THE EFFECTS OF SCAPULAR KINEMATICS, GLENOHUMERAL RANGE-OF-MOTION, AND SHOULDER MUSCLE STRENGTH ON KINEMATICS AND KINETICS OF MAXIMUM EFFORT BASEBALL THROWING

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A wide spectrum of shoulder injuries has been identified in baseball players. Scapular kinematics during pace-controlled scaption, glenohumeral joint range of motion, and shoulder muscle strength have been associated with shoulder injuries in baseball players. The purpose of this study was to investigate scapular kinematics during maximum effort baseball throwing and to identify the potential association among these measures and scapular kinematics during pace-controlled scaption, glenohumeral range of motion, shoulder muscle strength, and shoulder kinetics during maximum effort baseball throwing.

Thirty-five subjects (age 23.3±5.8yrs, height 180.1±7.8cm, weight 83.3±13.8kg) with previous experience in organized baseball (15.2±5.8yrs) were recruited. Passive video-based motion analysis was used for capturing maximum effort throwing and pace-controlled scaption. Glenohumeral range of motion and shoulder muscle strength were measured. Pearson's product-moment correlation coefficient was used to evaluate the correlation among the measured variables.

Positive correlations were observed between scapular kinematics during scaption and throwing at the same arm elevation angle at stride foot contact and the occurrence of maximum shoulder compression force, indicating that kinematic patterns that appeared during scaption also appeared during throwing. Maximum shoulder inferior force was negatively correlated to decreased posterior shoulder tightness and increased supraspinatus strength. Subjects with tighter

posterior shoulder and stronger supraspinatus tended to have greater shoulder inferior force. Scapular retraction and posterior tilt were both positively correlated to maximum shoulder compression force. Subjects with a more retracted and posteriorly tilted scapula generated greater shoulder compression force.

Evidential support for using a scaption test as a tool to evaluate baseball players' shoulder function was established. Examination of posterior shoulder tightness and supraspinatus strength may be appropriate for screening for high shoulder forces during throwing. The current findings also presented a potential approach to reduce shoulder force by adjusting scapular kinematics, although future research is needed to confirm the existence of causality.

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PREFACE

It has been a rewarding but challenging trip, and at the end, luckily, I am able to finish all these works. It has never been easy from the beginning, but each step toward the end was harder and harder. Looking back to the path I walked through, there were multiple times I almost gave up. Sometimes I was shocked by how I have gone this far, and immediately I was overwhelmed by numerous obstacles still in front of me. Sometimes I felt I was moving inch by inch without knowing if the direction was forward. And on one day, the last thing on my to-do list was checked. While I felt much relieved, to be honest, I was not sure how I got there. I was then told by my previous mentor and some old friends that this is normal, though.

It is for sure that I would not able to achieve these without the contributions from several significant individuals. First, I would like to thank Dr. Scott Lephart for giving me the opportunity to pursue this degree and supporting me for four years at the Neuromuscular Research Laboratory. With his continuous effort and passion bringing sciences to real life applications, he have established an expanding research program with multiple facilities, and made significant contribution to the United States. I feel honored to have this opportunity to work for him and make some contribution to this great country.

I would also like to thank Dr. Timothy Sell for his guidance, not only as my dissertation committee chair, but also as a mentor throughout these years. Under his direction, I enjoyed four years of rewarding life as a researcher, conducting multiple studies in different areas. None of

my achievement over these years would be possible without the advice, support and encouragement from Dr. Sell.

I would like to thank the rest of my dissertation committee: Dr. John Abt, Dr. Mita Lovalekar, Dr. Ray Burdett, and Dr. David Stone. Their help in the development and completion of this study has been extremely valuable and I cannot thank them enough.

It has been a blessing to have the privilege working with the best colleagues I could ever imagine. This study could not be completed without the help of Karen Keenan, who provided lots of insights helping me designing the clinical measurements. Jon Akins also gave tremendous help when I was developing one of the key techniques used in this study. Karen, Megan Turchek, Dierdre McFate, Gordon Huang, and Jon Pederson all provided me a lot of help with data collection and processing. In addition to all these help, I simply want to mention that Karen Keenan and Jon Pederson are the most hilarious people I have ever met. Whenever I felt exhausted, it was them making me laugh to crazy. They are even able to make a serious research discussion extremely funny. It has been so great to have them as colleagues and friends. And I think I need to put this on record: We really need to publish the Journal of Useless Research at some point in our lives.

A lot of thank will be given to my wife Naomi Chiunghsien Huang. Being the wife of a doctoral student can be one of the most boring things one can imagine. It is definitely not interesting to wake up in the morning with me already left to work and would not get home until dark. What easily made thing worse is that I usually felt too tired during the weekend and just wanted to go nowhere. I just want to thank her for being supportive during her prime years of life, and taking care of the housework that I had no energy to do. I just could not ask for a better partner of my life.

Finally, I would like to thank God, who has guided me all the way since I accepted Him as my Savior and heavenly Father. He gave me some hard lessons. Most of the time, I simply did not know what He was thinking and why He did those things to me. But years later I always found His arrangements were good for me. Over these years I have got better idea what my life is all about. Pursuing a doctoral degree can be very discouraging. In addition to all those difficulties easier to think of, the most frustrating thing is that the more you learn, the less you feel you understand. At the beginning I wanted to solve so many sports science questions, and I was sure that I am capable to make some impact. But at the end, I do not have the assurance anymore. I get lost in the field of knowledge and find myself stranded in the middle of nowhere. With all the complexity and limitations I feel almost impossible to conduct a research to solve real issues or confidently generalizing any findings to real world. I think that is what the Scripture said: For in much wisdom is much grief, and he who increases knowledge increases sorrow (Ecclesiastes 1:18). I admit that I am kind of lost at this moment, and feel that I am grasping for the wind. But I know He is not going to let my effort be fruitless. I can only rely on God that one day He will use the knowledge and skills I acquired over these years in the way He wants. On that day, He will show me the path, and I just need to be patient.

I probably have earned two degrees over these couple years here in the United States, but what I have lost was extremely significant. When I was pursing my master's, my dog Apo (1988 – May 11, 2005) passed away at the opposite side of the earth and I was not with her. Five years later, when I was struggling in my doctoral program, my another dog Doggy (1992 – May 5, 2010) passed away, and I was still not with her. Apo was an elegant lady, while Doggy was a cheerful girl. These two dogs supported and accompanied me throughout my most helpless years, and I felt so sad that they died without me with them. Once I was able to establish my

residence in 2010, and I immediately took my cat Meetow (1997-Present) here. It was a long trip for a 13-year old cat, but she made it, and this could be the best decision I ever made in my life. This cat became extremely happy living here, reclaiming her playful characteristics and energy lost for more than eight years. Her companion helped me to overcome the struggles finishing my degree. I just want to dedicate this dissertation to my two dogs and my cat, although I know they would rather to have a can of meat than a pile of paper.

1.0 INTRODUCTION

Baseball is one of the most popular sports in the United States. According to USA Baseball, the National Governing Body for the sport of baseball in the United States, it was estimated that approximately 20 million Americans play organized baseball per year.[1] As a sport involving repetitive overhead throwing, a wide spectrum of injuries relating to the glenohumeral joint has been identified in baseball players.[2] The glenohumeral joint is comprised of the humerus and the scapula, and the coordinated movement between these two bones is considered critical for both throwing performance and minimized risk of shoulder injury.[3] Although the biomechanics during baseball pitching has been well documented, the shoulder joint was roughly modeled as the humerus with respect to the trunk, and the term "shoulder external rotation" used in such analyses involved both humeral external rotation and scapular posterior tilt.[4-9] Without the scapula being modeled, it was impossible to identify the contribution from the glenohumeral joint and from the scapulothoracic joint to the resultant shoulder external rotation angle.[10] The glenohumeral head places greater stress on the anterior and inferior ligamentous structures with increased humeral external rotation;[11,12] however, two pitchers with 170° of external rotation may not have the same risk of shoulder injury if one has 150° at the glenohumeral joint and 20° at the scapulothoracic joint and the other has a 140°-30° combination. As of now, little is known regarding the role of the scapula and scapular kinematics during baseball throwing. It is therefore imperative to understand the scapular kinematics during maximum effort baseball throwing, as well as factors that may affect the kinematic characteristics. Such knowledge may facilitate further understanding of shoulder injury mechanisms in the throwing athlete as well as in the development of injury prevention and performance optimization guidelines.

1.1 EPIDEMIOLOGY OF SHOULDER INJURIES IN BASEBALL

Baseball players are at an increased risk for shoulder pain and injuries due to the repetitive overhead motion necessary for the sport. Epidemiological research has demonstrated that baseball has the third highest shoulder injury rate among high school sports.[13] In addition, the shoulder is the most frequent site of injury in high school baseball[14] and the same trend extends at higher levels of competition. Several studies have demonstrated that the shoulder is the most common injury site during competition and practice in college[15-17] and minor league baseball.[18] Further, the shoulder was the injury site resulting in the most disabled list days in Major League Baseball.[19]

The risk of shoulder injury is likely associated with the intensity and volume of throwing, as pitchers are more likely to sustain a shoulder injury than their position player counterparts. Among different positions in high school baseball, injuries at shoulder were more common in pitchers but less in infielders.[14] Thirty-eight percent of shoulder injuries in high school baseball occurred in pitchers.[20] Pitchers represented approximately half of all players and accounted for half of disabled list visits in Major League Baseball.[19] In a 5-year prospective study that followed 144 professional pitchers, 59% of the recorded injuries occurred at the shoulder.[21]

Throwing intensity and volume also play an important role in shoulder injury within pitchers. Adolescent pitchers with average fastball velocity greater than 85mph were at higher risk of requiring shoulder or elbow surgery.[22] Increased risk of shoulder pain has been associated with increased pitch count per game and per season in youth baseball pitchers.[23] The number of warm-up pitches, pitching appearances per year, innings pitched per year, pitches per game, pitches per year, and months per year of pitching have been identified as risk factors for shoulder surgery in adolescent baseball pitchers.[22] Between 1999 and 2003, 73% of Major League Baseball players placed on the disabled list had injuries classified as "wear and tear" or as "caused by overuse or insufficient rest."[24] Sports medicine experts generally agree that the microtrauma accumulated with repetitive throwing for months or years results in clinically-identifiable structural damage.[25,26] Complaints of shoulder pain, common in youth baseball, can be an early indicator of the beginnings of an overuse injury.[23]

1.2 BASEBALL THROWING: A BIOMECHANICS POINT OF VIEW

From a biomechanics point of view, baseball throwing is a very demanding task. Most of the baseball throwing motion analysis studies have focused only on pitching, the most intense throwing task in baseball.[5,6,27-32] Baseball pitching is usually divided into six phases by five critical events (Figure 1).[10] The critical events are balance position (BAL), stride foot contact (SFC), maximum shoulder external rotation (MER), ball release (REL), and maximum shoulder internal rotation (MIR). The six phases are windup, stride, arm cocking, arm acceleration, arm deceleration, and follow-through. Pitching is the most rapid human movement currently known and the shoulder is the most rapidly moving joint during baseball pitching. The maximum shoulder internal rotation velocity has been reported to be more than 8000°/s.[9] Such rapid movement is accompanied with considerable amounts of kinetic loads. In adult baseball pitchers, average force applied to the shoulder has been reported to be greater than 300N in the anterior/posterior direction, 250N in the superior/inferior direction, and 1000N along the longitudinal axis of the humerus.[6] Such forces typically increase with competition levels.[7,9,33]

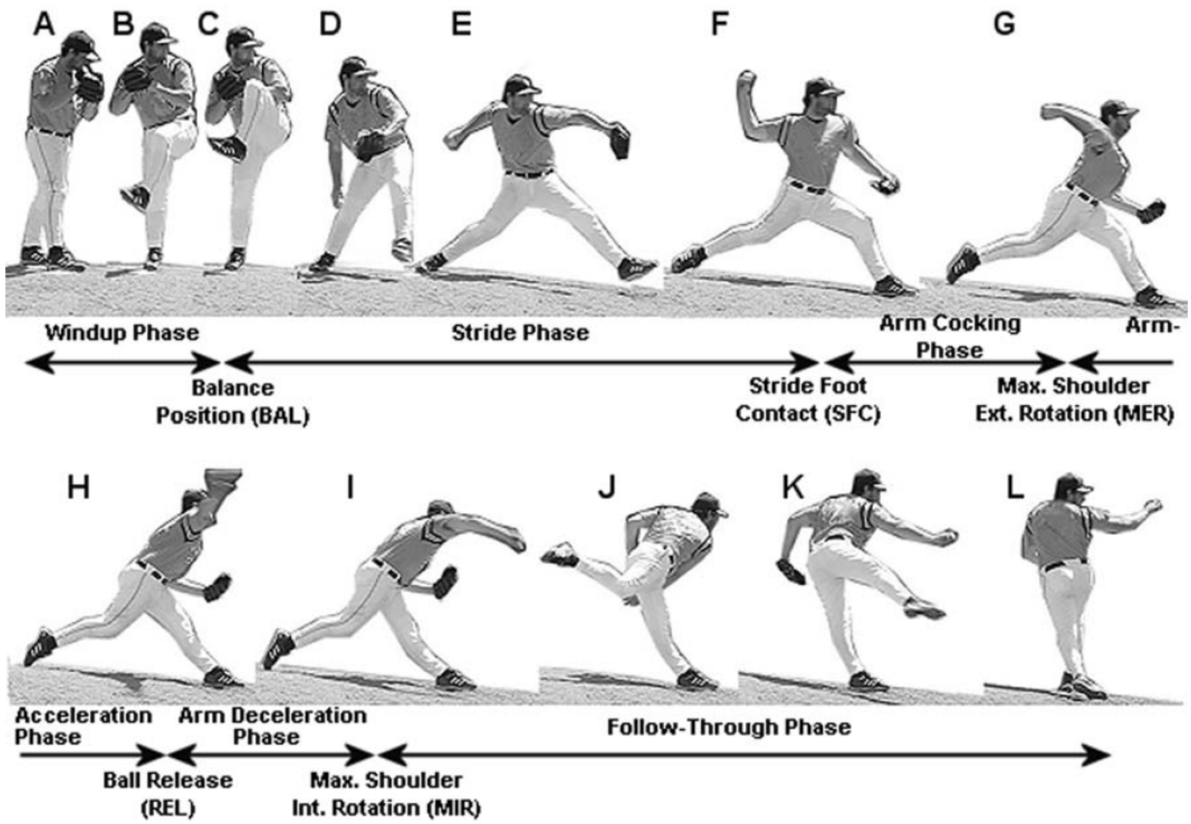

Figure 1. Critical events and phases defined in baseball pitching

Kinematics and kinetics of a baseball position player's maximum effort throwing has received less attention from researchers, but could be of slightly less magnitude for both kinematic and kinetic variables (e.g. range of motion, arm velocity, resultant forces) than those in pitching. Pitchers performing maximum effort long-toss on flat ground generated 91 to 98% of maximum shoulder internal rotation velocity and shoulder joint forces.[34] Fleisig et al.[6,10] summarized how the kinetic variables during overhead throwing could be associated with shoulder injuries. The critical events of SFC, MER, REL and MIR are closely related to the instances when high kinetics occurs. Stride foot contact is approximately the end of throwing arm elevation, during which the humerus is approaching a position in which the rotator cuff tendon could be impinged. High shoulder anterior force was detected at this instant.[6] Maximum shoulder anterior and superior forces occur at the late arm cocking right before MER; maximum compression force occurs right after REL; and maximum posterior and inferior forces occur right before MIR.[6]

1.3 SCAPULA KINEMATICS DURING THROWING

The kinematics of the scapula in overhead throwing is largely unknown and warrants further research. It has been reported that the shoulder external rotation angle measured during motion analysis of a throwing task is the combination of glenohumeral external rotation, scapular posterior tilt, and spine hyperextension.[10] This indicates that the gross movement is a combination of the movement at the glenohumeral joint, the scapulothoracic joint, and the intervertebral joints; yet, the contribution of each has never been quantified. The scapula, however, plays several important roles in throwing. It moves along the thoracic wall in coordination with movement of the humerus to increase the range of arm movement, elevates the acromion to clear the subacromial space, and serves as a link in the kinetic chain.[3] The proposed kinematic roles of the scapula cannot be evaluated without quantifying the scapular kinematics during throwing.

1.3.1 Technical difficulties

Scapular movement during throwing from motion analysis has been excluded from previous research mainly due to the limitation of equipment and techniques. Non-invasive in-vivo motion capture typically involves skin markers or sensors. Unlike segments such as the thorax or humerus, movement of the scapula is not easily captured with skin markers due to considerable soft tissue effects. As of today, researchers generally use passive video-based motion capture for throwing motion analysis. Video-based motion capture tracks the trajectories of reflective markers. To measure 3-D scapular kinematics with three degree-of-freedom in rotation, at least three markers are needed to define the scapula. It has been argued that the broad, flat portion over the acromion is subject to less soft tissue effects and therefore would be a good position to measure scapular kinematics.[35] However, with the previous limitation of camera resolution, it has been not possible to place three reflective markers over this relatively small area of the acromion.

For a decade, electromagnetic tracking devices were the most prevalent option for measuring dynamic 3-D scapular kinematics in a non-invasive manner. Electromagnetic tracking devices are equipped with sensors capable of detecting six degree-of-freedom movement (three linear and three rotational). The sensors are relatively small and a sensor can be affixed to the broad, flat portion of the acromion. Scapular kinematic measurements using electromagnetic tracking, however, were typically limited to slow and constrained movements such as arm elevation at a low movement velocity. Since the electromagnetic sensors are wired, it is difficult to use this equipment to measure complex, multi-plane movement such as throwing. Further, electromagnetic tracking devices usually have maximum sampling rate lower than 150Hz, limiting their use in rapid movements, including throwing and pitching. Another concern is that rapid body movement may result in cable movement artifacts, inducing noise in the recorded signals.[36]

1.3.2 What we already know

As result of these technical difficulties, scapular kinematics during throwing has not been investigated to a great extent. In a study using electromagnetic tracking to measure scapular kinematics in softball throwing, the researchers only utilized low-velocity throwing as the movements of sensor cables distorted the signals during high-velocity throwing, as revealed during pilot testing.[36] In another study, passive video-based motion capture with a two-marker bar attached to the acromion was used to measure scapular kinematics during baseball pitching.[37] This design can only measure one degree-of-freedom of scapular rotation; therefore validity issues may exist. As of now, the only study investigating scapular kinematics with three rotational degree-of-freedoms during maximum effort overhead athletic activity (tennis serve) was conducted with a new model of an electromagnetic tracking device capable of a 240Hz sampling rate.[38] No mention was made of any attempt to control cable movement or soft tissue effects. Although the tennis serve may share some similarity with baseball throwing, there still exists a gap of knowledge on how the scapula moves during maximum effort baseball throwing and how the throwing movement is associated with shoulder kinetic loads and pathologies.

1.4 SCAPULAR KINEMATIC DURING ARM ELEVATION

While scapular kinematics during maximum effort baseball throwing remains virtually unknown, research results from several different approaches have provided us some insights on the role of the scapula and the mechanisms of injuries in baseball players' shoulder. Scapular kinematics during pace-controlled arm elevation constrained in a specific plane (e.g. the frontal plane, the scapular plane, or the sagittal plane) has been extensively studied. A wide spectrum of measurement techniques from 2-D to 3-D, static to dynamic, and invasive to non-invasive has been used. Scapular kinematic patterns of normal, healthy subjects during arm elevation have been well established. Experts agreed that during arm elevation, the primary scapulothoracic movement is medial/lateral rotation followed by anterior/posterior tilt, with minimal protraction/retraction.[39] During arm elevation, both lateral rotation and posterior tilt are considered essential for normal scapular kinematics as these movements maintain the relative position of the scapula and humerus, allowing further humeral abduction without compromising the subacromial space.

1.4.1 Pathologic shoulders

1.4.1.1 Subacromial impingement

Comparisons of scapular kinematics between healthy and pathologic subjects during arm elevation have provided better understanding of the mechanism of common shoulder injuries. Subacromial impingement, sometimes referred as external impingement, is one of the common shoulder injuries that occur in people, not limited to athletes, who perform repetitive overhead movement. First described in the early 1970s, subacromial impingement is considered as the impingement of the rotator cuff tendons against the inferior surface of the acromion or the coracoacromial arch.[40] Results of dynamic scapular kinematics measurements in these subjects have been inconclusive, as both increased or decreased scapular lateral rotation and posterior tilt have been identified during humeral elevation.[41,42] Methodological issues in skin electromagnetic sensor placement may have contributed to these contradictory results. Static measurements have identified decreased posterior tilt and lateral rotation in subacromial impingement patients.[43,44] Both decreased lateral rotation and posterior tilt reduce the acromiohumeral distance. Decreased acromiohumeral distance was found in subacromial impingement patients' affected shoulders.[45] Experts agreed that the exact mechanism and the structures being impinged are not fully understood.[39]

In summary, more evidences indicate that patients with subacromial impingement have decreased lateral rotation and posterior tilt during arm elevation; therefore it has been surmised that subacromial impingement is due to the reduction of the subacromial space between the humeral head and the acromion of scapula.[39] It should be noted that these studies were conducted on non-athletic patients. Research of scapular kinematics in overhead athletes with subacromial impingement is limited. No significant decrease in lateral rotation was noted in swimmers with subacromial impingement.[46] So far there is insufficient evidence to make any conclusion on the potential scapular kinematic changes in baseball players with subacromial impingement.

1.4.1.2 Internal impingement

Internal impingement was first described in the early 1990s as the contact between the posterior rim of glenoid labrum and the rotator cuff tendons.[47] Although such contact may be observed in asymptomatic baseball players, repetitive contact can result in structural damage.[48] Compared with subacromial impingement, internal impingement was identified more recently, thus less related research is available. Unlike subacromial impingement, internal impingement typically occurs in overhead athletes as the result of athletic activities. For this reason, more research is available based on patients within the athletic population. Baseball players with internal impingement have increased scapular posterior tilt compared to healthy baseball players.[49] A different injury mechanism than that associated with subacromial impingement may exist as posterior tilt is considered preventive for subacromial impingement. Symptomatic internal impingement patients demonstrated decreased distance between the supraspinatus and infraspinatus tendons and the glenoid fossa.[50] Similar to subacromial impingement, the exact mechanism and impinged structure(s) are not fully understood.[39]

1.4.2 Participation in overhead athletic activities

Participation in overhead athletic activities such as baseball can alter scapular kinematics as measured during arm elevation, even in healthy, non-symptomatic athletes. Inclinometer measurements have shown that healthy pitchers have decreased scapular lateral rotation compared with position players.[51] Electromagnetic tracking data have demonstrated decreased posterior tilt in the throwing shoulder of professional baseball pitchers,[52] as well as increased protraction and decreased posterior tilt in overhead athletes.[53] One may hypothesize that repetitive and forceful throwing can reduce lateral rotation and posterior tilt, putting pitchers at greater risk of subacromial impingement. In a prospective study it was demonstrated that, after one season of competition, professional pitchers had decreased lateral rotation and increased protraction.[52] However, contradictory findings exist in the literature, as another study has demonstrated increased lateral rotation in baseball players.[54]

1.4.3 Gaps of knowledge

While a considerable amount of research has been conducted regarding scapular kinematics during pace-controlled arm elevation, several gaps of knowledge exist. First, studies to date were all of case-control design. By comparing healthy and pathologic subjects, the identified characteristics of the pathological group cannot be concluded to be the result of injury or the cause of injury. Similarly, identified differences in baseball pitchers compared with position players or normal subjects cannot be concluded to be protective adaptations or predisposing detrimental factors. The proposed mechanisms of injuries, although plausible, are still unverified.[39] Moreover, the clinical applications of the findings from arm elevation testing remain questionable. Methodological differences and inter-subject variability have prevented researchers from defining a solid range of normal values for scapular kinematics.[39]

In addition, the association between arm elevation and athletic tasks has not been established. Significantly different measurement values of scapular kinematics during arm elevation and daily functional tasks have been reported, although the kinematic patterns remained similar.[55] To date, no studies have investigated the relationship between pace-controlled arm elevation and overhead throwing. If we assume decreased scapular lateral rotation and posterior tilt increases the risk of subacromial impingement, it may be relevant to investigate if such characteristics exist when performing both athletic tasks and constrained movement as this may allow for the constrained arm elevation to be used as a screening tool. Improper scapular position and orientation at the end of the stride phase of pitching may induce increased kinetics and therefore greater risk of injury at the shoulder during the following arm cocking, arm acceleration, and arm deceleration phases.[10]

1.5 GLENOHUMERAL RANGE OF MOTION IN BASEBALL PLAYERS

With repetitive throwing, structural and functional changes can occur in baseball players' shoulders. One of the most prominent adaptations in baseball players is increased glenohumeral external rotation range of motion (ROM) and decreased internal rotation ROM. Since first documented by King et al. in the late 1960s,[56] this phenomenon has been described in a series of studies. Increased external rotation and decreased internal rotation were observed in the throwing shoulder of a baseball player compared with the non-throwing shoulder, pitchers compared with position players, and baseball players compared with non-throwing subjects.[57-59] Further evidence indicated that such change may be associated with the intensity and volume of throwing, as the total ROM was the greatest in pitchers, followed by catchers, outfielders, and infielders.[12] As throwing intensity and volume are linked with shoulder injuries, one may expect associations between external/internal ROM and shoulder injuries.

1.5.1 ROM changes and injury mechanisms

1.5.1.1 Anterior laxity theory

Researchers and clinicians have attempted to explain the ROM changes with several theories: anterior capsule laxity, humeral retroversion, and posterior capsule tightness. According to the anterior laxity theory, baseball throwing involves extreme shoulder external rotation to end ROM, stretching the capsular tissue, including the inferior glenohumeral ligament and part of the anterior glenohumeral ligament: repetitive stretching lengthens these structures, which can create anterior laxity and further increase external rotation ROM.[11,12] *In vitro* evidence has confirmed the effect of external rotation on the anterior band of the inferior glenohumeral ligament.[60] The throwing shoulders of pitchers have greater glenohumeral anterior translation than their non-throwing shoulders and both shoulders of positional players.[61] The anterior laxity theory does not explain the decreased internal rotation ROM. In addition, the increased external rotation ROM is considered a precursor of shoulder anterior instability and potentially further injury. This theory may explain the mechanism of shoulder internal impingement, as a more anteriorly located humeral head may lead to increased contact between the posterior glenoid rim and the rotator cuff tendons.[11]

1.5.1.2 Humeral retroversion theory

The humeral retroversion theory may better explain the increased external rotation range of motion accompanied by the relative decrease in internal rotation range of motion. The humeral retroversion theory states that repetitive torsion loads due to throwing results in increased humeral retroversion, resulting in an increased external rotation and decreased internal rotation angle at a given humeral head orientation. Such change in humeral retroversion is an osseous adaptation and is irreversible. Researchers started to notice this phenomenon in baseball players in the early 2000s.[62-64] This phonomenon is characterized by a shift of ROM toward the direction of external rotation, with the total arc of motion (i.e. the combination of external and internal rotation ROM) comparable between the throwing and non-throwing shoulder. It does not explain the decrease of internal rotation without simultaneous gain in external rotation in youth baseball players.[65] Humeral retroversion is considered protective, as it reduces the actual external rotation at the humeral head and decreases the stretch at the anterior and inferior ligamentous and capsular structures.

1.5.1.3 Posterior tightness theory

The posterior tightness theory indicates that repetitive throwing thickens and tightens the posterior glenohumeral capsule, reducing the internal rotation ROM.[66] According to this theory, tightness in the posterior shoulder is detrimental. Posterior shoulder tightness (PST) measurement has been correlated to decreased internal rotation ROM.[58,67] Furthermore, PST has been associated with a superior-posterior shift of the humeral head, which can potentially lead to a superior labrum anterior posterior (SLAP) lesion,[66] subacromial impingement,[68] or internal impingement.[69] This theory explains the further reduction in internal rotation ROM beyond the changes due to humeral retroversion. Reduced total motion of the throwing shoulder compared with the non-throwing shoulder can be an early indicator of future shoulder injury.[12,70] This theory does not explain the acute decrease of internal rotation after a pitching event, which may be attributed to microtrauma accumulated in posterior muscular structures as the result of repetitive eccentric contraction during deceleration.[71] It seems no single theory can fully explain the ROM changes observed in baseball players; it is likely that each plays a role.

1.5.2 Glenohumeral ROM and scapular kinematics

The relationship between glenohumeral external/internal rotation ROM and scapular kinematics has not been intensively studied. Among the limited work, weak and insignificant correlations between glenohumeral external/internal rotation ROM and scapular lateral rotation have been reported.[72] Baseball players with increased glenohumeral internal rotation ROM deficit have demonstrated decreased scapular lateral rotation at 60°, 90°, and 120° arm elevation as well as greater protraction at 90° humeral elevation.[73] One may expect scapular anterior/posterior tilt to be more relevant in the context of shoulder external/internal rotation. For example, with an increase of scapular posterior tilt during the arm cocking phase, the magnitude of external rotation occurring at the glenohumeral joint may decrease to reach the desired resultant shoulder external rotation, thereby reducing the chance of anterior laxity development. In other overhead athletes, it was demonstrated that glenohumeral external rotation ROM was not significantly correlated to maximum external rotation during a tennis serve.[74] Gaps in knowledge exist in the 3-D scapular kinematics during maximal effort baseball throwing, its potential association with glenohumeral external/internal rotation ROM, and its implications in injury mechanisms.

1.6 SHOULDER STRENGTH IN BASEBALL PLAYERS

The scapula and humerus are heavily involved during baseball throwing and the movements of these bones are achieved by the contraction of the surrounding muscles. These muscles can been categorized into three groups: scapular stabilizers, intrinsic muscles, and extrinsic muscles,[3] each of which has its own role during baseball throwing. The scapular stabilizers controls the motion and position of the scapula, the intrinsic muscles maintain the alignment between the scapula and humerus for better movement efficiency, and the extrinsic muscles perform the gross motor activities of the glenohumeral joint.[3] Since baseball throwing is a very high demand task, optimized strength of the shoulder muscles is essential to baseball throwing performance. Muscular weakness or imbalance of the shoulder muscles may result in shoulder pathology. Baseball players' shoulder muscle strength has been measured with both isokinetic and isometric dynamometers. Isokinetic measurement has been the most common technique, although recently the use of isometric measurement has increased. Specific strength characteristics of the throwing shoulder of baseball players' have been described, with some of these characteristics linked to performance or injuries.

1.6.1 Shoulder strength and injuries

1.6.1.1 Scapular stabilizers

Professional pitchers and catchers have demonstrated greater strength in the scapular protractors and elevators than other position players.[75] Except for infielders, baseball players had stronger depressors on their throwing side.[2] The agonist-antagonist strength ratios are believed to be important to the stability and mobility of the scapula as well as symptom-free function of the throwing shoulder.[2] Weaker lower trapezius[76] and scapular protractors[77] have been identified in pitchers and overhead athletes with pain or impingement symptoms.

1.6.1.2 Supraspinatus

The supraspinatus is one of the intrinsic muscles. It assumes the role of maintaining the proper alignment between the scapula and the humerus during throwing by attempting to maintain the position of the humeral head within the glenoid fossa. It is this muscle that is the proposed structure that produces impingement symptoms when the subacromial space is compromised. In asymptomatic baseball pitchers, weakness of the supraspinatus has been demonstrated.[59,78] This phenomenon could be the result of subclinical wear and tear and an early sign of structural damage. In a prospective study, it was reported that decreased supraspinatus strength is associated with increased risk of shoulder injuries in professional pitchers.[21]

1.6.1.3 External and internal rotators

The shoulder internal and external rotators involve both extrinsic and intrinsic muscles, and have been the primary focus of research regarding baseball players' shoulder strength. The internal rotators are important for the rapid shoulder internal rotation in the arm acceleration phase and the external rotators are critical for decelerating the throwing arm in the arm deceleration phase. Professional pitchers demonstrate greater internal rotator strength than their position player counterparts.[57] The relationship between shoulder internal rotation strength and throwing performance is not decisive. Some researchers found significant correlations,[79] while others did not.[80-82]

A more interesting strength characteristic in baseball players' throwing shoulder is weakness of the external rotators.[2] This phenomenon may have more implication for throwing-related injuries than performance. Weakened external rotators may be due to fatigue or micro-trauma accumulated in the external rotators with repetitive eccentric contraction, which reduces the muscle contractibility. Professional pitchers have weaker external rotators than professional position players.[57] Weakened external rotators may lead to humeral head anterior shift, resulting in anterior glenohumeral instability and further anterior structure damage. Throwing performance may also be compromised, as a thrower may not able to generate the desired acceleration with reduced deceleration capacity.

