FACTORS INFLUENCING UPPER EXTREMITY TISSUE

CHARACTERISTICS AND INJURY IN YOUTH OVERHEAD ATHLETES

by

Aaron Struminger

A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Biomechanics and Movement Science

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ABSTRACT

Despite previous research and proposed intervention strategies, upper extremity injuries and surgeries in youth overhead athletes continues to rise. A lack of knowledge about factors such as age, sport specialization, and overuse pathomechanics are likely reasons for the continued high injury rate. Incomplete information about underlying tissue characteristics and insufficient knowledge transfer from the laboratory to field setting, limits the ability of sports medicine professionals to fully understand these injuries. The purpose of this study was to investigate how upper extremity tissue characteristics and injury may differ among those who participate in separate sports, specialize earlier in their sport, and display various biomechanical patterns. Musculoskeletal ultrasound allowed measurement of tissue characteristics, and three-dimensional motion capture techniques examined the relationship between biomechanical variables and injury history. Biomechanical angles from high speed, commercially available video cameras were compared with laboratory data to determine whether clinically applicable tools can identify pitchers with injury history or higher upper extremity joint loads. Differing from non-overhead athlete controls, the results of this study indicated that humeral retrotorsion and range of motion are similar among athletes of various ages. Bilateral soft tissue differences are only present in collegiate athletes. Sport and degree of specialization did not

significantly impact tissue characteristics. These findings suggest that overhead sport participation produces bony adaptations participation before skeletal maturity, whereas the development of bilateral soft tissue differences occurs later. Three-dimensional biomechanical analysis accurately differentiated pitchers with and without injury history. Pitchers with a previous injury presented with limited shoulder abduction at the point of maximal external rotation. While some two-dimensional techniques were valid compared to three-dimensional analysis, they did not accurately identify previous injury. Separating groups based on normative and non-normative pitching mechanics did not differentiate between pitchers who experienced more upper extremity joint loading. Based on these findings, clinicians may want to identify pitchers who drop their arms at maximum external rotation. They should use caution when examining other biomechanics, as variability in pitching mechanics often supersedes injury group identification. Clinicians should also promote age specific intervention programs which specifically address underlying anatomical differences associated with each population.

Chapter 1

LITERATURE REVIEW

Shoulder

The shoulder is one of the most commonly injured joints in athletics, and 30% of collegiate overhead athletes seek medical attention during their athletic careers for shoulder injuries (Agel, Palmieri-Smith, Dick, Wojtys, & Marshall, 2007; Dick et al., 2007; Laudner & Sipes, 2009; S. W. Marshall, Hamstra-Wright, Dick, Grove, & Agel, 2007; Powell & Barber-Foss, 1999; Robinson, Corlette, Collins, & Comstock, 2014). The expense per injury is greater than that of all other joints (Knowles et al., 2007). The cost of this care may be so high because the chronic nature of shoulder injuries leads to high recurrence rates that may eventually require surgery (Bonza, Fields, Yard, & Dawn Comstock, 2009; Dick et al., 2007; Rechel, Collins, & Comstock, 2011). To effectively prevent and treat these injuries before surgery, clinicians should understand the potentially deleterious adaptations at the shoulder including limited range of motion, soft tissue hypertrophy, and abnormal bony development in overhead athletes and their effects on pain.

Most recent research has tried to explain upper extremity changes in overhead athletes by focusing on baseball and extrapolating those findings to other sports. Studies on adult baseball players consistently show greater external rotation, posterior

capsule thickness, and humeral retrotorsion are greater, but less internal rotation less on the dominant arm compared to the non-dominant arm (Hurd et al., 2011; Meister et al., 2005; Pieper, 1998; Tehranzadeh, Fronek, & Resnick, 2007; Thomas et al., 2011; R. J. Whiteley, Ginn, Nicholson, & Adams, 2009; Yamamoto et al., 2006). These adaptations may start at a young age because of the high UE loads experienced by youth athletes throwing a baseball. Growth changes can account for some of the deficits in strength in the youth population, as an extremely large increase in muscle area occurs between age 13 and 15 while fiber density drastically decreases and the percentage of type II muscle fibers grows (Lexell, Sjostrom, Nordlund, & Taylor, 1992). Research on children 13 or younger also indicates that voluntary muscle activation is lower compared to an adult population, and the power developed by pre-pubertal athletes (mean age = 10.8) is 13% less than that measured in teenagers (mean age – 16.3) (Belanger & McComas, 1989; Beneke, Hutler, & Leithauser, 2007). Even though the velocity and subsequent stress on the throwing arm is lower than in adults, the musculature still appears to be overloaded, as youth baseball players present with similar adaptations as adults on a smaller scale (Astolfi, Struminger, Royer, Kaminski, & Swanik, 2015). The changes suggest that the shoulders of overhead athletes are altered by sport participation at a young age.

Baseball may provide a good model for the shoulder because throwing and other dynamic overhead activities (i.e. spiking, serving, etc.) are divided into analogous phases and have similar muscle activation patterns (Pink, Perry, Browne, Scovazzo, & Kerrigan, 1991; Rokito, Jobe, Pink, Perry, & Brault, 1998; Ryu,

McCormick, Jobe, Moynes, & Antonelli, 1988). The model of baseball has also been used because overhead athletes commonly experience similar injuries, especially at the rotator cuff (Sein et al., 2010; van der Hoeven & Kibler, 2006; Walch, Boileau, Noel, & Donell, 1992; Wang & Cochrane, 2001). However, some differences exist between overhead sport movements that lead to variations in pain development, loss of function, and disability. For instance, the volleyball spike and swimming stroke only produce 55-70% of the muscular activity observed in the baseball throwing (Pink et al., 1991; Rokito et al., 1998; Ryu et al., 1988). A more in-depth examination of biomechanics has determined that shoulder, elbow, and wrist velocities actually occur earlier in the tennis serve than the baseball throw (Reid, Giblin, & Whiteside, 2015). These results suggest that slight sport differences, such as holding onto a racquet throughout the tennis serve, higher ball contact in volleyball, significantly more overhead repetitions with water resistance in swimming, and a slightly heavier ball in softball may produce small biomechanical variations that cause the shoulder to be stressed differently. If the shoulder mechanics are slightly altered in each sport, then different glenohumeral adaptations may occur and cause pain during an athlete's competitive career. Therefore, the purpose of this part of the literature review is to examine shoulder adaptations in response to overhead sports other than baseball in youth, adolescent, and adult athletes and examine their implications for injury.

Range of Motion

<u>Adults</u>

Athletes in overhead sports other than baseball commonly present with internal rotation deficits and external rotation gains on the dominant arm that are varied in magnitude based on sport. Tennis players exhibit the highest side-to-side range of motion differences, with professional and collegiate athletes experiencing a 12-16° reduction of internal rotation and a 6-9° increase in external rotation on the dominant arm compared to the non-dominant arm (Ellenbecker, Roetert, Bailie, Davies, & Brown, 2002; Moreno-Perez, Moreside, Barbado, & Vera-Garcia, 2015; Myers et al., 2007; Schmidt-Wiethoff, Rapp, Mauch, Schneider, & Appell, 2004). This range of motion difference is also observed in most amateur tennis players (Marcondes, de Jesus, Bryk, de Vasconcelos, & Fukuda, 2013; Torres & Gomes, 2009), but one study, which examined recreational females, did not observe a significant difference between the dominant and non-dominant arm (Stanley, McGann, Hall, McKenna, & Briffa, 2004). The variation between the studies on amateur tennis players is likely a result of the participation differences between the athletes studied. In professional tennis players, limited internal rotation has been previously correlated to years of play and age (Moreno-Perez et al., 2015). In the population of female players who did not reflect bilateral deficits, only 39% began tennis participation before 13 years of age, and most only participated in their sport two sessions per week (Stanley et al., 2004) whereas professional tennis players begin sport around 7 years of age on average and practice more often (Moreno-Perez et al., 2015). Therefore, the limited adaptation in

these recreational females may be a result of the age at which these athletes began playing tennis, and the intensity at which they play, rather than the sport itself. Based on this combined information, it appears that tennis participation does create significant range of motion changes on the dominant arm.

Although tennis players manifest with large side-to-side differences in range of motion, other unilateral athletes do not reflect as much difference between their dominant and non-dominant arms. Elite, adult softball and volleyball players only exhibit 3-6˚ of internal rotation loss and 1-4˚ of external rotation gain (Baltaci & Tunay, 2004; Dover, Kaminski, Meister, Powers, & Horodyski, 2003; Dwelly, Tripp, Tripp, Eberman, & Gorin, 2009; Forthomme, Croisier, Ciccarone, Crielaard, & Cloes, 2005; Hibberd, Oyama, Tatman, & Myers, 2014; Schwab & Blanch, 2009; Wang & Cochrane, 2001). These slight range of motion changes, while significant, are similar to those observed in adults who do not participate in overhead sports, suggesting that they may be acquired naturally rather than by sport-specific means (Shonk, Struminger, Kaminski, Edwards, & Swanik, 2015; Torres & Gomes, 2009). When examining amateurs, adult volleyball players present similar external rotation gains (2˚) but slightly more internal rotation loss (9˚) on the dominant arm compared to other elite softball and volleyball athletes (Reeser, Fleisig, Bolt, & Ruan, 2010). Unlike tennis athletes, amateur and elite volleyball players are well-matched regarding years of sport participation (Baltaci & Tunay, 2004; Reeser et al., 2010), so the range of motion adaptation produced specifically by high volume volleyball training and competition remains unclear.

Like volleyball players, softball players, and adult controls, most studies indicate that elite, adult swimmers present with a small, 4°, limitation in internal rotation on their dominant arms with a comparable 1-7° increase in external rotation (Beach, Whitney, & Dickoff-Hoffman, 1992; Riemann, Witt, & Davies, 2011). However, data on adult amateur swimmers are conflicting. For instance, one a study reported a similar motion shift for elite swimmers, while another found 12° of limited internal rotation on the dominant side compared to the non-dominant side (Riemann et al., 2011; Torres & Gomes, 2009). Because both authors controlled for sport history, the observed differences in range of motion between studies on recreational swimmers may have resulted from stroke technique differences. Adult swimmers who do not have as much training may use the dominant arm to create more propulsive force than the non-dominant arm, thereby creating the side-to-side range of motion difference (Torres & Gomes, 2009). In all cases, the amateur group started swimming approximately 10-20 years later than the elite group, who typically started swimming around 8-10 years old (Riemann et al., 2011; Tate et al., 2012; Torres & Gomes, 2009).

Youth/Adolescents

Across sports, youth and adolescent athletes demonstrate more internal rotation than their adult counterparts (Cools, Palmans, & Johansson, 2014; Ellenbecker et al., 2002; Riemann et al., 2011; Shanley & Thigpen, 2013; Tate et al., 2012; Werner et al., 2005). However, participating and specializing in sport at a young age may create

shoulder range of motion adaptations in overhead athletes that mimic those in adults. Upon observation, adolescent tennis (10-15°), softball (3°), and swimming (3-5°) athletes do exhibit almost identical side-to-side internal rotation differences as adults who participate in the same sport (Cools, Witvrouw, Declercq, Vanderstraeten, & Cambier, 2004; Ellenbecker, Roetert, Piorkowski, & Schulz, 1996; Riemann et al., 2011; Shanley, Rauh, Michener, & Ellenbecker, 2011; Werner et al., 2005). However, the effects of early participation and sport specialization cannot be determined because these athletes began playing their sport at an average age of 8-9 and were not divided into groups by age at which participation began (Moreno-Perez et al., 2015; Shanley, Michener, Ellenbecker, & Rauh, 2012; Tate et al., 2012). Furthermore, internal rotation adaptations have not been examined in volleyball, the only sport in which participation typically begins later, or around 10-12 years of age (Reeser et al., 2010; Schwab & Blanch, 2009).

While the effects of sport specialization on internal rotation are yet to be determined, a change in range of motion does appear to occur over time. Tennis athletes younger than 14 exhibit 5-6° more internal rotation than those 14-16 (Cools et al., 2014; Riemann et al., 2011; Tate et al., 2012). These tennis athletes under 14 also present with slightly smaller side-to-side internal rotation adaptations (Cools et al., 2014; Riemann et al., 2011), suggesting that sport participation continues to augment internal rotation loss as these youth athletes age. Even though tennis players lose internal rotation in adolescence, external rotation values do not appear to change in these athletes (Cools et al., 2014). This shift of range of motion at a young age seems

to indicate that adaptation in adult tennis players actually begins before these athletes reach skeletal maturity.

