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Review

Baseball pitching kinematics, joint loads, and injury prevention

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Abstract

There is a need for the prevention of upper extremity injuries that affect a large number of competitive baseball players. Currently available evidence alludes to three possible ways to prevent these injuries: 1) regulation of unsafe participation factors, 2) implementation of exercise intervention to modify suboptimal physical characteristics, and 3) instructional intervention to correct improper pitching techniques. Of these three strategies, instruction of proper pitching technique is under-explored as a method of injury prevention. Therefore, the purpose of this review was to explore the utility of pitching technique instruction in prevention of pitching-related upper extremity injuries by presenting evidence linking pitching technique and pitching-related upper extremity injuries, as well as identifying considerations and potential barriers in pursuing this approach to prevent injuries. Various kinematic parameters measured using laboratory-based motion capture system have been linked to excessive joint loading, and thus pitching-related upper extremity injuries. As we gain more knowledge about the influence of pitching kinematics on joint loading and injury risk, it is important to start exploring ways to modify pitching technique through instruction and feedback while considering the specific skill components to address, mode of instruction, target population, duration of program, and ways to effectively collaborate with coaches and parents.

Keywords: Athletic training; Baseball; Instruction; Intervention; Pitching biomechanics; Sport medicine

1. Pitching-related upper extremity injuries

Upper extremity injuries comprise more than half of all injuries occurring in baseball, and affect a large number of competitive baseball players.[1−11] Epidemiological studies demonstrate that approximately 32%−35%[6,7] and 17%−58%[4,6,7,11,12] of baseball players experience shoulder and elbow pain, respectively. In particular, pitchers are susceptible to upper extremity injuries as indicated by higher incidences of shoulder and elbow injury reported at high school,[5] collegiate,[3,8] and professional[13] levels when compared to position players. Furthermore, injuries sustained by pitchers tend to be more severe compared to injuries sustained by position players, as 73% of injuries that resulted in surgery in high school baseball were sustained by pitchers.[5]

Possible consequences of upper extremity injuries in baseball players include surgery,[5,8,14−16] prolonged time loss from sports,[3,8] decreased quality of life due to difficulty performing activities of daily living,[1] cost,[17] and retirement from baseball. It is estimated that approximately 10% of all shoulder injuries sustained by high school baseball players result in surgery.[5] Once surgery is performed, a prolonged time loss is expected, as many of the surgeries performed on baseball players require long recovery period. For example, recovery time from ulnar collateral ligament (UCL)

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reconstruction, which is one of the most commonly performed surgeries on baseball players, ranges from 12 to 18 months.[10,16,18] Following injury and/or surgery, difficulty using the affected elbow/shoulder may result in decreased quality of life. A study by Register-Mihalik et al.[1] demonstrated that some shoulder and elbow pain in high school baseball pitchers are associated with difficulties performing tasks at home and at school. In addition to pain and disability, injuries incur significant costs. It is estimated that each injury sustained in high school baseball results in an average of US$466 in direct medical costs and nearly US$8000 of total costs when reduced quality of life and average value of a day's work for the injured athlete and family members are taken into account.[17]

Considering the consequences of upper extremity injuries in baseball players and the fact that more and more young competitive pitchers are sustaining severe injuries, the need for research on injury prevention is greater than ever.[9] Potential risk factors for upper extremity injuries in baseball players can be categorized into unsafe participation practice,[1,6,7,10,19] suboptimal physical characteristics,[20−25] and improper pitching techniques.[26−33] These studies allude to three potential approaches to preventing pitching-related upper extremity injures: 1) regulation of unsafe participation factors, 2) exercise intervention to modify suboptimal physical characteristics, and 3) instructional intervention to correct improper pitching techniques.

Participation factors that have been linked to injuries include the number of pitches performed in a single outing and over a course of season.[1,6,7,10,19] Based on these findings, Little League™ Baseball mandates pitch count limits to participating pitchers, and USA Baseball Medical Safety Board recommends age-specific pitch counts and rest periods to protect pitchers from overuse injuries. Physical characteristics that have been linked to upper extremity injuries in baseball players include shoulder and trunk range of motion,[20,22,24,34−36] shoulder strength,[37] humeral retrotorsion,[38−40] and scapular kinematics.[25] It has been demonstrated in a number of studies that most of these physical characteristics could be improved with strengthening and stretching exercises.[35,41−47] Although there are few studies that demonstrates the effects of these exercises on injury risk reduction,[43] more and more sports medicine clinicians are implementing exercise programs in hopes to prevent injuries in overhead athletes.