In addition to strength of individual muscles, the strength ratio between shoulder external and internal rotators is believed to be critical to sport performance and joint stability. As the throwing shoulder has weaker external rotators and stronger internal rotators, the ratio would be lower than the non-throwing shoulder. The optimal ratio of the throwing shoulder has been documented in healthy baseball pitchers.[2] If the ratio is higher than the recommended range, then throwing performance may be compromised. On the other hand, if the ratio is lower than the recommendation, the risk of shoulder injury may considerably increase as the thrower could throw harder but with less deceleration capacity.

There have been several studies investigating the relationships between shoulder pain or injuries and the internal or external rotator strength. An insignificant trend of weaker external and internal rotation strength has been observed with baseball players with impingement symptoms[83] and shoulder pain.[76] In contrast, increased external strength was found in baseball players with throwing-related upper extremity injuries.[84] In baseball pitchers diagnosed with impingement syndrome, external and internal rotation strength dropped rapidly with increased isokinetic testing velocity in their impinged shoulders.[85] Pitchers with prior shoulder pain have demonstrated increased imbalance of internal rotator strength between the throwing and non-throwing shoulders.[86] Pitchers who spent more time in pitching activities per year have demonstrated significantly decreased external rotator strength and external/internal rotation strength ratio.[87] Prospective evidence has further demonstrated that decreased isometric external rotation strength as well as decreased external/internal rotator strength ratio are associated with throwing-related injuries.[21]

1.6.2 Shoulder strength and scapular kinematics

As the kinematics of the scapula and humerus during throwing are initiated and controlled by the aforementioned muscles, one may assume that the strength of these muscles has some effect on scapular kinematics. There has been very limited research regarding the relationship between strength of the muscles and scapular kinematics during the throwing motion. Isometric strength of the lower trapezius was positively correlated to scapular lateral rotation in professional pitchers.[88] It has not been investigated whether the stronger internal rotators and weaker external rotators in baseball players result in any scapular kinematic changes. Weakness of the supraspinatus in baseball players is an early sign of impingement,[21] but whether the weakness is associated with the altered scapular kinematics linked to the mechanism of impingement is unclear. A gap of knowledge exists regarding how shoulder strength affects the coordination between the scapula and humerus and how these potential effects relate to shoulder pathologies in baseball players.

1.7 A NEW APPROACH TO SCAPULAR KINEMATIC TRACKING

Recently, a new approach to evaluate scapular kinematics using passive video-based motion capture was developed by the investigators. Improved camera resolution made it possible to place three markers in a relatively small area over the acromion. In a pilot study, we compared this technique to electromagnetic tracking. The concurrent validity of this technique was established by demonstrating highly correlated measurements between the two approaches (r>0.950), with small inconsistency between the two measurements mostly due to the differences in the measured thorax movement. With passive video-based motion capture, a reflective marker was placed on four anatomical landmarks on the thorax. With electromagnetic tracking, only a single sensor accounted for the thorax movement, defining the four anatomical landmarks in its local coordinate system (LCS). Using four markers may provide better redundancy and may be subject to less soft tissue effect than using a single sensor. Compared with electromagnetic tracking, passive video-based motion capture had significantly better inter-trial reliability (ICC=0.947 vs. 0.937) and precision (SEM=0.94 vs. 1.23) in scapular kinematic measurements.

This technique was further validated against model-based roentgen stereophotogrammetry analysis (RSA) for both pace-controlled scaption (arm elevation in the scapular plane)[89] and simulated overhead throwing.[90] Model-based RSA is an accurate, precise, and valid gold standard of scapular kinematic tracking.[91] Passive video-based motion capture has the advantages of high sampling rate, wireless capture, and relatively large capture volume, which is appropriate for maximum effort throwing motion analysis. This new scapular kinematic tracking technique was used in the current study.

1.8 SUMMARY

Baseball throwing has been linked to a wide spectrum of injuries of the shoulder complex,[2] as the result of repetitive high kinetic load applied to the throwing shoulder.[6] While the importance of proper scapular movement during baseball throwing is acknowledged,[3] little is known regarding scapular kinematics during baseball throwing due to methodological limitations. There exists some evidence that glenohumeral ROM and shoulder strength are related to scapular kinematics during pace-controlled arm elevation and shoulder injuries in baseball players. However, the potential association between glenohumeral ROM, shoulder strength, and scapular kinematics during baseball throwing has not been investigated.

1.9 PURPOSE AND SIGNIFICANCE

Altered scapular kinematics during pace-controlled arm elevation, changes in the glenohumeral ROM, and shoulder muscle weakness and imbalances have been linked to throwing performance and shoulder injury in baseball players. Throwing performance and shoulder injury are likely affected by the position of the humerus and/or scapula, but there is very little evidence to support this due to the lack of scapular kinematic analyses during throwing. No research has demonstrated that the altered scapular positions that may contribute to shoulder injury seen during pace-controlled arm elevation also exist during throwing; therefore it is not appropriate to assume these alterations contribute to shoulder injuries in baseball players. Further, the high amount of kinetic load during maximum effort baseball throwing is thought to contribute to shoulder injuries. However, no research has verified that increased shoulder kinetics occur with altered scapular kinematics, changed glenohumeral ROM, and shoulder musculature weakness and imbalance. The focus of the current study was to address these knowledge gaps using the new, validated scapular tracking approach. If the theorized associations can be established, clinicians can use scapular kinematics during scaption, glenohumeral ROM, and shoulder muscle strength as screening tools to identify detrimental scapular kinematics during throwing that may increase the risk of shoulder injury in baseball players. Researchers or strength and conditioning coaches can design training programs for baseball players targeting the altered scapular kinematics. The associations can also provide better understanding of the mechanism of throwing-related shoulder injury.

Thus, the first purpose of this study was to investigate scapular kinematics during maximum effort baseball throwing, and the contribution from the glenohumeral joint and the scapulothoracic joint to shoulder maximum external rotation during maximum effort baseball throwing. The second purpose was to identify the potential association between scapular kinematics during maximum effort baseball throwing and scapular kinematics during pace-controlled scaption (i.e. arm elevation in the scapular plane), glenohumeral ROM, and shoulder muscle strength. The third purpose was to identify the potential association between all these factors and shoulder kinetics during maximum effort baseball throwing. Figure 2 summarizes the purpose and rationale for this study. Blue arrows represent current evidence, while the red arrows represent the gap in the knowledge that this study expects to fill.

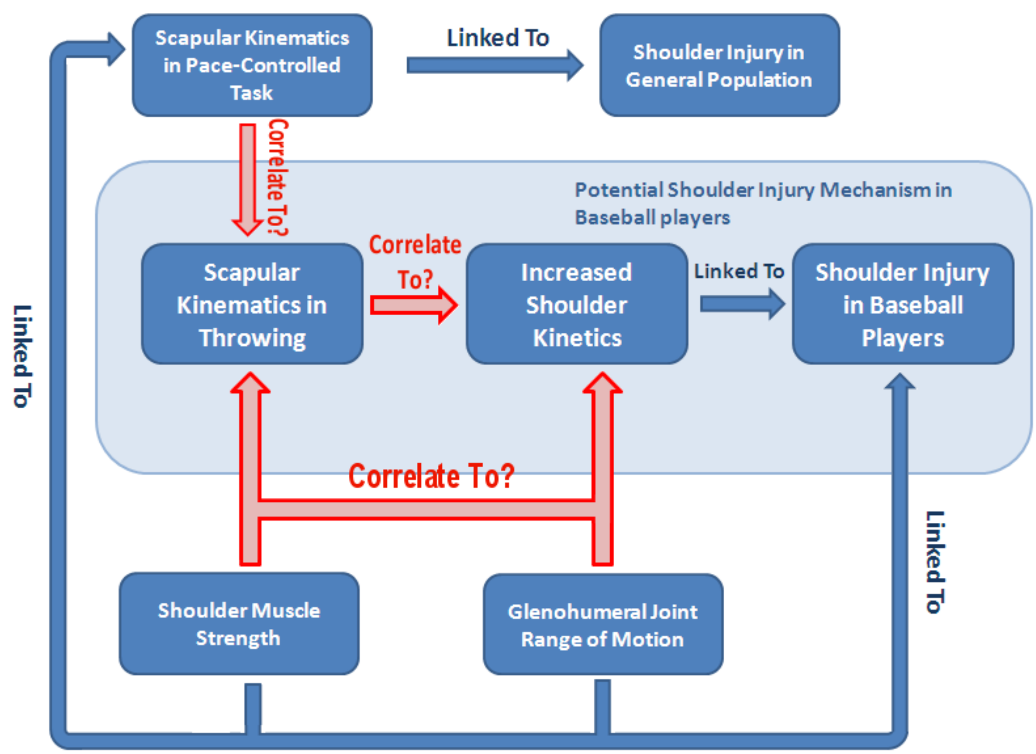

Figure 2. The purpose and expected knowledge gaps addressed in the study

1.10 SPECIFIC AIMS AND RESEARCH HYPOTHESES

Based on the declared research purpose, several specific aims and associated hypotheses are presented below:

Specific Aim 1: To investigate and describe scapular kinematics (protraction/retraction, medial/lateral rotation, and anterior/posterior tilt) during maximum effort baseball throwing at the following events: stride foot contact, maximum shoulder external rotation, ball release, maximum shoulder internal rotation, maximum shoulder anterior force (right before maximum shoulder external rotation), maximum shoulder superior force (right before maximum shoulder external rotation), maximum shoulder compression force (right after ball release), maximum shoulder posterior force (between ball release and maximum shoulder internal rotation) and maximum shoulder inferior force (right before maximum shoulder internal rotation), and to determine the contribution of glehonumeral external rotation and scapular posterior tilt to maximum shoulder external rotation during maximum effort baseball throwing

Specific Aim 2: To identify the potential association between scapular kinematics during maximum effort baseball throwing and pace-controlled scaption

Hypothesis 2-1: Scapular kinematics at stride foot contact during baseball throwing would be significantly correlated to scapular kinematics at the same arm elevation angle during pace-controlled scaption

Hypothesis 2-2: Scapular kinematics at the time of maximum shoulder compression force during baseball throwing would be significantly correlated to scapular kinematics at the same arm elevation angle during pace-controlled scaption

Specific Aim 3: To identify the potential association between glenohumeral range-of-motion (ROM) and scapular kinematics during maximum effort baseball throwing

Hypothesis 3-1: Maximum glenohumeral external rotation range of motion would be significantly correlated to scapular anterior/posterior tilt at the event of maximum shoulder external rotation during maximum effort baseball throwing

Hypothesis 3-2: Maximum glenohumeral internal rotation range of motion and posterior shoulder tightness would be significantly correlated to scapular anterior/posterior tilt at the events of ball release and maximum shoulder internal rotation during maximum effort baseball throwing

Specific Aim 4: To identify the potential association between shoulder strength and scapular kinematics during maximum effort baseball throwing

Hypothesis 4-1: Maximum scapular stabilizer (upper, middle, lower trapezius, rhomboid, and serratus anterior) isometric strength would be significantly correlated to scapular medial/lateral rotation at stride foot contact during maximum effort baseball throwing

Hypothesis 4-2: Maximum shoulder external and internal rotator strength, as well as external/internal strength ratio, would be significantly correlated to scapular protraction/retraction and anterior/posterior tilt at maximum shoulder anterior force and maximum shoulder posterior force during maximum effort baseball throwing

Hypothesis 4-3: Maximum supraspinatus strength would be significantly correlated to scapular medial/lateral rotation and anterior/posterior tilt at stride foot contact during maximum effort baseball throwing

Specific Aim 5: To identify the potential association between glenohumeral range of motion and shoulder kinetics during maximum effort baseball throwing

Hypothesis 5.1: Maximum glenohumeral external rotation range of motion would be significantly correlated to maximum shoulder anterior and superior force during maximum effort baseball throwing

Hypothesis 5.2: Maximum glenohumeral internal rotation range of motion and posterior shoulder tightness would be significantly correlated to maximum shoulder posterior and inferior force during maximum effort baseball throwing

Specific Aim 6: To identify the potential association between shoulder strength and shoulder kinetics during maximum effort baseball throwing

Hypothesis 6.1: Maximum shoulder external rotator strength would be significantly correlated to maximum shoulder posterior, inferior, and compression forces during maximum effort baseball throwing

Hypothesis 6.2: Maximum shoulder internal rotator strength would be significantly correlated to maximum shoulder anterior and superior forces during maximum effort baseball throwing

Hypothesis 6.3: Shoulder external/internal rotators strength ratio would be significantly correlated to maximum shoulder anterior and posterior forces during maximum effort baseball throwing

Hypothesis 6.4: Maximum supraspinatus strength would be significantly correlated to maximum shoulder superior and inferior forces during maximum effort baseball throwing

Specific Aim 7: To identify the potential association between scapular kinematics and shoulder kinetics during maximum effort baseball throwing

Hypothesis 7.1: Scapular kinematics at stride foot contact would be significantly correlated to maximum shoulder anterior, posterior, superior, inferior, and compression forces during maximum effort baseball throwing

Hypothesis 7.2: Scapular kinematics at the time of maximum shoulder compression force would be significantly correlated to maximum shoulder compression force during maximum effort baseball throwing

2.0 REVIEW OF LITERATURE

Baseball is a sport that involves repetitive throwing in both practice and competition. Baseball throwing, no matter if performed with maximum or sub-maximum effort, is a task in which very high kinetic demand is placed on the shoulder.[92] The shoulder has been shown to be the most commonly injured site in baseball players at a variety of competitive levels.[14,15,18] The coordinated movement between the scapula and the humerus is considered critical for throwing performance and minimized risk of shoulder injury.[3] While there has been some study of the biomechanics of maximum effort baseball throwing, a void exists in the investigation of scapular kinematics during throwing due to methodological limitations. Scapular kinematic measurement during pace-controlled arm movement is more technically viable and altered kinematic characteristics during pace-controlled arm movement have been linked to various shoulder pathologies.[41,42,49] It is unclear, however, whether such scapular kinematic characteristics are present during maximum effort baseball throwing. In addition, some evidence suggests that glenohumeral ROM and shoulder complex muscle strength may be related to scapular kinematics during pace-controlled arm movements.[88,93] The relationship of glenohumeral ROM and shoulder strength with scapular kinematics during throwing is unknown. In this chapter, the epidemiology of shoulder injuries as well as the kinematic and kinetic of maximum effort baseball throwing are discussed. In addition, the measurement methodologies and previous research findings are reviewed for scapular kinematics during pace-controlled arm movements, glenohumeral ROM, and shoulder strength in the context of baseball participation and shoulder injuries.

2.1 EPIDEMIOLOGY OF SHOULDER INJURY IN BASEBALL

Overhead athletes, including baseball players, are subject to an increased risk of shoulder pain and injuries. Shoulder injuries such as rotator cuff tendonitis, tendonosis, bursitis, tears, impingement, and superior labrum anterior posterior (SLAP) lesions are commonly seen in this population.[2] These injuries can account for over 90% of shoulder injuries observed in professional baseball pitchers.[21]

Baseball is a sport that involves repetitive overhead throwing during both competition and practice. As result, shoulder pain and injury are a common complaint among baseball players. Surveillance data have demonstrated that among high school sports from 2005 to 2007, baseball has the third highest shoulder injury rate, following football and wrestling;[13] however, the underlying mechanism of shoulder injury among these sports can be very different. Approximately 44% of shoulder injuries in baseball were non-contact, the highest percentage among the sports.[14] From 2005 to 2008, 43% of high school shoulder injuries in baseball were non-contact.[20] Sprains and strains accounted for 55% of shoulder injuries in baseball, second only to volleyball. Of the shoulder injuries reported in baseball, 24% and 33% resulted from throwing and pitching, respectively. Others have reported that the shoulder is the most frequent site of injury in high school baseball, accounting for 18% of the total baseball injuries.[14]

Similar results were observed in higher levels of competition as well. From 1992 to 2004, non-contact injuries accounted for 42% and 64% of all competition and practice injuries in

National Collegiate Athletic Association (NCAA) baseball.[15] Throwing and pitching accounted for 5% and 15% of all NCAA baseball injuries, respectively, and the shoulder was the most common injury site during competition (23%) and practice (16%). Two prospective studies of collegiate baseball players demonstrated that the shoulder was the first and second most frequent injury site, accounting for 24% and 13% of total injuries, respectively.[16,17] In minor league baseball, the shoulder was the most commonly injured site, with 24% of all injuries occurring at the shoulder.[18] Finally, in Major League baseball, injury of the shoulder caused the most disabled list days, at 28% of total, from 1989 to 1999.[19] In a 5-year prospective study that followed 144 professional pitchers, 59% of the recorded injuries occurred at the shoulder.[21]

Whether in baseball competition or practice, pitchers perform the greatest amount of maximum effort throwing, usually while pitching. Catchers perform the greatest amount of moderate effort throwing, typically when passing the ball back to pitchers, and some maximum effort throwing to pick off a runner. On average, catchers make 4.4 to 6.5 pick-off throws per game at an average 90 to 97% of maximum effort, with mean throwing distance approximately 31 meters.[94] Outfielders and infielders make fewer throws than pitchers and catchers, with outfielders performing more maximum effort throwing than infielders. The mean throwing distance of shortstops was about 24 meters, while the mean throwing distance of centerfielders ranged from 27 to 48 meters depending on competition levels.[94] Among different positions in high school baseball, Collins and Comstock[14] reported that injuries at shoulder were the most common in pitchers (34%), followed by catchers (25%), outfielders (24%), and infielders (7%). Similarly, Krajnik et al.[20] found that 38% of shoulder injuries in high school baseball occurred in pitchers, followed by outfielders (26%), infielders (18%), and catchers (9%). Pitchers represented 48% of disabled list reports and 56% disabled list days in Major League Baseball.[19]

Such patterns indicated that the risk of shoulder injuries in baseball is associated with both intensity and volume of throwing.

Epidemiological evidence further supports the influence of throwing intensity in baseball pitchers. Adolescent pitchers with a fastball more than 85mph were at significantly higher risk of undergoing shoulder or elbow surgery.[22] A prospective cohort study showed a significant association between pitch velocity and elbow injury in professional baseball.[95] Furthermore, the three pitchers with the highest pitch velocity in the injured group required surgical intervention, while non-operative rehabilitation was assigned to others. Although it is plausible to assume the existence of significant relationship between throwing intensity and shoulder injury, the exact relationship remains unclear.

Epidemiological evidence also supports that the volume of throwing can contribute to increased risk of shoulder pain and injury. In a prospective cohort study, increased risk of shoulder pain was associated with increased pitch count per game and per season in youth baseball pitchers.[23] In a case-control study, increased number of warm-up pitches, pitching appearance per year, innings pitched per year, pitches per game, pitches per year, and months per year of pitching were identified as risk factors for undergoing shoulder surgery in adolescent baseball pitchers.[22]

Pitching while fatigued or in pain were also identified as risk factors of shoulder surgery in adolescent baseball pitchers.[22] Between 1999 and 2003, 73% of Major League baseball players placed on the disabled list had injuries classified as “wear and tear” or as caused by “overuse” or “insufficient rest”.[24] Sports medicine experts generally agree that although baseball throwing is a very intense task, a single bout of throwing typically does not cause shoulder injury.[26] While a baseball player may be able to identify a single throwing event which precipitates the injury, it is the microtrauma accumulated with repetitive throwing over months or years that results in clinical structural damage.[25,26] Complaints of simple shoulder pain, common in youth baseball, can be an early indicator of the development of an overuse injury.[23]

2.2 BASEBALL THROWING MOTION ANALYSIS

Motion analysis has been widely applied in baseball throwing, especially pitching. In most cases, such analysis involves passive video-based motion capture technique to retrieve 3-D coordinates of anatomical landmarks for kinematic variable calculations. With kinematic data available, shoulder and elbow kinetic data can be estimated using inverse dynamics. Motion analysis has provided a considerable amount of knowledge regarding the biomechanics of throwing as well as the potential mechanisms of throwing-related injuries. In this section, the methodology of throwing motion analysis, previously reported shoulder kinematic and kinetic variables, and the relationship between these variables and shoulder injury mechanisms are reviewed.

2.2.1 Methodological considerations

The earliest quantitative throwing motion analysis may be by Atwater,[96] conducted in the late 1960s. In Atwater's study, kinematic data were collected with cameras carefully calibrated and placed perpendicular to each other. Due to the technical difficulties of 3-D data collection at that time, throwing motion analysis was not a practical idea due to the cumbersome equipment setup. In the early 1970s, a mathematical breakthrough was made by Abdel-Aziz and Karara,[97] who developed an algorithm called Direct Linear Transformation (DLT). This algorithm allows the 3-

D coordinate of a point to be calculated, given that the point is seen by two cameras placed in any positions and that the two cameras are calibrated with a set of points with known coordinates prior to data collection. In the late 1970s, this algorithm was validated for dynamic data by Shapiro,[98] formally making it available for motion analysis. Inverse dynamics were then applied to throwing motion analysis to estimate elbow and shoulder joint forces and moments, following the algorithm by Feltner and Dapena.[99]

In earlier studies, throwing motion was recorded with visible-spectrum still cameras or video cameras and the positions of the joint centers or markers were manually digitized. As manual digitizing is a time consuming process, typically only one throw per subject would be analyzed.[100] With the development of infrared video cameras, the 3-D coordinates of reflective markers can be identified, recorded, and labeled with a much faster, semi-automatic process. Multiple throws can therefore be analyzed and averaged per subject. Infrared video cameras usually have higher resolution than visible-spectrum cameras, allowing more and smaller markers to be placed per body segment resulting in a more detailed and complex human body model. The accuracy of infrared motion capture systems was reported between 0.42 to 2.77mm and 0.16 to 0.52°, while a visible-spectrum motion capture system had the accuracy of 3.54mm and 0.58°.[101] Most current studies use infrared motion capture for throwing motion analysis. However, visible-spectrum cameras are still utilized sometimes, particularly since they can be used for field studies to capture movement in real competitions.[4,9]

2.2.2 Throwing kinematics, kinetics, and injury mechanisms

Baseball throwing, especially pitching, involves extreme shoulder kinematics and kinetics. A summary of the shoulder kinematics and kinetics is available in Appendix A.1. Such extreme kinematics and kinetics have been linked to the mechanisms of shoulder injuries in baseball players. The two instants of the most extreme shoulder kinematics are maximum shoulder external rotation during the late arm cocking phase and maximum shoulder internal rotation angular velocity during the early arm deceleration phase.[6] Maximum shoulder kinetics occurs right before or after these two instants. Further, high shoulder anterior force has been detected at stride foot contact (SFC),[6] which occurs approximately the end of throwing arm elevation, during which the humerus is approaching a position in which the rotator cuff tendon could be impinged.

The maximum shoulder external rotation angle during pitching is greater than 170°. (Appendix A.1) Although this number also includes scapular posterior tilt and spine hyperextension, 73 to 86% of the motion still occurs at the glenohumeral joint.[38,102] This is equivalent to approximately 125 to 145° of glenohumeral external rotation, which is comparable to the passive glenohumeral external rotation ROM measurements of baseball players reported in multiple studies.[2,33,57] This suggests that external rotation of the glenohumeral joint during pitching is approximating the end range of motion of the joint. It is believed that this repetitive extreme external rotation can result in permanent deformation or stretch of the inferior glenohumeral ligament and inferior capsule of the glenohumeral joint, resulting in joint instability and subsequent injuries.[11] In addition, at the extremes of external rotation during the arm cocking phase, the humeral head pushes forward and the shoulder anterior force reaches a peak value of over 300N. Such forward movement coupled with the reduced stability provided by the stretched ligamentous and capsular structures can result in damage to the anterior labrum. Furthermore, the shoulder superior force reaches a peak value of over 300N at this point, placing high stress on the superior structures, potentially resulting in subacromial impingement. Bicep tendonitis and rotator cuff bursitis are all common shoulder injuries seen in baseball pitchers, with pain typically experienced approaching maximum shoulder external rotation.[2,21]

Maximum shoulder internal rotation angular velocity during pitching, which occurs right after ball release, can be greater than 7000°/s. In some pitchers this number can be closer to 9000 or 10,000°/s.[9,100] Compared to the strength required to generate such rapid movement in the arm acceleration phase, it is even more challenging to stop such movement in the arm deceleration phase, especially when considering that deceleration is achieved with the relatively small muscles of the posterior rotator cuff (the infraspinatus and teres minor). This may be the most kinetically demanding instance of baseball pitching. Maximum shoulder compression force, typically over 800N in adult baseball pitchers, must be generated by the posterior rotator cuff muscles, latissimus dorsi, and posterior deltoid to hold the humeral head within the glenoid fossa against the distraction force.[10] Maximum shoulder posterior and inferior forces of over 300 and 200N, respectively, are generated by these muscles to resist further humeral anterior and superior translation.[6] Failure to generate such forces can further damage the anterior and superior structures of the glenohumeral joint.[10] Repetitive eccentric overload of these muscles, especially the posterior rotator cuff, can result in accumulated microtrauma and tensile failure.[26] Baseball pitchers are known to have weaker external rotators in their throwing shoulder as compared to their non-throwing shoulder.[2] It has been demonstrated that pitching with 75% effort results in only a 15% reduction of kinetics, indicating that baseball position players are still subject to high kinetics and potential risk of shoulder injury.[92]

2.2.3 Throwing motion analysis, risk of injury, and performance

With throwing motion analysis, kinematics and kinetics of baseball throwing have been studied and the potential injury mechanisms have been proposed. One may expect these results to benefit baseball players by reducing their risk of injury. However, these results have not made considerable impacts on baseball coaching and training. One of the reasons is that the links among kinematics, kinetics, and risk of injury are not firmly established. Although the shoulder kinematics and kinetics of baseball throwing have been interpreted in the context of injury mechanisms, there is limited evidence to link the biomechanical factors directly to the risk of injury. Lyman et al.[23] attempted to associate qualitative kinematic analysis to risk of injuries in youth baseball pitchers, but failed to find any significant relationships. There has not been any research linking pitching kinematics or kinetics to shoulder injury. Anz et al.[103] established that increased elbow varus moment during pitching was associated with increased risk of elbow injuries in professional pitchers. The risk of shoulder injury has not been associated with throwing mechanics so far.

In addition, there exist some conflicts between the research results and the need of athletic performance, which can be explained by the following example. Maximum shoulder external rotation is thought to stretch the ligamentous structures of the glenohumeral joint. In addition, it is also associated with increased maximum shoulder compression force.[9] One may think that reducing maximum shoulder external rotation may prevent pitchers from sustaining shoulder injuries. However, maximum shoulder external rotation is also a predictor of ball velocity.[104] From the biomechanics point of view, increased shoulder external rotation angle indicates a longer path and time of acceleration until ball release. With a given acceleratory capacity of a pitcher, increased shoulder external rotation results in increased ball velocity.

Prospective research has demonstrated that professional pitchers with higher ball velocity are at greater risk of elbow injury.[95] On the other hand, the injured group had significantly longer careers than the non-injured group. This example suggested that while injuries can shorten an athlete's career, subpar performance, potentially as indicated by lower ball velocity, may impact an athlete's career even more. Fortenbaugh and Fleisig[105] attempted to compare the pitching kinematics of high-efficiency and low-efficiency pitchers by defining the efficiency of pitching kinematics based on higher ball velocity and lower shoulder forces. However, following such definition the high-efficiency group still had significantly faster ball velocity. With current knowledge, kinematic characteristics linked to decreased kinetics without negatively affecting ball velocity are still unclear. That is, it may not be prudent to opt for reducing potential risk of injury in athletes that would compromise performance.

2.3 SCAPULAR KINEMATIC ANALYSIS

Scapular kinematics has attracted some attention from clinicians since the late 19th century. Cathcart[106] found that the scapula rotated throughout the whole range of motion of arm elevation. Lockhart[107] then described the continuous and coordinated movements between the humerus and scapula during arm elevation, which was later named the scapulohumeral rhythm by Codman.[108] Since then, scapular kinematic measurement methods have been developed and improved; scapular kinematics in healthy, symptomatic, and athletic populations has been identified and the functions of the scapula as well as factors affecting scapular kinematics have been studied.

Scapular kinematics includes both linear and rotational components. For the purpose of this study, the term "scapular kinematics" refers to the rotational components only. To describe the humeral and scapular rotational movement, terms from the International Society of Biomechanics (ISB) are used.[109] As recommended, humeral movements are decomposed into an Euler angle series of plane of humeral elevation, humeral elevation, and humeral internal/external rotation. In this context, shoulder abduction is humeral elevation in the frontal plane and shoulder flexion is humeral elevation in the sagittal plane. In scapular kinematic studies, arm elevation is frequently performed in the scapular plane, which is sometimes termed as shoulder scaption, which is humeral elevation 30° anterior in the frontal plane. If not specifically mentioned, the aforementioned terms are used to describe the humeral movement with respect to the thorax. Scapular movements are decomposed into an Euler angle series of protraction/retraction, medial/lateral rotation, and anterior/posterior tilt, with respect to the thorax. When referred in two-dimensional scapular kinematic studies, these three sets of movement indicate rotation in the transverse, frontal, and sagittal plane, respectively. It should be noted that the ISB terms for scapular kinematics are different to those used in many previous studies. Scapular protraction/retraction was sometimes called scapular internal/external rotation, and scapular medial/lateral rotation was called scapular downward/upward rotation.

Clinicians and researchers have been seeking valid and effective approaches to quantify scapular kinematics. With technological improvements and methodological innovations, scapular kinematics measurement approaches have evolved from static to dynamic and from two-dimensional (2-D) to three-dimensional (3-D). Invasive and non-invasive approaches were developed with different focuses and for different purposes. Overall, a wide spectrum of scapular kinematic measurement approaches has been used in research and clinical observations, contributing to better understanding of the functions of and pathologies related to the scapula. Measurement results may differ with the different approaches used; therefore, interpretations of reported values must be made with caution. In this section, scapular kinematics measurement methods and their reliability, accuracy, validity, limitations, applications as well as how these methods evolved in history are reviewed.

2.3.1 Static 2-D analysis

2.3.1.1 Traditional Radiography

The continuous lateral rotation of the scapula during arm elevation was observed in the early 1880s.[106] Other than naked-eye clinical observation, traditional radiography is arguably the earliest method to study scapular kinematics. The use of traditional radiography in scapular kinematics can be traced back to no later than 1930, as Lockhart[107] discussed the continuous and simultaneous movement of the scapula and humerus during arm elevation. About the same time, Codman[108] proposed the same finding and named this simultaneous movement scapulohumeral rhythm. Such works were based on both clinical observation and X-rays. While an experienced clinician should be capable of identifying scapular pathology by observation, it is of moderate intra- and inter-rater reliability and the results cannot be quantified.[110] In 1944, Inman et al.[111] presented one of the earliest quantitative observation reports on scapular movements. Freedman and Munro[112] conducted a similar study in the scapular plane instead of the frontal plane. X-ray images provided valuable information regarding the functions and movements of the scapula. Traditional radiography was also used to describe scapular kinematics in symptomatic shoulders.[113]

Traditional radiography has been employed in multiple research studies with similar protocols. An X-ray image is taken with a subject at the posture of interest, with different anatomical structures selected as reference. Typically, one line is drawn on the image along a ridge on the scapula and another line is drawn for reference, with the intersection forming the angle of interest that can then be measured with a protractor. The ridge on the scapula could be the scapular spine, the medial border, or the glenoid. The reference line, depending on the angle of interest, could be drawn along the humerus for measuring the scapulohumeral angle[111] or drawn vertically for the scapulothoracic angle.[114] With the consideration of human body and scapula morphology as well as clinical relevance, usually the image is taken in the frontal or scapular plane and the scapula kinematic component of interest frequently is medial/lateral rotation. Images in the transverse plane are occasionally taken.[115] Since ionizing radiation is involved, this method is radiologically invasive.

Whether a 2-D projection image is sufficient to accurately determine the true scapular movement is questionable. Mandalidis et al.[116] established good intra- and inter-rater reliability of scapular lateral rotation measurement during scapular plane arm elevation, with the intraclass correlation coefficients (ICC) at different points across the range of motion ranging between 0.97 to 0.99 and 0.96 to 0.99, respectively. However, de Groot[117] measured scapular kinematics in 3-D and simulated the projection onto a plane and found that the scapulohumeral rhythm based on 2-D angles differed considerably when a different ridge of the scapula, such as the medial border or the scapular spine, was chosen. That is, the relative orientation of the humerus to the projected ridges does not remain constant as previously thought. The scapular lateral rotation angle calculated from X-ray images can be overestimated by 35%.[118] It was also argued that the uncontrolled variability of scapular and trunk orientations with respect to the X-ray source and projection plane as well as difficulty in identifying anatomical landmarks made this method inappropriate for any inter-subject comparison.[117] This excludes traditional radiography from being used in many research settings. The application of traditional radiography should be limited to intra-subject purposes. Interestingly, while it makes sense to take the X-ray image in the scapular plane for a projection more perpendicular to the scapula,[112,114,118] de Groot[117] found the optimal projection for accuracy was in the frontal plane instead.

