceed the elbow varus torque of full-effort pitching in any study (Figure 4). While elbow varus torque systematically increases with effort, percent of elbow torque and percent of effort are not equal. Pitching with 50% effort produced about 75% of the elbow torque during full-effort pitching. Pitching with 75% to 80% effort produced 80% to 95% of the elbow torque during full-effort pitching.

A secondary purpose of this study was to determine if the kinematics produced during interval throwing programs are similar to baseball pitching kinematics. Despite limited kinematic data, it appears that kinematics of flat-ground throwing are similar to full-effort pitching, in general. However, some significant differences were reported. Compared to full-effort pitching, flat-ground throwing demonstrated a shorter stride, less distance landing to the closed side, and a more upright trunk position.[12,24,30] As flat-ground throwing distance increases, both maximum shoulder external rotation and shoulder internal rotation velocities increase. The distance at which maximum shoulder external rotation exceeded shoulder external rotation during full-effort pitching varied between studies.[12,21,24,25] Clinicians should be aware of these differences and ensure that proper pitching biomechanics are restored when the athlete returns to pitching on the mound.

At ball release, arm slot decreased as throwing distance increased.[21,23,31] In these studies, the IMU sensor calculated arm slot as the angle created between the forearm and horizontal plane at ball release.[32] It should be noted that arm slot for optical motion capture has been reported as the angle created by a vertical line and the vector connecting the shoulder joint center to the hand at ball release.[33,34] Arm slot is affected by shoulder abduction, lateral trunk tilt, and elbow flexion.[33,34] Interestingly, both shoulder abduction and lateral trunk tilt at ball release were similar in flat-ground throwing to full-effort pitching values. However, only three studies reported shoulder abduction[12,24,30] and two reported lateral trunk tilt,[12,30] so more research is needed on flat-ground throwing kinematics using optical motion capture in order to confirm the arm slot trends observed in the studies that used the IMU sensor.

Melugin et al.[26] investigated partial-effort flat-ground throwing. In their study, the authors had subjects throw "on