Compared to a large number of studies that investigate participation factors and physical characteristics that are linked to injuries, there are a limited number of studies examining pitching techniques that are associated with injuries. Furthermore, no studies to date have examined the effects of pitching technique instruction on joint loading or reports of injury. Better understanding of pitching techniques that place undue stress on the shoulder and elbow joints, and implementation of an instructional program on proper pitching technique may help prevent pitching-related upper extremity injuries that occur due to poor technique. Therefore, the purpose of this review is to explore the utility of pitching technique instruction on prevention of pitching-related upper extremity injuries. The first part of the review will discuss evidence linking pitching technique and pitching-related upper extremity injuries, and the second part will discuss considerations and potential barriers in pursuing this approach to preventing injuries.

2. Pitching biomechanics and pitching-related upper extremity injuries

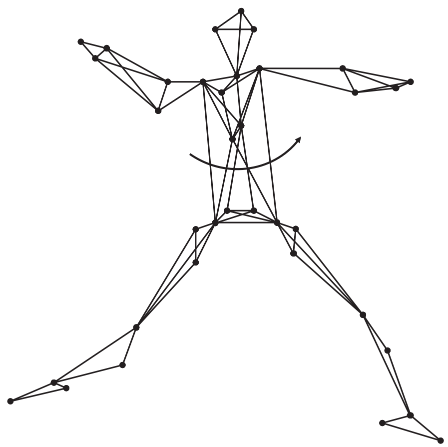
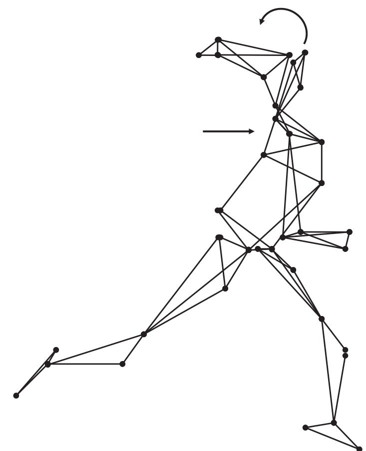
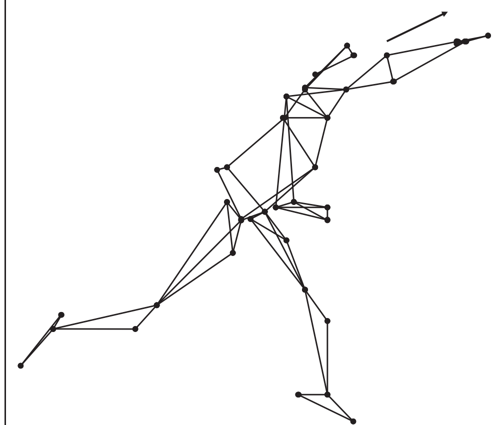
It is theorized that "improper" pitching technique leads to injury by placing added stress on the shoulder and elbow joints, and creating shoulder and elbow pain and pitching-related upper extremity injuries.[27,29,30,33,48−51] However, evidence that directly links pitching technique to pitching-related upper extremity injuries is limited. In 1978, Albright et al.[32] investigated the association between arm position (i.e., angle of humerus) during delivery and reports of shoulder and elbow symptoms at the end of the baseball season in youth and collegiate pitchers. The study reported that 73% of the pitchers who exhibited a more horizontal arm delivery reported shoulder or elbow symptoms compared to 21% among the pitchers who exhibited a more vertical arm delivery, and that the reported elbow symptoms were more severe in pitchers with a more horizontal arm delivery. The limitations of this study, however, were that the study did not take pitch volume over the season into account and that the study used crude and subjective assessments of "arm angle" and symptoms.

In another study, Huang et al.[52] demonstrated differences in throwing kinematics between youth baseball players with and without a history of medial elbow pain. This study demonstrated that youth baseball players with a history of elbow pain threw with a more extended elbow at maximum shoulder external rotation and greater lateral trunk tilt at ball release. However, a retrospective nature of the analysis precludes us from determining whether the pitchers with an injury history demonstrated the error prior to the time of injury, or if the error developed after the injury. To this date, these are the only studies that directly link pitching technique to upper extremity pain and injury. Lyman et al.[6] attempted to link quality of the pitching technique to risk of shoulder and elbow pain in youth baseball pitchers. However, the study failed to demonstrate a significant relationship between pitching technique and complaints of shoulder or elbow pain. While evidence directly linking pitching technique to injury is limited, there is evidence to support that increased joint loading during pitching is associated with upper extremity injuries, and there are separate sets of evidence demonstrating the effects of pitching technique on joint loading. These sets of evidence will be discussed next.

2.1. Joint stress and pitching-related upper extremity injuries

Evidence linking increased joint loading and injuries comes from studies that describe pitching biomechanics and anatomy. Traditionally, pitching is described in six phases: wind up,

Table 1
Summary of kinematics and joint loading during pitching.