2.3.1.2 Goniometry and inclinometry

Another widely used method to measure 2-D scapular kinematics is goniometry or inclinometry. A goniometer has two arms that are each aligned with a segment. For scapular kinematics, one arm is aligned with a ridge of the scapula and the other is aligned with a reference segment (e.g. humerus, spine, thorax), and the angle between the two arms is measured. The alignment of the center of the goniometer varies, depending on the angle of interest. The measurement can be performed with a subject in virtually any position. An inclinometer measures inclination with respect to gravity. The inclinometer is aligned with a ridge of the scapula, usually the spine of the scapula, and the reading indicates the angle between the ridge and horizontal plane. As the reference is gravity, an inclinometer should be placed in a plane perpendicular to the ground for the best accuracy. That is, the measurement should be done with a subject standing or sitting upright.

A goniometer or an inclinometer is a portable, easy-to-use, quick, and non-invasive measurement. A limitation to such measurements is that the readings can only be obtained during static positioning; therefore how the orientation changes during movement cannot be assessed. The use of goniometers in scapular kinematics can be traced to the late 1960s,[119,120] but the reliability is questionable.[121] Inclinometers were not used for scapular kinematic measurement until the late 1990s.[122] An inclinometer may provide more reliable reading than a goniometer for the current application, as it minimizes the error coming from alignment with the reference. Inclinometer measurement for scapular lateral rotation during arm elevation has demonstrated good intra-rater reliability, with the ICC between 0.81 to 0.96 at different points across the range of motion.[122,123] Inter-trial and inter-session reliability of scapular lateral rotation has also been reported, with ICC ranging from 0.97 to 0.99 and 0.56 to 0.94, respectively.[124] Concurrent validity of such measurements was evaluated against both static and dynamic 3-D scapular lateral rotation and showed moderate to good results, with the Pearson's r (product-moment correlation coefficient) ranging from 0.74 to 0.92 and 0.59 to 0.73, respectively.[122] Although these are still 2-D measurement, goniometric or inclinometric measurement does not involve projection, thereby eliminating error associated with image distortion. Inclinometry is still being used in scapular kinematics research.[46,124]

2.3.2 Dynamic 2-D analysis

2.3.2.1 Digital fluoroscopy

Dynamic 2-D scapular kinematic measurement is possible but is less common. A digital fluoroscopic video device (frequently called "C-Arm") is capable of capturing sequential X-ray images at a sampling rate between 30 and 60Hz.[125] The X-ray image sequences can be used to measure 2-D scapular kinematics during movement which is not possible using traditional radiography methods. de Groot et al.[118] used this technology to determine the effect of movement velocity on scapulohumeral rhythm with a 50Hz sampling rate. The same limitations that applied to traditional radiography, according to de Groot,[117] also apply to digital fluoroscopic video. Teyhen et al.[126] used this technology to evaluate the translation of the humeral head during arm elevation and reported good intra-rater reliability (ICC=0.89 to 0.98) and inter-rater reliability (ICC=0.83 to 0.92) at different points across the range of motion.

2.3.3 Static 3-D Analysis

2.3.3.1 Roentgen stereophotogrammetry analysis (RSA)

Methods to quantify 3-D scapular kinematics were developed by expanding the general ideas of the 2-D measurements. As stereo vision requires two angles of view, the 3-D coordinate of an anatomical landmark can be determined by taking X-ray images from two different angles. Attempts to determine 3-D position with two X-ray images can be traced back to less than three years after Roentgen discovered X-ray.[127] By identifying three anatomical landmarks on the scapula, a plane that models the scapula can be defined and the orientation of this plane can be calculated. The difficulties identifying the landmarks on X-ray images still apply.[117] Digitization errors made on each of the two X-ray images can compound the error associated with the 3-D estimations, raising the question of accuracy and validity.

A method to address such difficulties, called roentgen stereophotogrammetry analysis (RSA), was developed in the mid-1970s by Selvik.[128,129] Small tantalum beads are implanted into the bones of interest. The beads are radiopaque and can be clearly identified on X-ray images, resulting in very small digitizing errors. The high accuracy of RSA was well documented, around 0.25mm and 0.5° *in vivo*, and 0.05mm and 0.1° *in vitro*.[130] While RSA can capture 3-D coordinates with high accuracy and validity, implanting the tantalum beads requires surgical procedures, making this method not only radiologically but also physically invasive. When a traditional radiography device is used, this measurement method is static.

2.3.3.2 Electromechanical, electromagnetic, and active optical digitizers

In the early 1990s Pronk and van der Helm[131] developed an electromechanical digitizer, which is a machine arm with several linked segments. It can calculate the 3-D coordinate of its pointer based on the angles among the linked segments with an accuracy of 1.43mm. The accuracy of this device in measuring scapular kinematics was reported as 2°.[132] de Groot and Brand[133] used the electromagnetic digitizer to develop a regression equation estimating scapulohumeral rhythm.

In the late 1980s An et al.[134] determined that an electromagnetic tracking device had good accuracy for kinematic studies. This technology involves a transmitter that generates an electromagnetic field and a sensor that is capable of detecting the electromagnetic field. The sensor can be used as a pointer and its 3-D coordinates can be determined. The accuracy of this device in measuring scapular kinematics has been reported to be about 2°, which is comparable to the electromechanical digitizer.[135] A clinician must palpate the anatomical landmarks of the subject's scapula so their 3-D positions can be recorded. The measurement is non-invasive but can only be performed statically. Barnett et al.[136] later designed a special attachment for an electromagnetic tracking device, with legs simultaneously pointing to the anatomical landmarks on the scapula. This attachment enabled faster measurement and was reported to be reliable and more valid than digitizing the landmarks sequentially. Bourne et al.[137] used an active optical digitizer to measure scapular kinematics and concluded that the method was accurate and valid except for measurement of frontal plane arm elevation. A similar active optical digitizer approach was reported accurate, reliable, and valid by Hebert et al.[138] The reliability of an active optical digitizer was comparable when measuring scapular kinematics in healthy and impingement patients.[139]

2.3.3.3 Advanced imaging technologies

Advanced imaging technologies allow more options for 3-D scapular kinematics. Computer tomography (CT) can capture "sliced" images of the human body. With some image processing techniques, bones can be isolated from other tissues on the images and the processed bone images can be stacked to create 3-D bone models. The orientations and the relative positions among the bones can therefore be calculated.[140] The same technique can be used with magnetic resonance imaging (MRI) instead of CT, with the advantage of no ionizing radiation.[45,141] However, MRI takes a longer time to capture an image than CT. As both CT and MRI scan take time to capture an image, the measurement technique can only be static. Further, while scapular kinematics studies usually involve elevated arm postures, the design of CT and MRI equipment typically requires a subject to remain supine in a small cylindrical space, thereby preventing such arm postures. This issue, however, can be partially addressed with an open-MRI device.[142]

2.3.3.4 Model-based RSA

To address the limitation of being physically invasive, a modified RSA approach, sometimes called model-based RSA, was developed. Instead of tracking implanted metal beads, this method tracks the shape of an object. Similar to traditional RSA, this approach involves two X-ray sources that project the shape of a bone onto two images. An X-ray source and its corresponding image plane can be thought of as a camera with its own internal parameters, such as focal length and principal points, etc. With a pair of such cameras, there exists a set of external parameters that describes the spatial relationships between the cameras. For any rigid object with a fixed and asymmetric shape, such as a bone, its projection is unique for each camera. With the internal and external parameters known, there exists only one 3-D position and orientation of the object so that the projections of the bone simultaneously satisfy the two images. Initially, this method was applied to locate objects with known geometry, such as a prosthesis implant. An early application of this method occurred in late 1970s, when Baldursson et al.[143] located the center of the femoral head in a total hip replacement patient. The estimation of projection was not difficult with the simple sphere geometry of a metal femoral head; however, matching objects with a more complex shape was not possible without advanced computing power for 3-D vision and iterative optimization. According to a review by Karrholm et al.,[144] applications of this method on implants with more complex geometry, such as knee or spinal implants, did not occur until the late 1990s. This method has high accuracy, with errors around 0.1mm and 0.1°, if a precise model created with laser-scanning is used.[145]

As computing power increased, it became possible to apply model-based RSA on real human bones, which typically have a more complex shape and surface texture than prostheses. Instead of matching a prosthesis model with known geometry, the bone model of a patient must be created with imaging techniques. This model matching technique, as well as the algorithm, was presented by You et al.[146] In practice, a subject undergoes both a CT-scan and a dual X-ray session. A 3-D bone model is created from the CT images and the postures of interest are performed and captured with the dual X-ray. In post-processing, a virtual space is created based on the internal and external parameters in which the 3-D bone model can be placed. The bone model is then projected onto the two X-ray images. By adjusting the position and orientation of the bone model until its projections match the two X-ray images with minimal errors, the true position and orientation of the bone are uniquely determined. The 3-D positions of the anatomical landmarks can be retrieved by marking these landmarks on the bone model. The model matching technique can also be performed using single images,[147,148] although having two views should provide better matching certainty and accuracy.

2.3.4 Dynamic 3-D analysis

2.3.4.1 Traditional and model-based RSA

Image-based 3-D scapular kinematic measurement methods, such as traditional and model-based RSA, were developed as static only because of hardware capacity limitations. Once improved imaging technology made the device fast enough to take continuous images, the methods could be used for dynamic kinematic measurements. In late 1980s, traditional RSA was applied *in vivo* for dynamic knee kinematics at the sampling frequency between 2 to 4Hz.[149] Such imaging rates were only appropriate for some specifically planned slow movements. This design is still being used for scapular kinematics during the arm elevation task, but the movement is performed slowly, at 12 seconds per cycle.[150,151]

Further improvement in hardware allowed for increased imaging rates and expanded the application of RSA to more functional tasks. A dual plane digital fluoroscopic video device is simply a double "C-Arm", capable of recording X-ray images at 30 to 60Hz. Using this device, Massimini et al.[152] validated model-based RSA scapular kinematic measurements against traditional RSA in a dynamic *in vitro* setting. A cadaver's arm was manipulated into arm elevation in the frontal plane and into internal/external rotation. The movement duration was 1.5 to 6 seconds per cycle, depending on tasks. The difference between model-based and traditional RSA was 0.3mm and 0.5°. An inter-trial difference of 0.2mm and 0.4° was reported. A custom-made dual X-ray device, later called dynamic stereo X-ray (DSX), is capable of a maximum sampling rate of 250Hz and 1/2000 sec shutter speed, which is appropriate for evaluating scapular kinematics during rapid movement.[146] With DSX running at a 50Hz sampling rate and 1/500 sec shutter speed, Bey et al.[91] validated model-based RSA scapular kinematic measurements against traditional RSA in a similar dynamic *in vitro* setting. Three cadavers' arms were manipulated into arm elevation in both the frontal and the scapular planes as well as external rotation. The differences between model-based and traditional RSA were around 0.4mm and 0.25°.

Although valid and highly accurate, such image-based methods have limitations. The 3-D capture volume is limited to within the intersected area between the two X-ray beams. Theoretically, such volume can be increased by increasing the distance between the X-ray sources and image intensifiers as well as by increasing the size of the image intensifiers. Although this is technically possible, it is ethically not permitted as increased capture volume can also increase the area of the human body exposed to ionizing radiation. With limited capture volume, this method is useful during constrained movement such as arm elevation, but may be considerably difficult for capturing scapular kinematics during multi-plane, large range-of-motion tasks such as overhead throwing.[152]

2.3.4.2 Electromagnetic and active optical tracking with bone pins

Electromagnetic and active optical tracking have been used in response to the need for 3-D dynamic scapular kinematic measurement methods that are non-radiological and subject to less spatial constraint. Electromagnetic sensors are capable of detecting the electromagnetic field generated by a transmitter. With the three coils installed perpendicular to each other in the sensor, both translations and three degree-of-freedom rotations can be determined. Active optical tracking involves a receiver detecting optical signals generated by light or infrared emitting markers. A single marker carries only translational information and at least three markers on a rigid body are necessary to determine three degree-of-freedom rotations.

By attaching an electromagnetic sensor or a rigid plate with at least three infrared emitting markers to the scapula, the movement of the scapula can be measured. The most direct way to attach the sensor is to use bone pins. Although muscles and skin could pinch the bone pins during movement and inserting bone pins involves local anesthetics, this measurement approach is considered valid and viable. Bourne et al.[153] used an active optical tracking device with bone pins to evaluate scapular kinematics during frontal plane arm elevation, forward reaching, horizontal abduction, and hand-behind-the-back positioning in healthy subjects. McClure et al.[154] attached an electromagnetic sensor to bone pins to measure scapular kinematics during scaption, flexion, and internal/external rotation. High inter-session reliability was reported, with ICCs greater than 0.94 in all but the hand-behind-the-back task. However, being physically invasive largely limits the application of this method in research. Typically, bone pins are used only in validation studies serving as the gold standard.[35,137,155]

2.3.4.3 Electromagnetic and active optical tracking with skin sensors

Non-invasive 3-D dynamic scapular kinematic measurement approaches were developed and have been used in many research settings. In this case, sensors or markers must be attached to the skin. However, the large skin displacement over the scapula can create considerable soft tissue effects and distort the measurements. In his work that would later form the foundation of the ISB upper body kinematics recommendations, van der Helm[156] stated that due to the soft tissue effects, video recording using markers attached to the skin for this purpose is “not feasible” unless the collected data are corrected with regression equations. While van der Helm used video recording using markers as his example, this comment should apply to any skin-based approach.

Intuitively, markers can be directly placed on a subject’s back directly over the scapula. Bourne et al.[155] validated a design using an eight active optical markers grid over the scapula during frontal plane arm elevation, forward reaching, horizontal abduction, and hand-behind-back tasks. Correction factors were created individually for each subject by evaluating the relative movement between the skin markers and the scapular anatomical landmarks palpated and digitized. After correction, the root-mean-square (RMS) errors ranged from 1.8° to 2.8° for protraction/retraction, 1.6° to 2.8° for medial/lateral rotation, and 1.4° to 3.0° for anterior/posterior tilt as compared to bone pin measurements.[155] Bourne et al.[157] later reported that different optical markers subsets should be chosen among the eight-marker grid for optimal accuracy. The reliability of this method was reported as moderate to high.[157]

Another approach that has been widely used with an electromagnetic tracking device involves placing an electromagnetic sensor over the flat, broad portion of the acromion where the soft tissue effect is considered minimal. As an electromagnetic sensor is capable of measuring three degree-of-freedom rotation, a 3-D Cartesian local coordinate system (LCS) can be established within the sensor. With the sensor attached over the scapula, the scapular anatomical landmarks can be digitized with a second sensor, with their 3-D positions presented and recorded in the scapular sensor's LCS. By assuming the scapular sensor moves with the scapula, the 3-D positions of the anatomical landmarks can always be determined by converting their coordinates in the LCS back to the global coordinate system (GCS).

Karduna et al.[35] validated this approach during scapular and sagittal plane arm elevation, horizontal abduction, and external rotation. A universal correction factor was created based on the group average but only for scapular medial/lateral rotation. Compared to bone-pin measurements, the RMS errors were 6.2° to 11.4° for protraction/retraction, 4.4° to 6.3° (2.0° to 4.1° after corrected) for medial/lateral rotation, and 3.7° to 8.6° for anterior/posterior tilt. The RMS error increased steadily with increased arm elevation for medial/lateral rotation, but for protraction/retraction and anterior/posterior tilt the RMS error increased dramatically beyond 120° of scaption. While the errors looked slightly higher than those found in Bourne et al.,[155] it should be noted that Bourne et al. used subject-specific correction factors that must be determined for each subject with some relatively time-consuming palpating and digitizing procedures. Meskers et al.[158] also conducted a validation study for this approach against the measurement from an electromagnetic sensor attached to a three-leg scapular digitizing device similar to the one described earlier.[136,159] High inter-trial reliability of ICC=0.97 was reported. The RMS error for protraction/retraction, medial/lateral rotation, and anterior/posterior tilt was 3.88°, 6.47°, and 1.00°, respectively. After regression correction, the RMS errors further reduced to 0.92°, 2,00°, and 0.45°. Karduna et al.[35] also evaluated a method placing the electromagnetic sensor on a special rig that fits over the scapular spine and the acromion; however, the results produced were generally inferior except for protraction/retraction.

Currently, the electromagnetic tracking device with the sensor placed over the acromion is arguably the most prevalent approach in scapular kinematic research. Numerous studies using this method have contributed to better understanding in normal, adapted, pathological, and fatigued scapular kinematics.[41,51,54,160,161] High inter-trial and inter-session reliability (ICCs between 0.74 and 0.99) and precision (SEM between 1.0° to 2.9°) were reported for this approach.[162-164] Between-day reliability was lower, between ICC=0.19 to 0.70.[165] According to Thigpen,[166] protraction/retraction measurement was of lower repeatability than medial/lateral rotation and anterior/posterior tilt; scapular kinematic measurements had higher repeatability during flexion than abduction and scaption.

2.3.4.4 Limited use of passive video-based motion capture

Passive video-based motion capture was derived from the earliest and most intuitive idea of kinematic analysis: to analyze a human motion, first take a picture. With technical and algorithmic improvement, this method improved from static photography to dynamic cinematography, and from 2-D to 3-D. Traditionally, joint centers or anatomical landmarks were manually digitized over a visible-light photo or video frames. The 2-D coordinates of the markers were reconstructed into 3-D trajectories. To increase reliability and accuracy, reflective markers were developed to be attached on the skin over anatomical landmarks of interest. The markers can be identified in video frames with some image processing techniques, largely reducing data processing time. Infrared cameras were then used to replace visible-light cameras, thereby reducing image capture information to only the markers, enabling even faster and semi-automatic processing.

As of now, passive video-based motion capture is one of the most widely used methods in general kinematic research. Interestingly, attempts of applying this technology to measure dynamic scapular kinematics have been limited and were not seen until recently. In 2006, Jones et al.[167] studied scapular kinematics during frontal and sagittal plane arm elevation and internal/external rotation by directly attaching reflective markers over the three anatomical landmarks. It was concluded that the measured scapular movement patterns were similar to those previously published using electromagnetic systems. However, no quantitative evidence was provided to support these conclusions. Nakamura et al.[168] used an open-MRI to evaluate the deviation caused by soft tissue effects when placing reflective markers over the anatomical landmarks. The deviations ranged from 20.7 to 66.4mm, or 9.0 to 19.0mm after correction equations were applied. Even with the correction, the scapular orientation errors were still high, with errors of 1.7° in protraction/retraction, 8.0° in medial/lateral rotation, and 10.1° in anterior/posterior tilt. Salvia et al.[169] designed a three-marker cluster to be attached over the flat, broad portion of the scapula. Scapular kinematics were evaluated during frontal and sagittal plane arm elevation, internal rotation, and a functional task that involved free arm elevation and circumduction. This research claimed to agree with previous literature, although no quantitative evidence was found. Van Andel et al.[170] evaluated the validity of a similar approach using an acromion cluster with three active optical markers compared against the measurements made with a three-leg scapular palpator. Results indicated good reliability except for anterior/posterior tilt, with a maximum RMS error of 8.4°. Due to the limitation of the reference method (the palpator), the measurements were actually static.

Several factors may be attributed to the limited use of passive video-based motion capture in scapular kinematics. Researchers were hesitant to use this method as van der Helm[156] specifically indicated the difficulty with using a video-based approach in scapular kinematics. However, as noted, the difficulty was attributed to soft tissue effects and this limitation may apply to any skin-based approaches with or without the use of video capture. Van der Helm also indicated that this limitation can be addressed with regression equations, which have been adopted in the electromagnetic and active optical approaches.[35,155]

The limited the use of passive video-based motion capture in scapular kinematics is likely due to hardware limitations. A single reflective marker carries only translational information and three markers are needed to present three degree-of-freedom rotation. Specifically, to imitate the approach that researchers used with electromagnetic tracking devices, three markers must be placed on the flat, broad portion of the acromion. Unfortunately, until recently reflective markers had a diameter greater than 3cm due to limited camera resolutions. Three markers of that size cannot be placed on the small area of acromion while remaining separated far enough from each other to be captured and identified correctly by cameras. Ueda et al.[171] used a T-shaped rig attached to the acromion to place three markers, but the relatively large rig lacked support when attached and was subject to gravity and increased soft tissue effects; therefore the validity of such measurement is questionable.

2.3.5 Applications of video-based motion analysis for scapular kinematics

2.3.5.1 Validation for pace-controlled arm elevation tasks

In recent years, improvements in camera resolution have made the use of smaller markers possible. Once the cameras were capable of detecting the trajectories of smaller markers, the protocol utilized with electromagnetic tracking devices to measure dynamic scapular kinematics could be fully replicated with a passive video-based motion capture system. In a pilot study, we compared scapular kinematics measured with passive video-based motion capture and electromagnetic tracking. Frontal and sagittal plane arm elevation were evaluated. The anatomical landmarks chosen were based on the ISB recommendations.[109] Concurrent validity was established by demonstrating highly correlated measurements between the two approaches ($r>0.950$), with small inconsistencies between the two measurements mostly due to the differences in the measured thorax movement. With passive video-based motion capture, four reflective markers were placed on four anatomical landmarks on the thorax. With electromagnetic tracking, only a single sensor accounted for the thorax movement, defining the four anatomical landmarks in its LCS. Using four markers may provide better redundancy and may be subject to less soft tissue effect than using a single sensor. It was also determined that, compared with electromagnetic tracking, passive video-based motion capture had slightly but significantly better inter-trial reliability (ICC=0.947 vs. 0.937) and precision (SEM 0.94 vs. 1.23) in scapular kinematic measurements.

The use of video-based motion analysis in scapular kinematics during pace-controlled scaption was further validated against a gold standard: model-based RSA.[89] Model-based RSA is an accurate, precise, and valid gold standard of scapular kinematic tracking.[91] During scaption, the Pearson's product-moment correlation coefficient was between 0.701 and 0.953 (individual data) or 0.939 and 0.961 (group average data) for all the three scapular orientation components: protraction/retraction, medial/lateral rotation, and anterior/posterior tilt.

2.3.5.2 Advantages of video-based motion analysis

Passive video-based motion capture has several advantages over electromagnetic or active optical tracking when researchers want to extend scapular kinematic studies to more functional or athletic tasks. First, passive video-based motion capture typically has greater flexibility in capture volume. An electromagnetic tracking device, even equipped with a long-range transmitter, only works within a hemisphere with a 3 to 4.6 meter radius in front of the transmitter. Similarly, the active optical signals can be detected only in a pyramid-shaped capture volume within three meters in front of the receiver. Passive video-based motion capture, however, can have a much bigger capture volume by simply adjusting the camera setup.

Second, since reflective markers are wireless, the subject's movement is not constrained by wires. Electromagnetic sensors and active optical markers are all wired. Some wireless electromagnetic tracking systems are available, but they either have limited tracking capacity of no more than four sensors or are not connected to a computer but still wired to a backpack that must be carried by the subject. Constrained capture volume and wired attachments limit the use of electromagnetic and active optical tracking in multi-plane, large range-of-motion tasks.

Third, with the current camera resolution, passive video-based motion capture can track more than a hundred reflective markers, which is especially useful for tracking complex, multisegment movements. Active optical and electromagnetic tracking systems typically have limited data channels, limiting the numbers of segments that can be tracked. While some high-end electromagnetic tracking systems have more than 20 sensors, tracking multiple segments is almost impossible considering the wired nature of this technology.

Finally, passive video-based motion capture is capable of a much higher sampling rate. Currently, most models used for biomechanical research can work at over 1000Hz. An active optical tracking device works no faster than 60Hz. Most electromagnetic tracking devices operate with a maximum sampling rate of less than 150Hz, and only one commercially available model can work at 240Hz. Sampling rates below 150Hz are sufficient for daily functional tasks. Amasay et al.[55] used an electromagnetic tracking device with a 120Hz sampling rate to evaluate scapular kinematics in several functional tasks such as pulling a seat belt or reaching up to a shelf. But the applications of such devices in rapid movements could be limited. Konda et al.,[38] who studied the kinematics of the tennis serve, was the first using the new high-speed electromagnetic tracking device in athletic activities.

2.3.5.3 Potential applications

Overhead throwing is an example of a rapid, complex, multi-plane, large range-of-motion task. Kinematics during various overhead throwing tasks include, but are not limited to, baseball pitching,[4,6,31,99,100,172,173] football passing,[174] and cricket bowling.[175] Passive video-based motion capture was used in most of overhead throwing kinematic studies. While a 120Hz sampling rate was used sometimes,[4,9,27,175] sampling rates of 200 or 240Hz were used in most studies,[8,31-33,99,100] with rates as high as 500Hz occasionally.[176-178] Electromagnetic tracking was utilized at times in baseball pitching kinematic studies, with the sampling rate of no greater than 120Hz.[179]

Very few studies, however, have investigated scapular kinematics during overhead throwing. Meyer et al.[36] used an electromagnetic tracking device, with a low sampling rate of 100Hz, to investigate scapular kinematics during baseball/softball throwing. Although subjects had at least high school baseball or softball experience and were able to throw fast, Meyer et al. instructed the subjects to perform “low-velocity throws” as wire movement artifact was found during high-velocity throwing during pilot testing. Using passive video-based motion capture, Nakamura et al.[178] evaluated shoulder kinematics and kinetics during baseball pitching. While scapular kinematics was not studied specifically, the shoulder girdle was roughly modeled as a LCS using two thorax markers (the seventh cervical spinous process and jugular notch) and an acromion marker. Sharing an axis with the thorax segment, the shoulder girdle had only two degree-of-freedom in rotation. Miyashita et al.[37] may be the first to study scapular kinematics during baseball pitching using passive video-based motion capture. A stick with two reflective markers was attached to the acromion, forming a plane with the seventh cervical spinous process (C7). The C7 marker and one of the markers on the stick formed another plane with the eighth thoracic spinous process. With the two markers shared, only one degree-of-freedom of rotation can be determined by the two planes, which was the anterior/posterior tilt of the scapula. To the best knowledge of the author, three degree-of-freedom rotation of the scapula during maximum effort overhead throwing has not been studied by any researchers with any measurement device.

Recently, we validated the video-based motion analysis approach for measuring scapular kinematics described previously during simulated overhead throwing against the model-based RSA.[90] At the sampling rate of 150Hz, the Pearson’s product-moment correlation coefficient between the video-based motion analysis and the model-based RSA data ranged from 0.693 to 0.969 for all the three scapular orientation components: protraction/retraction, medial/lateral rotation, and anterior/posterior tilt. It is noteworthy that the Pearson's product-moment correlation coefficient in the simulated throwing task was comparable to the pace-controlled scaption task.[89] Soft tissue effect, threatening the validity of any skin-based measurement technique, was not further increased due to the rapid nature of the simulated throwing task. Although the velocity of the simulated throwing task was not as fast as throwing in sports activities, the proposed video-based motion analysis approach should be appropriate for evaluating scapular kinematics during high velocity throwing in overhead athletes.

2.3.6 Scapular kinematics during pace-controlled arm elevation tasks

2.3.6.1 Scapular kinematics in healthy subjects

Medial/lateral rotation is the earliest and most commonly studied component of scapular kinematics due to its large range of motion, ease of observation, and clinical relevance. One can plainly see this movement by watching a subject's back during arm elevation. With the compelling radiological evidence that emerged after 1930, clinicians and researchers gradually agreed that the scapula laterally rotates in a continuous and coordinated way while the arm moves into elevation. However, divergent and mixed opinions on the kinematic interaction between the humerus and scapula still exist.[180] Inman et al.[111] outlined the relationship that for every 15° of frontal plane arm elevation, 10°occurred at the glenohumeral joint and 5° occurred at the scapula; this 2:1 ratio of scapulohumeral rhythm, after a short "setting" phase about 30° of arm elevation, remained constant throughout the range of motion up to 170°. Michiels and Grevenstein[114] agreed upon a ratio of 2:1. But different ratios, ranging from 1.52 to 1.74:1, were also reported in other studies.[112,116,120] Bagg et al.[180] reported a ratio of 1.25 to 1.33:1 during dynamic testing. Borsa et al.,[124] using an inclinometer, reported an average of 18° scapular lateral rotation with 120° scaption, and an unconventional 5.1:1 ratio. Evidence also showed that between-subject variation in the scapulohumeral rhythm pattern may exist.[112,120] Bagg et al.[180] identified and categorized three different scapulohumeral rhythm patterns among subjects. It should be noted that all these values were from 2-D measurements, with the limitations of such assessments addressed in earlier sections.

Using 3-D electromagnetic tracking, Fung et al.[181] reported an in-vitro 2.1:1 ratio during scaption. In-vivo ratio of 1.7:1 for scaption was reported by McClure et al.[154] using bone pins and 3-D electromagnetic tracking. With the high variability in scapulohumeral rhythm ratios reported across multiple studies, it is likely that no single and definite value exists. In addition, as a ratio, this variable is affected by both the numerator and denominator. Choosing different start and end angles of arm elevation can largely affect the calculated results. Varying definitions of arm elevation angle may also affect the results.[154]

Recently, the focus of scapular kinematic studies has shifted away from the scapulohumeral rhythm ratio. The scapulohumeral rhythm ratio is not the only way to describe scapular medial/lateral rotation and medial/lateral rotation is not the only aspect of scapular kinematics. It is more straightforward to report the measured humeral and scapular orientations instead of calculating a ratio. Plus, with 3-D measurement methods available, measuring scapular kinematics in all the three degree-of-freedom provides a more complete view and allows for better understanding of how the scapula moves in relation to the arm.

Inconclusive results have been reported for protraction/retraction and anterior/posterior tilt. Ebaugh et al.[165] found posterior tilt and retraction until 90° of arm elevation, after which the amount of posterior tilt and retraction decreased. In another study, the same research group reported retraction throughout 120° arm elevation, and posterior tilt until 60° arm elevation.[163]

McClure et al.[41] identified posterior tilt throughout the range of motion, but protraction until 60° of scaption after which retraction started. Fayad et al.[164] found retraction and posterior tilt between 60° and 120° abduction. In healthy construction workers, a retraction-then-protraction pattern and continuing posterior tilt were found.[42] Healthy baseball players, on the other hand, demonstrated protraction instead of retraction throughout the range of motion.[49]

All these results were from 3-D dynamic electromagnetic tracking with skin-based sensors and the mixed results may be due to soft tissue effects. In 2001, Karduna et al.[35] developed a soft tissue correction factor for electromagnetic tracking, but it was for medial/lateral rotation only and not made available to public. Meskers et al.[158] published regression corrections for all three scapular orientation components in 2007, but the corrections were not used by other researcher groups. Static measurement with 3-D digitizers showed retraction and posterior tilt during scaption,[43,182,183] although protraction and anterior tilt may be involved in early and late abduction.[183] Data collected dynamically with bone pins demonstrated retraction and posterior tilt during abduction and scaption, and with considerably greater range of motion.[153,154] Bourne et al.[153] found some subjects showed protraction in early range of motion. It was likely that dynamic skin-based electromagnetic tracking distorted and underestimated both protraction/retraction and anterior/posterior tilt. This was especially notable when comparing the skin-based and bone-pin results from the same research group.[41,154]

In Appendix A.2, the scapular ranges of motion of healthy subjects in all three components of scapular kinematics reported in previous research are presented. Note that the interpretation must be conducted within the context of arm elevation range of motion and methods of measurement.

2.3.6.2 Effects of shoulder pathology

Traditional radiography has shown decreased scapular lateral rotation at 90° abduction in subacromial impingement patients' affected shoulders.[44] McClure et al.[41] reported that subacromial impingement patients showed a different scapular kinematic pattern during scaption. At 90° of scaption, patients had increased lateral rotation. Increased posterior tilt was also observed at 120° of scaption in patients. Ludewig et al.,[42] however, reported almost opposite findings. Compared with healthy construction workers, those who had subacromial impingement demonstrated decreased lateral rotation at 60° and decreased posterior tilt at 120° of scaption. In addition, while the scapula tilted posteriorly throughout the range of motion of 60° to 120° in healthy workers, workers with impingement demonstrated an anterior scapular tilt.