Unlike tennis players, swimmers do experience external rotation losses in addition to their slight internal rotation deficits over time (Riemann et al., 2011; Tate et al., 2012). This divergent result may be a result of sport biomechanics, as tennis players experience high loads forcing their shoulders into external rotation during the serve, while the swimming stroke does not require such excessive shoulder motion. Another factor that may elucidate differences between tennis players and swimmers is overhead movement volume. While both groups continue to increase volume with age, tennis players can focus on strokes that do not focus on overhead movement while a large proportion of the increased activity in swimmers remains overhead in nature (Afework, ; Amateur Swimming Association,). Therefore, the shoulder may tighten to counteract these excessive quantities of dynamic overhead load in swimmers but not in tennis players. While differences exist between tennis players and swimmers, a comparison of shoulder rotation in youth volleyball and softball players is not possible due to a lack of information and differences in data collection methodologies across studies. However, from the previous research on swimming and tennis, it does appear that participation in overhead activity produces discrete range of motion changes at a young age that are dependent on sport participation.

Implications

Many studies are dedicated to assessing range of motion differences among overhead athletes, but few examine the implications of these adaptations in regards to pain and injury. Burkhart et al. (2003) suggested that internal rotation loss was the "seminal event" that leads to pain in overhead throwers. This motion restriction may create more stress on the soft tissue of the shoulder because the posterior musculature would be required to decelerate the arm in a shorter time frame. However, the authors do not specify whether this theory also applies to other overhead athletes.

Examining the relationship between pain and range of motion on overhead athletes, other than baseball players, produces contradictory results depending on the motion being measured. An analysis of amateur tennis athletes observed that those with current pain have significant external rotation gains compared to those without pain (Marcondes et al., 2013). These results have not been supported by other literature, and the age of the athletes, undocumented sport history, or the time of data collection could have confounded the results.

While the relationship between external rotation and pain is inconclusive, internal rotation loss is consistently observed in unilateral athletes with current pain and previous injury history (Marcondes et al., 2013; Moreno-Perez et al., 2015). Prospectively, a loss of internal rotation on the dominant arm also appears to precede shoulder injury in youth softball pitchers, but the scope of that study is limited because of a small sample size (Shanley et al., 2011). In athletes who compete in a sport that produces bilateral overhead stress, the relationship between internal rotation loss and

pain does not appear, as current pain across age groups in swimmers does not correlate well with limited internal rotation (Beach et al., 1992; Tate et al., 2012). Overall, these findings seem to indicate that internal rotation loss and pain are related in unilateral overhead athletes, but the lesser forces required for swimming propulsion may not produce enough of a range of motion change to be clinically meaningful.

Posterior Shoulder Tightness

Adults

While a plethora of literature exists examining internal and external range of motion in overhead athletes who participate in sports other than baseball, much less exists quantifying measures of posterior shoulder tightness. Internal rotation has been commonly used to measure posterior capsular contracture, but it does not account for the potential involvement of other anatomical structures, such as the rotator cuff and deltoid, which also contribute to tightness in the posterior shoulder (Michener, McClure, & Karduna, 2003; Myers et al., 2007). Instead, horizontal adduction measures have been used to estimate posterior shoulder tightness. When examining these measures, tennis players do exhibit side-to-side differences (Marcondes et al., 2013; Myers et al., 2007). Collegiate and amateur tennis athletes present with 8-9° more tightness on the dominant arm compared to the non-dominant arm (Marcondes et al., 2013; Myers et al., 2007). Professional volleyball players also display an increased distance from the lateral epicondyle to the acromion of the dominant arm during

horizontal adduction when compared bilaterally, but, like range of motion, it is about half of the difference (2.5-4°) of that observed in tennis players (Baltaci & Tunay, 2004; Kugler, Kruger-Franke, Reininger, Trouillier, & Rosemeyer, 1996). Swimmers do not appear to present with this side-to-side adaptations, as the difference between arms on posterior shoulder tightness is less than 1° (Shonk et al., 2015). Even though no variation exists bilaterally, the shoulders of swimmers still seem to adapt, as their observed horizontal adduction is similar to that of the dominant arms of tennis players and significantly less than age-matched controls (Amateur Swimming Association, ; Myers et al., 2007; Shonk et al., 2015). While differences in posterior shoulder tightness do appear between sports, inconsistencies in scapular stabilization between studies may have confounded the results (Baltaci & Tunay, 2004; Kugler et al., 1996; Myers et al., 2007). Because of the lack of consistent methodology and limited number of studies, more research is needed to determine the extent of posterior shoulder tightness on adults in a variety of overhead sports.

Youth/Adolescents

    Data on posterior shoulder tightness in youth and adolescent overhead sports, other than baseball, are also lacking. As, to our knowledge, only 2 studies have examined measures of posterior shoulder tightness in young athletes (Shanley et al., 2012; Struminger & Swanik, 2015). One of these studies, which evaluated adolescent softball players, found 6° more posterior shoulder tightness on the dominant side compared to the non-dominant side (Shanley et al., 2012). Conversely, youth

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swimmers had no observable difference between shoulders (Struminger & Swanik, 2015). These studies show the development of posterior shoulder tightness in unilateral, but not bilateral, overhead athletes at a young age. However, the interpretability of those investigations is limited by small sample sizes. Combined, only 32 young overhead athletes were examined. Therefore, larger samples are needed across multiple sports to determine whether these posterior shoulder tightness changes are consistent across youth/adolescent populations in overhead sports.

Implications

Using theoretical cadaver models, a tightening of the posterior capsule can lead to a superior shift of the humeral head that increases contact pressure on the coracoacromial ligament and rotator cuff (Harryman et al., 1990; Mihata et al., 2012; Muraki et al., 2010). This relationship between posterior capsule tightness and pain is confirmed when examining athletes in various overhead sports. Adult tennis and volleyball players who reported current shoulder pain exhibited significantly greater posterior tightness on the dominant shoulder than athletes who did not report pain (Kugler et al., 1996; Marcondes et al., 2013). Prospective data on youth softball pitchers also indicate that players who went on to suffer injury had 12° more posterior shoulder tightness on the dominant arm at the beginning of the season compared to those who did not get injured (Shanley et al., 2012). However, this association between posterior shoulder tightness and pain was not present in youth or adult swimmers (Shonk et al., 2015; Struminger & Swanik, 2015). These inconsistencies

between posterior shoulder tightness and pain likely indicate that different adaptations may lead to pain in various overhead sports. Another potential explanation for the differences detected between sports is the magnitude of posterior capsule tightness observed. The studies demonstrating a significant relationship between posterior capsule tightness and pain found relative group differences of more than double than that of the swimming studies in which posterior capsule tightness was not related to pain (Kugler et al., 1996; Marcondes et al., 2013; Shanley et al., 2012; Shonk et al., 2015; Struminger & Swanik, 2015). Therefore, a certain magnitude of posterior shoulder tightness may need to be reached before shoulder pain develops in overhead athletes, but this theory has not been examined in previous research.

Humeral Retrotorsion

<u>Adults</u>

Like posterior capsule tightness, little research has been conducted to determine the magnitude of humeral retrotorsion in adult athletes who play overhead sports other than baseball. While not directly measured in tennis, computer simulations predict that a twisted humerus is a likely consequence of serving (Taylor et al., 2009). In other unilateral overhead sports, adult athletes present with more humeral retrotorsion on the dominant arm compared to the non-dominant arm (Hibberd et al., 2014; Schwab & Blanch, 2009; R. J. Whiteley et al., 2009). However, the data provided in previous literature on softball players were inconsistent, as one study noted a 7.9° side-to-side difference in collegiate athletes while the other noted a

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13.7° difference in Master's athletes (Hibberd et al., 2014; R. J. Whiteley et al., 2009). If the humeral retrotorsion values from these two softball studies are averaged, they are very similar to the 9.6° humeral retrotorsion difference between shoulders observed in adult volleyball players (Schwab & Blanch, 2009). The discrepancy between the softball studies may be a direct result of population age examined because proximal physeal growth plate of the humerus may not close in some subjects until after 17 years of age (Kwong, Kothary, & Poncinelli, 2014). Furthermore, the Master's athletes had been playing their sports for a much longer period, so the dominant humerus could continue to slightly adapt over time in response to external stresses.

Based on the bilateral nature of the sport, one may not expect to observe side-to-side humeral retrotorsion differences in adult swimmers. This assumption was confirmed by Shonk et al. (2015), who observed similar humeral retrotorsion variations when comparing the dominant and non-dominant shoulders of swimmers and adults who do not participate in overhead sports (R. J. Whiteley et al., 2009). Furthermore, these authors found that humeral retrotorsion was almost equal between groups, suggesting that swimming does not create humeral adaptation (Shonk et al., 2015). Based on the small sample of studies, swimming does not seem to create side-to-side humeral retrotorsion differences greater than those observed in adults who do not participate in overhead sport (Shonk et al., 2015; R. J. Whiteley et al., 2009). However, unilateral overhead sport participation appears to produce humeral retrotorsion differences between shoulders in adults that are only slightly less than

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those observed in baseball players, but the limited number of subjects in these previous studies limits generalization to all overhead athletes (Hibberd et al., 2014; Thomas et al., 2012; R. J. Whiteley et al., 2009).

Youth/Adolescents

While no data are available on young volleyball or tennis players, adolescent softball players display humeral retrotorsion values (11.7˚) comparable to adults who play the same sport (R. J. Whiteley et al., 2009). Unlike their adult counterparts, youth swimmers do present with slight side-to-side differences in humeral retrotorsion, but these changes are similar to those observed in non-overhead athletes (Greenberg, Lawrence, Fernandez-Fernandez, & McClure, 2017; Struminger & Swanik, 2015; R. J. Whiteley et al., 2009). The discrepancies between these studies on youth and adult athletes may be present because sport history, a potentially confounding variable, was not controlled. Despite the results, the magnitude of side-to-side humeral retrotorsion difference in youth and adolescent swimmers is similar to non-overhead athletes of the same age and much less than that observed in unilateral sports (Struminger & Swanik, 2015). Therefore, the bilateral sport of swimming may not provide enough shoulder stress to cause humeral adaptation at a young age, while softball seems produce humeral adaptation at an early age. However, few studies are available to confirm these results.

While the measurement of humeral retrotorsion has recently increased with the affordability and precision of musculoskeletal ultrasound, its consequences have not been well explored. Theoretically, adaptation towards more retrotorsion may be advantageous by limiting anterior capsular stress and improving the available space for the rotator cuff tendons (Meister et al., 2005; Pieper, 1998; Yamamoto et al., 2006). However, the impact of these changes on shoulder pain as a result of tennis, softball, volleyball, and swimming is relatively unknown. The only studies examining the relationship between humeral retrotorsion and injury in these populations come from swimming. Previously injured adult swimmers exhibited significantly less more humeral retrotorsion than the non-injured group, but no relationship between groups was observed in youth swimmers (Shonk et al., 2015; Struminger & Swanik, 2015). The lack of data on the effects of humeral retrotorsion limit the applicability of the results across sports. The deficiency of high quality studies highlights a need for more quantitative investigations on the effects humeral retrotorsion in tennis, volleyball, softball, and swimming. Further prospective studies are also needed to determine the long-term ramifications of bony adaptation in specific overhead sports.

Summary of Shoulder

An adaptation towards greater external rotation, posterior shoulder tightness, and humeral retrotorsion with less internal rotation seems occur at an early age in athletes who participate in unilateral overhead sports. However, the excessive humeral

retrotorsion does not appear to occur in swimmers, and these adaptations occur at different magnitudes depending on sport participation. While the lack of data on posterior shoulder tightness and humeral retrotorsion limits the application of these results, clinicians should begin to consider an athlete's primary sport before developing shoulder prevention and treatment programs.