Time point	**Stride foot contact** 		**Maximal shoulder external rotation** 		**Ball release** 	
Phase	**Arm cocking**				**Acceleration**	**Deceleration**
Kinematics	Rapid upper torso rotation causes the arm to lag behind the upper torso and force the throwing shoulder into horizontal abduction		Forearm lag behind the arm and force the shoulder into external rotation (170-190°)		Rapid shoulder internal rotation (6000-7000°) and elbow extension	Deceleration of shoulder rotation
Kinetics*	Shoulder anterior force	Shoulder horizontal abduction moment	Shoulder external rotation moment	Elbow valgus moment	Shoulder and elbow joint distraction forces	Shoulder distraction force; Horizontal adduction moment
Tissue (stress)	Anterior capsule/ligament (tension)	Posterior rotator cuff and labrum (compression)	Superior labrum (tension/sheer); Posterior rotator cuff and labrum (compression)	Flexor-pronator mass, ulnar nerve, UCL (tension); Radial head (compressive); Olecranon (sheer)	Biceps tendon, rotator cuff, joint capsule, UCL, flexor-pronator mass, joint capsule, ligament (tension)	Biceps tendon, superior labrum, posterior rotator cuff, joint capsule (tension); Biceps tendon and rotator cuff (compression)
Injury	Anterior instability	Posterior impingement	SLAP lesion, posterior and subacromial impingement, growth plate injury	UCL sprain, medial epicondylitis, ulnar neuritis, stress fracture, osteochondral defect	Biceps tendonitis, rotator cuff strain, sprain, medial epicondylitis, UCL sprain	Biceps tendonitis, SLAP lesion, rotator cuff strain, subacromial impingement

Abbreviations: SLAP= superior labrum anterior-posterior; UCL= ulnar collateral ligament.
* External forces and moments applied at the joint by distal segment to proximal segment.

stride, arm cocking, acceleration, deceleration, and follow through.[53,54] Of these phases, the arm-cocking, acceleration, and deceleration phases are the phases when high magnitudes of forces and moments are experienced at the shoulder and elbow joints.

During arm-cocking and acceleration phases, rapid sequential rotation of the pelvis, upper torso, and shoulder causes distal segments to lag behind the proximal segment (Table 1). The temporal lag between the proximal and distal segment rotations allows the proximal segment to reach a high angular velocity before initiation of distal segment rotation, which results in effective transfer of momentum to the distal segment.[55,56] The lag also results in acute elongation of muscles that cross the segments, which allows the muscles to produce force effectively through utilization of the stretch shortening cycle and strain energy stored within the parallel elastic component of the muscle-tendon unit.[57] While the sequential segment rotation and distal segment lag is necessary for effective pitching, it also places the joints in a vulnerable position for injuries. The lagging of the segments can force the proximal joints to move beyond the normal range of motion, and thereby stress the structures that support the joints.[56,58]

In the arm-cocking phase, rapid upper torso rotation toward the target causes the arm to lag behind the upper torso and force the throwing shoulder into 17–21° of horizontal abduction.[59,60] Horizontal abduction and anterior force at the shoulder that peak during this phase result in tensile stress within the anterior shoulder structures, and compression/impingement of the posterior rotator cuff and labrum between the posterior glenoid and the humeral head, a condition referred to as posterior impingement. While posterior impingement is primarily associated with excessive shoulder external rotation,[49,61] excessive shoulder horizontal abduction has been demonstrated to increase contact pressure on the posterior shoulder structures during arm-cocking.[62]

Once the arm starts to move into horizontal adduction, rapid upper torso rotation and shoulder horizontal adduction cause the forearm to lag behind the arm and force the shoulder into external rotation.[58] It has been demonstrated that pitchers' shoulder external rotation angles reach as high as 170–190° at the instant of maximal shoulder external rotation,[59] which is far beyond what is normally attained during clinical examinations (120–140°).[24,63,64] While part of this discrepancy is due to the fact that external rotation during pitching includes glenohumeral rotation, scapulothoracic motion, and thoracic extension, the extreme glenohumeral external rotation has been linked to a variety of shoulder injuries including, subacromial impingement,[65] posterior impingement,[61] and superior labrum anterior-posterior (SLAP) lesion.[49,66] The SLAP lesion is an injury to the superior margin of the glenoid labrum, which serves as an anchor to the long head of the biceps tendon (biceps–labral complex).[67,68] The long head of the biceps has been demonstrated to provide anterior shoulder stability and provide restraint to shoulder external rotation.[69] Therefore, extreme shoulder external rotation results in increased tension on the biceps–labral complex. When the shoulder is in extreme external rotation, tension on the long head of the biceps pulls the superior labrum posteriorly ("peel back"), which creates additional sheer stress on the superior labrum.[70–72] Combination of tensile loading and sheer stress is theorized as the most probable cause of SLAP lesions in overhead athletes.[73]