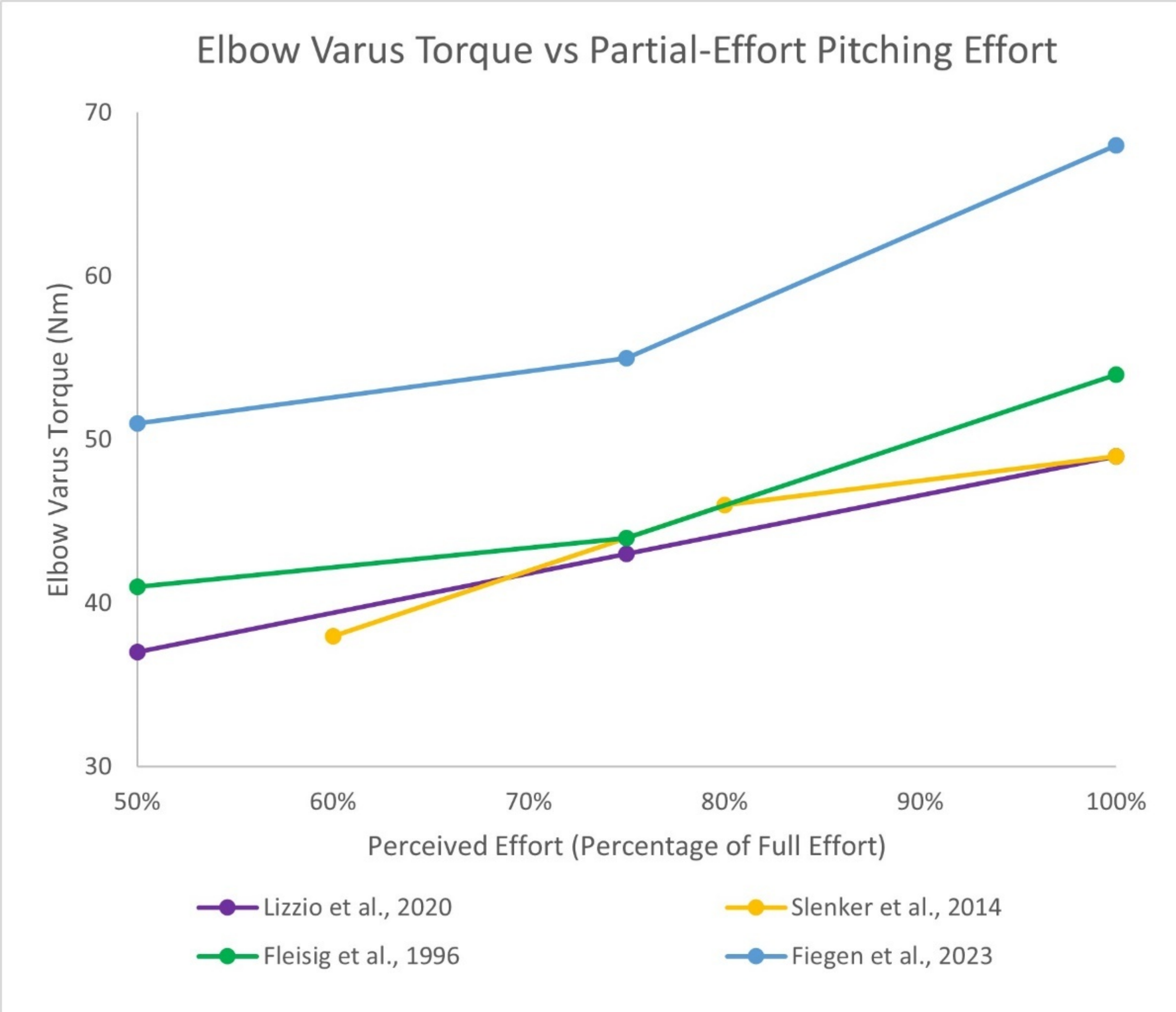

Figure 3. Elbow varus torque versus partial-effort pitching (Percentage of full-effort) across four included studies.

a line" without a crow hop at 37 meters. The authors instructed subjects to throw at 50%, 75%, and 100% intensity. Similar to the trends observed in partial-effort pitching, the authors found that at 50% throwing intensity, players threw at 78% of maximum ball velocity and experienced 86% maximum elbow varus torque. When players threw at 75% intensity, ball velocity was 86% of maximum and elbow varus torque was 93% of maximum. Unlike the trend observed during partial-effort pitching, an unexpected finding was that shoulder external rotation remained constant regardless of flat-ground throwing intensity. However, both arm slot and arm speed increased as throwing intensity increased.

Unfortunately, only one study reported kinematics in partial-effort pitching. Fleisig et al. reported partial-effort kinematics at 50%, 75%, and 100% perceived effort.[18] Shoulder external rotation, shoulder internal rotation velocities, and elbow extension velocities were all significantly decreased during partial-effort pitching. While stride length remained similar across effort levels, lead knee flexion was significantly lower during 50% and 75% effort pitches. Full-effort pitching requires coordinated movements of the legs, trunk, and arms, and the lack of knee extension observed during the 50%- and 75%-effort pitches results in less energy transferred up the kinetic chain and onto the ball.[35] This kinetic chain concept has been supported by a recent study showing that high-velocity professional pitchers had greater lead knee extension and lead knee velocity than low-velocity professional pitchers.[36] These results provide evidence that the partial-effort pitching phase of an interval throwing program does in fact systematically increase joint velocities as perceived effort increases, but partial-effort pitching does have kinematic differences from full-effort pitching.

Four studies reported ball velocity during partial-effort pitching.[18-20,27] While ball velocity increases with effort as expected, the percent of ball velocity and percent of effort are not equal (Figure 5). Fleisig et al.[18] and Fiegen et al.[27] both found that at 50% effort, pitchers threw at 85% of maximum ball velocity. At 75% effort, pitchers threw at 90% of maximum ball velocity. Similarly, Lizzio et al.[19] found that at 50% effort, pitchers threw with 79% of maximum ball velocity. At 75% effort, pitchers threw at 89% maximum ball velocity. Slenker et al.[20] did a similar study by instruct-

Table 4. Kinematics of partial-effort pitching from Fleisig et al., 1996.[18]

Foot Contact	50% effort	75% effort	100% effort
Stride length (% of subject's height)			
Fleisig et al., 1996	69 ± 4	70 ± 7	71 ± 4
Lead knee flexion			
Fleisig et al., 1996	**40 ± 9**	**41 ± 10**	47 ± 10
Maximum Values			
Shoulder external rotation			
Fleisig et al., 1996	**167 ± 11**	**169 ± 12**	172 ± 12
Elbow flexion			
Fleisig et al., 1996	**101 ± 11**	102 ± 10	105 ± 10
Shoulder internal rotation velocity			
Fleisig et al., 1996	**5820 ± 1110**	**6400 ± 1050**	7290 ± 1090
Elbow extension velocity			
Fleisig et al., 1996	**1940 ± 270**	**2130 ± 280**	2350 ± 250
Ball Release			
Lead knee flexion			
Fleisig et al., 1996	**49 ± 10**	**44 ± 10**	36 ± 12
Trunk angle above horizontal			
Fleisig et al., 1996	**66 ± 9**	**64 ± 9**	59 ± 8

Data are presented in degrees as mean ± standard deviation unless otherwise noted. Bold values denote a significant ($p < 0.05$) difference from full-effort pitching.