Medial Elbow/Ulnar Collateral Ligament

The shoulder has likely received more research attention than other upper extremity joints because of its complexity and the multitude of muscles that help produce movement. However, shoulder malposition and strength can affect other joints down the kinetic chain, such as the elbow (Miyashita et al., 2008; Shanley & Thigpen, 2013; Werner, Murray, Hawkins, & Gill, 2002). The elbow warrants more research consideration because of the perceived "Tommy John surgery epidemic" in professional baseball and the fact that, since 2009, shoulder surgeries in Major League Baseball have declined while elbow surgeries have risen sharply (Arthur, 2015). This trend is also evident in high school baseball, as the percentage of injuries to the elbow compared to other parts of the body has steadily increased almost 75% while the same comparison at the shoulder has decreased by about 10% since 2006 (Comstock, Yard, & Collins, 2007; Comstock, Currie, & Pierpoint, 2015). Additionally, the rate of surgery per 100,000 people in the general population has increased threefold in New York State in the past 10 years, with the primary rise in frequency due to the growing amount of surgeries performed on 17-20 year olds (Hodgins, Vitale, Arons, & Ahmad,

2016). While much of this increase has been attributed to playing baseball, overhead athletes who play tennis and softball have medial elbow pain and experience UCL injuries as well (Azar, Andrews, Wilk, & Groh, 2000; Thompson, Jobe, Yocum, & Pink, 2001).

Valgus stress placed on the UCL is the primary cause of medial elbow injuries (Hotchkiss & Weiland, 1987; King, Brelsford, & Tullos, 1969). This valgus load primarily occurs just before maximum external rotation and at the beginning of the acceleration phase during dynamic overhead activity (Nissen et al., 2007; Wight, Richards, & Hall, 2004). Elbow range of motion in these phases generally ranges between 20-85˚of flexion (Fleisig et al., 2006; Nissen et al., 2007), corresponding to the angles in which the anterior band of the UCL is taut (Callaway et al., 1997). Therefore, the anterior bundle of the UCL, which is responsible of the majority of elbow stability (M. C. Ciccotti et al., 2014), is a common the site of a medial elbow injury. While UCL sprains may happen acutely, more often repetitive stress from overhead activity creates medial elbow laxity over period of time (Chen, Rokito, & Jobe, 2001). These chronic stresses could then cause adaptation to the bony and soft tissue structures of elbow, similar to those observed at the shoulder (Hibberd et al., 2014; Tehranzadeh et al., 2007; Thomas et al., 2012; R. J. Whiteley et al., 2009). However, little data exist to quantify those changes in softball and tennis athletes. Therefore, the purpose of this section of the literature review is to examine adaptation to the medial elbow in baseball athletes.

Radiography

        The first diagnostic test performed after clinical evaluation of an acute elbow injury is often a plain radiographic image (Kane, Lynch, & Taylor, 2014). These radiographs can also help physicians evaluate the presence of chronic conditions that can occur at the medial elbow, such as bone spurs and osteochondral defects (Shapiro & Preston, 2009). Wright et al. (2007) found that even asymptomatic pitchers had an average of 7 elbow abnormalities upon review of X-ray film, the most common of which are olecranon, medial humerus, and ulna osteophytes. These radiographic findings were correlated to innings pitched, suggesting that a progressive change occurs to the elbow as a result of throwing. The chronic bony changes do not impact injury risk, as pitchers who went on to be placed on the disabled list displayed a similar number of abnormalities than those who did not suffer an injury (Wright et al., 2007). Therefore, other diagnostic tests may give more information about elbow adaptation than plain radiographs.

Magnetic Resonance Imaging

        Magnetic resonance imaging (MRI) is the preferred diagnostic test for physicians when evaluating chronic elbow pain (Stevens & McNally, 2010). MRI can also be used to determine elbow tissue changes in asymptomatic athletes. An examination of a small group of professional baseball players with no injury history determined that 87% demonstrated some sort of UCL abnormality (Kooima, Anderson, Craig, Teeter, & van Holsbeeck, 2004). These adaptations ranged from avulsion of the UCL from the medial epicondyle in one participant to thickening in 13

of 16 athletes (Kooima et al., 2004). Since these baseball players were asymptomatic at the time of testing, the authors hypothesized that the adaptations could be a result of normal accommodation to throwing (Kooima et al., 2004). In a younger population, changes to the medial elbow on MRI are not as prevalent. Only 28% of athletes in this population demonstrated UCL thickness (Jazrawi et al., 2006). Furthermore, only 21% were observed to have a grade 1 change to the ligament, which is described as focal, linear, or diffuse signal present in the UCL (Jazrawi et al., 2006). The differences observed between the UCL adaptation in professional and adolescent baseball players may simply be a result of age and exposure. Professional pitchers have thrown more throughout their careers, and the ligament may undergo further tissue alteration as a result of that increased exposure. However, some youth athletes do experience morphological changes to the medial elbow, indicating that other factors such as sports specialization or poor mechanics may cause UCL adaptation.

Ultrasonography

Adults

Its lower cost with better portability and the ability to perform dynamic studies allow ultrasonography to be used instead of MRI to evaluate UCL injuries (Nazarian, McShane, Ciccotti, O'Kane, & Harwood, 2003). These factors also allow the UCL to be evaluated for abnormalities before symptoms become severe enough to seek medical attention. When examining the medial elbow via ultrasound, some adaptation does appear to take place in throwing athletes across age groups. The first study to

examine these changes was completed by Nazarian et al. (2003), who observed hypoechoic foci in 18 asymptomatic pitchers and anterior band calcifications in nine of the 26 pitchers studied. Conversely, few hypoechoic foci and no calcifications were observed on the non-dominant side of these athletes (Nazarian et al., 2003). The pitchers who displayed these abnormal findings had significantly greater professional sport participation than those with normal ultrasound grey-scale appearances (Nazarian et al., 2003). An examination of younger professional pitchers, aged 17-21 who had not played more than four professional seasons seems to corroborate this data, as significantly fewer of these athletes (26% hypoechoic foci, 30% calcifications) displayed anomalies in the UCL (A. Atanda Jr et al., 2015). While these findings are not surprising based on data from radiography and MRI, ultrasound findings do appear to predict UCL injury better than other diagnostic imaging techniques. The proportion of players with hypoechoic foci was 12% higher in athletes who went on to suffer a UCL injury than those who did not (M. G. Ciccotti et al., 2014). While these results were non-significant because of small sample size (M. G. Ciccotti et al., 2014), it does appear that performing ultrasonography in asymptomatic overhead throwers may be an important step in identifying athletes at risk for UCL injury.

Besides abnormal grey-scale appearance, valgus extension overload from pitching can create excess tissue proliferation and joint laxity. The dominant UCL of professional baseball pitchers has been measured to be between 6.2 and 6.3mm (A. Atanda Jr et al., 2015; Nazarian et al., 2003), which is about 1mm (16%) thicker than the non-dominant arm. As an athlete continues to pitch at the professional level, the

UCL continues to thicken (A. Atanda Jr et al., 2015). However, chronological age does not differentiate pitchers with medial elbow tissue proliferation (A. Atanda Jr et al., 2015). Medial elbow laxity has been found to occur along with adaptive UCL thickening at the medial elbow (Nazarian et al., 2003; Sasaki et al., 2002). At rest, there appears to be no difference in ulnohumeral joint gapping between arms of adult pitchers. As a manual valgus stress is applied or the arm is allowed to hang in a 90°/90° position off of the table the difference between arms becomes significant, with the space between trochlea of the humerus and coronoid process of the ulna being about one millimeter greater on the dominant arm (Nazarian et al., 2003; Sasaki et al., 2002). Unlike UCL thickness, ulnohumeral joint gapping is not affected by years of professional participation in pitchers aged 17-21. The average value of joint laxity observed in a younger group of professional pitchers was the same as that found in older pitchers (A. Atanda Jr et al., 2015; Nazarian et al., 2003). In terms of injury rate, it appears that professional athletes who suffer a subsequent UCL injury originally present with greater mean thickness (.73mm) and joint space gapping (.46mm) than those who do not become injured. These data suggest that evaluating UCL thickness and laxity via ultrasound may give clinicians an idea of at-risk athletes. Furthermore, the lack of change in ulnohumeral space with an applied joint stress in young professional athletes suggests that these changes may happen sometime in adolescence and supports future research in a young population.

Youth/Adolescents

The success of identifying UCL adaptation in adult athletes has led to the use
of similar methods on youth and adolescent baseball players. Because of its portability
Harada et al. (2006) attempted to use ultrasound to detect early injury in baseball
players aged 9-12 and encouraged further examination when sonographic
abnormalities were observed. While they were successful in noting abnormalities,
such as medial epicondylar fragmentation in 35 athletes (23%), a greater number, 62,
reported pain when throwing (Harada et al., 2006). Furthermore, medial epicondylar
tenderness was not present in 25% of the athletes with abnormalities (Harada et al.,
2006), suggesting that elbow adaptation can exist without pain in this population.

The adaptation of UCL thickening and medial elbow laxity does not appear to
exist as much in youth and adolescent baseball players as it does in adults. No
significant difference in UCL thickness or ulnohumeral joint space with stress as
measured with bilateral ultrasound (N. E. Marshall, Keller, Van Holsbeeck, &
Moutzouros, 2015). However, MRI does indicate that some (4/14) 12-18 year old
baseball players experience an adaptive thickening of the anterior band of the UCL,
and over the course of the season, the ligament becomes thicker (Jazrawi et al., 2006;
Keller et al., 2015). Changes in UCL thickness from pre- to postseason were
associated with an increased number of bullpen sessions. Since only a fraction of
youth athletes experience UCL thickening and tissue proliferation is exacerbated by
throwing more, it can be speculated that medial elbow adaptation is not a typical
adaptation in youth athletes. Instead, abnormal stress from poor mechanics or sport

specialization may cause these tissue alterations that have been associated with injury in adult pitchers.

Summary of Elbow

An adaptation towards abnormal appearance of the medial elbow, including osteophytes, UCL thickening, and ulnohumeral joint gapping when stress is applied, results from overhead throwing. This change appears to occur in professional and collegiate athletes around 17 or 18 years of age. However, some youth athletes do present with alterations in the medial elbow as well. These youth athletes seem to experience abnormal tissue proliferation because of increase load, but more research is needed to examine the exact causes of medial elbow adaptation in youth overhead athletes.

Chapter 2

OVERHEAD SPORT AND AGE IMPACT BILATERAL UPPER EXTREMITY TISSUE CHARACTERISTICS

Introduction

The upper extremity is a common site of injury in athletics. During dynamic overhead activity, the shoulder can rotate at speeds up to 7,500 degrees per second, creating excessive stress on the upper extremity (Fleisig, Andrews, Dillman, & Escamilla, 1995). The attempt to dissipate those high loads can lead to injury, and approximately 30% of overhead athletes will seek treatment for a shoulder injury during their collegiate careers (Laudner & Sipes, 2009). Repetitive valgus loading during the late cocking phase of the overhead motion can place the medial elbow structures at risk for injury (Fleisig et al., 1995). Based on increasing reconstruction rates in youth and adult athletes, the number of ulnar collateral ligament (UCL) failures has increased in recent years (Arthur, 2015; Fleisig & Andrews, 2012). Those rising injury rates at the elbow, and data suggesting almost half of these shoulder injuries are recurrent (Rechel et al., 2011), creates a need for better knowledge of underlying tissues and techniques to adequately prevent and treat these upper extremity pathologies.

While UCL reconstruction rates and the proportion of shoulder overuse injuries are increasing by 4.2% per year and 25% from 2007 to 2012, respectively (Bonza et al., 2009; Erickson et al., 2015; Robinson et al., 2014), the proportion of specific injuries across sport remains different. Baseball players suffer a higher percentage of elbow injuries on their throwing arm compared to athletes in other unilateral overhead sports such as softball and tennis (Roos et al., 2015). Superficial examination of that disproportion may initially be surprising because the biomechanics and muscle activation patterns required for optimal performance across overhead sports are almost identical (Pink et al., 1991; Reid et al., 2015; Ryu et al., 1988). Although similarities do exist, a more in-depth examination of sport biomechanics suggests that the tennis serve produces peak shoulder, elbow, and wrist velocities significantly earlier than the baseball throw when normalizing each activity to its endpoint (ball release in baseball and ball impact in the serve (Reid et al., 2015). Those variations indicate that the shoulder and elbow are likely positioned differently when peak loading occurs during each sport, creating discrepancies in the magnitude of tissue strain. External factors, like holding onto an object throughout the tennis serve, arm position at impact or release location, and bigger, heavier items like a softball or tennis racquet may also produce biomechanical variations that create sport-specific joint loading, tissue changes, and chronic injury.