Effects of shoulder movement and joint loading during arm-cocking phase on shoulder injuries is supported by a study that reported labral abnormality in 78% of professional baseball players. Additionally, fraying of posterior rotator cuff muscles and labrum in the area corresponding to the site of posterior impingement has been reported in arthroscopic examination of overhead athletes' shoulders.[61] The arm-cocking movement also creates high torsional stress on the humerus.[74] In youth baseball players, this torsional stress has been linked to shoulder pain and growth plate injuries at proximal humeral physis.[75]

Excessive shoulder external rotation also results in high valgus moments at the elbow.[27,29,48,51,53,58,76] The valgus moment creates tensile stress on the medial elbow structures, compressive stress on the lateral joint structures, and a combination of compression and sheer stress on the postero-medial elbow, and therefore is theorized to result in a variety of pitching-related elbow injuries including UCL sprain, medial epicondylitis, ulnar neuropathy, stress fracture, and osteochondral defect.[77–84] The damaging effect of valgus moment on the medial elbow structures is evidenced by studies demonstrating high prevalence of hypertrophy, separation, and fragmentation of the medial epicondyle in a group of Little League players,[85] increased valgus laxity reported in collegiate and professional pitchers,[86,87] and adaptive thickening of the UCL reported in high school pitchers who exhibit high elbow valgus loading during pitching.[88] Similarly, the effect of valgus moment on lateral and postero-medial elbow structures is evidenced in radiographic studies that demonstrated osseous changes, including loose body and osteophyte formation on the radial head and posterior olecranon process in professional baseball pitchers.[89] More recently, Anz et al.[28] conducted a small prospective study that investigated the effect of shoulder and elbow loading during pitching on development of elbow injury over three baseball seasons in 23 professional baseball pitchers. The study found that the joint loading was higher in pitchers who proceeded to sustain elbow injuries. However, this observation need to be interpreted with caution due to a small number of pitchers that were included in the study. Almost 30% (4 out of 14) of the non-injured pitchers, pitched in less than 20 innings over the three seasons, leaving a room for speculation that pitch volume may have played a role in injury development.

As the shoulder internal rotation velocity reaches 6000–7000°/s due to contraction of the shoulder internal rotators and forward acceleration of forearm,[58,59,90] momentum produced by the rapid shoulder and upper torso movement results in rapid elbow extension reaching as high as 2000°/s before ball release.[48,59] While overall magnitude of elbow valgus loading decreases during the acceleration phase, an elbow extension results in lengthening of the anterior-most part of the UCL, increasing the tension within the ligament.[79,91] The anterior portion of the anterior band of UCL is considered the primary ligamentous restraint to valgus moment.[81,83,91,92] This is evidenced by the fact that this part of the UCL is thicker and stiffer compared to the rest of the ligament.[93,94]

As the pitching motion approaches ball release, the magnitude of joint distraction forces at the shoulder and elbow rapidly increase to 1−1.5 times the body mass.[48,58,59] The long head of the biceps resists this distraction force at both the shoulder and elbow joints.[95,96] Therefore, distraction force during this phase is associated with tendinopathy of the long head of the biceps and SLAP lesion. In addition, rotator cuff, joint capsule, and ligaments resist distraction forces at the shoulder, and flexor-pronator mass, joint capsule, and ligaments resist distraction forces at the elbow.[97] Tensile stress on these structures can also lead to injuries. Following the ball release, the shoulder rotation decelerates from 7000°/s of internal rotation velocity to a complete stop within this phase that lasts approximately 50 ms (deceleration phase).[54] The deceleration is achieved by the eccentric work of the posterior shoulder muscles, biceps, and the trunk musculatures.[54] The tensile loading on the posterior shoulder structures during this phase had been linked to increased tensile loading on the glenoid labum, leading to an increased risk of SLAP lesion and loss of posterior shoulder flexibility. The loss of posterior shoulder flexibility, which occurs due to thickening of the glenohumeral joint capsule[49] and muscle contracture,[34,98] has been linked to alterations in glenohumeral[99,100] and scapulothoracic movement,[101] and variety of pitching-related upper extremity injuries.[22,24,35,102,103] In addition, the position of upper extremity during the deceleration phase (i.e., shoulder flexion and internal rotation) resembles the arm positioning during the clinical exam for subacromial impingement (Hawkins−Kennedy test), which results in increased compression of the subacromial structures, and thus increased risk of impingement.[104−106]

As described so far, studies on pitching biomechanics and anatomy demonstrate that high joint loading experienced during pitching leads to pitching-related upper extremity injuries. While pitchers' joints may be able to withstand this stress under normal circumstances, performing repetitive pitches with mechanics that place additional stress on the joints may potentially lead to gradual attenuation of soft tissue structures, and ultimately injury.[33] While it has not been demonstrated in research studies, some experts in baseball pitching hypothesize that early signs of injury (i.e., pain) may lead to compensatory changes in pitching technique, which may lead to alteration in stress distribution within anatomical structures, and ultimately injury. Future studies are necessary to confirm this hypothesis.