The contradictory results may be due to sampling difference, individual variance, and the method of attaching skin sensors. In McClure et al.,[41] the scapular sensor was attached to a plastic rig instead of directly over the acromion. Using the rig seemed to yield better accuracy in anterior/posterior tilt below 120° scaption, but worse accuracy in protraction/retraction.[35] Using an active optical digitizer, Hebert et al.[184] identified increased protraction in impingement patients at 110° flexion but no difference in abduction as compared to healthy subjects. Using a similar method, decreased posterior tilt was found at 90° and maximum scaption in symptomatic impingement patients as compared to asymptomatic patients and healthy subjects.[43]

In rotator cuff tear patients, increased scapular lateral rotation relative to humeral abduction was identified in full range-of-motion (ROM) or over 90° scaption with traditional radiography[113,185] and in mid ROM with electromagnetic tracking.[186] McCully et al.[187] used a suprascapular nerve block to simulate rotator cuff dysfunction in healthy subjects and found increased lateral rotation below 90° scaption and increased retraction beyond 70° scaption.

Studies involving symptomatic overhead athletes are limited. Inclinometer readings showed no significant decrease in lateral rotation in swimmers with impingement.[46] In baseball players with internal impingement, increased scapular posterior tilt was observed using 3-D dynamic electromagnetic tracking during scaption, compared with healthy baseball players.[49]

2.3.6.3 Effects of overhead athletic activities participation

Inclinometer measurements demonstrated that healthy pitchers had decreased scapular lateral rotation compared with position players.[51] Increased lateral rotation was identified in the throwing shoulder of baseball pitchers, compared with their non-throwing shoulder.[72] Older youth baseball players had decreased lateral rotation than younger youth players.[188] Three-dimensional dynamic electromagnetic tracking demonstrated increased lateral rotation and decreased retraction in baseball players throughout arm elevation.[54] Another study reported decreased retraction and posterior tilt in a group of overhead athletes at resting position.[53] In healthy baseball pitchers, isometric lower trapezius strength was strongly correlated to scapular lateral rotation at 90° and 120° scaption, but no significant correlation was found between isometric serratus anterior strength and lateral rotation.[88]

Inclinometer measurements also revealed that baseball players with greater glenohumeral internal rotation deficits (GIRD) had decreased scapular lateral rotation at 60° to 120° abduction in their dominant shoulders.[73] In addition, collegiate baseball players had increased GIRD, as well as decreased scapular lateral rotation at 90° and 120° abduction as compared to high school players.[189] Interestingly, these differences were observed in both their dominant and non-dominant shoulders.

2.4 GLENOHUMERAL RANGE OF MOTION CHANGES

Changes of glenohumeral ROM in baseball players have been well documented in a series of studies involving physical examinations. Baseball players have increased glenohumeral external rotation and decreased internal rotation in their throwing shoulders. This phenomenon was noticed as early as the late 1960s,[56] but did not receive much attention until the 1980s. Evidence has shown that such a change may be associated with the intensity and frequency of throwing as the external and internal rotation ROM changes were the greatest in pitchers, followed by catchers, outfielders, and infielders.[12] Typically, the throwing shoulder has greater external rotation and less internal rotation ROM than the non-throwing shoulder. Pitchers have greater external rotation and less internal rotation ROM than position players and baseball players have greater external rotation and less internal rotation ROM than non-throwing subjects. In high school pitchers, months participating in pitching activities per year were correlated with decreased internal rotation ROM ($r=0.292$, $p=0.005$).[87] A summary of previously published shoulder ROM measurements is available in Appendix A.3. In this section, the measurement methods of shoulder ROM are discussed. Then, a discussion regarding the mechanism of shoulder ROM changes, their implications for shoulder injuries, and their association with scapular kinematics follow.

2.4.1 Methodological considerations

Glenohumeral external and internal rotation can be measured in different arm positions. For baseball players, the measurements are typically performed with 90° shoulder abduction (90° arm elevation in the frontal plane), as this is the functional position of overhead throwing.

Measurements are usually performed with a universal goniometer, although sometimes an inclinometer is used.[93,190] The elbow joint is flexed to 90°, so the longitudinal axis of the forearm is approximately perpendicular to the axis of the elbow joint. One arm of the goniometer is aligned with the longitudinal axis of the forearm and the other arm of the goniometer remains perpendicular to the floor. Zero degree of external/internal rotation is defined as when the forearm is pointing up vertically. The ROM measurement can be either active or passive. Active ROM is measured with the subject rotating the forearm by himself, while passive ROM is measured with the tester rotating the subject's forearm. Most research studying baseball players utilizes passive ROM.

For an experienced clinician, passive ROM measurements of shoulder external/internal rotation are highly reliable. In a reliability study by Riddle et al.,[191]16 physical therapists with an average of 6.3 years of clinical experience demonstrated high intra-rater reliability for external and for internal rotation (ICC=0.99 and 0.94, respectively), even when blinded to the goniometer readings. Multiple studies using baseball pitchers or players agreed that the intra-rater reliability of such measurements is high, with ICCs ranging from 0.79 to 0.95 and from 0.81 to 0.99 for external and internal rotation, respectively.[70,71,192-195]

Inter-rater reliability can be another story. In Riddle et al.,[191] the 16 physical therapists demonstrated high inter-rater reliability (ICC=0.88) for external rotation, but moderate reliability (ICC=0.55) for internal rotation. Similarly, Dwelly et al.[190] reported inter-rater reliability of ICC=0.95 for external rotation and 0.76 for internal rotation with inclinometer measurements. The relatively lower inter-rater reliability was thought to be due to scapular movements. Typically, when the shoulder external/internal rotation ROM is evaluated, the movement of interest is at the glenohumeral joint only as it is relevant to common shoulder injuries in overhead athletes at the rotator cuff muscles or tendons, ligaments, capsule, or labrum. If the scapula is not stabilized, glenohumeral external rotation can be accompanied with scapular posterior tilt and depression along the thoracic wall. Similarly, glenohumeral internal rotation can be accompanied with scapular anterior tilt and elevation. When the subject is in supine position, the trunk pushes the scapula against the treatment table and the weight of the trunk minimizes posterior tilt and depression during glenohumeral external rotation. However, the trunk cannot limit anterior tilt and elevation during glenohumeral internal rotation. If a clinician wants to isolate glenohumeral internal rotation, he/she must manually stabilize the scapula. Not every clinician stabilizes the scapula and each clinician may have different technique of stabilization. In Riddle et al.,[191] there was no specific instruction given to the therapists on whether or how to stabilize the scapula, so the low inter-rater reliability of internal rotation ROM measurement is not surprising.

Some researchers have attempted to evaluate the effects of scapular stabilization on ROM measurements. Boon et al.[196] had two groups of therapists with more than 10 years of experience measure shoulder internal/external rotation in 50 high school athletes. Inter-rater reliability for external rotation was ICC=0.78 with glenohumeral stabilization (pressing the glenohumeral head down) and 0.84 without; for internal rotation, it was 0.38 with glenohumeral stabilization and 0.13 without. Awan et al.[197] evaluated three different techniques during internal rotation ROM measurement: no-stabilization, glenohumeral stabilization, and visual inspection of scapular movement in 56 high school athletes. The inter-rater reliability was 0.66, 0.52, and 0.51, respectively. Glenohumeral stabilization and visual inspection yielded similar readings. Wilk et al.[198] also evaluated three techniques: glenohumeral stabilization, scapular stabilization (holding the scapula by grasping the coracoid process and the spine of the scapula), and visual inspection.

The inter-rater reliability was 0.45, 0.43, and 0.47, respectively. These findings indicate that scapular stabilization does not necessarily increase the inter-rater reliability of these ROM measurements.

So far there is no consensus regarding how to stabilize the scapula during glenohumeral internal rotation ROM measurement. Wilk et al.[198] indicated that glenohumeral stabilization can restrict the normal arthrokinematics of the glenohumeral joint and recommended holding the coracoid process for stabilization. The use of different scapular stabilization techniques makes across-literature interpretation difficult. Moreover, researchers may not provide very detailed methodology and most of times the technique used cannot be fully understood with the published descriptions or illustrations.[198] Even if the technique used is known, individual variability across clinicians on how to perform the technique, such as the criteria of visual inspection, the amount of force applied to stabilize the scapular, and the amount of force applied to rotate the shoulder, can affect the measurement values. With the low inter-rater reliability being an issue, researchers should use the same clinician to measure all subjects and readers should be careful when comparing the results of studies from different research groups.

2.4.2 Mechanisms of ROM changes and potential shoulder injury

2.4.2.1 Anterior laxity theory

Multiple theories have been proposed to explain the external/internal rotation changes in overhead athletes. One proposed theory was that the increased external rotation was due to repetitive stretch of the ligamentous structures surrounding the glenohumeral joint.[11,12] Throwing involves shoulder external rotation to the end ROM. Motion analysis has demonstrated that the maximum shoulder external rotation reaches approximately 170° during baseball pitching.[10]

Although the ROM of 170° also includes the combination of scapular posterior tilt and spine hyperextension,[10] glenohumeral external rotation is still the primary component. Konda et al.[38] determined that for the maximum shoulder external rotation of 137.6° during a tennis serve, glenohumeral external rotation accounted for 118.1°, or 85.8%. Miyashita et al.[37] estimated that for the maximum shoulder external rotation of 144.2° during baseball pitching, glenohumeral external rotation accounted for 105.7°, or 73.3%. At the end ROM of external rotation, the inferior glenohumeral ligament and inferior capsule rotate anteriorly and are stretched to limit further external rotation and humeral head anterior shift.[199] With repetitive stretching, microtrauma can accumulate and lengthen these structures, reducing their capacity of limiting external rotation. As result of this lengthening, the ROM of glenohumeral external rotation can increase. It is believed that such change can be detrimental, as decreased anterior stability of the glenohumeral joint makes it harder to maintain the humeral head within the glenoid fossa, and may result in damage to the anterior labrum.[26]

Since the inferior glenohumeral ligament and capsule limit both glenohumeral external rotation and humeral head anterior shift, and if the theory of ligament stretch holds true, one may see increased anterior glenohumeral joint laxity together with increased glenohumeral external rotation. However, several studies failed to support this theory. Borsa et al.[200] found no difference in humeral head anterior translation between the throwing and non-throwing shoulders in professional pitchers and a weak correlation between the translation and glenohumeral external/internal rotation ROM. Ellenbecker et al.[201] also found no side-to-side translational difference in professional baseball pitchers. Crawford[202] did not find translational asymmetry in high school pitchers. Similarly, translation was found to be symmetric in several other studies with professional pitchers.[62,203] Friscia et al.[204] even noted less anterior laxity in high school baseball players as compared to non-throwing controls. These studies, however, shared a major limitation in that glenohumeral joint laxity was tested at the position of 60 to 90° external rotation. In mid ROM of glenohumeral external rotation, the dynamic muscular stabilizers instead of static ligamentous structures resist humeral head translation, as the ligament of interest (inferior glenohumeral ligament) has not rotated to the anterior position to assume the majority of the stress. In other words, these studies did not evaluate the proposed theory appropriately.

On the other hand, some studies may provide indirect evidence to support this theory. Mourtacos et al.[188] found greater glenohumeral external rotation ROM in older youth baseball players than younger players. Baeyens[140] used CT-scan bone models to compare the humeral position between handball players with and without minor anterior instability and found a more anteriorly-placed glenohumeral head in those players with minor instability. However, the reliability of glenohumeral translation measurement used in these studies is questionable.[61] In a study using another measurement approach claimed to be more accurate and reliable, pitchers' throwing shoulders had greater glenohumeral translation than their non-throwing shoulders and the both shoulders of positional players.[61] In addition, the measured anterior translation kept a moderate but significant linear relationship with glenohumeral external rotation ROM ($r=0.452$, $p<0.001$). From 90° to maximal external rotation, handball players with minor anterior instability demonstrated more anterior humeral head position than healthy players.[140] An in-vitro study showed that excessive external rotation resulted in lengthening of the anterior band of the inferior glenohumeral ligament.[60] One of the major limitations of the anterior laxity theory is that it can only explain the increased external rotation but not the decreased internal rotation.

2.4.2.2 Humeral retroversion theory

Another theory is that, with repetitive throwing, the torsion load applied to the humerus results in increased humeral retroversion. Humeral retroversion is the angle formed by the axis of the elbow joint and the axis through the center of the humeral head. Increased retroversion is equivalent to predisposed increase in glenohumeral external rotation and decrease in internal rotation, given that the orientation of the humeral head fixed. Kronberg et al.[205] evaluated the association between humeral retroversion and glenohumeral external/internal rotation ROM in 50 healthy non-throwing subjects. The average retroversion was 33° and 29° for the dominant and non-dominant shoulder, respectively. It was found that subjects with greater humeral retroversion typically had greater external rotation ROM.

The phenomenon that overhead athletes have increased humeral retroversion was first observed in the late 1990s in European handball players.[206] It is more precise to describe the “increased” humeral retroversion in overhead athletes as the “reduced decrease” of humeral retroversion. Cadaveric evidence suggested that humeral retroversion starts to decrease at birth.[207] The process peaks around 8 years of age and then slows down.

In the early 2000s, researchers started to report increased humeral retroversion in baseball players. Crockett et al.[62] studied 25 professional baseball pitchers and reported average humeral retroversion as 40° for the throwing shoulder and 23° for the non-throwing shoulder. Significant greater glenohumeral external rotation ROM and smaller internal rotation ROM were observed in the throwing shoulder. The control group in this study consisted of 25 healthy subjects; no differences in humeral retroversion (18° and 19°) and ROM between their dominant and non-dominant shoulder were observed. Osbahr et al.[63] conducted a similar study on 19 college baseball pitchers and reported 33° humeral retroversion for the throwing shoulder and 23° for the non-throwing shoulder. A significant correlation between humeral retroversion and external rotation ROM (r=0.864, p<0.001) was detected, but not between humeral retroversion and internal rotation ROM. Reagan et al.[64] measured the average humeral retroversion of 54 college baseball players as 36.6° and 26.0° for the throwing and non-throwing shoulder, respectively. Humeral retroversion was moderately correlated with increased external rotation ROM (r=0.432, p=0.001) and decreased internal rotation ROM (r=0.403, p=0.003).

Additional studies followed and demonstrated similar findings. Chant et al.[192] reported an average value of 44.9° humeral retroversion in 19 baseball players' throwing shoulders, significantly greater than the 34.3° retroversion in their non-throwing shoulders. In addition, humeral retroversion of the throwing shoulder was moderately correlated with increased external rotation ROM (r=0.548, p<0.001) and decreased internal rotation ROM (r=0.417, p=0.001). The control group showed no significant difference between the dominant and non-dominant shoulder, with values of 35.9° and 33.6°, respectively. Average humeral retroversion of 29.7° for the throwing shoulder and 18.5° for the non-throwing shoulder were reported by Tokish et al.[203] in Major League pitchers. Whiteley et al.[208] studied 247 subjects including baseball players, softball players, swimmers, and controls. Increased retroversion in the dominant shoulder was found in all overhead athletes. So far there has been solid evidence to support that baseball players have increased humeral retroversion in the throwing shoulder and that such a change is associated with increased glenohumeral external rotation ROM and decreased internal rotation ROM.

Although the theory of humeral retroversion is well-supported and considered valid, there has not been any longitudinal or cross-sectional evidence demonstrating the change of humeral retroversion in overhead athletes across ages. Yamamoto[209] studied 66 youth baseball players ranging in age from 9 to 14 years. It was found that the bicipital-forearm angle, which was claimed to be negatively related to humeral retroversion, increased with age. Years of pitching may or may not be associated with humeral retroversion.[63,210] Increased humeral retroversion is considered protective, as it reduces the true amount of the maximum external rotation at the glenohumeral joint, and therefore decreases the stretch at the anterior capsule, inferior glenohumeral ligament, and inferior capsule.

The theory of humeral retroversion, however, does not fully explain the ROM changes in overhead athletes. Considering that humeral retroversion decreases from birth onward and can only be slowed down by overhead athletic activities, the glenohumeral external rotation ROM should keep decreasing and the internal rotation ROM should keep increasing with years of overhead activity. This assumption is not consistent with observations. Kibler et al.[211] divided 39 elite tennis players into three age groups and found that both external and internal rotation ROM of the dominant shoulder decreased with age. A similar result was found in baseball players from 8 to 16 years old; furthermore, the difference of internal rotation ROM between the dominant and non-dominant shoulder increased with age.[212] These findings contradict the assumption that shoulder ROM should decrease with age in overhead athletes like in non-athletes[213] and that the ROM difference between shoulders should remain the same as age increases. Mair et al.[65] followed a group of 32 youth baseball players for six years and found significantly decreased internal rotation ROM in the throwing shoulder but not the non-throwing shoulder. Internal rotation ROM was also decreased in older youth baseball players as compared to younger players.[188] This evidence suggests that overhead athletic activities further decrease the internal rotation ROM, especially as age increases.

2.4.2.3 Posterior shoulder tightness theory

The third theory is that repetitive stretching during the deceleration phase of throwing thickens and tightens the posterior glenohumeral capsule, reducing the internal rotation ROM.[66] Arthroscopic evidence has indicated that throwers with increased deficit of internal rotation ROM had a thickened and severely contracted posterior band of the inferior glenohumeral ligament.[66] Because of this theory, another clinical measurement to evaluate overhead athletes' shoulders, posterior shoulder tightness (PST), has received more attention in recent years.

Posterior shoulder tightness is assessed by passively moving the shoulder into horizontal adduction with the shoulder abducted to 90° and the scapula stabilized to isolate glenohumeral joint movement. The first article to quantitatively describe PST was by Warner et al.[214] in 1990. Subjects were placed in supine position with 90° shoulder flexion and then the humerus was horizontally adducted across the chest until the scapula began to lift off the treatment table. The horizontal adduction angle was recorded at this moment, with greater angles indicating decreased PST. Warner et al.[214] failed to link this PST measurement to decreased internal rotation ROM. The reliability of this method was not evaluated. Likewise, it is difficult to identify the initiation of scapular movement without actually palpating the scapula, leaving the validity of this method questionable.[67]

Tyler et al.[67] presented another measurement method with the subject lying on his side. The clinician held the scapula and performed passive horizontal adduction to end ROM. The distance from the treatment table surface to the medial epicondyle of the humerus was measured, with greater distance indicating increased PST. This method has good intra-rater reliability of ICC=0.92 to 0.95, as well as good inter-rater reliability of 0.80.[67] The validity of this measurement was established as baseball pitchers demonstrated increased measurement value in the throwing shoulder, compared with the non-throwing shoulder and control subjects. Myers et al.[69] also reported good intra-rater reliability of ICC=0.85 to 0.94 measuring baseball players. This measurement method, however, was considered difficult to perform, as the subject must be placed at a position with the trunk perpendicular to the treatment table. Myers et al.[58] identified that subjects may have problems relaxing the periscapular muscles in this position. The measurement of distance instead of angle has a considerable limitation that, in addition to the trunk position, the reading can also be affected by the arm length of subject. As result, comparisons can be made between the throwing and non-throwing arm of a subject but not between groups unless arm length is controlled.

The supine measurement method presented by Warner et al.[215] was improved by adding manual scapular stabilization into the protocol. Several researchers assessed the reliability of this method with scapular stabilization. In a series of studies, Laudner et al.[93,193,216] reported good intra-rater reliability of ICC=0.84 to 0.93 and good inter-rater reliability of ICC=0.91. This method was also compared against Tyler's side-lying methods, and the conclusion was that the supine method with scapular stabilization had greater intra-rater (intra-session ICC=0.91 vs. 0.83, inter-session ICC=0.75 vs. 0.42) and inter-rater reliability (ICC=0.94 vs. 0.69).[58] This method is easier to perform, with fewer factors affecting the measurements, although it may be harder to control the resting position of the scapula.[67] The validity of this method was also established by comparing the throwing and non-throwing arm of overhead athletes.[58]

There is inconclusive evidence from both measurement methods regarding the association between PST and decreased internal rotation ROM in baseball players. In Tyler et al.,[67] side-lying measurement was significantly correlated to internal rotation ROM (r=-0.610, p=0.003). Myers et al.[58] found that internal rotation ROM was significantly correlated with supine PST (r=0.347, p=0.023), but not with side-lying PST (r=-0.164, p=0.295). Downer[72] found a weak negative correlation between side-lying PST and external or internal rotation ROM. Tokish et al.[203] also reported a weak and insignificant positive correlation between supine PST and internal rotation ROM. The theory of posterior tightness is supported by the fact that stretching of the posterior shoulder structures had an acute effect of reducing PST and increasing internal rotation ROM in college baseball players,[216] and regular participation in a stretching program resulted in an additional 20° of internal rotation ROM in professional pitchers.[217] This theory does not explain the acute loss of internal rotation ROM after pitching.[71]

2.4.3 Evidence linking the shoulder ROM changes to shoulder injuries

Change in external/internal rotation ROM has been associated with a wide spectrum of shoulder symptoms and injuries in overhead athletes. For example, it was proposed that extreme external rotation and accompanied anterior laxity results in a more anterior position of the humeral head and increases the contact between the posterior glenoid rim and the rotator cuff tendons, which can lead to internal impingement.[11] Anterior laxity may also result in damage to the anterior labrum.[26]

On the other hand, reduced internal rotation and increased PST has been associated with a superior posterior shift of the humeral head, which can further develop into a superior labrum anterior posterior (SLAP) lesion,[66] subacromial impingement,[68] or internal impingement.[69] Myers et al.[69] reported that baseball players with internal impingement had decreased glenohumeral internal rotation ROM and increased PST as compared to baseball players without internal impingement. Wilk et al.[12] presented the idea of “total motion concept” that a healthy throwing athlete should have the total glenohumeral ROM (i.e. the combination of external and internal rotation) comparable between the throwing and non-throwing shoulder. That is, the decrease in internal rotation should be equal to the increase in external rotation in the throwing shoulder. This concept implicitly assumes an ideal condition that the change of ROM is all attributed to humeral retroversion. In such a case, however, it is possible that there is no anterior laxity or posterior tightness effects or that the effects of these two factors cancel each other out. If the decrease of internal rotation surpasses the increase of external rotation, then the throwing athlete may be at increased risk of shoulder injury. Wilk et al.[70] found a shoulder injury odds ratio of 2.5 (p=0.03) for professional pitchers with total motion deficit over 5°. Similarly, Buckhart et al.[66] presented the idea of glenohumeral internal rotation deficit (GIRD), defined as the decrease of internal rotation at the throwing shoulder compared with the non-throwing shoulder. It was reported that asymptomatic professional pitchers had an average GIRD of 13° preseason and 16° postseason, while a group of 124 pitchers receiving surgery due to SLAP lesions all had severe GIRD, with an average at 53°. However, Wilk et al.[70] did not find GIRD over 20° as a significant risk factor of shoulder injury in professional pitchers.

2.4.4 Shoulder ROM changes and scapular kinematics

Limited research exists regarding the relationship between shoulder external/internal rotation ROM and scapular kinematics. Downer et al.[72] reported weak and non-significant correlations between scapular lateral rotation and glenohumeral external/internal rotation ROM in professional baseball players. Thomas et al.[73] noted that baseball players with GIRD greater than 15° had decreased scapular lateral rotation. It has also been reported that college baseball players had increased GIRD, increased total motion deficit, and decreased scapular lateral rotation when compared to high school baseball players.[189] The major limitation of these studies was that scapular kinematics was measured with an inclinometer, which only measures in 2-D, resulting in lateral rotation being the only measurable orientation component of scapular kinematics. However, lateral rotation is not the primary component of scapular kinematics during shoulder external/internal rotation. It was shown that scapular lateral rotation was positively correlated to shoulder flexion (i.e. arm elevation in the sagittal plane) ROM.[218] Based on the injury mechanisms reviewed earlier and anatomical rationales, scapular anterior/posterior tilt should be more relevant to external/internal rotation ROM. Increased PST has been correlated with a more anterior scapula position (r=0.707, p=0.001).[93] Three-dimensional measurement is necessary to investigate the association between anterior/posterior tilt and shoulder external/internal ROM.

2.5 SHOULDER STRENGTH CHARATERISTICS

Baseball throwing is a task with very high demands placed on the shoulder. Optimal strength of the muscles surrounding the shoulder is therefore critical for desired throwing performance and improper or imbalanced strength of the muscles may result in shoulder injuries. Kibler[3] categorized these muscles into three groups: scapular stabilizers, extrinsic muscles, and intrinsic muscles. Each group of muscles has its own role during baseball throwing. The scapula stabilizers originate on the thorax or vertebrae and insert on the medial, superior, or inferior borders of the scapula, and control the movement and position of the scapula throughout throwing. The extrinsic muscles include deltoid, teres major, latissimus dorsi, pectoralis major, biceps, and triceps. They perform the gross motor activities of the glenohumeral joint. The intrinsic muscles are the rotator cuff muscles, connecting the surface of the scapula and the humeral head to maintain the alignment between the bones, facilitating efficient movement.

There has been a considerable amount of research documenting the strength of these muscles in baseball players. The relationships between the strength and throwing performance, as well as shoulder pathologies, have also been investigated. The strength of these muscles were measured either isokinetically or isometrically. Each approach has its own advantages and disadvantages. In this section, shoulder strength measurement methods are reviewed, followed by the effects of shoulder strength on throwing performance and injury mechanisms.

2.5.1 Isokinetic strength

Isokinetic measurement is the technique used in many studies investigating baseball players' shoulder strength. The term isokinetic means constant velocity. During isokinetic testing, the subject's limb of interest is fixed to an attachment of the isokinetic dynamometer. The subject is asked to move the limb as fast and hard as possible while the velocity of movement remains constant, controlled by the dynamometer. In most cases, the angular velocity remains constant and the variable of measurement is moment. In some movements where the linear velocity of movement can be controlled, the variable of measurement is force.

2.5.1.1 Methodological considerations

When evaluating the isokinetic strength of baseball players, most studies focused on the shoulder external and internal rotators. Internal rotators are critical for performance, as shoulder internal rotation is the most rapid movement during throwing. On the other hand, external rotators are important as they are responsible for decelerating shoulder internal rotation. Isokinetic testing is known to be highly reliable. Perrin[219] established high test-retest reliability of isokinetic shoulder external/internal strength measurement (r=0.91 to 0.93 and 0.88 to 0.92 for external rotation, 0.86 to 0.92 and 0.74 to 0.84 for internal rotation, at 60 and 180°/s, respectively). Similar results were presented by Greenfield et al. [220] (r=0.81 for external and 0.92 for internal rotation). van Meeteren et al.[221] reported high test-retest reliability for external (ICC=0.87) and internal rotation (ICC=0.92). Hellwig and Perrin[222] reported good test-retest reliability of concentric (ICC=0.93 for external rotation and 0.90 for internal rotation) and eccentric (ICC=0.94 for both external and internal rotation) isokinetic shoulder strength measurements.

Isokinetic measurement was once very popular, as its dynamic nature was believed to be more functional. Such belief was then questioned, as human movement is rarely of a constant velocity. Isokinetic testing has two major limitations. First, it requires a more complex and time-consuming subject setup. In addition, due to its size and weight, an isokinetic dynamometer is not portable. These two factors limit its application in field study. Field studies are more practical if researchers want to have elite athletes as their subjects, due to scheduling difficulty. As result, the number of studies reporting elite baseball players' isokinetic strength has dramatically decreased from its peak between mid 1980s and mid 1990s. To the best knowledge of the author, the last isokinetic strength study in the United States with professional baseball players as subjects was published in 1997 by Sirota et al.[223] Since then there have been only three isokinetic studies using college baseball players.[224-226] With its difficulty of setup and low portability, the application of isokinetic testing in large-scale study, which is necessary to identify risk factors, is also limited.

Barring the limitations of isokinetic testing, its major advantage is that comparison across multiple studies is relatively easy. Although there are several factors that may affect the isokinetic measurement results, the testing protocols are generally standardized with little variability. Three protocol factors need to be acknowledged: testing position, type of muscle contraction, and movement velocity. For shoulder external/internal strength, the testing position can be either 90° arm abduction or neutral (arm adducted). In the work by Hinton[227] using high school pitchers, both of the testing positions were used. Testing in 90° abduction resulted in approximately 2.5 to 3.5Nm or 9 to 18% greater external rotation strength depending on movement velocity ($p<0.05$) but no significant difference in internal rotation strength was noted.

Isokinetic testing can be performed either concentrically or eccentrically. Testing eccentric external rotation strength may be more relevant than concentric, as shoulder external rotators eccentrically contract in the arm deceleration phase. Most studies used concentric protocols only, as eccentric isokinetic movement is not familiar to most subjects. Researchers may choose not to test elite athletes eccentrically, as eccentric exercise has been linked to significant amount of delayed onset muscle soreness.[228] Some studies tested baseball players both concentrically and eccentrically.[81,84,223,225]

As baseball throwing is a rapid movement, isokinetic movement velocity was typically set high. Usually, the velocities were set between 90 and 360°/s, with more than one velocity often used in a single study. Occasionally, a velocity of 450°/s or above was used,[82,224,226] although there is evidence indicating that testing reliability reduces as testing velocity increases.[219,229] These velocities are still not comparable to the peak shoulder internal rotation velocity of around 7000°/s seen during baseball pitching or maximal effort throwing.

With the protocol comparability, the studies accumulated so far have provided a solid base of knowledge regarding the external/internal rotation strength of baseball players, as summarized in Appendix A.4. Most of these studies focused on healthy baseball pitchers. The studies demonstrated some interesting findings even in these asymptomatic throwers, regarding the potential association among strength, performance, and injury mechanisms.

2.5.1.2 Shoulder internal rotators

Typically, the throwing shoulder of baseball players has greater internal rotation strength than their non-throwing shoulder. This is not surprising, as they are trained to throw hard and the internal rotators are supposed to be critical for hard-throwing. Professional pitchers demonstrated greater internal rotation strength than their position player counterparts.[57] However, the relationship between shoulder internal rotation strength and throwing velocity is not clear. Pedegana et al.[80] studied the relationship between strength and throwing velocity on eight professional baseball players. Shoulder internal rotation strength, surprisingly, was not significantly correlated with throwing velocity. With the data of 25 college pitchers, Mikesky et al.[81] also found no significant correlation between pitching velocity and internal rotation strength, whether tested concentrically or eccentrically. Similar results were reported by Chen[82] with 10 Taiwanese college pitchers. These results did not imply that shoulder internal rotation strength was not related to throwing velocity, but rather that there may be other factors that affect the relationship. On the other hand, Pawlowski[79] found that internal rotation strength at 240°/s was significantly correlated with pitch velocity ($r=0.81$, $p<0.05$).

2.5.1.3 Shoulder external rotators

Research investigating the strength of the shoulder external rotators revealed that baseball players have weaker external rotators in the throwing shoulder than the non-throwing shoulder. The relationship between external rotation strength and performance is conflicting, as shoulder external rotation strength has been reported to be positively ($r=0.87$, $p<0.05$),[79] negatively ($r=-0.53$, $p<0.01$),[80] or not correlated with throwing velocity.[81] Instead of throwing performance, weakened external rotators may provide greater insight about throwing-related injuries. The weakened external rotators may be the result of fatigue or micro-trauma accumulated in the external rotators with repetitive eccentric contraction, reducing the contractibility of these muscles.[2] This can be further supported by the fact that professional pitchers had weaker external rotators than professional position players.[57] Weaker external rotators in the throwing shoulder can also be observed with eccentric testing,[81,225] although one study found no significant difference.[223] As the external rotators, including the infraspinatus and teres minor, are also responsible for providing a posterior force to the humeral head, weakened external rotators may lead to humeral head anterior shift, resulting in anterior glenohumeral instability and further anterior structure damage.[2] Throwing performance may also be negatively impacted, as a thrower may not able to generate the desired acceleration with compromised deceleration capacity.

2.5.1.4 Balance between the external and internal rotators

In addition to strength, the balance between agonist and antagonist muscle strength is critical to sport performance and joint stability. Clinicians' believe that the ratio between shoulder external and internal rotation strength is a relevant measure when evaluating a baseball player's shoulder.[2] As the throwing shoulder has weaker external rotators and stronger internal rotators, the ratio would be lower than the non-throwing shoulder. Based on the isokinetic testing results on healthy baseball pitchers, the optimal ratio of the throwing shoulder should be 0.66 to 0.75.[2] If the ratio is higher than the recommended range, throwing performance may be compromised. On the other hand, if the ratio is lower than the recommendation, the risk of shoulder injury may considerably increase as the thrower could throw harder but with lesser deceleration capacity. Most studies reported the ratio within the recommended range except for Sirota et al.,[223] who reported an external/internal rotation strength ratio over 0.97. Sirota et al. attempted to attribute their numbers to better external rotation strength development in professional pitchers and slower testing velocity. However, this finding was not supported by other studies also using professional baseball subjects[57,228,230] and no studies supported that slower testing velocity resulted in higher external/internal strength ratio.