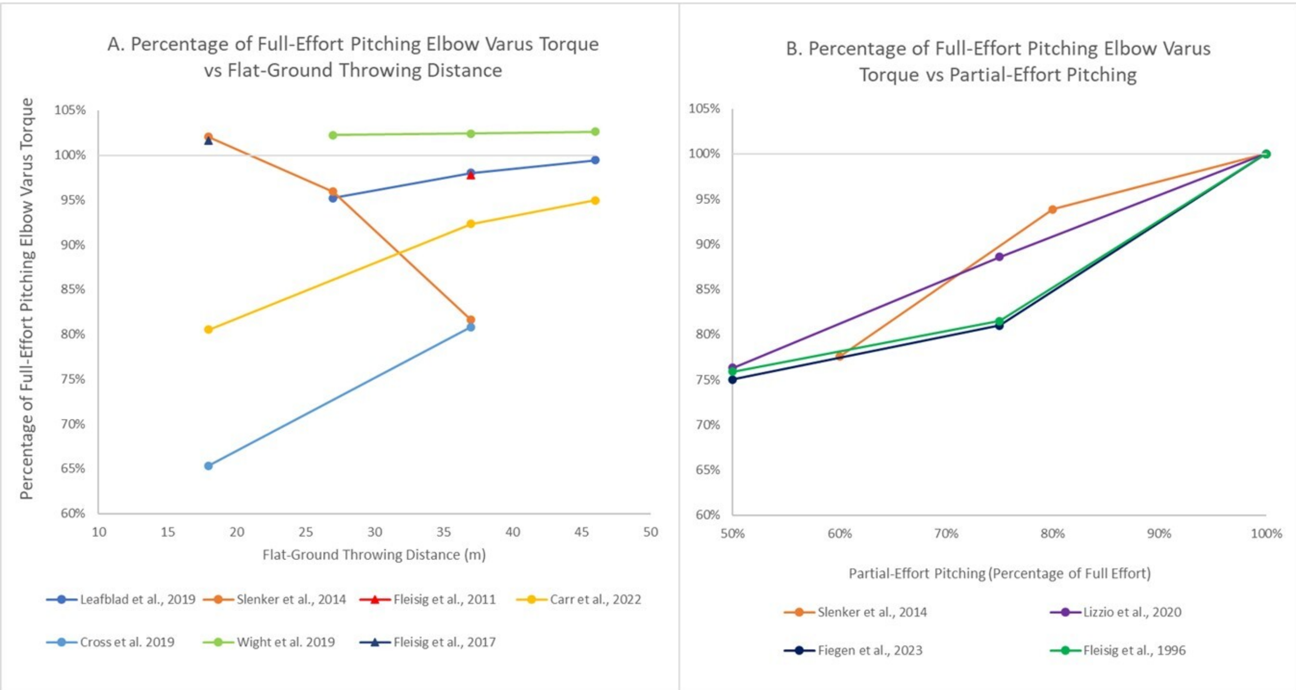

Figure 4. Percentage of maximum pitching elbow varus torque achieved in interval throwing program for pitchers. This includes (A) flat-ground throwing up to 45 m and (B) partial-effort pitching.

ing pitchers to pitch at 60%, 80%, and 100% effort. Similar to the other studies, Slenker et al. found that at 60% effort, pitchers threw at 85% of maximum ball velocity. At 80% effort, pitchers threw at 91% of maximum ball velocity. These findings do not invalidate the use of partial-effort pitching in interval throwing programs, as no interval throwing pro-