2.2. Pitching technique associated with increased joint loading

Evidence linking joint loading during pitching and common injuries in baseball pitchers has lead to the investigation of pitching techniques that are linked to greater joint loading at the shoulder and elbow joints. A common approach taken by many of these studies is to use regression models,[26,29,30,50,51] group comparisons,[27,31] and simulations[107] to identify biomechanical predictors of joint loading. More recently, Davis et al.[33] took a unique approach of examining the effects of observable pitching technical errors on joint stress.

In these studies, maximal shoulder external rotation angle,[29,50] having more extended elbow at various time points,[27,29,30,50,51,108] and upper torso kinematics were identified as kinematic parameters associated with increased joint loading. A study by Sabick et al.[29] demonstrated that 33% of the variance in valgus moment can be explained by the variance in maximum shoulder external rotation angle, linking greater shoulder external rotation angle to greater elbow valgus moment, and thus injuries. Greater maximal shoulder external rotation angle has also been linked to greater shoulder distraction force.[30,50] Having more extended elbow at specific time points have been linked to greater shoulder distraction force[30,50] and greater elbow valgus moment.[27,50] Having the elbow in a more extended position would increase the distance between the forearm mass and the longitudinal axis of the upper torso, and thereby increase joint forces and moments that are attributed to trunk rotation.[26]

In recent years, there is a growing interest in the role of upper torso kinematics on joint loading. A study by Aguinaldo and Chambers[27] demonstrated that pitchers who started rotating their upper torso before stride foot contact experienced greater elbow valgus moment, compared to pitchers who delayed upper torso rotation until after stride foot contact. This finding is supported by the observation by Davis et al.[33] that youth pitchers who demonstrated open shoulder (i.e., upper torso had already started facing the hitter at stride foot contact) experienced higher shoulder and elbow joint loading. These studies suggest that timing of upper torso rotation influences the magnitude of stress experienced at upper extremity joints. In addition to the trunk kinematics in the transverse plane, effects of lateral trunk tilt on joint loading has been investigated.[26,107] Using simulation, Mastuo and Fleisig[107] demonstrated that greater lateral trunk tilt at ball release is associated with greater peak elbow valgus moment when the shoulder elevation angle is above 90°. The trend of association between lateral trunk tilt angle and peak elbow valgus moment has also been reported in a study by Aguinaldo et al.[26] Supporting these finding, Huang et al.[52] demonstrated that youth pitchers with a history of elbow pain exhibited greater trunk lateral tilt compared to pitchers without history of injuries. However, the mechanism by which the trunk movement influences upper extremity joint loading is not well understood, and warrants further investigation.

Most of the studies discussed thus far are conducted in a laboratory setting using motion capture systems, which are useful in describing three-dimensional joint kinematics and kinetics. However, the motion capture systems are rarely available to baseball pitchers, coaches, and parents. Therefore, Davis et al.[33] took a unique approach that is more relevant to baseball coaches and parents by investigating the effects of observable technical errors on joint loading. The study demonstrated that having an “open shoulder” at stride foot contact and having a hand under the ball (i.e., forearm in supination) during stride were associated with greater elbow valgus and shoulder internal rotation moments.[33] This finding is meaningful in that baseball coaches or sports medicine professionals can use this information to identify pitchers who may be at higher risks of injuries. Biomechanical studies discussed here provide evidence that pitching technique affects the magnitude of stress experienced at the shoulder and elbow joints and risk of injury, which suggests that instruction of proper pitching technique that minimize stress on upper extremity joints may lead to prevention of injury.

3. Injury prevention through instruction of proper pitching technique

Most of the studies investigating pitching technique associated with increased joint loading conclude that their findings should be used to design instructional programs to decrease joint loading and thus prevent injuries. However, there has been no study that attempted to implement such a program. The goal of the second part of this review is to discuss consideration and potential barriers in utilizing instructional programming on pitching technique to prevent pitching-related upper extremity injuries.