2.5.1.5 Shoulder isokinetic strength and injuries

With the limitations of isokinetic testing discussed earlier, there is no large-scale study using this technique for injury risk factor identification. There are, however, several studies comparing the strength characteristics between healthy and symptomatic baseball players. Hasegawa[83] compared a group of healthy Japanese college baseball players against a group of Japanese college baseball players with impingement symptoms. An insignificant trend of weaker external and internal rotation strength was observed with the impingement group. A similar trend was found by Tai[76] when comparing a group of healthy Taiwanese college baseball players against a group of Taiwanese college baseball players with shoulder pain. In contrast, a trend of increased shoulder strength was found in a group of Taiwanese college baseball players with throwing-related upper extremity injuries and external rotation strength at 240°/s was a significant risk factor.[84] To the best knowledge of the author, the only isokinetic study conducted on symptomatic baseball players in the United States was by Timm.[85] In that study, 241 high school pitchers diagnosed with impingement symptom were tested. Both external and internal rotation strength dropped rapidly with increased testing velocity in the impinged throwing shoulder. However, no healthy pitchers were recruited as controls and it is hard to conclude whether the decrease in strength was due to impingement. Although strength measurements always decrease with increased testing velocity, the measurements in healthy players do not drop as much as impinged players.

2.5.1.6 Shoulder isokinetic strength and scapular kinematics

The author is not aware of any studies investigating the relationship between isokinetic shoulder external/internal strength and scapular kinematics. The shoulder external and internal rotators are not directly responsible for scapular position. However, if these muscles are strong and tight, glenohumeral external/internal rotation ROM may be reduced. One may also surmise that strong and tight external/internal rotators are associated with a more retracted and posteriorly-tilted scapula during arm cocking and a more protracted and anteriorly-tilted scapula during arm deceleration. Isokinetic dynamometry can also be used to evaluate the strength of scapula protractors and retractors with constant-velocity linear movement; however this technique has not used in baseball players yet. Cools et al.[77] compared overhead athletes with impingement symptoms against their healthy counterparts. The impingement group demonstrated weaker isokinetic scapular protractor strength in the affected shoulder, compared to both the unaffected shoulder and the control group. The potential effects of weaker protractors on scapular kinematics were not investigated.

2.5.2 Isometric strength

Recently there has been an increase of published studies evaluating baseball players' isometric shoulder strength. The term isometric means constant length, indicating a static strength measurement without change in muscle length. An isokinetic dynamometer is also capable of measuring isometric strength, but typically isometric strength is measured with a hand-held dynamometer. With this technique, a baseball player is asked to place his limb of interest at a specific position and provide maximum effort against the force applied by the tester.

2.5.2.1 Methodological considerations

Isometric strength measurement using a hand-held dynamometer has the advantage of easy subject setup, fast measurement, and portable equipment that can be easily carried with the tester. This technique also allows more flexibility with testing positions. Therefore, this technique is suitable for large-scale and field studies. In addition, at certain testing positions, a single muscle can be isolated with the minimal contribution from synergist muscles, allowing clinicians to identify potential sites of pathology.

On the other hand, isometric strength measurement also has its disadvantages. First, the measurement is made at a specific joint position and strength throughout the range of motion cannot be identified with a single test. In addition, greater flexibility of measurement protocols also indicates more variability. The measurement technique with a hand-held dynamometer was derived from the manual muscle testing technique. However, there may exist more than one position for testing a single muscle or muscle group.[231] For example, shoulder external rotation strength may be tested with the subject seated with the arm adducted to 90° or prone with the arm abducted to 90°. The median difference in measurement between these two positions can be about 10kg.[21] Even if the positioning of the subject is the same, the tester may place the hand-held dynamometer at a different position, producing different results due to a change in length of the moment arm. Within a subject, when the subject is placed in the testing position, the moment arm between the muscle and the bone remains the same. But the magnitude of force applied by the tester depends on the point at which the force is applied. If the point of application is more toward the fulcrum, then the moment arm is shorter and the tester must generate greater force to balance the moment generated by the subject and vice versa. During an isometric strength test, a hand-held dynamometer measures the force applied to it, which is equal to the force the tester exerts on it. That is, depending on the position a tester chooses, the reading can be different even if the subject always generates the same moment. Most studies reported baseball players' strength directly with the measured force values and these values must be interpreted in the context of dynamometer position. Some researchers would convert the force measurement to moment by measuring the moment arm between the dynamometer and the joint center.[59,83] With all of the variability due to different subject testing position and dynamometer placement position, comparisons among studies can be difficult. It is not uncommon that the measured strength of a given muscle varies considerably across multiple studies (Appendix A.5 and A.6).

Both muscle groups and single muscles of baseball players have been evaluated in previous studies. For muscle groups, the strength of shoulder external and internal rotators as well as the scapular elevators, depressors, protractors, and retractors have been evaluated (Appendix A.5). For single muscles, the upper trapezius, middle trapezius, lower trapezius, rhomboids, serratus anterior, and supraspinatus have been tested (Appendix A.6).

2.5.2.2 Shoulder external and internal rotators

The roles of the shoulder external and internal rotators have been discussed in earlier sections. Mullaney et al.[78] found significant fatigue effect in the internal rotators after a pitching event. Hand-held isometric dynamometry on external/internal rotation strength can be highly reliable with a between-day correlation of $r=0.986$ ($p<0.005$).[232] Intra-rater reliability was reported as ICC=0.96 for external rotators and 0.96 for internal rotators.[195]

Isometric strength of shoulder external and internal rotators has been associated with shoulder pain or injuries in baseball players. Trakis et al.[86] found that high school pitchers with prior shoulder pain had increased imbalance of internal rotator strength between the throwing and non-throwing shoulders. Byram et al.[21] prospectively followed 144 professional baseball pitchers for five years and concluded that weaker external rotators were significantly associated with severe throwing-related injuries that required surgery. In addition, there was a trend that decreased external/internal rotation strength ratio was associated with throwing related injury ($p=0.051$). Magnusson et al.[59] divided 47 asymptomatic professional pitchers into three groups: no past history of shoulder injury, a history of shoulder injury that requires conservative intervention, and a history of shoulder injury that requires surgical intervention. There was no significant difference in external or internal strength among these three groups.

Isometric external rotator strength was also linked to throwing volume. Kaplan et al.[87] compared 50 high school pitchers living in a warmer area (Arizona and California) and another 50 high school pitchers living in a colder area (Minnesota). Pitchers living in the warmer area spent an average of 9 months per year in pitching activities, while those living in the colder area spent 6 months. The warmer group demonstrated significantly decreased external rotator strength and external/internal rotation strength ratio than the colder group. Additionally, in the warmer group, the months participating in pitching activities was correlated to decreased external rotator strength ($r=0.292$, $p=0.05$).

2.5.2.3 Scapular stabilizers

The scapular elevators, depressors, protractors, and retractors are the scapular stabilizer muscles described by Kibler[3]. These muscles play a vital role of stabilizing and maintaining a proper position of the scapular during throwing.[2] Throwing intensity and volume may be associated with the strength of the scapular stabilizers. By evaluating the strength of 112 professional baseball players, Wilk et al.[75] found pitchers and catchers had stronger protractors and elevators than other position players. Except for infielders, all baseball players had stronger depressors on the throwing side.[2] It is believed that the agonist-antagonist strength ratios among these muscles are important to the stability and mobility of the scapula as well as symptom-free function of the throwing shoulder.[2]

The isometric strength of the scapular stabilizers, including the upper trapezius, middle trapezius, lower trapezius, rhomboids, and serratus anterior, were also evaluated at the level of individual muscles. The upper trapezius is a scapular elevator; the middle trapezius and rhomboids are scapular retractors; the lower trapezius is a scapular depressor; and the serratus anterior is a scapular protractor. In addition to these linear movements, these muscles form a force couple for smooth and balanced scapular rotation during overhead activities. In a study based on 172 healthy, athletic subjects, the intra-rater reliability of isometric strength measurement on these muscles ranged from ICC=0.54 for the middle trapezius to 0.82 for rhomboids, and the inter-rater reliability ranged from 0.56 for the upper trapezius to 0.79 for rhomboids.[233] Isometric strength measurement for the upper trapezius could be difficult as a clinician must resist the “shrugging” movement of the seated subject with his hands pushing down at the acromion.[231] With limited moment arm in this position it is hard to produce enough force to resist the movement. An isokinetic dynamometer with a closed-chain attachment can be set at the isometric mode for measuring the isometric strength of the upper trapezius. The reliability has not been evaluated, although the machine should be capable of resisting the movement and provide more reliable measurement. In another study with 40 subjects with shoulder pain or functional loss, the inter-trial reliability was reported as ICC=0.93 to 0.95 for upper, middle, lower trapezius and serratus anterior and the inter-day reliability for these muscles was 0.89 to 0.96.[234] Donatelli et al.[195] measured 39 professional pitchers, and reported high intra-rater reliability of ICC=0.93 for middle trapezius and 0.89 for lower trapezius, but low intra-rater reliability for serratus anterior of ICC=0.27. The reliability of the isometric strength measurement for the serratus anterior needs further evaluation.

Significant fatigue effect of middle trapezius was identified in college and professional baseball pitchers after a pitching event.[78] Tai[76] identified weaker lower trapezius in Taiwanese college baseball players with shoulder pain, compared with their non-symptomatic counterparts. The isometric strength of lower trapezius was found significantly correlated to scapular lateral rotation at 90° and 120° scaption (r=0.728 and 0.748, p=0.001) in professional pitchers.[88] However, the relationship between the strength of these muscles and scapular kinematics was not investigated.

2.5.2.4 Supraspinatus

The supraspinatus is the muscle involved in subacromial and internal impingement symptoms. Its isometric strength can be measured with a hand-held dynamometer with high reliability (ICC=0.96) in professional pitchers.[195] Magnusson et al.[59] detected significantly weaker supraspinatus of professional baseball pitchers' throwing shoulders, as compared with the non-throwing shoulder and healthy controls. It was interpreted that this phenomenon could be attributed to functional fatigue or subclinical pathology. Mullaney et al.[78] also detected weaker supraspinatus at the throwing shoulder of baseball pitchers, but no significant fatigue effect was found after a pitching event. It is possible that the decreased supraspinatus strength is the result of micro-damage resulting from contact between the supraspinatus and scapular structures, and therefore can be a precursor of clinical impingement symptoms. This hypothesis was supported by a prospective study following 144 professional baseball pitchers for five years.[21] Decreased supraspinatus strength was associated with increased risk of shoulder injuries (p=0.031) and severe shoulder injuries that required surgical intervention (p=0.038). If such hypothesis holds true, one may further expect a weaker supraspinatus can result in altered humeral head position relative to the glenoid, and the scapular kinematics is altered to avoid an impinged position. The relationship between supraspinatus strength and scapular kinematics, however, was not investigated.

2.6 SUMMARY

Baseball throwing requires coordinated movements of the humerus and the scapula.[3] Every throw places high amounts of kinetic load on the shoulder.[92] Due to the high number of repetitions of throwing that occurs during baseball practices and competitions, there is a high potential for shoulder injury in baseball players.[14,15,18]

With multiple potential factors that may contribute to shoulder injury in baseball players, identification of the injury mechanisms is difficult. Several scapular kinematic characteristics during pace-controlled arm movements have been linked to shoulder pathologies.[41,42,49] However, it is unclear whether such scapular kinematic characteristics also are present during baseball throwing, as limited studies regarding scapular kinematics during overhead sport activities are available due to methodological concerns.[36-38] Glenohumeral ROM and shoulder strength have been linked to shoulder injuries in baseball players.[21,70] Some evidence suggested that glenohumeral ROM and shoulder strength may be associated scapular kinematics during pace-controlled arm movements.[88,93] It is unknown whether glenohumeral ROM and shoulder strength also are related to scapular kinematics during throwing.

As of now, the three degrees of freedom scapular kinematics during maximum effort baseball throwing has not been investigated. A new passive video-based motion capture approach, which has been validated against a gold standard,[89,90] may provide valid measurement of scapular kinematics during maximum effort baseball throwing. With this new approach, the purpose of the current study was to investigate the relationships between scapular kinematics during pace-controlled arm movements, glenohumeral ROM, shoulder strength, and scapular kinematics during maximum effort baseball throwing. Understanding scapular kinematics during maximum effort baseball throwing may facilitate further understanding of shoulder injury mechanisms in baseball players. Identifying the potential relationship between scapular kinematics during pace-controlled arm movements and maximum effort baseball throwing may establish pace-controlled arm movements as a screening tool for evaluating the risk of shoulder injuries in baseball players. Finally, discovering the possible association among glenohumeral ROM, shoulder strength, and scapular kinematics during maximum effort baseball throwing may assist the development of shoulder stretching and strength training programs in baseball players for improved performance and reduced risk of shoulder injury.

3.0 METHODOLOGY

3.1 DESIGN OF THE STUDY AND VARIABLES OF INTEREST

This was a descriptive, correlational laboratory study. Variables of interest that were measured in the current study are presented in Table 1. Scapular kinematics and humeral kinematics at selected events were presented as specified in Specific Aim 1. Correlations were calculated among these variables as specified in Specific Aims 2 through 7.

Table 1. Variables of interest

Measure	Variables	
Scapular Kinematics during Throwing	Scapular protraction/retraction (°) Scapular medial/lateral rotation (°) Scapular anterior/posterior tilt (°)	Values measured at 9 events of throwing: SFC, MER, REL, MIR, maximum shoulder anterior, posterior, superior, inferior, and compression force
Humeral Kinematics during Throwing	Humeral external rotation (°)	Value measured at maximum shoulder external rotation
Scapular Kinematics during Pace-Controlled Arm Movements	Scapular protraction/retraction (°) Scapular medial/lateral rotation (°) Scapular anterior/posterior tilt (°)	Values measured during scaption at the same arm elevation angles of SFC and the occurrence of maximum shoulder compression force of throwing
Shoulder Kinetics during Throwing	Maximum shoulder anterior force (N) Maximum shoulder posterior force (N) Maximum shoulder superior force (N) Maximum shoulder inferior force (N) Maximum shoulder compression force (N)	
ROM	Glenohumeral external rotation ROM (°) Glenohumeral internal rotation ROM (°) Posterior shoulder tightness – Supine (°)	
Isokinetic Strength	Shoulder external rotation peak moment at 180° /s (Nm) Shoulder internal rotation peak moment at 180° /s (Nm) External / Internal Strength Ratio	

Table 1. (Continued)

Measure	Variables
Isometric Strength	Upper trapezius peak force (N) Middle trapezius peak force (N) Lower trapezius peak force (N) Rhomboids peak force (N) Serratus anterior peak force (N) Supraspinatus peak force (N)

All data were collected in the Neuromuscular Research Laboratory, University of Pittsburgh. Subjects visited the facility for a single 2-hour data collection session that included written informed consent followed by completion of an injury history questionnaire, ROM testing, strength testing, as well as throwing and arm scaption capture.

3.2 SUBJECTS

A total of 35 subjects with organized baseball experience and who remained active in organized baseball or softball were recruited for this study. Organized baseball or softball was operationally defined as baseball teams with scheduled practices and games. Subject provided written informed consent prior to participation in this study in accordance with the University of Pittsburgh Institutional Review Board. Eligibility was determined by the following inclusion and exclusion criteria. Exclusion criteria were defined to minimize potential confounding factors that may distort the associations between the variables of interest.

3.2.1 Inclusion criteria

- 18 to 40 years old, inclusive
- Organized baseball experience
- Playing baseball or softball at recreational level or above within the past one year

3.2.2 Exclusion criteria

- Current musculoskeletal injuries preventing the potential subject from performing maximum effort baseball throwing
- Current musculoskeletal injuries preventing the potential subject from receiving passive maximum glenohumeral range-of-motion measurements
- Current musculoskeletal injuries preventing the potential subject from performing maximum effort muscle exertion for strength measurements
- Previous or current history of neurological disorder
- Previous history of throwing shoulder fracture, surgery, injection, injuries that interfered daily activities for more than two weeks, and injuries that required more than two weeks off from baseball following the order of physicians or other health care professionals
- Glenohumeral internal rotation deficit (GIRD) of more than 50° in the throwing arm

3.2.3 Power analysis

In Table 2, the subject numbers needed to reach the power of 0.80 at alpha=0.05 with different levels of expected correlation are presented. By assuming that a correlation between scapular kinematics and strength lower than r=0.20 would be insignificant, this r was set as the threshold value. Based on these criteria, 35 subjects are needed to reach the power of 0.80 at 2-sided alpha=0.05 if a correlation of r=0.60 is expected.

Table 2. Subject numbers needed to reach the expected power

		Expected Correlation								
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Reference Correlation	0.0	782	193	84	**46**	**29**	**19**	**13**	**9**	**6**
	0.1		751	182	78	**41**	**25**	**16**	**11**	**7**
	0.2			691	163	68	**35**	**20**	**12**	**8**
	0.3				605	139	56	**28**	**15**	**9**
	0.4					500	111	**43**	**20**	**10**
	0.5						382	80	**29**	**12**
	0.6							262	51	**16**
	0.7								149	24
	0.8									59

3.3 INSTRUMENTATION

In this study, kinematic, passive ROM, and strength were the variables of interest. Shoulder and scapula kinematics during pace-controlled scaption and during maximum effort baseball throwing were tracked with a passive video-based motion capture system with eight synchronized high-speed infrared cameras (Nexus software and MX13 cameras, Vicon, Centennial, CO). This system is designed to capture 3-D coordinate data. Each camera is equipped with an infrared light emitter module, generating infrared light when operating. Infrared light is reflected by reflective markers attached to the human body. The cameras capture the trajectories of reflective markers in the capture volume and the 3-D coordinates of a reflective marker can be reconstructed, provided that the marker is seen by at least two cameras. Six of the eight cameras were fixed on the walls and were aimed down toward the center of the capture volume (Figure 3). A five-point wand was used to establish the global coordinate system (GCS), with the X axis pointing backward with respect to a subject facing the target net, the Y axis pointing right, and the Z axis pointing upward. Two additional cameras were placed at the right side for right-handed subjects and left side for left-handed subjects to minimize view obstruction of subjects' arms. In the current study, the sampling frequency of this system was set at 240Hz for maximum effort throwing. In the facility where this study was conducted, the accuracy of this system was determined to be 0.39mm and 0.08°.

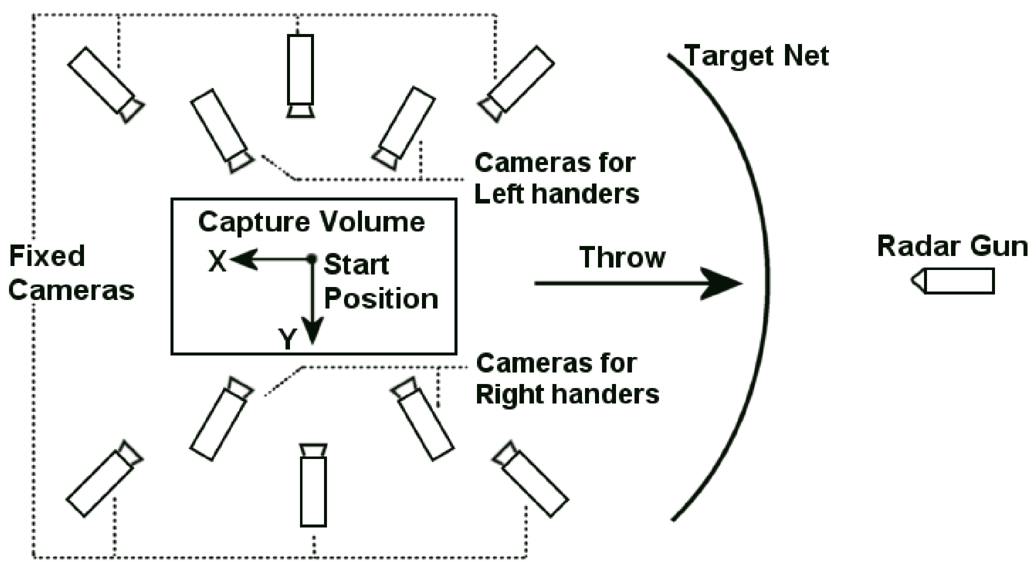

Figure 3. Motion capture setting

A digital inclinometer (Saunders Digital Inclinometer, Saunders Group, Inc., Chaska, MN) was used for passive ROM measurements. The inclination of the device is measured with respect to the direction of gravity, with 1° resolution. An isokinetic dynamometer (System III, Biodex, Shirley, NY) and a hand-held dynamometer (Lafayette Manual Muscle Test System, Lafayette Instrument Company, Lafayette, IN) were used for strength measurements. The isokinetic dynamometer is capable of measuring isokinetic and isometric strength. In the isokinetic mode, it is capable of concentric (up to 680Nm) and eccentric (up to 540Nm) measurements with 1Nm resolution and has a testing speed range of 0-500°/s, as controlled with custom software from the manufacturer. In this study, the concentric mode was used for shoulder internal/external rotation strength testing and the isometric mode was used for measuring the strength of the upper trapezius. The upper end of the measurement range of the hand-held dynamometer is 136kg with 0.2kg resolution. The hand-held dynamometer was used to measure the isometric strength of the middle trapezius, lower trapezius, rhomboids, supraspinatus, and serratus anterior. The reliability, accuracy, and validity of these devices or comparable devices using the same or similar equipment reported previously were discussed in Chapter 2.

In addition to the variables of interest, several parameters, including body height and weight, anthropometric measurements, and ball velocity, were required for data processing. Body height was measured with a wall stadiometer and body weight was measured with a digital scale. Anthropometric measurements were made with a tape measure and an anthropometer (Model 01291, Lafayette Instrument Company, Lafayette, IN). Ball velocity was measured with a radar gun (Stalker Sport, Applied Concepts, Inc., Plano, TX). Finally, statistical analyses were performed with a commercially-available statistics software package (Matlab Statistics Toolbox, Mathworks, Natick, MA).

3.4 TESTING PROCEDURES

3.4.1 Subject preparation

Written informed consent was obtained prior to participation in accordance with the University's Institutional Review Board. Subjects then filled out a questionnaire to determine their eligibility for the study as defined by the inclusion and exclusion criteria. The questionnaire also determined the subjects' history of previous shoulder pain or injury. Ineligible subjects were dismissed and eligible subjects underwent the procedures described below.

The testing procedures were performed in the following order: passive glenohumeral ROM measurements, strength measurements, followed by passive video-based motion capture (pace-controlled scaption and maximum effort baseball throwing). Glenohumeral ROM and strength were measured before the throwing session as their results can change after maximum effort throwing.[78,194]

After strength measurements, each subject first was asked to change into spandex shorts (plus a spandex sport bra for female subjects). Body height and weight measurements, followed by anthropometric measurements (Table 3), were then obtained. Reflective markers of 1.4cm diameter were attached to 28 anatomical landmarks of the subject's body (Table 4). Two scapular triads were attached to the flat portion of the acromion. The triad is a thin, triangular wooden plate with each edge length equal to approximately 5cm. Three reflective markers of 0.9cm diameter are attached to the three corners of the triad (Figure 4). The triad would move with the scapula and the movement can be captured by the passive video-based motion capture system.

After all the markers were attached to the subject's body, static motion capture of the subject was collected. The subject was instructed to stand up straight with both arms relaxed and adducted. After the capture, three scapular reference markers (the acromial angle, the root of the spine of scapula, and inferior angle of each scapula) were removed.

Table 3. Anthropometric measurements

Anthropometric Measurement	Definition	Measured With
Arm Length	Distance between the estimated center of humeral head and estimated center of radiocarpal joint	Tape Measure
Shoulder Offset	Distance between the acromioclavicular joint to the estimated center of humeral head	Anthropometer
Elbow Width	Distance between the medial and lateral humeral epicondyles	Anthropometer
Wrist Width	Distance between the ulnar styloid process and radial styloid process	Anthropometer
Hand Thickness	Thickness of the hand measured at the 3rd metacarpophalangeal joint	Anthropometer
Leg Length	Distance between the anterior superior iliac spine and medial malleolus	Tape Measure
Knee Width	Distance between the medial and lateral femoral epicondyles	Anthropometer
Ankle Width	Distance between the medial and lateral malleoli	Anthropometer

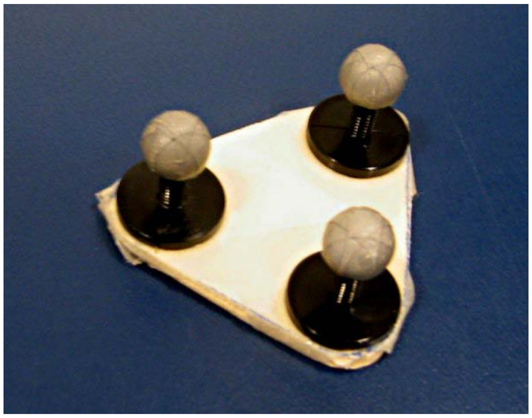

Figure 4. The triad for scapular movement tracking

Table 4. Anatomical landmarks for reflective marker placement

Body Segments	Anatomical Landmarks
Head (4 markers)	Left Anterior Head Right Anterior Head Left Posterior Head Right Posterior Head
Thorax (4 markers)	The Spinous Process of the 7th Cervical Vertebra (C7) The Spinous Process of the 8th Thoracic Vertebra (T8) Jugular Notch (Incisura Jugularis, IJ) Xiphoid Process (Processus Xiphoideus, PX)
Scapula (4 markers)	Acromioclavicular Joint Acromial Angle (Angulus Acromalis, AA) Root of the Spine of Scapula (Trigonum Spinae Scapulae, TS) Inferior Angle (Angulus Inferior, AI)
Arms and Hands (5 markers for each arm, 10 markers total)	Medial Humeral Epicondyle (EM) Lateral Humeral Epicondyle (EL) Ulnar Styloid Process (US) Radial Styloid Process (RS) The 3rd Metacarpophalangeal Joint
Pelvis (4 markers)	Left Anterior Superior Iliac Spine Right Anterior Superior Iliac Spine Left Posterior Superior Iliac Spine Right Posterior Superior Iliac Spine
Foot (2 markers)	Subtalar Joint The 3rd Metatarsophalangeal Joint

3.4.2 Passive glenohumeral range of motion measurements

The subject was asked to lie down on a treatment table in the supine position for passive ROM testing. Maximum external rotation, maximum internal rotation, and posterior shoulder tightness were measured on the dominant limb. Due to the lower inter-rater reliability of this testing,[198] all subjects were evaluated by the same tester. During the external rotation testing, a certified athletic trainer moved the subject's dominant arm to end ROM when capsular end feel was perceived, and an assistant aligned the inclinometer to the longitudinal axis of the forearm and recorded the angle between the forearm and the vertical plane from the lateral aspect of the shoulder.[70] For the internal rotation testing, the certified athletic trainer moved the subject's dominant arm and stabilized the subject's scapula by grasping the coracoid process and the spine of the scapula, and determined the end range of motion based on the combination of end feel, palpation of the coracoid process, and visualization of compensatory movement.[70] This technique of scapula stabilization is of higher reliability and has less restriction on normal arthokinematics.[198] The assistant aligned the inclinometer and measure the angle in the same way as in the external rotation measurement. For the posterior shoulder tightness testing, the certified athletic trainer stood beside the treatment table of the shoulder being tested, stabilized the scapula with one hand and passively moved the subject's arm into horizontal adduction with the other hand.[58] The assistant aligned the inclinometer to measure the angle between the longitudinal axis of the arm and the horizontal plane from the superior aspect of the shoulder. For each ROM, three measurements were made.

3.4.3 Isokinetic strength measurements

The subject was stabilized on the seat of the isokinetic dynamometer for isokinetic shoulder external/internal rotation strength testing (Figure 5). Perrin's recommendations for testing procedures were followed to improve the reliability of testing.[219] Belts were tightened across the subject's chest and the thighs to stabilize the subject. The concentric strength of the external rotators and internal rotators were evaluated in 90° of external rotation and of abduction at the movement velocity of 180°/s. The longitudinal axis of the humerus was aligned to the axis of rotation with the dynamometer. Gravity correction of limb weight was applied. For each movement, the subject first performed three reciprocal external/internal rotation repetitions with 50% effort, and another three repetitions with maximum effort. Then a one-minute rest was given and the test trial of five repetitions with maximum effort was performed and recorded. The subject was instructed to move the arm back and forth as hard and fast as possible for the maximum effort repetitions.

Figure 5. Isokinetic strength measurements

3.4.4 Isometric strength measurements

The subject remained seated on the isokinetic dynamometer chair for the isometric upper trapezius strength testing (Figure 6). A closed chain attachment was fixed to the dynamometer in a vertical position (pointing down). The subject was instructed to grab the handgrip of the attachment with the shoulder in a slightly forward flexed position so that the arm was parallel to the torso and elbow extended. A single test trial consisting of three 5 second contractions with a 50 second rest between each contraction was conducted. During each contraction, the subject was instructed to maximally pull the handgrip up by shrugging the shoulder without flexing the elbow.

Figure 6. Isometric upper trapezius strength measurement

All muscles strengths measured with handheld dynamometry involved three 5 second contractions with a 50 second rest between each contraction. "Make" instead of "break" tests were chosen due to higher reliability.[235] The strength of the middle trapezius, rhomboids, and lower trapezius were measured in the prone position following the standard manual muscle testing guide by Kendall et al.[231] The measurements were performed by a single certified athletic trainer. For the middle trapezius, the subject was asked to abduct the arm to 90° with the thumb pointing toward the ceiling and the cervical spine in a neutral position. For the rhomboids, the arm was abducted to approximately 90° with the thumb pointing toward the floor and the cervical spine in a neutral position. For the lower trapezius, the arm was abducted to approximately 145° with the thumb pointing toward the ceiling and the head was rotated to the non-test side. The elbow remained extended for the duration of each test. For each muscle, the subject was asked to exert maximum effort against the downward force applied by the tester through the handheld dynamometer placed at the distal end of the subject's forearm.

Then the subject changed to the supine position for measuring the strength of the serratus anterior.[231] The subject was asked to flex the shoulder to 90° with the elbow extended. The mid-range of shoulder protraction/retraction ROM was identified and, from this position, the subject pushed the arm up toward the ceiling with maximum effort, keeping the elbow straight, against the downward force applied by the tester through the handheld dynamometer placed at the top of the subject's fist.

Finally, the subject changed to the sitting position for supraspinatus strength measurement. The subject was asked to move the arm to 90° scaption with the thumb pointing toward the floor.[195] The subject pushed the arm up toward the ceiling with maximum effort against the downward force applied by the tester through the handheld dynamometer placed at the distal end of the subject's forearm.

3.4.5 Pace-controlled scaption

The subject was instructed to perform pace-controlled scaption (i.e. arm elevation in the scapular plane). The scapular plane is defined as 30° anterior from the frontal plane. Scaption was chosen due to the availability of previous research on impingement patients and baseball players.[41,42,49]

Two plastic guides were used to ensure that the movement was performed in the scapular plane (Figure 7). The pace of movement was set by a metronome at 2 seconds per repetition or 0.5Hz. The subject was asked to perform the movement repeatedly following the metronome so that he/she was at the minimum or maximum ROM on each beat. The subject was encouraged to reach maximum active ROM during the testing. Once the researcher determined that the subject's movement was smooth and on pace, five full repetitions of the movement were recorded with the passive video-based motion capture system. When the subject did not perform the movement to the maximum active ROM, did not perform the movement following the metronome, or there were markers missing and could not be interpolated, the researcher would recollect the data until satisfactory data were collected.

Figure 7. Pace-controlled scaption

3.4.6 Maximum Effort Baseball Throwing

The subject first underwent a standardized warm up protocol for the maximum effort baseball throwing task. The subject ran on a treadmill at a self-selected pace for three minutes to warm up the body. The subject performed seven resistance-tube exercises designed to warm up the rotator cuff, the primary humeral movers and the scapular stabilizers.[236] The exercises included humeral flexion, humeral extension, humeral external rotation at 90° of abduction, throwing acceleration, throwing deceleration, low scapular rows, and scapular punch. Five repetitions were performed for each exercise under the instruction and supervision of a certified athletic trainer. Finally, the subject threw a baseball toward the target net at 25%, 50%, 75%, and maximum effort. Five throws were performed at each effort level.

After warm up, the subject was asked to perform 15 maximum effort throws toward the target net with an official-sized baseball (Figure 8). Of the 15 throws, only the middle five throws were analyzed. The subject was instructed to stand at a start position near the center of the capture volume, make a stride, and throw the ball. No hops during the approach were allowed. The throwing movements were recorded with the passive video-based motion capture system. The ball velocity was recorded with the radar gun. The data were examined by the researcher after each throw. When there were markers missing and could not be interpolated, the trial would be recollected.