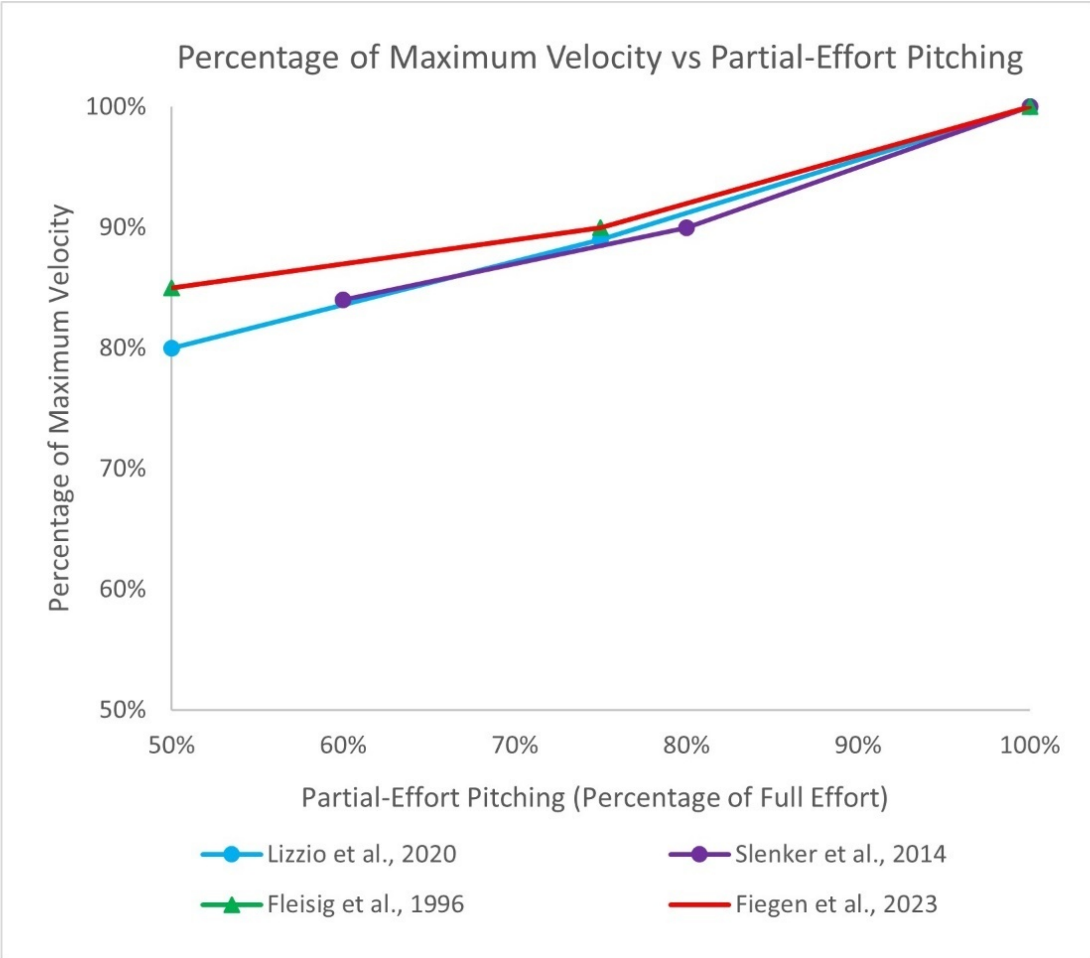

Figure 5. Percentage of maximum velocity versus partial-effort pitching (percentage of full-effort) for four of the included studies. Note that both Fiegen et al. and Fleisig et al. found nearly identical values.

gram states that the percentage of perceived effort should equal the percentage of maximum pitch velocity.

LIMITATIONS AND FUTURE RESEARCH

Like all studies, this systematic review had limitations. Although PRISMA guidelines were followed to search multiple databases, there is a possibility that articles with relevant data were missed by this search. Furthermore, two of the included studies were conference abstracts, however, the inclusion of abstracts in a systematic review is permissible when there is limited published articles on a topic.[37] Additionally, the articles identified varied regarding which biomechanical parameters they measured. This review was focused on kinetic and kinematic parameters that were reported often and are considered relevant to injury risk and return to proper mechanics.

It also is important to note that the literature used two different technologies for collecting biomechanical data. Optical motion capture, which was used in six of the studies, is considered the "gold standard" of biomechanical data collection. The other seven studies used a wearable IMU. The wearable IMU in all seven studies was the MotusBASEBALL sensor, now called Driveline Pulse (Driveline Baseball, Kent, WA). Unfortunately, data from MotusBASEBALL sensors and optical motion capture are not directly comparable.[32,38] Despite an initial pilot study that showed good to excellent correlations between the MotusBASEBALL sensor and optical motion capture values for elbow varus torque, arm rotation, arm slot, and arm speed,[39] other studies have found only moderate correlations between IMU and optical motion data.[32,38,40] Thus, the effect of throwing distance and pitching effort on elbow torque can be analyzed within IMU studies to analyze trends; however, the raw numbers from the IMU's cannot be combined with optical motion data into a meta-analysis.