3.1. “Proper” pitching technique

From observation of pitchers playing in Major League Baseball, it is clear that no two elite pitchers perform pitches in an identical manner. It needs to be noted that being a successful professional pitcher has to do with more than just pitching technique. Therefore, it would be a mistake to believe that technique used by elite professional baseball pitchers is always “proper”. In fact, many of the conventional wisdom on pitching technique prevailing in baseball community today are not supported by scientific evidence.[109] In order to design an evidence-based injury prevention program, evaluation of pitching technique should be based on presence of parameters that have been linked to increased joint loading and performance through research. These parameters are summarized in a recent review article by Fortenbaugh et al.[110] The review article concluded that pitchers need to learn proper pitching technique at an early age in order to enhance performance and reduce injury risk.

3.2. Identifying improper technique

In practice, coaches often analyze pitching technique through real-time observation of pitching techniques (high level coaches/instructors also uses video analysis).[109,111] However, efficacy of real-time observation in identifying specific technical parameters is questionable, considering that pitching is a movement with high degrees of freedom that occurs at a very high velocity. Due to our limited attentional capacity, it is difficult to capture and process all in-coming visual information from real-time observations.[112] For this reason, use of video recordings are recommended when observing pitching technique and comparing technique between pitchers.[33,109,111,113] In addition, video recordings can be used as a visual feedback when modifying pitching technique (Section 4.3).

While video recordings are useful in observation of pitching technique, visualizing joint/segment angles are often very difficult from two-dimensional images. The American Sports Medicine Institute developed a pitching evaluation form based on biomechanical data collected at their laboratory.[6,114] The evaluation form is the only available tool that can be used to systematically assess pitchers’ technique without the use of motion capture system. However, a study conducted by Nicholls et al.[114] demonstrated that while most of the 24 items on the evaluation form could be assessed reliably, visual assessments of segment and joint angles had poor validity.

Difficulty in visualizing three-dimensional angles poses a challenge in translating biomechanical findings to injury prevention in community settings. Perhaps, this is where the approach to investigate the effects of observable technical errors on joint loading, as seen in a study by Davis et al.,[33] may be useful. Visual assessment of pitching technique does not provide the same level of accuracy as the motion capture system, yet is meaningful in that it is what is available for baseball coaches, parents, and pitchers. More studies investigating the effects of observable movement patterns on joint loading may lead to the development of valid pitching evaluation tool that help us identify pitchers with high injury risk. In lower extremity injury prevention, Landing Error Scoring System, which is a 17-item check-list of errors visually observed during a jump-landing task, has been developed and used to identify those individuals with landing technique that are associated with injurious knee joint loading.[115] Similar efforts should be made to develop pitching screening tools to identify pitchers who are experiencing high joint loading at the shoulder and elbow joints.

4. Instructional intervention program

From an injury prevention perspective, the primary goal of the intervention is to instruct pitching technique that minimizes stress on the shoulder and elbow joints. However, it is also important to consider the effects on performance (i.e., ball velocity and accuracy). This is because compliance from coaches, pitchers, and parents is one of the key factors in successful implementation of any intervention program. While potential effects of an intervention program on injury prevention would appeal to most participants, programs that compromise performance would be met with strong resistance and poor compliance from coaches and athletes. On the other hand, programs that help prevent injury and also improve performance will likely ensure high compliance from coaches, parents, and players, which may help achieve the primary goal of preventing injuries.

4.1. Injury prevention vs. performance

There is some evidence to suggest that production of high ball velocity causes high joint loading. Greater maximal shoulder external rotation angle during pitching and higher shoulder and elbow distraction forces have been linked to both higher ball velocity and higher shoulder and elbow joint moments.[27,29,116,117] In a prospective study, Bushnell et al.[118] demonstrated that pitchers with higher ball velocity may be more susceptible to sustaining elbow injuries. However, it needs to be noted that only 23 pitchers were included in this analysis, which limits the generalizability of this observation.

On the other hand, there is also evidence to suggest that production of higher ball velocity does not necessarily incur high joint loads. In a study by Werner et al.[117] that investigated biomechanical predictors of ball speed, none of the kinetic variables were found to be predictive of ball speed. In a study by Wight et al.,[31] pitchers who demonstrated a more closed pelvis experienced higher shoulder and elbow joint loading compared to pitchers who demonstrated more open pelvis. However, ball velocity was similar between groups. In the previously mentioned study by Aguinaldo et al.,[26] professional pitchers who presumably (ball speed was not reported in the study) pitched faster than high school and collegiate pitchers,[59] did so while experiencing lower absolute and normalized shoulder external rotation moments. Additionally, several kinematic variables (e.g., greater peak ground reaction force during a push-off,[119] greater knee flexion at stride foot contact,[117] greater knee extension angle and velocity at ball release,[117,120] and forward trunk tilt angle at ball release[116,117,120]) have been linked to higher ball velocity, but not to increased joint loading. This evidence indicates that reduction of joint loading can be achieved without compromising performance.