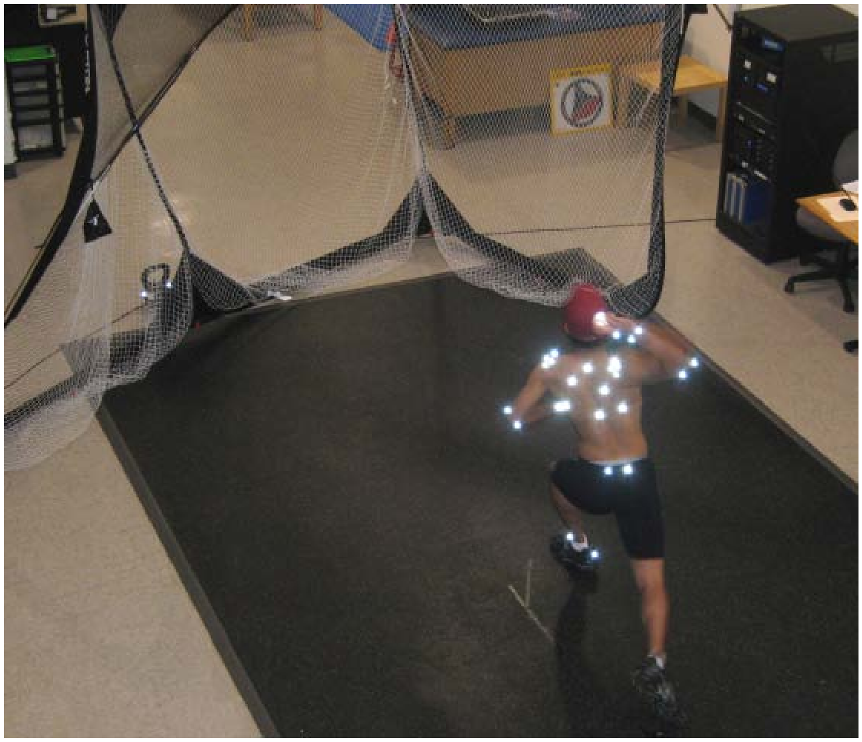

Figure 8. Maximum effort baseball throwing

3.5 DATA ANALYSIS

3.5.1 Kinematic and Kinetic Data Reduction

The 3-D coordinates of the reflective markers were reconstructed with Nexus software. The virtual 3-D coordinates of the joint centers were estimated with the same software based on the positions of markers and the measured anthropometric parameters using a human body model (PlugInGait, Vicon, Centennial, CO). The 3-D coordinates of markers and virtual joint centers were exported by the software. A custom program written in Matlab (Mathworks, Natick, MA) was used for the following post-processing procedures.

3.5.1.1 Humeral and scapular kinematics

All the 3-D coordinates were filtered. The virtual 3-D coordinates of the removed scapular reference markers over the scapular anatomical landmarks (i.e. the acromion angle, the root of the spine of scapula, and the inferior angle) were calculated. With the captured static motion, a local coordinate system (LCS) was established with the three-marker triad. Then, the positions of the scapular reference markers in the static trial were converted from the global coordinate system (GCS) into the scapula LCS. The spatial relationships between the triad and the scapular anatomical landmarks were assumed to be constant during testing. The virtual 3-D coordinates of the scapular reference markers were therefore reconstructed back from the scapular LCS established with the 3-D coordinates of the scapular triad during the dynamic trials of pace-controlled scaption and maximum effort baseball throwing.

Kinematics of the humerus and scapula were calculated following the International Society of Biomechanics (ISB) recommendations.[109] First, LCSs were created for the thorax, humerus, and scapula for each time frame during the dynamic trials (Figure 9). The following four markers were utilized to define the thorax LCS: the spinous processes of the 7th cervical vertebra (C7) and the 8th thoracic vertebra (T8), the jugular notch (IJ), and the xiphoid process (PX). The Y axis was defined as the line connecting the midpoint between T8 and PX with the midpoint between IJ and C7, pointing upward. The Z axis was defined as the line perpendicular to the plane formed by IJ, C7, and the midpoint between PX and T8, pointing to the right. The X axis was defined as the common line perpendicular to the Z and Y axes, pointing forward.

The virtual position of the glenohumeral joint center (GH), the lateral epicondyle of the humerus (EL), and the medial epicondyle of the humerus (EM) were utilized to define the humerus LCS. The Y axis was defined as the line connecting GH and the midpoint of EL and

EM, pointing to GH. The X axis was defined as the line perpendicular to the plane formed by EL, EM, and GH, pointing forward. The Z axis was defined as the common line perpendicular to the Y and X axes, pointing to the right.

The virtual positions of the acromial angle (AA), the root of the spine of the scapula (TS), and the inferior angle (AI) were utilized to define the scapula LCS. The Z axis was defined as the line connecting TS and AA, pointing to AA. The X axis was defined as the line perpendicular to the plane formed by AI, AA, and TS, pointing forward. The Y axis was defined as the common line perpendicular to the X and Z axes, pointing upward.

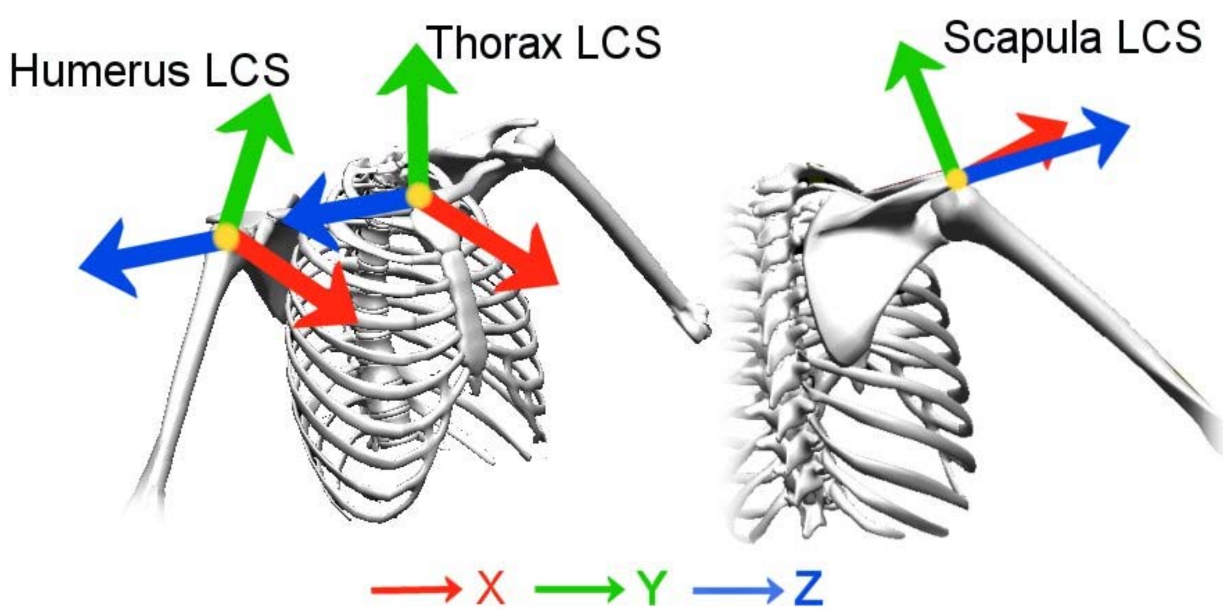

Figure 9. The local coordinate systems of the thorax, humerus, and scapula

The humeral angular kinematics was defined as the humerus LCS with respect to the thorax LCS. The decomposition sequence was Y-X'-Y'' and the three decomposed orientation elements were plane of humeral elevation, humeral elevation, and humeral external/internal rotation. The scapular angular kinematics was defined as the scapula LCS with respect to the thorax LCS. The decomposition sequence was Y-X'-Z'' and the three decomposed orientation elements were scapular protraction/retraction, medial/lateral rotation, and anterior/posterior tilt. The signs of scapular kinematics values were defined as such: protraction (+), retraction (-); medial rotation (+), lateral rotation (-); anterior tilt (-), posterior tilt (+). In several previous studies, terms used for scapular kinematics were different to the ISB recommendations: protraction/retraction was called internal/external rotation, and medial/lateral rotation was called downward/upward rotation.[35,49,162]

3.5.1.2 Shoulder kinetics during baseball throwing

The shoulder kinetic data of the throwing shoulder were calculated using inverse dynamics, following the algorithm presented by Feltner and Dapena.[99] The calculations required the joint center trajectories of the wrist, elbow, and shoulder of the throwing arm. Kinetic calculations began with determination of the linear acceleration of the joint centers utilizing a 5-point central differentiation equation. Next, for the arm and forearm of each subject, the segment mass and the center of mass coordinates were calculated based on the subject's body height and weight using the regression equations presented by Zatsiorsky.[237] These regression equations for inertial properties were chosen for two reasons: they were created with accurate Gamma-scanning method *in vivo* and the data were based on young and physically active subjects. With the information of segment mass, acceleration, and center of mass, forces applied at the shoulder during throwing were estimated inversely with force equilibrium equations, following the calculation of wrist and elbow forces. The calculated shoulder forces were initially represented in the X, Y, and Z axes of the GCS and then transformed into the humeral LCS for anatomical relevance. The shoulder forces mapped onto the humeral LCS have three components: anterior/posterior, superior/inferior, and longitudinal (compression/distraction).[99]

3.5.1.3 Identification of events during baseball throwing

In the current study, multiple variables were correlated to scapular kinematics at SFC, and the occurrence of maximum shoulder anterior, posterior, superior, inferior, and compression forces. The event of SFC was defined as the point in time when both the linear velocity of the subtalar joint marker and the 3rd metatarsophalangeal marker decreased to below 0.7 m/s, determined with a pilot study involving ground reaction force measurements. Maximum forces were located before or after certain critical events. Maximum shoulder anterior and superior forces were located near MER; maximum shoulder compression force was located near REL, and maximum posterior and inferior forces were located near MIR. The event of MER and MIR were defined as the humerus reaching the maximum external and internal rotation angle, respectively. The event of REL was defined as one frame after the wrist joint center reaching a more anterior position than the elbow joint center.

3.5.2 Statistical Analysis

Scapular and humeral kinematics during maximum effort baseball throwing were described to fulfill Specific Aim 1. Data were extracted at the events of stride foot contact, maximum shoulder external rotation, maximum shoulder anterior force, maximum shoulder compression force, and maximum shoulder inferior force. Data were presented in the format of mean ± SD.

Pearson’s product-moment correlation coefficients or Spearman’s rank correlation coefficients were calculated to identify the potential associations among multiple pairs of variables, as indicated in Specific Aims 2 through 7, based on the normality of the variables. The normality was evaluated using the Shapiro-Wilk test at alpha = 0.05. Scapular kinematic and shoulder kinetic variables at specified events during throwing were averaged across the selected five throws for each subject. For each item of passive range of motion measurements, the three recorded values for each subject were averaged. For each item of isokinetic strength testing, the peak moments across five repetitions for each subject were averaged and exported by the isokinetic dynamometer. For each item of isometric strength testing, the maximum forces across the three measurements for each subject were averaged. Correlation coefficients were calculated involving data from every subject. The significance level was set *a priori* at alpha = 0.05.

4.0 RESULTS

Thirty-five baseball players participated in this study. The demographics for the subjects are presented in Table 5 in the format of mean ± SD. Among the 35 subjects, one was a professional baseball player, five had college varsity level experience, 14 played for college club teams, 11 played in amateur adult leagues, and four had high-school level experience. Five among the 35 were left-handed. Twelve subjects were pitchers, two were catchers, two were first basemen, four were second basemen, two were shortstops, four were third basemen, and 11 were outfielders.

Table 5. Subject demographics

Variables	Values
Sex	33 Males, 2 Females
Age (years)	23.3±5.7
Height (cm)	180.1±7.8
Weight (kg)	83.3±13.7
Organized Baseball Experience (years)	15.2±5.7

4.1 OUTCOMES OF TESTING

In this section, outcomes of scaption, maximum effort baseball throwing, range of motion, and strength testing are presented. All data are in the format of mean ± SD.

Scapular and humeral kinematics during pace-controlled scaption and maximum effort baseball throwing are presented in Table 6. The signs of scapular kinematics values were defined as such: protraction (+), retraction (-); medial rotation (+), lateral rotation (-); anterior tilt (-), posterior tilt (+). During scaption, the mean arm elevation plane angle was 29.8° (horizontally adducted) at the arm elevation angle of stride foot contact (SFC); the mean arm elevation plane angle was 30.6° at the arm elevation angle of the occurrence of maximum shoulder compression force. During maximum effort baseball throwing, the average ball velocity was 29.7±3.3m/s (66.5±7.4mph). The mean arm elevation angles were 90.1° at SFC, and 95.8° and the occurrence of maximum shoulder compression force. At the moment of maximum shoulder external rotation, the scapula tilted posteriorly to 18.0°, accounting for 12.6% of the gross shoulder external rotation angle of 142.7±12.5°. Maximum shoulder forces during maximum effort baseball throwing were calculated in five directions. Anterior force was 207.4±52.3N; posterior force was 202.7±61.0N; superior force was 106.4±61.9N; inferior force was 396.6±110.1N; compression force was 639.3±162.4N.

The glenohumeral ROM was 127.7±14.2° for external rotation and 58.5±12.4° for internal rotation. Posterior shoulder tightness was 130.8±7.9°. The isokinetic strength of the shoulder was 33.1±9.0Nm for the external rotators and 58.5±12.4Nm for the internal rotators. The ratio between the shoulder external and internal rotators strength was 0.89±0.20. Isometric shoulder strength was 576.5±128.5N for the upper trapezius, 58.7±14.6N for the middle trapezius, 53.8±14.7N for the lower trapezius, 72.9±20.5N for the rhomboids, 249.6±41.8N for the serratus anterior, and 74.1±21.7N for the supraspinatus.

Table 6. Scapular kinematics

	Scapular Protraction / Retraction	Scapular Medial / Lateral Rotation	Scapular Anterior / Posterior Tilt
Pace-Controlled Scaption			
Arm elevation angle of SFC (°)	30.3±8.7	-25.7±7.4	-6.2±7.1
Arm elevation angle of maximum compression force (°)	30.2±9.5	-27.4±7.4	-4.9±7.3
Maximum Effort Baseball Throwing			
Stride foot contact (°)	0.9±14.4	-23.3±9.8	8.1±13.4
Maximum shoulder external rotation (°)	11.3±13.4	-33.8±7.2	18.0±14.1
Ball release (°)	22.0±13.1	-31.4±8.1	5.1±13.9
Maximum shoulder internal rotation (°)	58.1±11.1	-22.3±11.2	-22.0±11.1
Maximum shoulder anterior force (°)	4.3±14.6	-28.5±7.2	17.0±11.4
Maximum shoulder posterior force (°)	54.1±24.1	-23.1±12.3	-10.8±17.1
Maximum shoulder superior force (°)	2.7±14.2	-26.6±6.9	18.1±11.7
Maximum shoulder inferior force (°)	46.7±11.2	-23.7±10.8	-16.8±11.8
Maximum shoulder compression force (°)	25.3±13.4	-30.3±7.9	1.5±13.5

4.2 CORRELATION CALCULATIONS

In this section, correlation data are presented as indicated in Specific Aims 2 through 7. Data are presented in the format of r (p-value). The results of the Shapiro-Wilk test demonstrated that all the variables were normally distributed; therefore, Pearson's product-moment correlation coefficient was used for all correlation analyses in this study. In upcoming discussion, the term correlation always refers to Pearson's r.

4.2.1 Scapular kinematics between scaption and throwing

Correlations between scapular kinematics during maximum effort baseball throwing and pace-controlled scaption are presented in Table 7. A moderate positive correlation existed between the scapular protraction/retraction angle during scaption and during throwing at the same arm elevation angle when the stride foot contacted the floor during throwing (90.1±10.6°). This indicates that subjects who were more retracted during scaption were also more retracted during throwing at SFC. Moderate positive correlations existed in both scapular medial/lateral rotation and scapular anterior/posterior tilt at the same arm elevation angle when maximum shoulder compression force occurred during throwing (95.8±8.3°). This indicates that subjects who were more laterally rotated or who were more posteriorly tilted during scaption also were more laterally rotated or posteriorly tilted during throwing, respectively.

Table 7. Correlations between scapular kinematics during scaption and throwing

	Scapular Protraction / Retraction	Scapular Medial / Lateral Rotation	Scapular Anterior / Posterior Tilt
Same Arm Elevation Angle at SFC	0.438 (0.009)*	0.277 (0.107)	0.309 (0.070)
Same Arm Elevation Angle at Maximum Compression force	0.080 (0.650)	0.399 (0.018)*	0.358 (0.035)*

* Significant correlation, alpha = 0.05
Data presented in the format of ‘r’ (p value)

4.2.2 Glenohumeral ROM and scapular kinematics

Correlations between glenohumeral ROM and scapular kinematics during maximum effort baseball throwing are presented in Table 8. None of these correlations reached statistical significance.

Table 8. Correlations between glenohumeral ROM and scapular kinematics

	Scapular Anterior / Posterior Tilt		
	At MER	At REL	At MIR
Glenohumeral External Rotation ROM	0.099 (0.571)	--	--
Glenohumeral Internal Rotation ROM	--	-0.072 (0.681)	0.209 (0.229)
Posterior Shoulder Tightness	--	-0.091 (0.601)	0.054 (0.756)

* Significant correlation, alpha = 0.05
Data presented in the format of ‘r’ (p value)
MER: Maximum shoulder external rotation, REL: Ball release, MIR: Maximum shoulder internal rotation
‘--’ indicated that the correlation was not calculated as it was not one of the Specific Aims

4.2.3 Shoulder strength and scapular kinematics

Correlations between shoulder strength and scapular kinematics during maximum effort baseball throwing are presented in Table 9. None of these correlations reached statistical significance.

4.2.4 Glenohumeral ROM and shoulder kinetics

Correlations between glenohumeral ROM and shoulder kinetics during maximum effort baseball throwing are presented in Table 10. Posterior shoulder tightness (PST) was moderately negatively correlated to maximum shoulder inferior force, indicating that subjects with greater PST measurement (i.e. less tightness) had decreased maximum shoulder inferior force.

Table 9. Correlations between shoulder strength and scapular kinematics

	Scapular Protraction / Retraction	Scapular Medial / Lateral Rotation	Scapular Anterior / Posterior Tilt
Scapular Kinematics at SFC			
Isometric Upper Trapezius Strength	--	-0.170 (0.330)	--
Isometric Middle Trapezius Strength	--	-0.259 (0.132)	--
Isometric Lower Trapezius Strength	--	-0.286 (0.097)	--
Isometric Rhomboids Strength	--	-0.017 (0.921)	--
Isometric Serratus Anterior Strength	--	-0.107 (0.540)	--
Isometric Supraspinatus Strength	--	-0.282 (0.100)	0.192 (0.268)
Scapular Kinematics at Maximum Anterior Force			
Isokinetic Shoulder External Rotators Strength	-0.276 (0.109)	--	0.153 (0.381)
Isokinetic Shoulder Internal Rotators Strength	-0.064 (0.715)	--	0.053 (0.763)
External / Internal Rotators Strength Ratio	-0.198 (0.254)	--	0.090 (0.606)
Scapular Kinematics at Maximum Posterior Force			
Isokinetic Shoulder External Rotators Strength	-0.271 (0.115)	--	0.209 (0.229)
Isokinetic Shoulder Internal Rotators Strength	-0.190 (0.274)	--	0.213 (0.219)
External / Internal Rotators Strength Ratio	-0.071 (0.688)	--	-0.154 (0.377)

* Significant correlation, alpha = 0.05
Data presented in the format of 'r' (p value)
'--' indicated that the correlation was not calculated as it was not one of the Specific Aims

Table 10. Correlations between glenohumeral ROM and shoulder kinetics

	Maximum Shoulder Forces			
	Anterior	Posterior	Superior	Inferior
Glenohumeral External Rotation ROM	-0.211 (0.224)	--	-0.015(0.932)	--
Glenohumeral Internal Rotation ROM	--	-0.074 (0.671)	--	-0.129 (0.461)
Posterior Shoulder Tightness	--	-0.295 (0.085)	--	-0.352 (0.038)*

* Significant correlation, alpha = 0.05
Data presented in the format of 'r' (p value)
'--' indicated that the correlation was not calculated as it was not one of the Specific Aims

4.2.5 Shoulder strength and shoulder kinetics

Correlations between shoulder strength and shoulder kinetics during maximum effort baseball throwing are presented in Table 11. Supraspinatus strength was moderately positively correlated to maximum shoulder inferior force. Subjects with greater supraspinatus strength had increased maximum shoulder inferior force during maximum effort baseball throwing.

Table 11. Correlations between shoulder strength and shoulder kinetics

	Maximum Shoulder Forces				
	Anterior	Posterior	Superior	Inferior	Compression
Shoulder External Rotators Strength	--	-0.035 (0.840)	--	0.029 (0.869)	0.042 (0.809)
Shoulder Internal Rotators Strength	0.030 (0.866)	--	0.020 (0.909)	--	--
ER/IR Strength Ratio	-0.213 (0.220)	0.088 (0.617)	--	--	--
Supraspinatus Strength	--	--	0.240 (0.165)	0.413 (0.013)*	--

* Significant correlation, alpha = 0.05
Data presented in the format of ‘r’ (p value)
‘--’ indicated that the correlation was not calculated as it was not one of the Specific Aims

4.2.6 Scapular kinematics and shoulder kinetics

Correlations between shoulder kinetics and scapular kinematics during maximum effort baseball throwing are presented in Table 12. Scapular protraction/retraction at SFC demonstrated a moderate negative correlation with maximum shoulder compression force. This indicates that, at SFC, subjects with increased compression force tended to have increased scapular retraction. The correlation between scapular anterior/posterior tilt at SFC and maximum shoulder superior force failed to reach statistical significance.

At the occurrence of shoulder maximum compression force, a strong negative correlation was found between scapular protraction and maximum shoulder compression force. In other words, subjects with higher maximum compression forces tended to demonstrate increased scapular retraction at this instant. In addition, a moderate positive correlation was found between scapular anterior tilt and maximum compression force. Subjects with higher maximum compression forces also presented increased posterior tilt at this instant.

Table 12. Correlations between shoulder kinetics and scapular kinematics

	Scapular Protraction / Retraction	Scapular Medial / Lateral Rotation	Scapular Anterior / Posterior Tilt
Scapular Kinematics at SFC			
Maximum Shoulder Anterior Force	-0.028 (0.875)	-0.006 (0.971)	-0.172 (0.323)
Maximum Shoulder Posterior Force	-0.259 (0.133)	<0.001 (0.998)	-0.040 (0.818)
Maximum Shoulder Superior Force	-0.170 (0.330)	-0.025 (0.886)	0.323 (0.059)
Maximum Shoulder Inferior Force	-0.273 (0.112)	-0.063 (0.721)	-0.047 (0.787)
Maximum Shoulder Compression Force	-0.399 (0.018)*	-0.001 (0.993)	0.190 (0.273)
Scapular Kinematics at Maximum Shoulder Compression Force			
Maximum Shoulder Compression Force	-0.594 (<0.001)*	-0.250 (0.147)	0.340 (0.046)*

* Significant correlation, alpha = 0.05
Data presented in the format of ‘r’ (p value)

5.0 DISCUSSION

Altered scapular kinematics during pace-controlled arm elevation, changes in the glenohumeral ROM, and shoulder muscle weakness and imbalances have been linked to throwing performance, shoulder injuries, and to the mechanism of shoulder injury in baseball players. The purpose of this study was to describe scapular kinematics during maximum effort baseball throwing, and to identify the potential association between scapular kinematics during maximum effort baseball throwing and scapular kinematics during pace-controlled scaption, glenohumeral ROM, shoulder muscle strength, and shoulder kinetics during maximum effort baseball throwing. Thirty-five subjects who had organized baseball experience and played baseball or softball within the past one year participated in this study.

It was hypothesized that significant correlations exist between scapular kinematics during maximum effort baseball throwing and pace-controlled scaption, between scapular kinematics and glenohumeral ROM, between scapular kinematics and shoulder muscle strength, between shoulder kinetics and glenohumeral ROM, between shoulder kinetics and shoulder muscle strength, and between scapular kinematics and shoulder kinetics.

Several pairs of correlation were identified significant as hypothesized. The correlations between scapular kinematics during throwing and scaption were significant in scapular protraction/retraction at the arm elevation angle at SFC, and in scapular medial/lateral rotation and anterior/posterior tilt at the arm elevation angle at maximum compression force. Maximum shoulder inferior force was found significantly correlated to posterior shoulder tightness and supraspinatus strength. Scapular protraction/retraction at SFC was significantly correlated to maximum shoulder compression force. Scapular protraction/retraction and anterior/posterior tilt at the occurrence of maximum shoulder compression force were both significantly correlated to the force. No significant correlations were found between scapular kinematics and glenohumeral ROM, or between scapular kinematics and shoulder muscle strength.

5.1 DESCRIPTION OF SCAPULAR AND HUMERAL KINEMATICS

Previous literature concluded that the scapula plays several critical roles during overhead throwing and is essential to the overall functioning and efficiency of the throwing shoulder.[3] However, scapular kinematics and the coordinated movement between the scapula and humerus during maximum effort baseball throwing have not been documented in 3-D. In this section, scapular and humeral kinematics throughout maximum effort baseball throwing, as well as the contribution of glehonumeral external rotation and scapular posterior tilt to maximum shoulder external rotation, are described as indicated in Specific Aim 1.

Evaluation of humeral and scapular kinematics at the time of stride foot contact (SFC) requires correct event identification consistent with other reported research so the current results can be compared and generalized. In the current study, the humerus of the throwing shoulder horizontally abducted 24.5±14.3°, elevated (abducted) 90.1±10.6° and externally rotated 51.2±27.0° at SFC. The amount of shoulder external rotation at SFC was consistent to that reported in previous literature. Fleisig et al.[7] tested 115 college pitchers and reported shoulder external rotation of 55±29° at SFC. Similarly, according to Chu et al.,[4] the shoulder external rotation of 11 Olympic pitchers was 54±24° at SFC. In the current study, at the event of SFC, the scapula was positioned at 0.9±14.4° protraction, 23.3±9.8° lateral rotation, and 8.1±13.4° posterior tilt. These numbers could not be compared with previous literature as scapular kinematics at SFC have not been previously investigated.

In the current study, measurement of humeral external rotation at the time of maximum shoulder external rotation (MER) was 142.7±12.5°. The humerus was also horizontally adducted 16.3±9.3°, and elevated 95.1±8.2° at MER. Previous studies have indicated that maximum external rotation is approximately 170° in baseball pitchers (Appendix A.1) which is much higher than the current study. The discrepancy between the finding in the current study and previous work is likely due to the differences in biomechanical models employed in each study. In the current study, the shoulder external rotation angle was calculated between the humerus and the thorax; therefore, the contributions to this angle included both glenohumeral external rotation and scapular posterior tilt. In most previous studies, shoulder external rotation also encompassed trunk extension.[10] With a model like the one used in the current study, Konda et al.[38] reported MER during tennis serve to be 137.6±7.8°, similar to the findings of the current study. It is likely that during maximum effort throwing the trunk extends approximately 25 to 30° at MER. Scapular kinematic findings in the current study showed the scapula was protracted to 11.3±13.4° at MER. The scapula was rotated laterally to 33.8±7.2°, and posteriorly tilted to 18.0±14.1°.

Continuing through the phase of throwing, after the point of MER the humerus began internally rotating, and the scapula moved into further protraction and began to tilt anteriorly. Scapular lateral rotation remained relatively constant. At the event of ball release (REL), the humerus was in the position of 14.6±9.7° horizontal adduction, 94.0±8.8° elevation, and

102.2±16.3° external rotation. The scapula was in the position of 22.0±13.1° protraction, 31.4±8.1° lateral rotation, and 5.1±13.9° posterior tilt. When the throwing shoulder reached maximum internal rotation (MIR), the humerus was in 35.3±10.5° horizontal adduction, 102.6±8.8° elevation, and 27.8±17.1° internal rotation. The scapula was protracted 58.1±11.1°, laterally rotated 22.3±11.2°, and anteriorly tilted 22.0±11.1°.

According to Kibler,[3] the scapula moves in coordination with movement of the humerus, increasing the range of arm movement and serving as a link in the kinetic chain. The current results demonstrated similar coordinated movement. Overall, the scapula continued to move into retraction through SFC and then began to protract at a point between SFC and MER. The protraction of the scapula was coordinated with humeral horizontal adduction (Figure 10). That is, as the humerus horizontally adducted, the scapula also protracted. The scapula also tilted posteriorly as the humerus rotated externally until MER, and started to tilt anteriorly as the humerus moved into internal rotation (Figure 11). The scapular lateral rotation angle remained nearly constant throughout these events. While Figure 10 and 11 show the data from a single subject, similar patterns were observed across subjects.

No previous studies have reported the scapular kinematics during maximum effort baseball throwing with three degrees of freedom in rotation (protraction/retraction, medial/lateral rotation, and anterior/posterior tilt). Using a model that accounted for only one degree of freedom, Miyashita et al.[37] reported that the scapula tilted posteriorly from the initiation of throwing but started to tilt anteriorly right before the event of MER (still in a posteriorly tilted position). Konda et al.[38] has examined scapular kinematics based on three degrees-of-freedom, and, similar to the current results, the scapula first retracted and tilted posteriorly from the initiation of tennis serve. The scapula then started to protract approximately 0.05 seconds before

MER, and started to tilt anteriorly right after MER. The scapula maintained a nearly constant lateral rotation angle of approximately 32° throughout the serve.

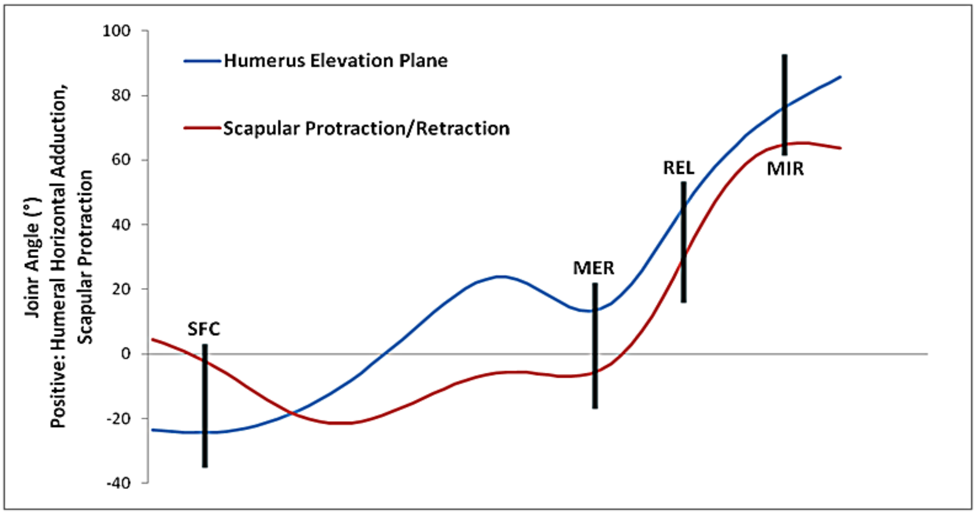

Figure 10. Humerus adduction and scapular protraction/retraction throughout maximal effort throwing (single subject)

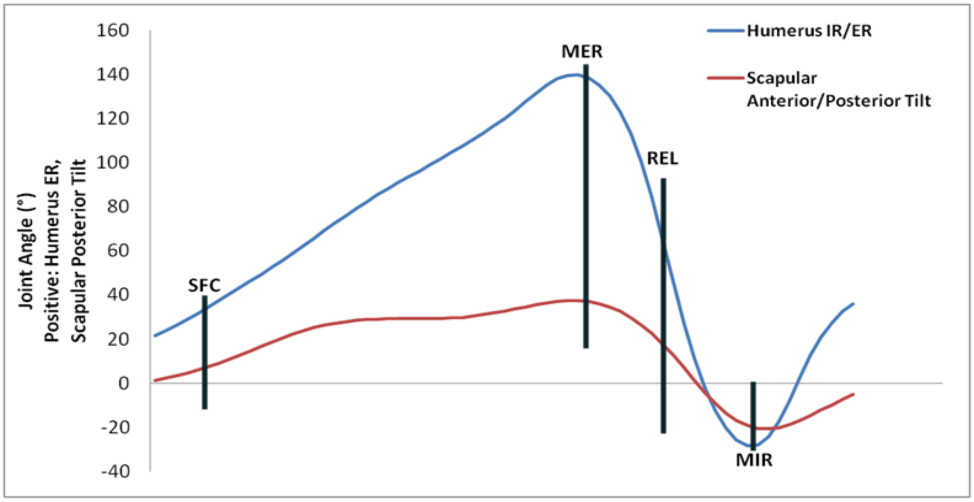

Figure 11. Humerus external/internal rotation and scapular anterior/posterior tilt throughout maximal effort throwing (single subject)

The contribution of scapular posterior tilt to the gross shoulder external rotation angle was investigated in the current study. At the event of MER, the scapula posterior tilt was 18.0±14.1°, accounting for 12.6% of the resultant shoulder external rotation angle (142.7±12.5°). The posterior tilt angles in the current study are lower than those published previously despite the similar kinematic patterns. Previous studies have reported scapular posterior tilt ranging from 16.3%-19.4% of shoulder external range of motion. Miyashita et al.[37] reported 23.5±13.9° of scapular posterior tilt during baseball throwing, accounting for 16.3% of the shoulder external rotation angle (144.2±11.0°). Konda et al.[38] found 26.7±12.0° of scapular posterior tilt during the tennis serve, accounting for 19.4% of the shoulder external rotation angle (137.6±7.8°). Several factors might have contributed to these differences. In Miyashita et al.,[37] subjects threw off a pitching mound (the current study did not use a mound), and the human body model used was 2-D only. On the other hand, despite the similar human body model used in Konda et al.,[38] the scapular movement during tennis serve is not necessarily the same as during baseball throwing. Although they share some similarities, differences do exist between these two overhead athletic activities. In baseball throwing, the stride foot is planted on the ground at ball release, while the both feet are off the ground in tennis serve as the impact between the racket and ball occurs. Olympic tennis players demonstrated slower upper torso rotation, elbow extension, and shoulder external rotation velocity, as well as greater trunk tilt than Olympic baseball pitchers.[238,239] It is unclear whether these kinematic differences have any effect on scapular kinematics. No previous studies compared the difference in scapular kinematics between baseball throwing and tennis serve.