Since many of these injuries to the upper extremity are a result of overuse, questions regarding the timing of when those pathologies begin are relevant. Previous research indicates that 32% of youth baseball pitchers, some as young as 9 years old,

report shoulder pain on their dominant arms within a two year period (Lyman et al., 2001). This patient related outcome is important because it may affect a young athlete's enjoyment of sport (Paul J McCarthy & Marc V Jones, 2007). One reason youth athletes may start having pain is that they use the same equipment as their adult counterparts, with developing tissues that could react differently to upper extremity loading. However, the majority of studies on overhead athletes focus on high school, collegiate, or professional athletes who have gone through puberty and are likely close to skeletal maturation. These studies may not be applicable to youth athletes, whose upper extremity growth plates have not closed and neuromuscular control is lacking (Beunen & Malina, 1988; Cline, 2009; Patel & Lyne, 2009). Therefore, an identification of early differences between the dominant and non-dominant arms of young overhead athletes, instead of relying on high school and collegiate data, may lead to better age specific prevention and rehabilitation programs.

To provide the best prevention and care to the injured shoulder in both youth and adult athletes, an exploration of the underlying tissue characteristics, which may lead to injury and pain, is needed. Most traditional research has focused on clinically-based measurements, such as posterior shoulder tightness and glenohumeral range of motion (ROM), to examine differences between the dominant and non-dominant arms of overhead athletes. Those techniques are often used because they have been linked to injury and recovery (Moreno-Perez et al., 2015; Myers, Laudner, Pasquale, Bradley, & Lephart, 2006; Tyler, Nicholas, Lee, Mullaney, & McHugh, 2010). Posterior shoulder tightness can increase contact pressure on the coacoacromial ligament and

rotator cuff, thereby heightening an athlete's risk for rotator cuff degredation and subacromial impingement (Mihata et al., 2012; Muraki et al., 2010). ROM deficits, especially in internal rotation are thought to be the seminal event in a pathological cascade leading to shoulder and elbow injuries (Burkhart et al., 2003). However, some authors have suggested that injuries are not statistically different in overhead athletes with and without glenohumeral internal rotation deficit (Shanley et al., 2011; Wilk et al., 2011), so more investigation on the relationship of those variables to pain is needed in a variety of overhead athletes.

One reason for the inconsistent data on these measurements may be that these variables fail to assess the underlying tissue changes that produce bilateral differences in range of motion. Advances in musculoskeletal ultrasound allow a cost-effective, quick, and safe alternative to examine shoulder tissue structures compared to Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) (Saini et al., 2000). Using novel techniques, sonographers can measure humeral retrotorsion (HR) and posterior capsule thickness to examine glenohumeral bony and soft tissue differences between arms in athletes who compete in unilateral overhead sports (Thomas et al., 2011; Thomas et al., 2012; R. J. Whiteley et al., 2009). Excessive posterior capsule thickness can limit glenohumeral ROM and precipitate glenohumeral joint pathomechanics in cadavers, similar to posterior shoulder tightness (Mihata et al., 2012; Muraki et al., 2010; Thomas et al., 2011). The relationship between HR is more complex, especially in youth athletes, because it may reduce load on the anterior capsule during overhead activity but may also create excessive stress to the growth

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plate leading to epiphyseal plate injuries (Pieper, 1998; Shanley & Thigpen, 2013). These sonographic techniques are relatively new and primarily focus on skeletally mature baseball athletes, but little is known about tissue development in young athletes or other unilateral overhead athletes who do not play baseball.

Unlike at the shoulder, sport and age comparisons of elbow clinical and anatomical measurements is possible because data on the elbow are lacking. The reason for this gap in the literature may be due to the fact that tightness in the ligamentous structures of elbow does not significantly restrict the flexion and extension ranges of motion that are the easiest to evaluate. Exposure to repetitive loads over time can create ligamentous laxity in some athletes, which has been measured by examining ulnohumeral joint space via ultrasound (M. G. Ciccotti et al., 2014; Nazarian et al., 2003). The UCL provides the largest restraint to medial elbow laxity and may adaptively thicken to compensate or safely absorb the valgus stress from dynamic overhead activity, (M. C. Ciccotti et al., 2014; M. G. Ciccotti et al., 2014; Nazarian et al., 2003). However, these changes have been primarily examined in adult pitchers with limited recent data published on youth and high school pitchers (A. Atanda et al., 2016; Tajika et al., 2016).

Because many tissue characteristics have not been examined among athletes at various ages or who participate in unilateral overhead sports other than baseball, the purpose of this study was to determine whether athletes who differ in age and sport participation exhibit distinctive tissue characteristics on their dominant arms compared to their non-dominant arms. A secondary purpose was to examine whether any of

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those tissue characteristics were related to pain history. We hypothesized that college-aged athletes would present with more side-to-side tissue differences than youth athletes and that baseball players would exhibit more bilateral asymmetry than softball and tennis players.

Specific Aim 1: Description and Results

To identify whether athletes who differ in age, sport, degree of specialization, and pain exhibit distinctive upper extremity tissue characteristics.

H1.1 Tennis and softball athletes will present with less side-to-side differences in upper extremity tissue characteristics than baseball athletes.

>Collegiate softball players exhibited less total range of motion on their dominant side than youth softball players, a result that was not present in other sports. Baseball players exhibited more posterior capsule and ulnar collateral ligament thickness than softball or tennis athletes, but those differences did not reach statistical significance.

H1.2 Youth athletes will present with less side-to side differences in upper extremity tissue characteristics than college-aged athletes.

>Youth athletes presented with less side-to-side differences in posterior shoulder tightness, posterior capsule thickness, and ulnar collateral ligament thickness than college-aged athletes. However, glenohumeral range of motion, humeral retrotorsion, and ulnohumeral joint space were similar among populations.

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H1.3 Glenohumeral internal rotation, humeral retrotorsion, posterior capsular thickness, UCL thickness, and ulnohumeral joint gapping will be significantly correlated to pain in overhead athletes.

No significant correlations were present when examining the entire population. However, posterior shoulder tightness and range of motion measures were related to pain in softball players. Posterior capsule thickness was related to elbow pain in both youth softball and tennis athletes.

Methods

Experimental Design

This study utilized a post-test only design. The independent variables were age and sport played. The dependent variables were glenohumeral internal rotation (°), glenohumeral external rotation (°), posterior shoulder tightness (°), posterior capsule thickness (mm), humeral retrotorsion (°), UCL thickness (mm), and ulnohumeral joint space (mm). Measures of maximum shoulder and elbow pain over an athlete's career were also collected. Exploratory variables of the age which the athlete began playing his/her sport and maturational stage were collected to ensure that they did not influence analysis of the primary variables. Arm tested first was randomized for each participant.

Participants

132 male and female volunteers were recruited for this study. All participants were overhead athletes, who were currently competing in organized baseball, softball, or tennis competitions and had maintained that status for at least two competitive seasons. Participants were excluded from the study if they had undergone a shoulder or elbow surgery within the last year or had been diagnosed with any disorder that prevents typical anatomical development. Participants were stratified into groups based on age and sport (Table 1). Youth athletes ranged from 11-14 years of age, and college-aged athletes ranged from 18-23 years of age. If an athlete played more than one overhead sport, he/she was placed in the group that corresponded to the sport in which he/she had participated in for the greatest number of years.

Instrumentation

Glenohumeral internal rotation, glenohumeral external rotation, and posterior shoulder tightness were measured using a digital inclinometer (Fabrication Enterprises Inc., White Plains, NY). A GE Logiq e ultrasound unity (General Electric Healthcare, Waukesha, WI) with a 12 L-RS probe was used to measure posterior capsule thickness, humeral retrotorsion, UCL thickness, and ulnohumeral joint space. The measurement accuracy of the device reported by the manufacturer is 0.1mm. A Telos device (METAX-GmbH, Hungen, Germany) was also used to stress the medial elbow during ulnohumeral joint space measurement (M. G. Ciccotti et al., 2014). The Telos consists of a screw mechanism for exerting force, a counter support, and a hand grip

attached to a frame. When the device is engaged, a screen indicates how much force is applied to the joint.

Procedures

Demographic and Anthropometric Data

To begin the study, all participants provided written consent via a document approved by the institution's Institutional Review Board. In the case of minors, the child assented to the protocol, as described by the primary investigator, and his/her parent or guardian signed the consent form. After consent was obtained, the participants completed a questionnaire containing general data such as height, weight, dominant arm, age, maturation stage, and injury history. They also filled out a survey that described history of sport participation. This survey was constructed in a column format and included a list of sports. For each sport, the athletes indicated when they began participating in organized competitions and the age at which they stopped sport participation, if applicable (Figure 1). Youth athletes' parents completed the injury history and sport participation forms with input from their children. Athletes' self-reported outcome measures were completed by questionnaires asking them to rate their shoulder and elbow pain currently, in the past month, and over their competitive lifetimes. Finally, youth athletes completed the Pubertal Development Scale (PDS), which is valid and reliable for predicting maturation stage (Carskadon & Acebo, 1993). After completing the surveys, range of motion and ultrasound testing was conducted.

Posterior Shoulder Tightness

        To assess posterior shoulder tightness, the participant lay supine on a treatment table and was asked to retract the dominant scapula into the table. At this time, the tester placed one hand on the lateral border of the scapula for stabilization. The tester used his other hand to passively adduct the participant's arm while ensuring no humeral rotation. After the participant reached the end range, an inclinometer was placed on the humerus (Figure 2), and the measurement was recorded. Construct validity has been previously established for this method of measuring posterior shoulder tightness (Myers et al., 2007).

Glenohumeral Internal (IR) and External Rotation (ER) Range of Motion

        Passive internal and external rotation was recorded with the participant in a supine position and the glenohumeral joint in 90° of abduction. The scapula was stabilized by the examiner, and the arm was rotated until scapular motion was detected or end range of motion was reached. At that moment, a measurement was taken with the inclinometer on the dorsal surface of the forearm (Figure 3). Following the measurement, the shoulder was then moved back into neutral position. Previous research has established validity of these clinical range of motion measurements (Awan, Smith, & Boon, 2002; Myers et al., 2007).

Posterior Capsule Thickness

        Participants prepared for the posterior capsule thickness measurement by sitting upright in a chair with their arms at the side and hands on their thighs. The transducer of the musculoskeletal ultrasound unit was placed on the posterior aspect of

the shoulder using standard acoustic gel. The primary investigator moved the transducer around until the humeral head, glenoid labrum, and rotator cuff were visualized. The image was then frozen and saved for each measurement. Posterior capsule thickness was measured by the caliper system on the ultrasound unit, identified by the tissue between the tip of the labrum and rotator cuff tendon/s (Figure 4). (Thomas et al., 2011).

Humeral Retrotorsion (HR)

To measure HR, participants would lay supine with their shoulders abducted and elbows flexed to 90° angles. The ultrasound transducer, with a leveling device, was placed on the anterior shoulder over the bicipital groove along the horizontal plane. The shoulder was then rotated internally and externally until the lesser and greater tubercles were parallel on the ultrasound scanning system screen (Figure 5). At the point where the tubercles were parallel with the screen, the digital inclinometer was placed on the surface of the ulna, as with the glenohumeral range of motion, to measure the level of humeral torsion. The use of ultrasound to measure humeral retrotorsion has been validated compared to CT scan (Myers, Oyama, & Clarke, 2012).

UCL Thickness

Participants sat with their elbows on the table flexed to 70˚, which is the preferred elbow angle for UCL measurement (Lueders, Pourcho, Sellon, Dahm, & Smith, 2015). Standard coupling gel was applied to the medial elbow, and the transducer was positioned until a hyperechoic structure spans the ulnohumeral joint

(Figure 6) (Lueders et al., 2015; Nazarian et al., 2003). The image was then frozen and saved. The thickness of mid-portion of the anterior band of the UCL was measured by the caliper system on the ultrasound. Validity of UCL thickness has been shown through cadaver analysis (Nazarian et al., 2003).