4.2. Verbal instruction

Verbal instruction is one of the most common ways to modify specific skill components in pitching. In order for the verbal instruction to be effective, quantity of instruction and location of attentional focus directed by the instruction needs to be considered.[121] It is theorized that individuals experience difficulty performing a task when the attention required to perform the task exceeds the available attentional resources.[112] Therefore, it is important that the number of instructions given to pitchers is kept within their attentional capacity. This means that if there is limited amount of time available to work with the pitcher, instruction should be limited to a few that are the most important. In longer interventions, instructions should be given in stages so as not to overwhelm the pitcher at any one point.

Prinz[122] proposed an action effect hypothesis, which states that the actions are best planned and controlled by the intended effects. Based on this hypothesis, skill performance is optimized when an individual's attention is directed to the outcome of the movement (external focus), instead of on the movement itself (internal focus).[121] A series of studies conducted by Wulf et al.[123−129] consistently demonstrated that learners perform better in various sports-related skills when they were given external focus instructions that direct their attention to the movement outcome such as trajectories and movement of the external objects (e.g., ball and golf club).

It was theorized that external focus instructions may result in better skill performance because such instructions allow the neuromuscular system to naturally self-organize without being constrained by the conscious control attempts.[130,131] On the other hand, internal focus instruction that directs attention to the movement itself results in unwanted interference of the automatic control process that would regulate the movement.[130,131] To support this hypothesis, it has been demonstrated that external focus instructions require less attentional demand,[130,131] and result in more economical coordination patterns, as determined by a decreased level of muscle activity when performing the task.[123,129,130] Applying this theory to instruction of baseball pitching, instruction such as "keep the elbow up" and "keep your shoulders closed" may direct the pitcher's focus to the movement itself, and may disrupt their automatic movement. Though it may be challenging, instructions that direct pitchers attention to external objects, such as trajectory of baseball, movement of the glove, and a marked point on the pitching mound, may help facilitate learning while minimizing disruption of their automatic movement. However, the effectiveness of external *vs.* internal focus instruction has not been investigated in learning of baseball pitching technique.

In sports medicine, several studies have successfully demonstrated the effects of verbal instructions on modifying lower extremity kinematics to decrease joint loading associated with anterior cruciate ligament (ACL) injury.[132−136] These studies demonstrated that verbal instruction can be used to decrease vertical ground reaction force during jump landing[133,135] and alter muscle activation patterns during single leg landing.[132] Additionally, verbal instructions have been shown to mitigate altered inter-segment coordination pattern and increased vertical ground reaction force and joint loading that resulted from muscular fatigue.[137]

4.3. Visual feedback

In conjunction with verbal instructions, feedback is often used to facilitate skill acquisition.[112,128,138−140] Feedback is information about the skill performed that is received during or after the performance.[112,140] The two types of feedback are task-intrinsic feedback, which include sensory information received from sensory organs (e.g., touch, proprioception, vision, and auditory information) and augmented feedback, which is information about the performance received from a source external to an individual.[112,140] The augmented feedback is commonly provided verbally and/or visually. According to Magill,[112,140] augmented feedback is considered especially important in learning a skill in which a link between intrinsic feedback and the movement pattern has not been established. When a pitcher is learning or modifying technique, he is unfamiliar with the sensory feedback that are expected from performing the new movement. Therefore, augmented feedback may be essential in modifying pitching technique.

The augmented feedback can either provide information about the outcome of the performance (knowledge of result) or about the movement pattern that leads to the performance outcome (knowledge of performance).[112] While both types of feedback provide valuable information, knowledge of performance may be more important in pitching technique modification as it is thought to facilitate motor learning when a specific component of the complex movement needs to corrected. One of the ways to provide feedback on knowledge of performance is using video recordings as an augmented visual feedback tool.

While the use of video recording as a feedback tool has been used in coaching, there are very few research studies that demonstrate the effectiveness of augmented visual feedback using video recording. In 1976, Rothstein and Arnold[141] reviewed studies that investigated the effect of video feedback on athletic skills, and concluded that there was not enough evidence to either support or refute the use of the video feedback in skill acquisition. However, investigators identified that more experienced learners were able to use video feedback to improve performance on their own, while novice learners were unable to use video feedback unless assisted by coaches who pointed out specific skill components.[141] The investigators attributed this finding to novice learners' inability to distinguish critical *vs*. non-critical information from the video. This is an important piece of information when providing feedback to young pitchers. Pitchers will likely be unable to utilize video recording as feedback unless coaches or parents points out specific components of the technique that need modification. The use of reference lines/drawing on images and checklists may help enhance pitcher's attention to pertinent visual information.