5.2 CORRELATIONS

5.2.1 Between scaption and throwing scapular kinematics

Scaption is a task widely used to evaluate dynamic scapular function. The two primary scapular movements, lateral rotation and posterior tilt, are considered critical for maintaining the proper position between the scapula and humerus. Scapular kinematics of healthy, pathologic, and athletic subjects during scaption has been extensively studied.[41,42,49,54] However, the association between scaption and athletic tasks has not been established. As stated in Specific Aim 2, the current study investigated whether scapular kinematics during scaption was correlated to scapular kinematics during throwing.

Scapular kinematics during scaption in the current study was generally comparable to previous findings. At the resting position, the scapula of the throwing (dominant) shoulder was protracted 34.9±5.5°, laterally rotated 0.0±5.9°, and anteriorly tilted 14.4±5.0°. These results are consistent to the data based on 11 healthy baseball players from Laudner et al.[49] (31.4±5.9° protraction, 2.8±8.2° lateral rotation, and 12.8±7.8° anterior tilt). At approximately 90° scaption, the scapula was in the position of 30.3±8.7° protraction, 25.7±7.4° lateral rotation, and 6.2±7.1° anterior tilt. On average, the scapula retracted 4.6°, laterally rotated 25.7°, and posteriorly tilted 8.2° from resting position to 90° scaption. Scapular retraction as measured in the current study is consistent to most previous studies (Appendix A.2). In Laudner et al.,[49] the amount of scapular lateral rotation (22.9°) and posterior tilt (5.7°) in healthy baseball players from zero to 90° scaption were consistent to the current findings, but scapular protraction (12.6°) was detected instead of retraction. Similarly, Myers et al.[54] reported lateral rotation (22.9°) and posterior tilt (3.8°) in healthy baseball players from zero to 90° scaption, but identified 11.7° protraction.

Methodology differences such as location of sensor attachment and Euler decomposition sequence may have contributed to such discrepancy but cannot be confirmed.

In the current study, it was hypothesized that scapular kinematics at the event of SFC during throwing would be significantly correlated to scapular kinematics during scaption at the same arm elevation angle. Among the three orientation components of scapular kinematics, a significant positive moderate correlation was identified in protraction/retraction. That is, baseball players with greater scapular protraction at SFC had greater scapular protraction during scaption at the same arm elevation angle. The correlations between anterior/posterior tilt as well as medial/lateral rotation at SFC and the same arm elevation of scaption failed to reach statistical significance.

It was also hypothesized that scapular kinematics at the occurrence of maximum shoulder compression force would be significantly correlated to scapular kinematics during scaption at the same arm elevation angle. Significant positive moderate correlations were identified in both scapular medial/lateral rotation and anterior/posterior tilt. Baseball players with more laterally rotated and/or more posteriorly tilted scapulae at the occurrence of maximum shoulder compression force also had more laterally rotated and/or more posteriorly tilted scapulae during scaption at the same arm elevation angle. Protraction/retraction during scaption was not significantly correlated with protraction/retraction at maximum shoulder compression force.

The current study demonstrated that significant positive moderate correlations exist in all three scapular kinematics components between scaption and throwing at one of the selected events. Therefore, pace-controlled scaption testing may be an appropriate tool to evaluate scapular kinematics during throwing. Changes in all the three scapular kinematics components have been linked to shoulder pathology or overhead athletic participation. Previous studies showed that healthy overhead athletes demonstrate increased protraction, decreased lateral rotation, and decreased posterior tilt throughout the arc during scaption.[51-53] Decreased scapular lateral tilt and posterior tilt may be associated to subacromial impingement,[42-44] as such kinematic changes shown to be present in overhead athletes may reduce the subacromial space, and place them at greater risk of development of shoulder impingement pathologies.[39] On the other hand, increased scapular posterior tilt has been observed in baseball players with internal impingement.[49]

5.2.2 Between glenohumeral ROM and scapular kinematics

Glenohumeral ROM differences in baseball players have been well documented. The throwing shoulder in baseball players typically demonstrates increased glenohumeral external rotation and decreased glenohumeral internal rotation.[57,240] Such changes have been linked to various shoulder symptoms and injuries in baseball players. Increased glenohumeral external rotation has been associated with shoulder anterior laxity, which can contribute to the development of internal impingement and anterior labrum damage.[11,26] Decreased glenohumeral internal rotation and increased posterior shoulder tightness (PST) have been associated with superior posterior humeral head shift, which may lead to subacromial impingement, internal impingement, and superior labrum anterior posterior (SLAP) lesions.[66,68,69] Increased PST has also been correlated with a more anterior scapula position.[93] No previous study has investigated the relationship between scapular kinematics during throwing and glenohumeral ROM.

The average glenohumeral external and internal rotation ROM measured in the current study were 127.7±14.2° and 58.5±12.4°, respectively. These values are comparable to those previously reported (Appendix A.3). Wilk et al.[12] assessed glenohumeral external and internal rotation ROM in 372 professional baseball players and reported 129.9±10° and 62.6±9°, respectively. In the current study, PST was 130.8±7.9°, higher than reported in previous studies. A higher PST value indicates less tightness. In Laudner et al.,[93] the PST value was 103.8±7.9° in 40 healthy professional baseball players. Myers et al.[69] reported PST of 105.9±5.9° in 15 healthy college varsity pitchers. Repetitive throwing can result in a tighter posterior shoulder.[189] The subjects in Laudner et al. and Myers et al. competed at a higher level and threw more frequently than the subjects recruited in the current study, which may explain the differences. In addition, although testing procedures were followed as described in the literature,[58] some slight differences in testing and measurement technique are unavoidable and may contribute to these differences.

As proposed in Specific Aim 3, the current study attempted to identify the potential association between glenohumeral ROM and scapular kinematics during maximum effort baseball throwing. It was hypothesized that glenohumeral external rotation ROM would be correlated to scapular anterior/posterior tilt at the event of MER. It was also hypothesized that glenohumeral internal rotation ROM and PST would be correlated to scapular anterior/posterior tilt at REL and MIR. However, no significant correlations were identified between shoulder ROM variables and anterior/posterior tilt at any instant of the throwing process. It seems that glenohumeral ROM is not related to scapular anterior/posterior tilt during throwing in the population tested in the current study. No previous studies have investigated the relationship between shoulder ROM and scapular kinematics during throwing. Downer et al.[72] did investigate the relationship between shoulder ROM and scapular kinematics during scaption. They found insignificant weak correlations between shoulder ROM (external rotation, internal rotation, and PST) and static scapular lateral rotation.

5.2.3 Between shoulder strength and scapular kinematics

The strength of the scapular stabilizers, shoulder external and internal rotators, and supraspinatus has been linked to shoulder pain and pathologies in baseball players.[21,77,85] Previous studies have not investigated the relationship between shoulder strength and scapular kinematics during throwing. As stated in Specific Aim 4, a purpose of the current study was to identify the potential association between shoulder strength and scapular kinematics during maximum effort baseball throwing. It was hypothesized that scapular stabilizer strength, shoulder external and internal rotator strength, and supraspinatus strength would be significantly correlated to scapular kinematics during maximum effort baseball throwing. However, no significant correlation was found.

Although the scapular stabilizers maintain the position and orientation of the scapula, no significant correlation was found between the strength of any of the scapular stabilizers and scapular medial/lateral rotation at SFC. Previous literature on this topic is limited and inconclusive. The upper, middle, and lower trapezius, and serratus anterior create a force couple that contribute to scapula lateral rotation, while the rhomboids rotates the scapula medially. Laudner et al.[88] identified a significant positive correlation between the lower trapezius and scapular lateral rotation at 90° and 120° scaption. In the current study, the trapezius muscles and rhomboids failed to correlate with scapular medial/lateral rotation. Interestingly, further exploration of the current data showed that rhomboids strength was moderately correlated to scapular lateral rotation during scaption at the same humeral elevation angle of SFC ($r=-0.336$, $p=0.049$). The measured scapular stabilizer strength was lower than previous data based on college and professional baseball players.[78,195] The lower values may be explained by different populations and testing protocols.

Decreased shoulder external rotator strength and increased shoulder internal rotator strength have been associated to the intensity and volume of throwing.[57] Such changes may result in a strength imbalance, which is proposed to increase the risk of shoulder injury in baseball players.[2] The measured shoulder external and internal rotator strength was lower than previous data based on college and professional baseball players but higher than high school players, which is consistent to the skill and development level of our recruited group (Appendix A.4). The external/internal rotators strength ratio was higher than the recommended value,[2] but still within the range of previous data. The current study found no significant correlation between the external and internal rotators strength and scapular kinematics in healthy amateur baseball players performing a limited number of throws, implying that the proposed injury mechanism does not involve scapular kinematics in these conditions.

The supraspinatus assists in maintaining proper alignment between the scapula and the humerus during throwing, keeping the humeral head in proper position within the glenoid fossa. Weakness in the supraspinatus has been identified as a risk factor of shoulder injuries in professional baseball pitchers.[21] In the currently study the strength of supraspinatus was not significantly correlated to scapular kinematics. These findings suggest that scapular kinematics may not contribute mechanism that links supraspinatus strength to shoulder injury in baseball players. Other potential mechanisms, such as the effect of supraspinatus strength on humeral head translation, are worthy of future investigation. The measured supraspinatus strength in the current study was 74.1±21.7N, which is less than professional pitchers (86.3±19.6N),[195] but greater than high school pitchers (40.2N).[86]

5.2.4 Between glenohumeral ROM and shoulder kinetics

High shoulder kinetics are considered a key factor contributing to shoulder injuries in baseball players.[10] Increased glenohumeral external rotation, decreased glenohumeral internal rotation, and tighter posterior shoulder have been linked to shoulder pathology in baseball players.[11,66] Professional baseball clubs have initiated stretch programs to increase glenohumeral internal rotation ROM in attempt to reduce shoulder injuries.[217] However, the relationship between glenohumeral ROM and shoulder kinetics during throwing has not been investigated. As stated in Specific Aim 5, a purpose of the current study was to identify the potential association between glenohumeral ROM and shoulder kinetics during maximum effort baseball throwing. It was hypothesized that glenohumeral external rotation ROM would be correlated to shoulder anterior and superior forces, and glenohumeral internal rotation ROM and PST would be correlated to shoulder posterior and inferior forces. The current results demonstrated that greater PST measurement, which indicated less tightness, was significantly correlated to decreased maximum shoulder inferior force. Maximum shoulder inferior force measured in the current study was 396.6±110.1N. This value was consistent to the data based on adult baseball pitchers (310±80N).[6]

Shoulder inferior force tends to move the humeral head downward, potentially placing stress on the glenoid labrum, ligament, and capsule structures inferior to the humeral head. However, failure to generate an appropriate inferior force can lead to superior translation of the humeral head, causing impingement of the supraspinatus against the acromion.[6] Maximum shoulder inferior force occurred near the end of the arm deceleration phase, right before maximum shoulder internal rotation (MIR).[6] The identified negative correlation between maximum shoulder inferior force and PST is interesting. The arm deceleration phase is when the posterior shoulder muscles are eccentrically contracting, and the posterior glenohumeral capsule is stretched.[66] The current result was not sufficient to specify the mechanism behind the observed correlation. It is possible that increased tightness reduced the available range of motion for humeral internal rotation for arm deceleration, resulting in shorter deceleration time. To decelerate the arm within a decreased range of motion and time, higher force must be generated. In other studies, decreased PST measurement (tighter posterior shoulder) has been linked to superior translation of the humeral head, which can potentially lead to a superior labrum anterior posterior (SLAP) lesion and subacromial impingement.[66,68] Decreased PST measurement has also been associated with glenohumeral internal rotation deficit (GIRD), considered as a risk factor of shoulder injuries in baseball players.[66,70] Future research should investigate if shoulder inferior force is involved in the mechanism linking PST and shoulder injuries.

5.2.5 Between shoulder strength and shoulder kinetics

Forces applied to the shoulder during throwing are mainly the result of muscle activation. Multiple muscles co-contract to create force couples that enable the rapid, multi-axis shoulder movements during throwing. As demonstrated in Figure 10 and 11, the humerus horizontally adducts from SFC through approximately three-fourth of the arm cocking phase, then horizontally abducts to MER. Right after MER, the humerus starts to adduct horizontally again throughout the arm acceleration and deceleration phases. The pectoralis major and anterior deltoid concentrically contract to horizontally adduct the humerus, while the posterior deltoid, infraspinatus, and teres minor contract eccentrically to control the humeral movement.[241,242] During the short period of humeral horizontal abduction before MER, the roles of these two groups of muscles switch. The humerus also rotates externally from SFC to MER, during which the infraspinatus, teres minor, and posterior deltoid contract concentrically and the anterior deltoid, pectoralis major, subscapularis, teres major, and latissimus dorsi contract eccentrically.[241,242] The roles of these two groups of muscles switch after MER all the way through MIR, as the humerus rotates internally. Previous research demonstrated that maximum shoulder anterior and superior forces are created by muscles such as the anterior deltoid, pectoralis major, and subscapularis.[242] These forces reach the peak values at MER.[10] Maximum shoulder posterior and inferior forces are generated by the infraspinatus, supraspinatus, teres minor and major, latissimus dorsi, and posterior deltoid.[242] These forces reach the peak values between REL and MIR.[10] It is therefore intuitive to think that the strength of the muscles surrounding the shoulder would be correlated to shoulder kinetics. However, the relationship between shoulder strength and shoulder kinetics during baseball throwing has not been identified.

As indicated in Specific Aim 6, the purpose of the current study was to identify the potential association between shoulder strength and shoulder kinetics during maximum effort baseball throwing. The shoulder external rotators have been reported to be highly activated during deceleration of the humerus at the occurrence of maximum shoulder posterior and inferior forces, while the shoulder internal rotators have been reported to be highly activated during acceleration of the humerus at the occurrence of maximum shoulder anterior and superior forces.[242,243] The supraspinatus plays an important role maintaining the alignment between the humerus and scapula, preventing the humeral head from excessive superior/inferior shift, through compression of the humeral head into the glenoid fossa, and is highly activated at the occurrence of shoulder maximum compression force.[242] While it sounds plausible to assume the existence of correlation among these variables, only the strength of supraspinatus was significantly correlated to maximum shoulder inferior force.

The current study demonstrated that subjects who had greater supraspinatus strength tended to have increased shoulder inferior force. The supraspinatus is highly activated during arm deceleration,[242] the phase that maximum shoulder inferior force occurs.[6] The mechanism behind the observed correlation is unclear. A correlation does not warrant a causal relationship, and the result did not necessarily indicate that greater supraspinatus strength can cause increased shoulder inferior force. Since the supraspinatus prevents inferior translation of the humeral head, it is also plausible that the supraspinatus must get stronger to resist greater shoulder inferior force. An attempt to reduce maximum shoulder inferior force by decreasing supraspinatus strength is not appropriate, as prospective epidemiological evidence has demonstrated that weaker supraspinatus is associated with greater risk of shoulder injuries in professional pitchers.[21]

5.2.6 Between scapular kinematics and shoulder kinetics

Previous literature focusing on the relationship between throwing kinematics and kinetics are limited. Fleisig[244] examined the relationship between humeral, torso, and lower body kinematic characteristics and shoulder kinetics during baseball pitching. Fortenbaugh and Fleisig[105] attempted to determine the kinematic characteristics in pitchers with higher ball velocity and lower shoulder forces. No study has investigated the relationship between scapular kinematics and shoulder kinetics. As detailed in Specific Aim 7, a purpose of the current study was to identify the potential association between scapular kinematics and shoulder kinetics during maximum effort baseball throwing. In the current study, it was hypothesized that scapular kinematics at SFC would be correlated to maximum shoulder anterior, posterior, superior, inferior, and compression forces. It was also hypothesized that scapular kinematics at the occurrence of maximum shoulder compression force would be correlated to maximum shoulder compression force.

No significant correlation was detected between scapular kinematics at SFC and maximum shoulder anterior, posterior, superior, and inferior forces. It should be noted that the correlation between scapular posterior tilt at SFC and maximum shoulder superior force only marginally failed to reach statistical significance (p=0.059). If this correlation had been significant, it would indicate that baseball players with more posteriorly tilted scapulae generated greater shoulder superior force. It is interesting to note that increased humeral external rotation at SFC has been found to be correlated to increased shoulder anterior force,[244] considering the fact that scapular posterior tilted in coordination with humeral external rotation (Figure 11). Maximum shoulder superior and anterior forces occurred at approximately the same instance, right before MER.[6] Maximum shoulder superior force calculated in the current study was 106.4±61.9N, lower than the data based on adult pitchers (250±80N).[6] Shoulder superior force tend to move the humeral head upward, potentially placing stress on glenoid labrum structures superior to the humeral head reducing the subacromial space. Baseball pitchers with bicep tendonitis and rotator cuff bursitis typically experienced pain when approaching MER,[2,21] where shoulder superior force reached the peak value.[10] Further research is needed to investigate the existence of the correlation between scapular anterior/posterior tilt at SFC and maximum shoulder superior force.

At the occurrence of SFC there was a moderate negative correlation between scapular protraction and maximum shoulder compression force. At the occurrence of maximum shoulder compression force, there was a strong negative correlation with scapular protraction. This was the strongest correlation identified in this study. At the same instance, maximum shoulder compression force was also moderately positively correlated to scapular posterior tilt. Among all the shoulder force components, shoulder compression force is of the greatest magnitude. Throwing motion generates a strong shoulder distraction force, which acts along the longitudinal axis of the humerus, tending to pull the humerus away from the glenoid fossa.[33] Muscles surrounding the glenohumeral joint must be highly activated to generate a compression force to resist the shoulder distraction force, holding the humeral head within the glenoid fossa. Among the activated muscles, the rotator cuff muscles, triceps, biceps, pectoralis major, latissimus dorsi, and deltoid, the posterior shoulder muscles assume the major role.[241,242] In the current study, maximum shoulder compression force calculated was 639.3±162.4N, lower than data based on adult baseball pitchers but comparable to the data based on high school pitchers (Appendix A.1).

As shoulder compression force increases the humeral head is pulled more forcefully into the glenoid fossa, potentially increasing the stability of the glenohumeral joint and preventing humeral head translation. However, the glenoid fossa and labrum also endure greater stress as the humeral head applies greater pressure to the glenoid. Compression and shear forces also create a resultant force pressing the glenoid rim. Moreover, shoulder compression force reached a peak value right after REL, about the same instance when shoulder internal rotation velocity reaches its maximum.[6,10] This velocity typically can exceed 7,000°/s in baseball pitchers (Appendix A.1). The strong compression force and rapid humeral head rotation combined can create a grinding effect, tearing the glenoid labrum.[10,245] Baseball players with greater shoulder compression force also place greater stress on the muscles listed above, resulting in higher chance of tissue damage and injuries. Accumulated tissue damage can further result in structure tensile failure, leading to common shoulder injuries among baseball players such as rotator cuff tear.[2,10,245] In addition, the greater demand to generating higher shoulder compression force potentially can also result in earlier fatigue during competition. When the fatigued muscles fail to generate a sufficient amount of compression force, the stability of the glenohumeral joint may decrease and injuries can occur. In an attempt to reduce maximum shoulder compression force, researchers have investigated various kinematic variables associated with the force during baseball pitching.[9,33,244,246] However, none of the variables investigated was of scapula.

The biomechanical rationale behind the identified correlation remains unclear. Stride foot contact can be viewed as the “ready position” of a baseball thrower. It is the end of throwing preparation and the moment to initiate the most explosive part of throwing. From this moment, energy is transferred from the lower body to the upper body. Stride foot contact also serves as a “checkpoint” used by baseball players and coaches, as it is easier to evaluate and change throwing mechanics at this time as the movement is relatively slower.[8] It has been proposed that good kinematics at SFC can lead to good kinematics throughout a throw.[7,244] It is likely that a more protracted scapular position at SFC improve a thrower’s readiness, or is a sign of improved readiness, for the following explosive phases. The term “readiness” here refers to a state that a thrower’s joints and body segments are in appropriate positions to efficiently and effectively initiate the kinetic chain from bottom up. Throwers with better readiness may be able to generate the high ball velocity with decreased joint forces.[105]

The current results also suggested that baseball players with more protracted and more anteriorly tilted scapulae at the occurrence of maximum shoulder compression force generated a decreased maximum shoulder compression force. Unlike SFC, the occurrence of maximum shoulder compression force is a kinetic event instead of kinematic event. A kinetic event is not intuitive for a kinematic “checkpoint”. Since the peak value of shoulder compression force occurs right after REL,[6] the current results may be loosely interpreted that baseball players with more protracted and more anteriorly tilted scapulae when releasing the ball produced less shoulder compression force. Increased scapular protraction and anterior tilt at resting position has been identified in healthy overhead athletes in the dominate shoulder compared to the non-dominate side.[53] At 90° arm elevation and above, asymptomatic baseball players demonstrated increased scapular protraction compared to healthy non-throwers.[54] It is likely that increased scapular protraction and anterior tilt are normal adaptation occurred due to repetitive throwing. Further research involving injured shoulders should be conducted to assess if such adaptation protective to baseball players.

Since correlations do not necessarily indicate causal relationships, it is not appropriate to conclude that baseball players should have their scapula more protracted and anteriorly tilted to reduce shoulder forces. Identifying scapular kinematics that can reduce shoulder loads should be a topic of future studies. Interestingly, the current findings are, to some degree, relevant to baseball coaching. Coaches may encourage players to release the ball in front of the body, which naturally leads to a more internally rotated humerus at REL and therefore a more anteriorly tilted scapula, as well as increased scapular protraction. Failure to do so results in early ball release, and such delivery is often described as “jerky” and considered harmful to players’ throwing shoulder. Early release indicates shorter path and time of both arm acceleration and deceleration. It is plausible that shoulder muscles must work harder to reach the same ball velocity and then decelerate the throwing arm, and therefore creating higher shoulder forces.

On the other hand, one may question if a more protracted and anteriorly tilted scapula can increase the risk of shoulder injury through other mechanisms. For example, more anteriorly tilted scapula has been identified in subacromial impingement patients at 90° arm elevation or above.[42,43] Current evidence, however, is not sufficient to support that the suggested changes poses greater risk of subacromial impingement in baseball players. Increased scapular posterior tilt was also found in subacromial impingement patients.[41] With the mechanisms causing subacromial impingement remaining debatable, the identified characteristics of patients cannot be concluded to be the result of injury or the cause of injury.[39] The mechanisms of shoulder injury can be complex, with multiple biomechanical factors involved in. For example, without increased humeral horizontal adduction, a more protracted and anteriorly tilted scapula may result in anterior shift of the humeral head and stretched anterior glenohumeral capsule.[247] Increased contact between the humerus and the posterior rim of the glenoid as well as entrapment of the rotator cuff muscles can also occur, resulting in internal impingement.[47] Such risk cannot be assessed by solely reviewing the scapular kinematics without looking at the humerus simultaneously. The risk of shoulder injury of a baseball player should be therefore evaluated on a case-by-case basis, with multiple biomechanical variables of the individual taken into consideration.

5.3 LIMITATIONS OF THE STUDY

There are several limitations of this study which merit mention. First, the range of the subjects' skill level was wide, from high school experience to professional. The results are valuable as they described the correlation trends in a general adult, competitive baseball population. However, it is uncertain if the results hold true within a more homogeneous and specific athlete group, such as professional players, collegiate players, or high school players. Second, due to the restriction of laboratory space, the distance between the subject and the target net was approximately 8m, shorter than a typical throw on a baseball field. Although the subjects were instructed to ignore the net and the kinematic results looked comparable to previous literature, it is unknown if the current results were affected by the shorter throwing distance. Third, the subjects were instructed to give their full effort in the throwing and strength tests, but it can only be assumed that they all followed these instructions when interpreting our results. Fourth, isometric hand-held dynamometry has good intra-rater reliability but its inter-rater reliability is questionable. In the current study a single rater was used. Interpretation of the current results should be focused on the relationships, not the measured numbers. Further, this study is a correlational study, and correlations do not necessarily indicate causal relationships. Recommendations based the current results require further examination and evaluation for efficacy. Finally, the observed linear relationships are not necessarily valid beyond the current range of data. Interpretation and application of the current results must be made cautiously.

5.4 CLINICAL SIGNIFICANCE

Given the lack of information regarding scapular kinematics of baseball players during maximum effort throwing, the results from this study can be used as normative data for healthy adult baseball players. Comparisons can be made between scapular kinematics of injured players and the current data. The current results also established the relevance of using pace-controlled scaption to evaluate baseball players' shoulder function, making it possible to interpret scaption data in the context of baseball throwing.

The effects of posterior shoulder tightness and supraspinatus strength on shoulder kinetics during maximum effort baseball throwing are also topics worthy of discussion. High shoulder kinetics has been proposed as one major factor that contribute to shoulder injury in throwers.[6] As shown in this study, posterior shoulder tightness in baseball players should be prevented with training programs. Further studies regarding the effect of supraspinatus strength on shoulder kinetics and pathology are recommended.

The correlations between scapular kinematics and shoulder kinetics during maximum effort baseball throwing were verified. Although a causal relationship was not identified, the current results may facilitate better understanding of the mechanism of throwing-related shoulder injuries, and provide a potential direction to design training programs for baseball players targeting the potentially dangerous scapular kinematics.

5.5 CONCLUSIONS AND FUTURE DIRECTIONS

The current study addressed several gaps of knowledge in sports biomechanics, resulting in better understanding in the coordinated movement between the humerus and scapular during baseball throwing, and factors that have potential effects on scapular movements in baseball players. The kinematics of the scapula and the isolated contribution of scapular posterior tilt to gross maximum shoulder external rotation during throwing were described. Positive correlations of scapular kinematics were identified between throwing and scaption, enhancing the rationale of using scaption to evaluate baseball players' shoulder function. We also found significant correlation between supraspinatus strength, posterior shoulder tightness, and shoulder kinetics. The results can be used for screening high-risk throwing mechanics. Last but not least, we established the correlations between scapular kinematics and shoulder maximum compression force during throwing. The findings provided preliminary results for researchers to further understand the effect of scapular kinematics on shoulder injuries in baseball players. The findings also presented a potential direction for coaches and players to adjust the throwing mechanics and potentially reduce the risk of shoulder injury.

Future research is needed to determine the scapular kinematics in baseball players with shoulder injury compared with healthy baseball players, and to explore the potential of using pace-controlled scaption test as a screening tool to identify or predict shoulder injuries in baseball players. Scapular kinematics in baseball players of different competition levels should be examined, and the potential relationship between kinematics and training should be explored. In addition, the correlations that marginally failed to reach statistical significance, such as the correlation between scapular posterior tilt and maximum shoulder superior force, are worthy of further investigation. Finally, experimental research is needed to evaluate if adjusting scapular kinematics based on the current results can actually reduce shoulder kinetics during throwing and if such changes reduce the risk of shoulder injury in long term.

APPENDIX A

SUMMARY OF PREVIOUS RESEARCH

A.1 KINEMATICS AND KINETICS DURING BASEBALL PITCHING

Table 13. Kinematics and kinetics during baseball pitching

Study	Subjects	Camera Sampling Rate	Point Identification Method	Maximum Kinematics		Maximum Kinetics*				
				Shoulder External Rotation (°)	Shoulder Internal Rotation Velocity (°/s)	Shoulder Compression force(N)	Shoulder Anterior Force (N)	Shoulder Posterior Force (N)	Shoulder Superior Force (N)	Shoulder Inferior Force (N)
Chen[82]	10 Twn Col Pitchers	250	Auto	172±20		485±74	205±42	109±70	140±38	110±85
Chu et al.[4]	11 Female Pitchers	120	Manual	180±10	5630±1590	510±108				
Dillman et al.[248]	29 Adult Pitchers	200	Auto	178	6940±1080					
Dun et al.[5]	10 Younger Pro Pitchers 12 Older Pro Pitchers	240	Auto	183±4 173±6	7254±1324 6642±669					
Dun et al.[249]	29 Youth Pitchers	240	Auto	178±12	7182±1313	466±170				
Escamilla et al.[250]	10 Col Pitchers, First Inning Last Inning	200	Auto	175±10 173±10	6382±895 6494±622	884±134 850±112	444±80 452±73	328±103 380±126		
Escamilla et al.[32]	16 Col Pitchers	200	Auto	171±6	7550±1110					
Escamilla et al.[238]	6 USA Olympic Pitchers	120	Manual	191±9	5202±1707					
Feltner and Dapena[99]	8 Col Pitchers	200	Manual	170	6100±1700	860±120				
Fleisig et al.[6]	26 Adult Pitchers	200	Auto	165±11		1090±110	310±100	400	250±80	310±80
Fleisig et al.[7]	23 Youth Pitchers 33 HS Pitchers 115 Col Pitchers 60 Pro Pitchers	200	Auto	177±12 174±9 173±10 175±11	6900±1050 6820±1380 7430±1270 7240±1090	480±100 750±170 910±130 1070±190	210±60 290±70 350±70 390±90	160±70 280±100 350±160 390±240		
Fleisig et al.[174]	26 HS and Col Pitchers	200	Auto	173±10	7550±1360	850±140	310±50	310±110		

Table 13. (Continued)

Fleisig et al.[34,92]	27 Col Pitchers, Full Effort Pitching	200	Auto	172±12	7290±1090	910±110	330±40	360±200
	75% Effort Pitching			169±12	6400±1050	790±130	310±50	280±120
	50% Effort Pitching			167±11	5820±1110	700±130	280±50	270±160
	180 Feet Flat-Ground Throwing			170±12	6830±1150	720±100	350±80	310±100
	120 Feet Flat-Ground Throwing			167±12	6740±1240	710±120	330±70	320±150
	60 Feet Flat-Ground Throwing			170±12	7060±1240	780±100	340±70	350±150
Matsuo et al.[172]	29 Col and Pro Pitchers, High Vel.	200	Auto	179±8	7724±1037			
	23 Col and Pro Pitchers, Low Vel.			166±9	7350±1283			
Pappas et al.[100]	15 Pro Pitchers (MLB)	200	Manual	160 - 180	6180			
Sabick et al.[251]	25 Pro Pitchers	120	Manual	182±13				
Stoddent et al.[252]	19 HS, Col, and Pro Pitchers	200	Auto	173±11		118±18%	46±9%	
Werner et al.[9]	40 Pro Pitchers	120	Manual	184±14	8286±2777	108±16%		
Werner et al.[33]	48 Col Pitchers	240	Auto	158±10	6239±1577	81±10%		

* When a percentage mark appears, the value is normalized to body weight and the unit is %BW

A.2 SCAPULAR KINEMATICS DURING HUMERAL ELEVATION

Table 14. Scapular kinematics during humeral elevation

Study	Protraction(+)/ Retraction(-)	Medial(+)/ Lateral(-) Rotation	Anterior(-)/ Posterior(+) Tilt	Arm Elevation[a]	Measurement Approach[b]
Barnett et al.[136]*	1° then -5°	-25°	5°	ABD 10-90, S	EMT (3 Leg Digitizer)
Bourne et al.[153]	-27±11°	-49±7°	44±11°	ABD 25-155°, D	AOT-BP
Ebaugh et al.[165]*	-2° then 1°	-55°	2.5° then -5°	SCA 30-150°, D	EMT-SK
Ebaugh et al.[163]	-2°	-40°	1° then -2°	SCA 30-120°, D	EMT-SK
Fayad et al.[164]	-0.3 to -1.4°	-26.4 to -29.6°	7.0 to 9.1°	ABD 60-120°, S/D	EMT-SK
Laudner et al.[49] (Baseball Players)	13.1°	-28.3°	13.6°	SCA 0-120°, D	EMT-SK
Ludewig et al.[42] (Cons. Workers)*	-5° then 2°	-19°	2.5°	SCA 60-120°, D	EMT-SK
Ludewig et al.[182]	-13°	-34°	15°	SCA 0-140°, S	EMD
Lukasiewicz et al.[43]	-7.1°	-28.2°	22.8°	SCA 0-139.5°, S	EMD
McClure et al.[154]	-24°	-50°	30°	SCA 11-147°, D	EMT-BP
McClure et al.[41]*	1° then -13°	-56°	12°	SCA 154°, D	EMT-SK
Meskers et al.[159]*	-6° then 6°	-60°	15° then -2°	ABD 0-150°,S	EMT (3 Leg Digitizer)
Pascoal et al.[183]*	3° then -3° -5°	-30° -30°	4° then -2° 6°	ABD 0-140°, S SCA 0-140°, S	EMT (3 Leg Digitizer)
Thigpen[166]	12±9° 12±9°	-27±8° -27±8°	24±8° 24±8°	ABD 30-120°, D SCA 30-120°, D	EMT-SK

a. ABD: Abduction. SCA: Scaption. S: Static. D: Dynamic.
b. AOT: Active optical tracking. EMT: Electromagnetic tracking. EMD: Electromechanical digitizer. BP: Bone pins. SK: Skin based
* Estimated from figures.
The presented data are changes from resting position.