Ulnohumeral Joint Space

Participants sat with their elbows supinated and flexed to 30° because the UCL is the primary restraint to valgus stress at that angle and appropriate elbow stress can only be applied by the Telos device at lower degrees of elbow flexion (M. G. Ciccotti et al., 2014). Participants then grabbed the hand grip portion of the Telos and aligned their upper arm with the counter support. An investigator placed the axis of the pressure mechanism on the elbow lateral joint line. When the participant's elbow was locked into the Telos device, the ultrasound probe was placed on the medial elbow to identify the trochlea of the humerus and sublime tubercle of the ulna (Figure 6). Once these landmarks were visualized, the image was frozen and saved. Later, the calipers on the ultrasound device were used to measure the distance between these two landmarks, which was recorded as ulnohumeral joint space at rest (M. G. Ciccotti et al., 2014). Then, a valgus stress of 100 N was applied to the medial elbow. As the force progresses, the ultrasound transducer was applied to the medial elbow, and the primary investigator maintained visualization of ulnohumeral joint space. Once the 100 N force was reached, a confirmation of the ulnohumeral joint space occurred

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quickly, and the image was frozen on the screen before the force was released. This image was then saved and measured via the caliper system on the ultrasound system. Previous literature used a 150N stress and confirmed validity of this measurement through cadaver analysis (Nazarian et al., 2003), but 100N was chosen in this study to ensure that excessive load was not being placed on developing joints of youth athletes. The 100N was determined through pilot data based on the largest value that did not produce discomfort and/or pain in youth athletes.

Data Reduction and Statistical Analysis

All dependent variables were measured twice on both the dominant and non-dominant arm by the primary investigator, who had five years of sonographic experience and has attended multiple workshops to improve and ensure his skills. The mean of those two measurements was then calculated for each side. The primary investigator was blind to arm dominance for all measurements. Total range of motion (tROM) was calculated by computing the sum of the IR and ER means (Wilk, Meister, & Andrews, 2002). For all dependent variables, the mean of those measures on the non-dominant arm was subtracted from the dominant arm so that the non-dominant arm acted as a control. Two potential covariates were identified that could have affected the analysis, age that athletes began their preferred sport and score on the PDS. However, simple Pearson correlation determined that neither variable was related to any of the dependent variables. Therefore, the resulting values were analyzed using a 2 way between subjects ANOVA. The only exception to this method was for ulnohumeral joint space, where the measurement at rest was subtracted from

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the ulnohumeral stress measurement. Then, the dominant to non-dominant arm comparison occurred, and an ANOVA was run for each dependent variable. The independent variables used for analysis were age group (youth vs. college-aged) and sport. Significant ANOVA models were evaluated post-hoc with a Tukey HSD test.

After the ANOVAs were completed, the maximum shoulder and elbow pain scores for each participant were identified. Those scores were correlated with the other dependent variables using Spearman rank correlations. Multiple Spearman rank correlations were run to determine the overall relationship between pain and the clinical/ultrasound measurements as well as the association of those variables for each sport and age subgroup. One athlete was removed from posterior shoulder tightness and HR analysis because of missing data. One athlete was also removed from UCL and ulnohumeral joint space analysis because of upper arm discomfort and guarding during the testing procedure. All data were analyzed using the Statistical Package for Social Sciences (SPSS, Chicago, IL). An *a priori* alpha level of .05 was used to denote statistical significance.

Results

Posterior Shoulder Tightness

No interaction effects were noted for posterior shoulder tightness (p = .483). Age comparison produced a significant main effect for age, as dominant vs. non-dominant arm differences were greater in college-aged athletes compared to youth ($F_{130,1}$ = 5.75, p = .018) (Figure 7). The effect size was small-to-medium (η^2 = .044),

and the total disparity between the two age groups was 2˚. No main effect for sport existed for this analysis (p = .932).

Glenohumeral Range of Motion

Glenohumeral range of motion values are presented in Table 2. Examination of ER produced no significant interaction or main effects, but an interaction effect existed for both IR ($F_{131,2}$ = 3.19, p = .045, η^2 = .048) and tROM ($F_{131,2}$ = 4.49, p = .013, η^2 = .067). Tukey HSD post-hoc testing for IR produced no significant differences between unconfounded comparisons (Heiman, 2013). However, descriptive statistics indicated that the IR of collegiate softball athletes (-9.9 ± 6.4˚) were 3˚ more asymmetric than the youth athletes (-6.9 ± 5.2˚) who played the same sport (Figure 8). On the contrary, the IR of collegiate tennis athletes (-6.7±6.6) was 4˚ more symmetric than their youth counterparts (-10.3 ± 3.8˚) (Figure 8). Tukey HSD post-hoc testing did determine a significant discrepancy between tROM of youth and collegiate softball athletes. Specifically, collegiate softball players exhibited 3.3 ± 8.6˚ less tROM, with youth softball players demonstrating 2.6 ± 7.0˚ more tROM on the dominant side compared to the non-dominant side.

Shoulder Ultrasound Measures

No significant interaction effects existed for posterior capsule thickness (p = .914) or HR (p = .161). Main effects for both age ($F_{131,1}$ = 24.13, p<.001, η^2 = .161) and sport ($F_{131,1}$ = 4.02, p = .020, η^2 = .060) existed for posterior capsule thickness (Figure 9). Post hoc testing identified that bilateral differences in posterior capsule

thickness was greater in collegiate athletes (0.16 ± 0.12mm) compared to youth athletes (0.07 ± 0.08mm). Additional post hoc testing indicated that baseball athletes also exhibited significantly greater thickness (0.15 ± 0.12mm) than softball athletes (0.10 ± 0.10mm). No significant main effects for age or sport for HR despite a large bilateral variation in both age groups (youth = 7.8 ± 6.7°; collegiate = 10.2 ± 6.0°)

Elbow Ultrasound Measures

Like at the shoulder, no significant interaction effects existed for any ultrasound measures at the elbow (UCL thickness, p = .110; ulnohumeral joint space, p = .663). A significant main effect for age ($F_{130,1}$ = 5.22, p = .024, η^2 = .040) was present for UCL thickness (Figure 9). Specifically, collegiate athletes exhibited bilateral differences 0.25mm greater than youth athletes. No main effect for sport was present for UCL thickness, and no significant main effects were observed for ulnohumeral joint space.

Pain

When all athletes were combined into the same analysis, no significant correlations existed between maximum shoulder or elbow pain over an athlete's career and any of the ultrasound measurements. Dividing athletes into subgroups based on sport and age did produce some significant correlations. Specifically, posterior shoulder tightness (r = -.495, p = .014) and tROM (r = -.525, p = .007) differences were significantly correlated with shoulder pain in collegiate softball players, meaning that athletes with more posterior shoulder tightness and less tROM on the dominant

side compared to the non-dominant side had a higher maximum shoulder pain over their careers (Figure 10). ER (r = .499, p = .021) was positively correlated to shoulder pain, and IR (r = -.440, p = .046) was negatively correlated to elbow pain in youth softball players (Figure 11). Finally, posterior capsule thickness was related to elbow pain in youth softball (r = .503, p = .020) and tennis (r = .668, p = .025) athletes. No significant correlations were observed for baseball or adult tennis athletes.

Discussion

The purpose of this study was to compare athletes of different ages and sports to determine which bilateral tissue characteristics were present in each population. Range of motion and humeral retrotorsion results were contrary to our hypotheses, as the bony morphology resulting from overhead activity appears to be present at an early age. Bilateral differences in range of motion were relatively consistent across age and independent of sport, with all groups of youth and collegiate athletes losing approximately 6-10˚ of internal rotation and gaining 6-10˚ of external rotation on the dominant arm compared to the non-dominant arm. Our hypotheses were correct when examining soft tissue changes, as older athletes exhibited more pronounced bilateral variation in posterior shoulder tightness, posterior capsule thickness and UCL thickness compared to youth athletes. Sport participation is likely an important factor in these age related soft tissue changes. Collegiate baseball athletes present with significantly greater bilateral capsular thickness difference than collegiate softball

players and at least twice as much bilateral ulnar collateral ligament thickness variation than any other group.

Age and Sport Effects on Clinical Measurements

The greater posterior shoulder tightness on the dominant arm, compared to the non-dominant arm, found in this investigation is similar to previous investigations on collegiate and youth athletes (Myers et al., 2007; Shanley et al., 2012). Our observation of a 5° and 3° difference in collegiate and youth athletes, respectively, was greater than the 1-1.5° differences previously observed in youth and college-aged non-overhead athletes (Struminger & Swanik, 2015). approximately 3° less than that seen previously in similar populations (Myers et al., 2007; Shanley et al., 2012). One potential explanation for those differences may be that our youth athletes were slightly younger (11-14 years old) than those studied previously (13-18 years old) (Myers et al., 2007; Shanley et al., 2012). Our results also support the impact of age on posterior shoulder tightness, as we found collegiate overhead athletes exhibit significantly more bilateral difference in horizontal adduction than younger athletes. The tightening of the posterior shoulder over with time may reflect the continued joint overload resulting from overhead sport. More repetitions at higher joint velocities require structures of the posterior shoulder to attenuate those forces (Burkhart et al., 2003). If the posterior shoulder is required to absorb excessive load, a compensatory collagen proliferation can occur and lead to adaptive shortening. To combat that restriction and in response to the recent data on the negative effects of posterior shoulder tightness

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(Burkhart et al., 2003; Tyler et al., 2010), preventative stretching has become more common in collegiate athletes. Anecdotal evidence would suggest that these interventions are being used in many collegiate athletes, thereby potentially reducing the bilateral discrepancies noted in previous literature. If these posterior shoulder stretching interventions are truly effective, overhead athletes may want to begin them earlier, as bilateral differences exist in 11-14 year old athletes.

Stretching of the glenohumeral joint may also be effective for glenohumeral ROM, as it can also be affected by collagen proliferation and adaptive shortening. The participants in this study exhibited a range of motion differences on their dominant arm compared to the non-dominant arm. Our finding of an approximate 8-10˚ loss of IR and subsequent 8-10˚ ER gain has been noted across various sports (Ellenbecker et al., 2002; Hibberd et al., 2014; Myers et al., 2007) and is greater than the 3-6˚ differences previously noted in non-overhead controls (Magnusson, Gleim, & Nicholas, 1994). However, the similarity in ROM between most collegiate and youth groups is an interesting finding, as overhead athletes naturally lose ROM as they age (Cools et al., 2014). That result indicates that ROM differences are already present by the age of 11 in overhead athletes. The continued overload placed on the upper extremity during overhead sport may then maintain that bilateral differences in ROM, rather than exacerbating it. The only sport in which interaction effects were observed was softball. In that subgroup of athletes, the tROM on both sides was less for the collegiate group (dominant = 174.1 ± 9.2˚, non-dominant = 177.6 ± 11.0˚) than the youth group (dominant = 187.8 ± 8.9˚, non-dominant = 185.2 ± 10.1˚), but the

dominant shoulder tROM varied between age groups more than the non-dominant side. IR exhibited the same pattern where the measurement was reduced in both arms of collegiate athletes, but the larger difference between the two age groups was present for the dominant arm. The reason for this inequality in softball only may be the fielding positions that these athletes play. Many youth baseball athletes play the position of pitcher in their young careers, which requires athletes to exert maximum force into each throw. However, young softball players are not exposed to this overhead pitching stress, so the IR and tROM changes may take longer to develop.

Relationship between Clinical Measurements and Patient Reported Outcomes

While ROM may be different in youth and collegiate athletes across sports, the question becomes whether bilateral variations are truly significant in terms of pain. Previous investigations determined that limited internal rotation may be a factor in developing injury, but those studies were completed primarily on baseball pitchers (Wilk et al., 2011; Wilk et al., 2014). Furthermore, cadaver data suggest that posterior shoulder tightness alters humeral arthrokinematics and increase glenohumeral contact pressure (Mihata et al., 2012; Muraki et al., 2010). In our study, softball players were the only subset of collegiate athletes to exhibit significant correlations between bilateral tissue differences and pain. In those athletes, less tROM on the dominant side compared to the non-dominant side was correlated with shoulder pain. This tROM asymmetry may not be meaningful upon examination of the whole subset of collegiate softball athletes because their 3˚ difference is within the 5˚ variability suggested by

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Wilk et al. (2002) to increase shoulder injury risk. When looking at individual data, limited tROM on the dominant side compared to the non-dominant side may be a factor in pain development of softball athletes, as two-thirds of the athletes with a 5° asymmetry reported a maximum career shoulder pain level of at least 5/10. Posterior shoulder tightness, which exhibited a main effect for age but not sport, also produced a negative correlation to shoulder pain, indicating that collegiate softball athletes who had greater bilateral posterior shoulder tightness differences experienced more shoulder pain. These results may provide more insight into the development of pain in softball players, but the results should be interpreted with caution because the observed relationships between pain and range of motion in collegiate softball players were primarily driven by several outliers per group (Figure 10, Figure 11). The small sample size (25 athletes) may have impacted the size of the correlation by giving more statistical weight to those outliers, but it may also indicate that ROM differences are more impactful for some athletes compared to others.