Another important difference between studies was the varying instructions surrounding flat-ground (long-toss) throwing technique. Some studies instructed participants to throw "hard, on a line" when performing their flat-ground throws.[20,25,30] Others simply instructed their participants to throw either "on line" or "on a line".[21,23,26] Carr et al. was a retrospective study and stated that participants threw at "full-effort" for all throws.[22] Conversely, Lizzio et al. instructed their participants to throw "on an arc" when flat-ground throwing.[31] In addition, throwing effort is not the only variable in flat-ground throwing. The crow hop, which is a sequence of steps of the front foot, back foot, and front foot, theoretically enhances lower extremity and core involvement to aid the throw.[10,12,23] While reviewing the literature, the authors noticed several different instructions regarding the use of a crow hop during flat-ground throws. Three studies[23-25] gave no instructions or constraints involving the crow hop and two studies[12,30] allowed players to use whatever crow hop technique they liked. Leafblad et al.[21] discouraged the use of a crow hop but allowed it if it was needed for the participant to reach the desired throwing distance. Slenker et al.[20] instructed participants to use a crow hop only during their longer (37 m and 55 m) throws and found decreased elbow varus torque during throws that used a crow hop. The investigators stated that the use of the crow hop with their long-distance throws was likely the reason elbow torque decreased. Lizzio et al.[31] specifically studied the effects of the crow hop during flat-ground throwing. They found that when a crow hop was used, there was greater elbow varus torque and ball velocity compared to when a crow hop was not used. We believe that compared to a flat-ground throw with no run-up, a crow hop throw creates kinetic energy that is passed up the kinetic chain to the throwing arm, leading to greater joint torque and ball velocity. This lack of consensus defining flat-ground baseball throwing is not unique to biomechanical studies, as a survey of professional pitchers, pitching coaches, and certified athletic trainers found varying responses to what is the proper technique for long-toss.[41]

Another limitation of this study was the relatively small sample sizes of participants used in some of the included studies, as five of the included studies had less than 20 subjects. Additionally, only one study, conducted over 25 years ago, investigated the kinematics of partial-effort pitching, which limits this study's ability to confidently assess partial-effort pitching kinematics.[18] Finally, most of the baseball players in the studies included in this review played at the high school or collegiate level. Further research including lower (i.e., youth) and higher (i.e., professional) level baseball players is needed.

Optimizing an interval throwing program is a combination of science and art. This systematic review of biomechanics revealed the stresses and mechanics used during interval throwing, but determining and monitoring the right progression was outside our scope. There has been much discussion on the future direction of interval throwing programs, with suggestions to adjust the throwing based on workloads. Some have suggested throwing programs should be performed with five-week blocks featuring a gradual increase in number of throws, effort, and distance for approximately four weeks followed by one week with reduced workload to allow the athlete to recover. Additional research is needed to determine the efficacy of this type of interval throwing program.

CONCLUSION

The results of this review indicate that elbow varus torque for most flat-ground throws does not exceed the torque produced during full-effort pitching. While most studies showed increased elbow varus torque with increased flat-ground throwing distance, the distance at which elbow varus torque matched or exceeded full-effort pitching elbow varus torque was not consistent. During the partial-effort pitching phase of an interval throwing program, elbow varus torque did not exceed the values observed during full-effort pitching.

As flat-ground throwing distance increased, shoulder external rotation angle and shoulder internal rotation velocity increased. Arm slot decreased as flat-ground throwing distance increased. Shoulder external rotation angle, shoulder internal rotation velocity, elbow extension velocity, and ball velocity increased as pitching effort increased. While the front knee extended from foot contact to ball release during full-effort pitching, the front knee flexed during partial-effort pitching.

Thus, the interval throwing program seems to be a reliable progression in building elbow varus torque up to the levels produced in full-effort pitching. Furthermore, while differences exist between interval throwing kinematics and pitching kinematics, the patterns are similar in general.

CONFLICT OF INTEREST

The authors report no conflicts of interest.

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SUPPLEMENTARY MATERIALS

Appendix A

Download: https://ijspt.scholasticahq.com/article/87811-biomechanical-basis-of-interval-throwing-programs-for-baseball-pitchers-a-systematic-review/attachment/180159.docx