A.3 GLENOHUMERAL ROM IN BASEBALL PLAYERS

Table 15. Glenohumeral ROM in baseball players

Study	Subjects	Age	Yrs Exp	Testing Time	Arm	External Rotation (°)	Internal Rotation (°)	Total Motion (°)
Bigliani et al.[253]	72 Pro Pitchers	22.9	3.1 in Pro	Pre Season	D	118.0		
					ND	102.8		
	76 Pro Position Players	22.6	3.3 in Pro		D	109.3		
					ND	97.1		
Borsa et al.[240]	34 Pro Pitchers	24.4±3.7	13.2±6.5	Pre Season	D	135.5±9.5	59.7±7.0	
					ND	130.4±10.7	68.2±8.6	
Borsa et al.[200]	43 Pro Pitchers (30 MLB)	25.1±3.3	13.4±6.4		D	134.8±10.2	68.6±9.2	203.4±9.7
					ND	125.5±8.7	78.3±10.6	204.1±9.7
Brown et al.[57]	18 Pro Pitchers (MLB)	27.0±4.3 (Pooled)	3.7±4.5 (Pooled Years in MLB)		D	141±14.7	83±13.9	
					ND	132±14.6	98±13.2	
	23 Pro Position Players (MLB)				D	132±9.8	85±11.9	
					ND	124±12.7	91±13.0	
Chant et al.[192]	19 Adult Baseball Players (15 Pro, 4 with Col. Exp.)	23.4±1.4			D	114.0±9.8	57.1±8.7	171.1±12.5
					ND	104.1±7.4	73.5±9.6	177.6±11.0
	6 Controls	24.7±1.2			D	112.4±8.9	67.8±10.3	180.2±9.3
					ND	108.5±7.9	76.8±11.4	185.3±9.1
Crockett et al.[62]	25 Pro Pitchers	18 to 35 (Pooled)			D	128±9.2	62±7.4	189±12.6
					ND	119±7.2	71±9.3	189±12.7
	25 Controls				D	113±14.6	92±13.9	179±17.7
					ND	112±13.9	88±13.3	181±15.3
Dines et al.[254]	29 UCL Recon. Baseball players (23 Pitchers;11 Pro, 10 Col, 8 HS)	21.2±5.6			D	104.5±11.4	29.0±13.2	133.5±16.9
					ND	94.2±8.0	57.5±14.1	
	29 Healthy Baseball Players (19 Pitchers; 12 Pro, 10 Col, 7 HS)	20.1±4.1			D	104.8±9.0	38.3±11.4	143.1±13.6
					ND	92.9±6.2	51.1±12.1	
Donatelli et al.[195]	39 Pro Pitchers(MiLB)	20.7	1.8 in Pro	Pre Season	D	103.7±8.8	40.3±9.0	
					ND	95.0±8.5	50.4±9.6	
Downer and Sauers[72]	27 Pro Pitchers	20±1.6		Post Season	D	108.9±9.0	56.6±12.5	165.5±14.4
					ND	101.9±5.9	68.6±12.6	170.4±10.5
Dwelly et al.[190]	29 Col Baseball Players (14 Pitchers)	20±1.5		Pre Fall	D	96.2±12.7	45.5±11.1	141.7±15.0
					ND	92.0±10.0	52.7±11.8	144.7±14.4
				Pre Season	D	104.0±17.0	47.5±8.5	151.4±16.9
					ND	101.7±15.2	52.6±10.2	145.3±15.0
				Post Season	D	106.9±19.9	45.8±10.0	152.4±19.9
					ND	104.4±17.8	52.2±11.3	156.6±17.3
Freehill et al.[255]	29 Entries of Data from 21 Pro Baseball Pitchers (MLB)	29.0±4.1	3.6±2.0 in MLB for 15 SP, 5.9±3.4 for 14 RP	Pre Season	D	124.8±19.5	70.9±11.8	196.5±22.1
					ND	116.3±12.7	76.3±12.4	193.6±19.9
				Post Season	D	126.3±21.6	73.6±13.2	199.9±26.0
					ND	119.0±16.4	81.4±10.4	200.4 ±22.0
Johnson[256]	9 Col Pitchers	20.4±1.4 (Pooled)	12.9±1.4 (Pooled)		D	136±14.6	111±15.2	
					ND	128±12.9	116±12.2	
	8 Col Infield Players				D	115±5.8	110±11.8	
					ND	109±7.8	114±11.9	
	9 Col Outfield Players				D	120±19.2	106±12.8	
					ND	114±8.0	106±10.6	
Kaplan et al.[87]	50 HS Pitchers Live in Warm States	16	7		D	134	62	196
					ND	123	77	200
	50 HS Pitchers Live in Cold States	17	6		D	126	57	183
					ND	114	69	183
Laudner et al.[93]	20 Pro Pitchers	22.6±3.6		Pre Season	D	115.5±7.8	44.7±6.3	170.7±9.1
					ND	107.0±7.8	58.0±9.8	163.1±10.5
	20 Pro Position Players	22.3±2.3			D	109.5±9.7	44.1±8.6	165.4±8.3
					ND	109.5±9.7	52.0±8.0	157.7±11.0
Launder et al.[216]	33 Col Baseball Players (15 Pitchers)	19.8±1.3			D	118.6±10.9	43.8±9.5	
	33 Controls	20.1±0.6			D	99.4±9.1	43.1±7.9	

Table 15. (Continued)

Lintner et al.[217]	44 Pro Pitchers in a Stretch Program	18 to 38		Pre Season	D	142.7	74.3	217.0
	41 Pro Pitchers not in the Program	(Pooled)			D	138.9	55.2	194.2
Magnusson et al.[59]	47 Pro Pitchers (MiLB)	23.6±0.4		Pre Season	D	134±1	61±1	
					ND	120±2	73±1	
	16 Controls	25.1±1.1			D	106±2	61±3	
					ND	102±2	67±2	
Miyashita et al.[102]	40 Jpn HS Baseball Players	17.0±0.7	7.7±2.0		D	118±14	45±14	
Mullaney et al.[78]	13 Col and Pro Pitchers	21±2		In Season	D	137.3±18.3	63.5±8.7	
					ND	120.8±11.9	74.4±9.8	
Myers et al.[69]	11 Adult Baseball Players with Internal Impingement (6 Pitchers)	22.1±3.5	16.2. ±3.5		D	125.8±13.1	42.5±12.1	
					ND	117.5±16.7	62.2±16.9	
	11 Adult Baseball Players w/o Internal Impingement (6 Pitchers)	21.2±1.7	13.4±2.7		D	121.1±8.7	51.1±14.4	
					ND	116.0±10.3	62.2±13.7	
Myers et al.[257]	29 Col Baseball Players	19.5±1.0	14.8±1.9		D	134.8±9.6	36.9±7.9	171.7±12.8
					ND	129.8±8.5	51.2±9.7	181.1±11.3
	25 Controls	20.1±1.1			D	123.3±10.5	48.7±11.1	172.0±11.8
					ND	118.7±12.3	53.4±8.8	172.2±15.4
Myers et al.[58]	15 Col Baseball Pitchers	20.0±1.1			D	132.0±10.4	41.7±5.9	
					ND	119.7±6.5	54.3±8.3	
	15 Col Non-Throwing Athletes	20.1±1.1			D	120.3 ±7.0	46.3±13.1	
					ND	114.0±6.1	47.5±13.0	
Nakayama[258]	20 Jpn Pro Pitchers				D	124.7±12.4	55.5±16.0	
					ND	116.0±13.1	68.8±16.4	
	22 Jpn Pro Position Players				D	121.3±11.3	60.0±8.4	
					ND	111.5±11.3	68.4±8.4	
Reagan et al.[64]	54 Col Baseball Players (25 Pitchers)	19.3	14.0		D	116.3±11.4	43.0±7.4	159.5±12.4
					ND	106.6±11.2	51.2±7.3	157.8±11.5
Reinold et al.[71]	67 Pro Pitchers Before Pitching	26±4		Pre Season	D	136.5±9.8	54.1±11.4	190.6±14.6
					ND	124.2±9.1	63.1±14.3	187.3±16.9
	The Same Group After Pitching				D	135.3±9.3	44.6±11.9	179.9±13.7
					ND	125.3±8.6	63.5±13.1	188.8±17.3
Scher et al.[259 a]	57 Pro Baseball Players (29 Pitchers)	26.3				125	53	
Sethi et al.[61 b]	37 Col and Pro Pitchers (20 Pro)	22.6±4.6			D	110±14	68±16	178±23
					ND	104±14	82±11	186±15
	19 Col Position Players				D	100±11	69±11	169±10
					ND	100±12	75±11	174±10
Thomas et al.[194]	19 HS Baseball Players (7 Pitchers)	16.6±0.8		Pre Season	D	91.8±3.0	41.6±4.9	133.5±5.6
					ND	87.6±3.6	53.2±5.6	140.8±5.4
				Post Season	D	91.3±3.1	42.5±4.0	133.8±5.2
					ND	86.3±3.7	53.6±6.2	139.8±6.6
Tokish et al.[203]	23 Pro Pitchers (MLB)	26.3±4.1			D	123.7±12.8	47.4±16.7	171.6±16.0
					ND	105.0±9.6	65.9±17.0	171.1±17.0
Trakis et al.[86 a]	23 HS Pitchers	15.7±1.4		Post Season	D	98	29	126
					ND	87	42	130
Tyler et al.[67]	22 Col Pitchers	20±1.2			D	109.7±2.4	50.0±2.0	
					ND	98.9±1.6	69.5±2.5	
	49 Controls	30±8.9			D	95.9±1.5	46.4±1.3	
					ND	95.2±1.6	50.2±1.4	
Werner et al.[33]	40 Col Pitchers	20±2			D	126±11	48±10	
					ND	117±11	56±10	
Wilk et al.[12]	372 Pro Baseball Players					129.9±10	62.6±9	
Wilk et al.[2]	879 Pro Pitchers					136.9±14.7	40.1±9.6	176.3±16.0
Wilk et al.[70]	122 Pro Pitchers	25.6±4.1			D	136.1±11.2	47.5±10.6	183.7±14.5
					ND	128.6±11.0	59.1±11.0	187.7±14.5

a. Estimated from figures
b. Electromagnetic tracking data

A.4 ISOKINETIC ER AND IR STRENGTH IN BASEBALL PLAYERS

Table 16. Isokinetic ER and IR strength in baseball players

Study	Subjects	Age	Velocity/ Position	Arm	External Rotation Strength		Internal Rotation Strength		ER/IR Strength Ratio
					Raw (Nm)	Normalized (Nm/Kg)	Raw (Nm)	Normalized (Nm/Kg)	
Alderink and Kuck[260]	26 HS and Col Pitchers	18.0±2.1	90, Abducted	D	35.7±8.1	0.444±0.075	53.0±10.6	0.665±0.101	0.66±0.09
				ND	36.3±7.5	0.456±0.069	52.1±9.9	0.656±0.110	0.70±0.09
			120, Abducted	D	34.0±7.2	0.427±0.063	50.6±9.6	0.635±0.095	0.68±0.10
				ND	35.3±6.9	0.444±0.066	49.1±9.5	0.620±0.107	0.72±0.07
			210, Abducted	D	31.9±5.8	0.400±0.051	45.0±8.5	0.567±0.084	0.71±0.10
				ND	34.2±6.0	0.430±0.054	45.0±8.7	0.570±0.098	0.76±0.09
			300, Abducted	D	30.0±6.0	0.376±0.018	43.0±8.8	0.540±0.087	0.70±0.08
				ND	32.0±6.2	0.400±0.018	42.4±8.5	0.534±0.098	0.76±0.11
Brown et al.[57]	18 Pro Pitchers (MLB)	27.0±4.3 (Pooled)	180, Neutral	D	38.2±6.0		57.7±10.5		0.67±0.10
				ND	38.1±6.6		52.7±7.9		0.71±0.10
			240, Neutral	D	33.8±4.7		54.9±7.2		0.61±0.10
				ND	32.6±5.1		49.2±6.2		0.66±0.07
			300, Neutral	D	30.8±5.7		52.4±8.4		0.65±0.06
				ND	29.2±5.2		44.9±7.1		0.65±0.09
	23 Pro Position Players (MLB)		180, Neutral	D	41.5±7.8		55.9±9.4		0.74±0.12
				ND	40.2±7.8		53.6±8.8		0.74±0.11
			240, Neutral	D	35.8±7.2		50.9±12.3		0.72±0.12
				ND	32.8±8.3		46.6±9.1		0.69±0.08
			300, Neutral	D	33.8±7.3		46.2±9.4		0.72±0.09
				ND	31.3±7.3		44.7±8.4		0.70±0.09
Chen[82]	10 Twn Col Pitchers	20.4±1.4	60, Abducted	D	32.5±5.1		45.4±10.7		
			180, Abducted	D	29.1±4.9		41.9±5.9		
			300, Abducted	D	23.0±4.4		36.8±9.5		
			500, Abducted	D	7.4±8.5		23.5±10.4		
Codine et al.[261]	Fra Baseball Players	19.8±2.6	60, Abducted	D	39.9±7.8		65.4±9.8		0.59±0.37
				ND	39.8±6.2		55.5±9.9		0.70±0.23
			180, Abducted	D	34.1±6.6		59.9±12.0		0.55±0.40
				ND	34.3±6.2		51.0±11.0		0.67±0.24
			300, Abducted	D	33.4±7.9		58.5±8.3		0.55±0.36
				ND	31.9±5.8		48.6±7.1		0.65±0.19
Cook et al.[262]	15 Col Pitchers	19.4±1.2	180	D					0.70
				ND					0.81
			300	D					0.70
				ND					0.81
	13 Controls	20.8±2.1	180	D					0.83
				ND					0.78
			300	D					0.87
				ND					0.79
Ellenbecker and Mattalino[230]	125 Pro Pitchers	22.6±2.0	210, Abducted	D	36.5±6.8	0.402±0.067	56.1±12.2	0.627±0.135	0.67
				ND	37.2±6.1	0.414±0.061	51.7±11.4	0.579±0.124	0.74
			300, Abducted	D	35.7±6.8	0.398±0.068	52.1±11.9	0.581±0.131	0.70
				ND	35.8±5.5	0.398±0.055	47.1±9.6	0.521±0.106	0.78
Hasegawa[83]	19 Jpn Col Baseball Players	19.3±0.9	180, Abducted	D		0.230±0.040		0.520±0.110	0.57
				ND		0.250±0.030		0.480±0.090	0.64
			300, Abducted	D		0.190±0.030		0.430±0.110	0.61
				ND		0.200±0.040		0.400±0.110	0.70
	17 Jpn Col Baseball Players w. Impingement	18.9±1.0	180, Abducted	D		0.220±0.050		0.490±0.080	0.56
				ND		0.230±0.040		0.440±0.090	0.65
			300, Abducted	D		0.170±0.005		0.400±0.100	0.60
				ND		0.190±0.040		0.380±0.120	0.69
Hasegawa[83]	12 Jpn Col Pitchers	19.6±1.1	60, Abducted	D	31.7±7.5		47.2±12.1		0.68±0.13
				ND	35.8±6.8		43.1±12.4		0.86±0.14
			180, Abducted	D	29.8±5.8		41.3±9.7		0.74±0.12
				ND	33.0±5.9		37.3±7.6		0.89±0.09
			300, Abducted	D	26.2±6.1		34.1±11.0		0.80±0.17
				ND	28.6±4.6		31.1±6.7		0.94±0.17

Table 16. (Continued)

Hinton[227]	26 HS Pitchers	16.4±0.8	90, Neutral	D	25.1±4.2	0.331±0.060	41.6±7.1	0.576±0.110	0.62±0.11
				ND	23.0±4.3	0.319±0.063	35.4±6.9	0.483±0.152	0.62±0.11
			90, Abducted	D	26.8±5.7	0.349±0.072	39.5±7.5	0.531±0.104	0.69±0.10
				ND	26.2±6.1	0.355±0.066	34.8±8.7	0.474±0.113	0.76±0.10
			240, Neutral	D	16.5±4.2	0.224±0.057	30.5±8.4	0.421±0.122	0.56±0.13
				ND	15.9±3.5	0.218±0.051	26.0±6.6	0.355±0.092	0.62±0.13
			240, Abducted	D	19.7±5.4	0.265±0.060	27.7±8.0	0.382±0.098	0.71±0.14
				ND	19.7±5.0	0.274±0.066	25.1±7.2	0.349±0.089	0.80±0.11
Mikesky et al.[81]	25 Col Pitchers	19.9±1.1	92, Abducted	D	62.1±3.1		96.3±8.9		0.69±0.05
				ND	60.7±2.8		88.0±7.2		0.76±0.05
			(Eccentric)	D	66.6±3.1		96.5±8.3		0.80±0.07
				ND	69.9±3.8		93.2±6.9		0.81±0.06
			212, Abducted	D	54.6±2.7		85.8±7.5		0.71±0.05
				ND	55.0±3.0		82.6±6.1		0.76±0.07
			(Eccentric)	D	64.9±3.5		102.1±7.5		0.72±0.06
				ND	67.9±3.5		98.2±6.2		0.74±0.05
			298, Abducted	D	53.2±2.8		84.0±7.7		0.72±0.05
				ND	50.3±2.8		80.1±6.4		0.75±0.09
			(Eccentric)	D	63.0±3.1		108.7±6.8		0.62±0.04
				ND	65.8±3.4		102.5±6.6		0.70±0.06
Nakayama and Kodama[263,264]	27 Jpn Pro Pitchers	24.7±4.4	90, Neutral	D	39.4±7.3		63.7±9.5		
				ND	38.5±6.3		59.9±9.0		
			180, Neutral	D	34.8±6.8		56.7±6.9		
				ND	33.9±6.0		52.8±8.0		
			270, Neutral	D	30.5±5.9		50.4±7.7		
				ND	29.4±5.7		46.9±7.5		
	28 Jpn Pro Position Players	25.0±4.5	90, Neutral	D	41.0±7.0		64.6±10.5		
				ND	41.7±7.1		63.8±10.1		
			180, Neutral	D	34.9±6.7		55.1±8.6		
				ND	36.2±6.1		54.3±9.7		
			270, Neutral	D	31.4±5.7		48.2±7.1		
				ND	31.3±4.9		48.0±9.0		
Nakayama and Kodama[265]	28 Jpn Pro Pitchers		90	D	41.6±6.0		66.4±11.7		
				ND	41.2±6.2		62.8±7.8		
			180	D	36.2±5.0		58.5±9.4		
				ND	35.7±4.9		55.6±7.4		
			270	D	31.9±5.2		52.2±9.2		
				ND	31.8±4.4		50.7±5.6		
	34 Jpn Pro Position Players		90	D	44.6±9.2		66.9±11.4		
				ND	44.4±7.2		65.9±10.5		
			180	D	38.9±8.4		57.3±9.6		
				ND	39.5±6.5		57.5±9.5		
			270	D	34.1±6.4		51.1±8.5		
				ND	34.6±5.4		51.7±7.7		
Newsham et al.[224]	16 Col Pitchers	19.3±0.9	180, Abducted	D	47.5±9.3	0.558±0.119	70.1±10.9	0.844±0.122	0.67
				ND	46.8±8.5	0.555±0.107	63.6±9.1	0.758±0.119	0.73
			300, Abducted	D	41.2±7.9	0.486±0.078	64.5±11.5	0.764±0.128	0.64
				ND	39.9±9.0	0.474±0.113	59.7±13.6	0.695±0.137	0.67
			450, Abducted	D	35.7±6.4	0.424±0.081	54.0±10.8	0.641±0.131	0.66
				ND	33.4±7.3	0.397±0.084	49.4±15.0	0.582±0.125	0.67
Noffal[225]	16 Col Position Players	20.1±1.3	300, Abducted	D	30.8±4.8		48.4±9.6		0.65
				ND	30.5±4.6		42.1±7.1		0.73
			(Eccentric)	D	55.0±6.6		71.8±9.4		
				ND	61.1±7.3		59.7±11.6		
	43 Controls	23.2±3.7	300, Abducted	D	30.4±5.4		41.9±11.0		0.75
				ND	29.1±5.0		30.4±5.4		0.80
			(Eccentric)	D	55.0±10.3		67.8±16.0		
				ND	59.4±12.8		53.8±9.4		
Pawlowski and Perrin[79]	10 Col Pitchers	19.6±1.4	60, Abducted	D	36.9±4.6		55.7±10.0		
			240, Abducted	D	27.7±3.5		40.0±6.0		
Shih[84]	10 Twn Col Baseball Players	20.6±1.5	60, Abducted	D		0.534±0.188		0.620±0.244	
			(Eccentric)	D		0.673±0.222		0.641±0.201	
			180, Abducted	D		0.409±0.158		0.487±0.247	
			(Eccentric)	D		0.818±0.213		0.768±0.225	
	17 Twn Col Baseball Players having UE injuries	20.1±1.4	60, Abducted	D		0.610±0.131		0.668±0.127	
			(Eccentric)	D		0.825±0.171		0.754±0.153	
			180, Abducted	D		0.538±0.129		0.529±0.086	
			(Eccentric)	D		0.894±0.171		0.848±0.171	

Table 16. (Continued)

Sirota et al.[223] [a]	25 Pro Pitchers (MiLB)	23.5±1.7	60, Abducted	D	66.2±18.0	0.865±0.239	70.0±20.5	0.895±0.268	0.98
				ND	59.9±15.5	0.776±0.209	70.9±16.7	0.925±0.239	0.85
			(Eccentric)	D	73.9±21.2	0.954±0.298	81.2±22.5	1.044±0.298	
				ND	68.6±15.7	0.895±0.209	79.2±21.3	1.044±0.298	
			120, Abducted	D	58.8±15.6	0.776±0.239	64.1±18.2	0.835±0.239	0.97
				ND	56.7±13.8	0.746±0.179	64.3±15.0	0.835±0.209	0.91
			(Eccentric)	D	76.5±18.0	0.984±0.268	84.5±21.2	1.104±0.298	
				ND	75.4±16.5	0.984±0.239	81.5±20.6	1.074±0.328	
Tai[76] [b]	45 Twn Col Baseball Players (No Shoulder Pain, 17 Pitchers)	21.1±2.6	90, Abducted		17.4±5.2		31.8±7.9		0.57±0.21
	36 Twn Col Baseball Players (Shoulder Pain, 14 Pitchers)	21.8±2.1			17.1±5.2		30.3±7.9		0.59±0.21
Timm[85]	241 HS Pitchers w. Impingement	16.2 (14 to 18)	60, Abducted(70°)	D	40.9±5.7		50.5±5.7		
				ND	35.6±3.5		46.5±5.3		
			120, Abducted	D	32.5±5.4		42.2±5.6		
				ND	28.8±4.2		39.6±4.4		
			180, Abducted	D	24.5±2.6		33.0±4.1		
				ND	26.8±3.0		33.0±3.7		
			240, Abducted	D	13.9±2.9		19.3±3.5		
				ND	16.6±2.4		22.3±1.2		
			300, Abducted	D	6.8±1.1		8.2±2.0		
				ND	10.9±0.4		11.3±1.5		
Wilk et al.[228]	150 Pro Pitchers (MLB)	23.4±3.4	180, Abducted	D	46.8±8.4	0.522±0.087	73.1±11.9	0.802±0.128	0.65±0.09
				ND	49.5±9.2	0.558±0.098	71.0±12.9	0.790±0.128	0.64±0.11
			300, Abducted	D	39.7±6.9	0.444±0.072	66.4±11.5	0.755±0.218	0.61±0.10
				ND	40.8±8.5	0.450±0.078	65.1±14.1	0.728±0.140	0.70±0.13
Wilkin and Haddock[226]	9 Col Pitchers, Pre Season	23±0.7	300, Abducted	D	30.2±1.7		50.7±2.3		
			450, Abducted	D	17.7±2.2		37.1±2.5		
	The Same Group, Mid Season		300, Abducted	D	29.5±2.2		49.7±2.5		
			450, Abducted	D	16.9±2.5		37.4±2.7		
	The Same Group, Post Season		300, Abducted	D	29.8±2.1		51.7±2.9		
			450, Abducted	D	18.2±2.4		38.3±2.5		

a. Normalized data relative to lean body weight instead of total body weight
b. External rotation strength measured eccentrically in this study

A.5 ISOMETRIC STRENGTH OF SHOULDER MUSCLE GROUPS IN BASEBALL PLAYERS

Table 17. Isometric strength of shoulder muscle groups in baseball players

Study	Subjects	Age	Arm	Elevators	Depressors	Protractors	Retractors	External	Internal	Unit
Chang et al.[266]	17 Twn Col Pitchers	19.8±1.0	D					16.2±2.9	14.9±2.3	Kg
Donatelli et al.[195]	39 Pro Pitchers (MiLB)	20.7	D					18.2±4.0	15.1±3.7	Kg
			ND					17.4±3.7	17.1±4.1	
Hasegawa[83]	12 Jpn Col Pitchers	19.6±1.1	D					29.1±1.9	39.3±9.3	Nm
			ND					27.6±2.6	38.3±9.2	
Kaplan et al.[87]	50 HS Pitchers Live in Warm States	16	D					16.1	18.7	Kg/Kg
			ND					16.8	18.4	
	50 HS Pitchers Live in Cold States	17	D					19.2	18.8	
			ND					19.2	17.2	
Miyashita et al.[102]	40 Jpn HS Baseball Players	17.0±0.7						0.55±0.15	0.57±0.16	Nm/Kg
Magnusson et al.[59]	47 Pro Pitchers (MiLB)	23.6±0.4	D					0.49±0.01	0.53±0.01	Nm/Kg
			ND					0.51±0.01	0.53±0.02	
	16 Controls	25.1±1.1	D					0.58±0.04	0.58±0.04	
			ND					0.55±0.03	0.51±0.03	
Mullaney et al.[78]	13 Col and Pro Pitchers	21±2	D					18.3±3.8	23.7±4.9	Kg
			ND					21.1±4.2	21.4±4.8	
Shiraki et al.[267]	8 Jpn Col Pitchers	21.8±1.3	D	20.7±4.0	11.3±2.8	13.9±1.3	14.1±0.6			Kg
			ND	20.8±2.7	12.1±2.4	12.6±1.3	13.4±1.1			
	8 Jpn Col Position Players	21.3±1.5	D	23.0±1.5	15.0±0.9	14.5±1.0	13.0±0.9			
			ND	22.0±2.3	12.6±3.1	14.4±2.3	13.7±1.1			
Tai[76]	44 Twn Col Baseball Players (No Shoulder Pain)	21.1±2.6	D			38.8±9.9	15.8±5.2			Kg
	35 Twn Col Baseball Players (Shoulder Pain)	21.8±2.1	D			38.1±10.0	15.0±5.2			
Trakis et al.[86] [a]	25 HS Pitchers	15.7±1.4	D					6.3	9.5	Kg
			ND					5.8	8.3	
Wilk et al.[75]	Pro Pitchers		D	37.6±6.4	10.0±2.7	32.2±4.5	28.1±3.6			Kg
	(Total n = 112)		ND	38.1±6.8	8.2±2.3	33.6±5.9	27.2±3.2			
	Pro Catchers		D	39.9±6.8	9.5±1.8	30.8±4.5	28.6±2.3			
			ND	38.6±3.6	7.3±2.3	33.1±4.5	26.8±3.2			
	Pro Position Players		D	29.5±5.4	8.6±2.3	26.3±4.5	25.9±2.7			
			ND	29.9±5.0	8.2±2.3	26.3±5.0	25.4±2.7			

a. Estimated from figures

A.6 ISOMETRIC STRENGTH OF INDIVIDUAL SHOULDER MUSCLES IN BASEBALL PLAYERS

Table 18. Isometric strength of individual shoulder muscles in baseball players

Study	Subjects	Age	Arm	Upper Trapezius	Middle Trapezius	Lower Trapezius	Rhomboid	Serratus Anterior	Supraspinatus	Unit
Chang et al.[266]	17 Twn Col Pitchers	19.8±1.0	D		13.7±2.2	17.8±3.4		30.9±5.2		Kg
Donatelli et al.[195]	39 Pro Pitchers (MiLB)	20.7	D ND		6.7±1.7 5.8±1.7	6.9±1.9 6.1±1.2			8.8±2.0 9.0±2.5	Kg
Laudner et al.[88]	24 Pro Pitchers	22.5±2.9	D			20.7±4.1		29.8±6.8		Kg
Magnusson et al.[59]	47 Pro Pitchers (MiLB)	23.6±0.4	D ND						0.65±0.01 0.71±0.02	Nm/Kg
	16 Controls	25.1±1.1	D ND						0.76±0.03 0.78±0.03	
Mullaney et al.[78]	13 Col and Pro Pitchers	21±2	D ND		9.4±2.2 9.6±2.3	9.9±2.9 9.8±2.8	10.5±2.6 10.3±3.0		11.5±1.9 13.0±2.8	Kg
Tai[76]	44 Twn Col Baseball Players (No Shoulder Pain)	21.1±2.6	D	47.1±9.2	21.4±5.4	15.0±3.7				Kg
	35 Twn Col Baseball Players (Shoulder Pain)	21.8±2.1	D	46.7±9.3	20.5±5.4	12.6±3.8				
Trakis et al.[86 a]	25 HS Pitchers	15.7±1.4	D ND		3.1 2.5	3.8 3.0	3.4 3.2		4.1 3.8	Kg

a. Estimated from figures

APPENDIX B

FREDDIE H. FU, MD. GRADUATE RESEARCH AWARD LETTER

University of Pittsburgh
School of Health and Rehabilitation Sciences
Department of Sports Medicine and Nutrition
Neuromuscular Research Laboratory
Department of Orthopaedic Surgery

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May 24, 2011

Dear Yungchien:

We are happy to inform you that your research application "The effect of scapular kinematics, glenohumeral range-of-motion, and shoulder muscle strength on kinematics and kinetics of maximum effort baseball throwing" has been awarded the 2011 Freddie H. Fu, MD Graduate Research Award.

The funding period for this award is June 1, 2011 through May 31, 2012. Your application and budget has been forwarded to our financial administrator. He will contact you regarding your budget and management of funds.

A progress report will be required after six months. Additionally, a final report, in the form of a thesis, dissertation, or manuscript submission must be submitted to the Department of Sports Medicine and Nutrition Faculty upon completion of the study.

Respectfully,

Timothy C. Sell, PhD, PT

Director, Graduate Studies in Sports Medicine
School of Health and Rehabilitation Sciences
University of Pittsburgh

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