The influence of posterior shoulder tightness and ROM on pain may not only be different between individuals, but between age groups as well. The correlations between shoulder posterior shoulder tightness, ROM, and pain found in this study were not the same in youth athletes compared to a collegiate population, indicating that different mechanisms or perceptions of of pain may be present in the two populations. Youth softball athletes exhibited higher levels shoulder pain with excessive dominant ER gain and elbow pain with IR loss. Even though loss of IR was correlated with elbow pain, clinicians should be aware that none of the youth softball

players exhibited a glenohumeral internal rotation deficit (GIRD) of greater than 20°, which has been established in previous literature as the cutoff for athletes with a higher risk of injury (Burkhart et al., 2003). Therefore, the definition of GIRD for youth athletes may need to be altered to 12°, which would encompass most of the athletes with elbow pain and only one athlete with minimal pain in this study. This redefinition would then more accurately fit the range of motion of youth athletes.

Influence of Independent Variables on Shoulder Ultrasound Measurements

The reason that glenohumeral ROM may not differ much in youth and collegiate athletes may be that HR is occurring at a young age. HR strongly correlates to ROM measures (Thomas et al., 2012), and the youth athletes in this investigation had a bilateral HR mean difference of almost 8°, only 2° less than that of collegiate athletes. That value is also greater than the previously observed 4.8° bilateral difference in non-overhead controls (Greenberg et al., 2017). Our data of early humeral torsion matches the proposed time course of HR in which the natural movement into an antetorted position is complete by the age of 8 (Edelson, 2000). Since almost all of the athletes who participated in this study began playing their sport by 8 years old, our data suggest that overhead stress on the dominant arm at an early age may alter normal humeral development. That limitation on the dominant arm implies that stress from throwing and tennis serving is being partially absorbed by the bone or epiphyseal plate, which then adapts to the stress placed upon it (Wolff, 1892). Our data are similar to that found in previous investigations of both youth and

collegiate baseball and softball players (Astolfi et al., 2015; Hibberd et al., 2014; R. J. Whiteley et al., 2009). These data are the first, to our knowledge, indicating that bilateral HR asymmetries exist in tennis athletes, and it confirms computer simulations that suggest tennis serving would create a torsional change (Taylor et al., 2009). Despite the identification of early humeral torsion differences in unilateral overhead athletes, the variations were not related to pain in any population. This finding may indicate that HR can have both a protective and harmful effect on the shoulder. For instance, excessive HR can protect the anterior capsule from stress but create excessive loading on the epiphyseal plate and limit internal rotation (Pieper, 1998; Shanley & Thigpen, 2013; Yamamoto et al., 2006). While HR does not directly relate to pain in his population, clinicians should note that normal ROM differences in young overhead athletes is likely of bony origin. It appears that multiple overhead sports can create enough strain on the humerus to produce HR differences between arms.

The overhead stress which leads to bilateral glenohumeral bony differences may also be absorbed by the soft tissue structures. Our data support that theory only in skeletally mature athletes, as collegiate athletes exhibited significantly greater (0.1mm) side-to-side posterior capsule thickness differences than skeletally immature youth athletes. These data suggest that the soft tissue structures only begin to adapt after closure of the epiphyseal plates. Partial validation of that theory may exist when examining injury rates, as relative risk for labrum tears is higher in more skeletally mature athletes (Han, Kim, Lim, Park, & Oh, 2009). Conversely, junior high baseball players experienced epiphyseal injuries much more often than high school and

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collegiate athletes (Han et al., 2009). We also found that baseball players exhibit more posterior capsule thickness than softball players (0.06mm), suggesting that baseball may be more stressful on the shoulder than softball. The data may also suggest that posterior capsule thickening is velocity dependent, as baseball players throw harder than softball players. This thickening of the posterior capsule in baseball players may have some adverse effects, similar to that of posterior shoulder tightening (Mihata, Gates, McGarry, Neo, & Lee, 2015; Muraki et al., 2010). Conversely, capsular thickening may also have some protective effect as suggested in previous work by Shonk et al. (2015), who noted that thickening of the capsule was present in swimmers but was not associated with pain. In our study, shoulder pain was not correlated to measures of posterior capsule thickness, but youth softball and tennis players who had more posterior capsule thickness reported more elbow pain over their careers. Since the posterior capsule is a relatively thin structure and clinically significant differences are still unknown, much more investigation is needed before making conclusions about the effect of excessive posterior capsule thickness on pain and changes in humeral arthrokinematics. Our findings may indicate a relationship between shoulder tissue characteristics and elbow pain, and research should be conducted to further elucidate that connection.

Even though our observed posterior capsule thickness values produced statistical significance, their clinical relevance requires additional research. Data from both this study and previous literature has indicated that 1.3-1.6mm of posterior capsule thickness is normal for non-overhead athletes and non-dominant arm of

throwing athletes (Shonk et al., 2015; Thomas et al., 2011). Therefore, the 0.1mm difference is approximately 7% of the entire capsule thickness. Also, this study adds to previous data on posterior capsule thickness, which consistently notes significant bilateral differences in athletes who play unilateral overhead sports (Astolfi et al., 2015; Thomas et al., 2011). However, the noted measurement error using the calipers of the ultrasound device is 0.1mm, so our values may be more indicative of computation inaccuracy than a true variation. In an attempt to attenuate the measurement error, multiple assessments of the capsule were conducted and results were compared bilaterally. Despite those efforts, we cannot be certain that some of our posterior capsule thickness differences, especially the bilateral differences in children, were outside of the ultrasound measurement error. The correlation between posterior capsule thickness and elbow pain in youth athletes may be suspect as well. Based on those findings, more accurate measures or new, innovative techniques may be needed to further understand how overhead sport affects the posterior capsule and the relationship between posterior capsule thickness and pain.

Influence of Independent Variables on Elbow Ultrasound Measurements

Our data on UCL thickening also promotes the theory that epiphyseal plate closure may be the time at which soft tissue changes begin to manifest in skeletally mature athletes. We noted that collegiate overhead athletes exhibited a 0.27 mm (6%) greater bilateral asymmetry in UCL thickening compared to our youth athletes. Our value of 0.42 mm of bilateral difference in collegiate athletes is much less than the

1.0mm value previously observed in professional baseball pitchers (Nazarian et al., 2003) but more closely matches the data (0.3mm) published on high school pitchers (A. Atanda et al., 2016). One possible explanation for the difference between studies may be the age factor alone. Our collegiate athletes were, on average, six years older than the youth pitchers but seven years younger than the professional athletes (Nazarian et al., 2003). These age differences between studies suggests that the UCL continues to thicken over time with continued sport participation and expected increases in velocity. However, the confounding variable of sport may impact the strength of these comparisons.

We did not observe an interaction effect or main effect for sport, but the finding that the bilateral UCL thickness difference in baseball is double (0.63mm) the values of softball (0.32mm) and tennis athletes (0.23mm) may be clinically significant, as it produced a small-to-medium effect size (η^2 = .035) that was similar to some of our other significant results. UCL thickening is important to note in this population because has been related to elbow pathology in high school and professional pitchers (M. G. Ciccotti et al., 2014; Tajika et al., 2016). Therefore, the excessive tissue proliferation may indicate more stress on the medial side of the joint in baseball athletes. Also, the tissue characteristics exhibited by our population may be related to the higher percentage of UCL reconstructions completed on baseball players compared to softball and tennis athletes (Cain et al., 2010). Despite this body of previous literature on tissue characteristics and injury, UCL thickness was not related to pain history in our study. However, our results suggest that baseball players

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undergo UCL thickening on their dominant arms, and that difference is likely a result of sport. Potential factors producing those changes, such as the number of overhead repetitions over the course of an athlete's career, intensity of those repetitions, and ball weight, warrant further investigation.

Despite the observed thickening of the UCL, no age or sport effects existed when examining ulnohumeral joint space. Our results indicated that there was an extremely small (.1mm), non-significant, bilateral difference when comparing bilaterally youth baseball players, which matches recent data produced on similar athletes in the same age group (Mickevicius et al., 2016). However, the collegiate athletes in our study, even when only examining baseball players, displayed less ulnohumeral joint space than that previously reported in adult baseball pitchers (Nazarian et al., 2003; Tajika et al., 2016). Our use of 100N of force to provide elbow stress instead of the 150N or manual valgus stress used in previous literature may be the reason for these differences (M. G. Ciccotti et al., 2014; Nazarian et al., 2003). The lower value was chosen in an attempt to make a direct comparison between youth and adult athletes without placing too much stress on the developing elbow in children. When analyzing our results in the scope of the larger body of literature, it appears that larger forces are required to adequately examine joint laxity in an adult population. While the absolute values may be slightly different, our overall results match previous trends that ulnohumeral joint space under stress is not affected by years of sport participation in 17-21 year old pitchers. Combined with other studies, these data indicate that the development of medial elbow joint laxity is not dependent on age

until at least the late professional level (A. Atanda Jr et al., 2015). Our findings may also suggest that factors other than sport and age, such as muscular strength or biomechanics, may play a bigger role in the development of elbow laxity than age alone.

Limitations

This study compared two discrete ages without any follow-up. Consequently, we can only compare groups and cannot make any conclusions about development of an individual athlete through his/her lifespan. Future longitudinal studies are needed to examine how tissue characteristics change throughout the course of an athlete's career. Future investigations are also needed to determine exactly when soft tissue adaptations occur and the sports that produce the greatest bilateral differences. Additionally, a natural sex bias existed in our data set. Our baseball and softball groups were comprised of athletes of one sex, but our tennis group was mixed. Males and females may have natural laxity differences that may have confounded our data on ulnohumeral joint space (Deep, 2014). Our ulnohumeral joint space data may have also been confounded by scanning in youth athletes. Some of these athletes did not have fused growth plates. Lack of skeletal maturity can create confusion for the sonographer as to which landmarks are used for joint space measurement. We analyzed the joint space from the bony landmarks on the humerus and ulna that were furthest apart in an attempt to use the most stable landmarks for measurement. This method was suggested to keep the imaging as consistent as possible, as suggested by a

sonographer with vast experience in pediatric imaging (Blumer, 2015). Finally, while excessive tissue proliferation may be one reason athletes develop pain, other variables such as strength, neuromuscular control, and tissue stiffness may be factors as well. Therefore, future studies should investigate how those factors vary in youth and collegiate athletes who play overhead sports.

Conclusion

We observed that humeral retrotorsion is greater on the dominant arm than the non-dominant arm in athletes who participate in a variety of unilateral overhead sports. That bony change in 11-14 year-olds is not significantly different than that in a collegiate population and likely produces much of the bilateral glenohumeral range of motion differences in these athletes because the magnitude of the discrepancy between those two variables is the same. The soft tissue structures of the shoulder and elbow, such as the posterior capsule and UCL, also appear to differ bilaterally, but those asymmetries are only present at the collegiate level. Furthermore, the excessive tissue proliferation in the dominant arm of collegiate athletes is primarily present in baseball players, which seems to indicate that baseball is the most stressful sport on the shoulder and elbow that was examined in this investigation. Given that tissue characteristics varied across groups, we promote the development of sport or age specific prevention and rehabilitation programs that specifically address the underlying anatomical differences associated with each population.

Chapter 3

EARLY SPORT SPECIALIZATION DOES NOT LEAD TO BILATERAL
UPPER EXTREMITY DIFFERENCES

Introduction

The origins of sport specialization can be traced to a belief that organized, year-round training at a young age produced substantial success in elite Eastern European athletes (Malina, 2010). This belief is supported by Ericsson et al. (1993), who suggested that engaging in early deliberate practice creates an advantage in that specific skill later in life. The trend towards early specialization and year-round sport participation may lead to excessive joint loading and injury, creating a growing concern among sports medicine professionals (Hill & Simons, 1989; Metzl, 2002; Nyland, 2014). The practice of sport specialization has become so worrying that the American Orthopaedic Society for Sports Medicine (AOSSM) and American Academy of Pediatrics (AAP) have published official statements warning of its impact on developing athletes (American Academy of Pediatrics. Committee on Sports Medicine and Fitness, 2000; LaPrade et al., 2016). Furthermore, the National Athletic Trainers' Association (NATA) and International Olympic Committee (IOC) both mention sport specialization in their official statements on youth injuries and athletic development, respectively (Bergeron et al., 2015; Valovich McLeod et al., 2011).