With proper instructions that points out the specific technical component of interest, a full-length mirror may also be used to provide feedback. Recent advancement in electronic devices (phones and tablet devices) also allows coaches, parents, and pitchers to record and instantly review the pitching technique on a same device. Furthermore, there are websites (e.g., www.3psports.com) that provides analysis of pitching technique. However, efficacy of use of these technology and service in modifying pitching technique has not been demonstrated.

Augmented video feedback has been successfully used to modify landing techniques associated with knee injuries.[138] In a study conducted by Onate et al.,[138] participants who were asked to review videos of their jumping trial and analyze the movement using a checklist of key technical points were able to land with less ground reaction force more knee bending compared to the participants who did not receive video feedback.

4.4. Target population

Baseball players start to pitch around 8−9 years of age. When implementing an intervention program, it is important to consider the age/developmental stage of the target population. Throwing is a fundamental motor skill that is acquired during early and late childhood (2−12 years of age).[142,143] During early childhood, children's throwing technique develops from an arm-dominated movement to a more coordinated movement incorporating trunk rotation, forward step with the contralateral leg, preparatory arm back swing, and horizontal arm adduction.[143−146] Acquisition of mature fundamental movement patterns leads to learning of sports-specific movement pattern in late childhood (6 and 12 years of age) and refinement of the skill during adolescence (12 and 18 years of age) from frequent use of the skill in sports settings.[142] Skill refinement results in a decrease in movement variability, improved consistency of the aim, and development of movement coordination that is more economical (use less energy) and utilize multiple linked segment in a manner that produces optimal performance.[112,142,147]

Considering this timeline for motor development in youth and adolescence, intervention may be better implemented in late childhood, when pitchers are still learning the basics of the throwing motion. Once the pitching movement becomes less variable and more automatic, it may become more difficult to change technique without disrupting automatic processes and thus compromising performance.

4.5. Duration of intervention

There is little research regarding duration of the intervention required to achieve modification of sports-specific skills. Typical intervention programs in sports medicine lasts 4−12 weeks. However, Padua et al.[148] recently demonstrated that duration of programs has a significant effect on the retention of the corrected movement pattern. The study demonstrated that a group of participants who performed a lower extremity injury prevention program for 9 months were able to retain the corrected movement pattern 3 months after the completion of the intervention, while another group of participants who performed intervention program for 3 months reverted back to their original movement pattern 3 months after completion of the injury prevention program. This study suggested that long term intervention is likely needed in order to modify a pitching technique with long term intervention.

4.6. Other considerations

While we gain scientific evidence to prevent injuries from a biomechanical perspective, it is important to acknowledge that there are many dedicated baseball coaches who have been directly working with pitchers relying on empirical evidence from their own experience. Collaboration between researchers and coaches is essential in a successful delivery of intervention programs. It is critical to understand their knowledge, attitudes, and beliefs about pitching-related upper extremity injuries and pitching technique when designing an intervention, so that potential barriers for successful intervention can be identified and addressed prior to program implementation.

When designing injury prevention programs, factors other than pitching technique also need to be considered. As stated earlier, unsafe participation practice and suboptimal physical characteristics have been identified as possible risk factors for pitching-related upper extremity injuries. A study by Robb et al.[149] demonstrated correlations between pitcher's hip flexibility and pelvis and trunk kinematics during pitching. Thus, there may be cases where modification of physical characteristics may lead to modification of pitching technique. Therefore, a comprehensive approach that addresses all three potential risk factor categories may be needed to prevent pitching-related upper extremity injuries. A recently published systematic review on ACL prevention programs reported promising effects of comprehensive programs on injury risk, with an estimated 52%−85% reduction of ACL injury risk following intervention.[150] This result suggests that prevention of pitching-related upper extremity injury is possible with continual investigation and development of effective interventions.

5. Conclusion

While direct evidence linking pitching technique to injury is limited, there is indirect evidence to support that pitching technique affects joint loading, and that joint loading experienced during pitching is associated with pitching-related upper extremity injuries. More studies that identify observable technical errors that are associated with increased joint loading are needed. Such studies will help develop validated qualitative pitching evaluation tools that can be used to screen pitchers for injury risk and track changes in technique on the field, and facilitate translation of scientific evidence to community-based injury prevention programs.

As we gain more knowledge about pitching techniques that influence joint loading and injury risk, it is important to start exploring ways to modify pitching technique through instruction and feedback while considering the specific skill component to address, mode of instruction, target population, duration of program, and ways to effectively collaborate with coaches and parents.

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