These organizations typically suggest that young athletes should pursue participation in multiple sports and take two-to-three months off from one sport over the course of one calendar year (Brenner & American Academy of Pediatrics Council on Sports Medicine and Fitness, 2007; Valovich McLeod et al., 2011). However, all these recommendations are given a Strength of Recommendation Taxonomy (SORT) grade of C because they are primarily based on anecdotal evidence, consensus, and usual practice (Myer et al., 2015; Valovich McLeod et al., 2011).

The only quantitative data to link sport specialization and injury examine the lower extremity. The most comprehensive of these studies examined 1190 athletes from 7-18 years of age (Jayanthi, LaBella, Fischer, Pasulka, & Dugas, 2015). Those authors found that highly specialized athletes had 2.25 times greater risk for developing a serious overuse injury compared to athletes that were not specialized even when controlling for other variables such as age and hours in sport activity (Jayanthi et al., 2015). In that study, specialization was defined as those athletes who had picked a main sport, quit all other sports to play that main sport, and played for more than eight months per year (Jayanthi et al., 2015). Two more focused studies on high school athletes also support the results of sport specialization being harmful for youth athletes (Bell et al., 2016; Hall, Barber Foss, Hewett, & Myer, 2015). In those investigations, high school athletes who trained more than eight months out of the year were 2.93 times more likely to have reported a chronic knee injury than athletes who did not, and females who were highly specialized in basketball, soccer or volleyball were more likely to report a history of patellofemoral pain (Bell et al., 2016; Hall et

al., 2015). These studies indicate that sport specialization has a negative effect on the lower extremity, but there are no studies to our knowledge which examine how focusing on one sport impacts the upper extremity.

The limited data on the impact of sport participation in youth overhead athletes is primarily focused on pitching. As stated by Dr. James Andrews in a speech given to the Amateur Sports Symposium in 2010, "Year-round baseball is producing an epidemic of injury to the elbow of young baseball players (Andrews, 2011)." Instead of examining true sport specialization, this body of literature evaluates the impact of overuse on injury and pain. Lyman et al. (2001) performed one of the first studies on this topic and found a significant relationship between pitch count and upper extremity pain, with every 10 pitches thrown increasing the odds of both shoulder and elbow pain (Lyman et al., 2001). Pitching more than 100 innings per year also increased injury risk while throwing a curveball at an early age did not (Fleisig et al., 2011). These studies indicate that a high frequency of repetitive upper extremity activity is the biggest factor in creating an overload on the upper extremity that manifests in shoulder and elbow pain in young athletes.

Injuries and pain in the upper extremity are likely a result of underlying tissue characteristics that are associated with arthrokinematic changes (Mihata et al., 2015; Nazarian et al., 2003; Pieper, 1998). These tissue characteristics may then precipitate the bilateral range of motion differences commonly observed in overhead athletes and can be early signs of pathology (M. G. Ciccotti et al., 2014; Hibberd et al., 2014; Myers et al., 2006; Thomas et al., 2011). Specialization in a unilateral overhead sport

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may create an overload on the upper extremity, similar to throwing too many pitches. That overload could then create enough stress for soft tissue and bony structures to adapt, but no research is currently available to confirm that theory. Therefore, the purpose of this study was to determine the effect of sport specialization on upper extremity tissue characteristics. We hypothesized that those athletes specializing in sport earlier would display more bilateral UE tissue differences than those who specialized later.

Dissertation Aim 1: Description and Results

To identify whether athletes who differ in age, sport, degree of specialization, and pain exhibit distinctive upper extremity tissue characteristics.

H1.4 Specializing in sport earlier will cause more side-to side differences in upper extremity tissue characteristics than later specialization.

Age of sport specialization did not create any bilateral differences in upper extremity tissue characteristics.

Methods

Experimental Design

This study used a post-test only design. The only independent variable was age of high sport specialization, although an athlete's primary sport was collected as a potential covariate. The dependent variables were glenohumeral internal rotation (˚), glenohumeral external rotation (˚), posterior shoulder tightness (˚), posterior capsule

thickness (mm), humeral retrotorsion (˚), UCL thickness (mm), and ulnohumeral joint space (mm). A randomization procedure was conducted to determine the arm tested first for each participant. The primary investigator, who conducted all ultrasound testing and measurement, was blinded to each participant's arm dominance.

Participants

76 male and female collegiate athletes (37 male, 39 female; age = 19.8 ± 1.4 years, height = 175.3 ± 10.4cm; weight = 76.0 ± 13.9kg) participated in this study, which was part of a larger investigation on the effect of sport and age on tissue characteristics in unilateral overhead athletes. All athletes were competing on varsity or elite club teams in the sports of baseball, softball, or tennis. Participants were excluded from the study if they had undergone a shoulder or elbow surgery within the last year or had been diagnosed with any disorder that prevented typical anatomical development. Participants were stratified into groups by age of high sport specialization, which was identified by the age that they picked a "main sport", stopped playing other sports, and trained in that sport for more than 8 months per year (Jayanthi et al., 2015). Early specialization athletes met these criteria at 10 years of age or younger; middle school age specialization athletes met these criteria from 11-14 years of age; late specialization athletes met these criteria at age 15 or older. Sport specialization groups were determined by recommendations from the National Association for Sport and Physical Education and previous research on the age at

which specialization is useful for elite athletes (Carlson, 1988; Gullich & Emrich, 2006).

Instrumentation

Glenohumeral rotation and posterior shoulder tightness were measured using a digital inclinometer (Fabrication Enterprises Inc., White Plains, NY). Ultrasound images were taken via a Logiq e ultrasound unit (General Electric Healthcare, Waukesha, WI) equipped with a 12 L-RS probe. The caliper system on the ultrasound unit was used for all measurements. Medial elbow stress was applied with a Telos device (METAX-GmbH, Hungen, Germany) during ulnohumeral joint space evaluation.

Procedures

To begin the study, all participants read and signed an informed consent document approved by the institution's Institutional Review Board. After consent was obtained, the athletes completed two surveys. The first confirmed their eligibility and provided demographic data. The second gave information of sport history (Figure 1). On that form, a list of possible sports was supplied and athletes were asked to list the age at which they began participating in organized competitions for that sport, the age that they stopped participation in that sport, and the total number of years of sport participation as applicable. Following the list of sports, athletes were asked directly if they could pick a main sport, at what age they quit other sports to focus on their main

activity, and when they started training for more than eight months per year (Jayanthi et al., 2015).

Following the completion of the surveys, the participant underwent clinical range of motion testing consisting of glenohumeral internal rotation, glenohumeral external rotation, and posterior shoulder tightness, the procedures for which have been described in previous literature (Awan et al., 2002; Myers et al., 2007) (Chapter 2). Then, each participant's posterior capsule thickness and humeral retrotorsion were identified via ultrasound with the methodology also described in prior investigations (Thomas et al., 2011; Thomas et al., 2012; R. J. Whiteley et al., 2009). The final part of the testing battery took place at the elbow, and the landmarks used for measurement by the caliper system on the ultrasound unit have been previously described (M. G. Ciccotti et al., 2014; Nazarian et al., 2003) (Chapter 2). Ulnar collateral ligament (UCL) thickness was assessed by the ultrasound unit with the participants' elbows at 70˚ of flexion (Lueders et al., 2015). Ulnohumeral joint space was measured with participants' elbows at 30˚ of flexion because of the limitations of the Telos device. That measurement was completed at rest to create an individual baseline and at 100N stress to the medial elbow in an effort to quantify laxity with a consistent force in all participants.

Data Reduction and Statistics

All measurements of the dependent variables were performed twice each on the dominant and non-dominant side. The mean of those two measurements for each

arm was then calculated. Bilateral differences were then calculated as the dominant arm mean minus the non-dominant arm mean. The only exception to this method was for ulnohumeral joint space, where the measurement at rest was first subtracted from the ulnohumeral stress measurement. Then, the dominant to non-dominant arm comparison occurred.

After data processing, hierarchical multiple regressions analyses (MRA) were conducted with the Statistical Package for Social Sciences (SPSS, Chicago, IL) in order to examine whether age of high sport specialization (Early, Middle, Late) had an effect on the dependent variables. This statistical analysis was chosen because a categorical variable (sport) was a covariate for many of the dependent variables. The use of the hierarchical MRA allows for dummy coding of each of these variables, which removes the influence of sport on the analysis, allowing the focus to be placed on sport specialization. Early specialization was coded as 0 so that all groups would be compared to it. *A priori* alpha level was set at .05.

After review of our data, it was determined that a limited number of athletes met the qualifications for early specialization, as previously defined. To provide a less skewed analysis that still fit the purpose of the study, a secondary analysis was performed based on a redefinition of groups by the age at which they began to participate in their sport more than eight months per year. Therefore, the early year-round participation group started playing their sport for more than eight months per year at 10 years of age or younger; the middle school-age year-round participation group started playing their sport for more than eight months per year from 11-14 years

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of age; the late year-round participation group started playing their sport for more than eight months per year at age 15 or older. Hierarchical MRA for each dependent variable were then conducted in the same manner as the original analysis.

Results

Demographic Information

In total, 30 baseball, 25 softball, and 21 tennis athletes completed the testing protocol (Table 1). One baseball athlete did not correctly complete his sport history, so he was excluded from the analyses. Of these 75 athletes, only 4 (5%) reported high sport specialization by the age of 11 (Figure 12). 17 (23%) reached high specialization between the ages of 11-14. When dividing athletes by the age that they began playing their sport more than eight months per year, the groups were divided more evenly. The number of athletes who began playing more than eight months per year by age 11 was 23, 28 began playing more than eight months per year between the ages of 11-14, and 25 began playing more than eight months per year at age 15 or above.

Sport Specialization

Results from the statistical analyses on high sport specialization are presented in Tables 3-5. The primary MRA did not produce any significant results for any dependent variable. Results from the secondary analysis on when athletes began to participate in their sport for more than eight months per year are presented in Tables 6-8. The secondary analysis also did not produce any significant results for any

dependent variable. Therefore, specialization did not appear to be a factor in the unilateral overhead athlete's development of unique bilateral tissue differences.

Discussion

The most important finding of this study was that only 21 of the 75 (28%) collegiate level athletes in this study were only playing one sport and participating for more than eight months a year by the time they were 14 years old. Furthermore, only 4 (5%) met the high specialization criteria by the time they were 11. High sport specialization and playing one overhead sport for more than 8 months per year had no effect on the bilateral tissue morphology in these current collegiate athletes. The primary reason that many of these athletes did not meet the criteria for high specialization was that they were still participating in multiple sports, as 51 of 75 (68%) were playing more than eight months a year by the age of 14.

The finding that that only 5% of collegiate athletes were highly specialized by age 11 was unexpected based on anecdotal evidence on trends in youth athletes. However, the percentage of athletes in our study that were highly specialized by the age of 14 (28%) was slightly higher than another study on collegiate athletes, which found that only 17% were highly specialized by their freshman year of high school (Post et al., 2017). In that study, it took until sophomore year of high school, corresponding to age 15 or 16, for the percentage of highly specialized athletes to reach values similar to ours (Post et al., 2017). Since our data was collected in athletes born later chronologically, the data seem to indicate the increasing trend towards

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specializing in sport at a younger age. Those data are supported by a broader study which indicates that high school athletes are specializing at an earlier age than professional and collegiate athletes, who were born chronologically later (Buckley et al., 2017). However, the trend towards early focus on sport does not necessarily produce improvement in performance (Buckley et al., 2017). Two studies on elite athletes found that true sport specialization occurred later in life compared to athletes who did not make it to an elite level (Moesch, Elbe, Hauge, & Wikman, 2011; Quitiquit, DiFiori, Baker, & Gray, 2014). Because only a quarter of collegiate athletes are focusing on one sport by high school and playing that sport for more than eight months per year, it appears that early specialization may not be needed to produce athletes who compete at a high level.

Since a growing body of literature is beginning to negate the idea that early specialization is critical to athletic success (Moesch et al., 2011; Quitiquit et al., 2014), it is important for sports medicine professionals to understand other factors driving the trend so that they can properly educate young athletes and their parents. The biggest reason that youth athletes begin specializing in sport is likely pressure from coaches (Wojtys, 2013). Youth coaches can view sports specialization and guided practice as a way to create the most improvement in developing athletes. Coaches, as well as performance training centers, also have a large financial interest in promotion specialization. The average parent spends an estimated $671 annually on sports-related activities, and more than 20% of parents estimate a yearly expenditure of greater than $1,000 per child (Turbotaxjen, 2013). As children start participating on club teams,

which almost demand specialization because of practice hours and weekend tournaments, the cost can reach $4,000 or more annually (Butler, 2011). Some parents are willing to spend that money and push their children to one sport because they see it as an investment to offset the cost of college, if the athlete receives a scholarship (Merkel, 2013). In spite of those financial benefits, parents are often not the ones who emphasize participation (Wojtys, 2013). Instead, coaches push this decision, with the athletes and parents often succumbing to that pressure (Wojtys, 2013). Therefore, sports medicine professionals should continue to examine quantitative data on sports specialization and use it to educate the community, rather than relying on anecdotal reports on the potential harm of sport specialization.

Little data exist to identify the negative ramifications of early sport specialization on the upper extremity (Fleisig et al., 2011; Lyman et al., 2001). However, previous research has identified bilateral differences in upper extremity range of motion and sonographic data that are related to pain and/or injury in overhead athletes (M. G. Ciccotti et al., 2014; Ellenbecker et al., 2002; Hibberd et al., 2014; Myers et al., 2007; Shanley et al., 2012; Thomas et al., 2011). Our hypothesis was that specializing in sport would help exacerbate these bilateral differences and help explain why early sport specialization may be harmful for young athletes. While our measured tissue characteristics match the means of previous investigations (M. G. Ciccotti et al., 2014; Ellenbecker et al., 2002; Hibberd et al., 2014; Myers et al., 2007; Shanley et al., 2012; Thomas et al., 2011), no significant differences were evident when examining athletes in distinctive specialization groups. These findings were contrary to our

hypothesis that early specialization would impact our dependent variables. Posterior shoulder tightness was the only measured variable that exhibited a trend where the late high specialization group showed more bilateral difference than the early high specialization group, but these differences were around 3˚, not statistically significant, and likely not clinically significant (Figure 13). Similarly, Atanda et al. (2016) found that other factors which may imply specialization, such as participating in showcases, private pitching instruction, and pitching for multiple teams, were not related to UCL thickness. Instead, pitches per appearance, which was not measured in this investigation, was the one factor that significantly predicted ligament thickening (A. Atanda et al., 2016), suggesting that high repetitions or fatigue during multiple appearances over the course of a season may create a dose response, which triggers more microtrauma and compensatory soft tissue proliferation than participating in one sport for a majority of the year. However, playing a sport more than eight months out of the year may give young athletes more opportunities to experience acute fatigue, and the additive effect of sport specialization on acute overuse should be explored further.

Limitations

The biggest limitation for this study, as well as all other studies on sports specialization, is that we cannot measure athletes who have dropped out of sport or did not reach the collegiate level. A dramatic decline in sport participation has been noted between the ages of 11 and 13 in previous literature (Weiss & Petlichkoff, 1989). In

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some studies, being injured is the most important reason that youth athletes leave sport, with 58% of athletes citing this reason for attrition (Petlichkoff, 1982). It is possible that the athletes who have the greatest bilateral differences in tissue characteristics were not participating at the collegiate level and would not have been included in our study.

The other primary limitation for this study is that the ultrasound data were taken on anatomical structures that are already relatively thin. The maximum difference for any one participant on the ultrasound measures was 0.45mm for posterior capsule thickness, 2mm for UCL thickness, and 1.8mm for ulnohumeral joint space. Therefore, group disparities resulting from sport specialization may not be visible based on measuring tissue thickness and joint space alone. Other variables that were not collected in this study or the examination of individual athletes over time may provide better on the potential deleterious effects of early sport specialization,. Psychological burnout, abnormal biomechanics, or other properties of anatomical structures, such as strength or stiffness, should be used in future investigations. Finally, a selection bias may exist in this study. It is possible that our athletes, who competed at a school that is not championship caliber and were raised primarily in northern states, are not representative of the entire elite, overhead athlete population.

Conclusion

We observed that only one quarter of collegiate athletes are highly specialized in their sport by the time they are high school aged and that only 5% specialize before

11 years of age. While unilateral overhead sport does produce bilateral differences in posterior shoulder tightness, glenohumeral range of motion, posterior capsule thickness, and humeral retrotorsion, specialization does not appear to exacerbate these changes when examining collegiate athletes. That lack of difference may indicate that the normal dose of activity may be the primary factor driving bilateral tissue differences. For the average athlete, sport specialization may be of less concern than the overload from participation in an overhead sport. However, more data on different variables are needed to rule out concern on the effects focusing on one overhead sport at an early age.

Chapter 4

PITCHING MECHANICS CAN IDENTIFY INJURY HISTORY IN HIGH SCHOOL ATHLETES

Introduction

Baseball pitching is typically divided into 6 phases with the majority of shoulder and elbow kinetic forces occurring during arm cocking, acceleration, and deceleration (Feltner & Dapena, 1986; Fleisig et al., 1995; Werner, Fleisig, Dillman, & Andrews, 1993). These phases are marked by distinct time points, which have been used to define pitching mechanics. A large amount of variability naturally exists in biomechanics, and some aspects of the delivery may be similar between healthy and injured pitchers. However, some pitching styles may identify pitchers who have previously been injured, eliminating some of the need for self-reporting in a highly competitive population. Since almost half of shoulder injuries are recurrent (Rechel et al., 2011), an identification of those factors may also help clinicians create early intervention programs to prevent chronic injuries, but no current literature has addressed the differences between previously injured and healthy pitchers at an early age.

To identify differences in biomechanics, a full understanding of the pitching motion during the phases where the majority of loading occurs is needed. The cocking

begins at stride foot contact (SFC), which creates a stable base around which the pelvis rotates and begins the transfer of energy throughout the kinetic chain (Fortenbaugh, Fleisig, & Andrews, 2009). Since SFC provides the foundation for energy transfer, upper extremity angles at that position can contribute to shoulder and elbow joint loads (Sabick, Torry, Kim, & Hawkins, 2004; Werner et al., 2002), which are theoretically related to injury. Specifically, shoulder abduction and limited elbow flexion angles at this time point has been linked to higher humeral torque and medial elbow torque (Sabick et al., 2004; Werner et al., 2002). However, it remains unknown how those upper extremity forces are related to previous injury.

After SFC, the trunk begins to rotate quickly while the forearm flexors, pectoralis minor, anterior deltoid, and subscapularis contract eccentrically (Escamilla, Fleisig, Barrentine, Zheng, & Andrews, 1998; Fleisig et al., 1995). One purpose of those eccentric contractions is to control the resulting external rotation in this cocking phase (Escamilla et al., 1998; Fleisig et al., 1995). The other is to reduce internal elbow varus torques, which are highest immediately before the point of maximum external rotation (Escamilla et al., 1998; Fleisig et al., 1995; Wight et al., 2004). Controlling the amount of external rotation at the end of the cocking phase may help reduce those elbow loads (Aguinaldo & Chambers, 2009). Excessive lateral trunk tilt away from the throwing arm at the time of maximum external rotation has also been linked to higher internal elbow varus moments (Oyama et al., 2013). The problem with measuring upper extremity angles at arbitrary time points is that it does not provide an idea of arm position when the joint loads are the highest. Instead,

identifying joint angles at the point of the greatest elbow varus moment and shoulder distraction force may be a better indicator of injury.

After the arm reaches the cocking position, the rapid extension of the elbow occurs with a concomitant increase in activation of the shoulder internal rotators, causing the arm to accelerate (Aguinaldo & Chambers, 2009; Escamilla et al., 2007; Fleisig, Barrentine, Zheng, Escamilla, & Andrews, 1999). During this acceleration phase, which ends at ball release, the majority of velocity is developed (Dillman, Fleisig, & Andrews, 1993). In this phase, pitchers may exhibit excessive horizontal adduction, or "lead with the elbow", which is often noted as a mechanical fault by pitching coaches (R. Whiteley, 2007). Elbow flexion, shoulder abduction, and trunk lateral flexion at the end of the acceleration phase (ball release) can also impact the upper extremity forces and torques (Aguinaldo & Chambers, 2009; Matsuo & Fleisig, 2006; Werner, Gill, Murray, Cook, & Hawkins, 2001). Immediately following ball release, the soft tissue structures of the posterior shoulder must resist high shoulder distraction forces which can reach values equal to a thrower's body mass (Escamilla et al., 2007; Fleisig et al., 1995). Arm position at this point may be critical to optimize the mechanical advantage of the shoulder musculature, which would prevent stress on inert tissue and potentially reduce injury risk. However, no studies to our knowledge have examined the relationship of upper extremity kinematics at the point of maximum shoulder distraction force and injury.

The higher joint forces and torques reported by previous are thought to place more stress on the upper extremity and link to injury. However, tissue loading rates

can change depending on upper extremity joint angle (F. Lin et al., 2007), so a direct comparison between pitching biomechanics and injury cannot yet be made. Furthermore, pitching deliveries may change over an athlete's career, and previous injury may be one factor which influences those alterations. Only two studies have examined kinematics in pitchers after upper extremity surgery compared to healthy controls (Fleisig et al., 2015; Laughlin et al., 2014). Those investigations found that those who had undergone UCL reconstruction pitched with similar kinematics as controls and that limited external rotation was the only kinematic variable which differentiated pitchers with a previous labrum surgery from those who had not undergone surgery (Fleisig et al., 2015; Laughlin et al., 2014). However, both of these studies examined professional pitchers, who typically have access to better coaching and rehabilitation specialists than high school athletes. Instead of the injury itself, range of motion changes post-surgery or strength improvements from rehabilitation may have affected these athletes' pitching mechanics.

To prevent severe injuries, clinicians should know whether pitchers with an injury history, who have not undergone surgery, throw with different biomechanics than those who have previously uninjured pitchers. Early identification could then lead to better efficiency in the treatment process. Therefore, the purpose of this study was to determine whether pitching kinematics differ between high school baseball pitchers who have a history of injury and those who do not. We hypothesized that shoulder abduction and horizontal abduction at stride foot contact may help identify whether pitchers had previously been injured. We also hypothesized that maximum external

rotation, elbow extension throughout the pitching motion, and trunk tilt away from the dominant arm at release may also help differentiate between previously injured and uninjured groups.

Dissertation Aim 2: Description and Results

Aim 2: To determine whether pitching kinematics, measured by 3D analysis, vary in athletes with a history of injury.

H2.1 A combination of maximum external rotation, abduction, and horizontal abduction at the shoulder, elbow extension, and trunk lateral flexion away from the dominant arm will predict whether pitchers have been previously injured.

> Only the variable of shoulder abduction at maximum external rotation differentiated previously injured pitchers from those who did not have an injury history.

Methods

Study Design

This study used post-test only design. The outcome variable was injury history, which was defined as missing one day of competition as a result of shoulder or elbow injury (Kerr et al., 2014). Five joint angles previously related to increased upper extremity joint loading were collected at five time points and used as explanatory variables to predict injury history: shoulder abduction, shoulder horizontal abduction,

shoulder external rotation, elbow flexion, and lateral trunk tilt (Table 10). Ball velocity, height, and weight were also collected as independent variables.

Participants

      High school aged baseball pitchers (n=43) were included in the analysis. Injury group assignment was based on the results of a questionnaire completed by both the participant and his parent/guardian. That questionnaire included open-ended questions about all potential injuries to the shoulder or elbow. Participants were specifically asked whether they had missed practice/competition as a result of an arm injury. They were also asked to describe the injury in as much detail as possible, including information about date of onset, specific diagnosis, restrictions placed on activity, and length of time that those restrictions lasted. Participants who did not report any previous shoulder or elbow injury were classified as un-injured. Those athletes that a reported shoulder or elbow injury that caused them to miss one day of scheduled practices/games were placed into the injury group (Kerr et al., 2014). Demographics for each group are presented in Table 11. Baseball pitcher was defined as currently playing the position of pitcher on a competitive team and having maintained this status for at least two consecutive seasons (Oyama et al., 2013). Participants were excluded from the study if they had undergone shoulder or elbow surgery within the last year or had a current injury that prevents them from throwing with full velocity from a mound.

Instrumentation

3-dimensional coordinate data were recorded using a 12 camera motion-capture system (Motion Analysis Corporation, Santa Rosa CA) collecting at a speed of 240 Hz. Retroreflective markers were placed over anatomical landmarks, which were then be used to define joint centers and axes (Rab, Petuskey, & Bagley, 2002). Visual3D (C-Motion Inc, Germantown, MD) was used to calculate joint angles during specific phases of the pitching motion from the position of the retroreflective markers (Hurd et al., 2012). A radar gun (SpeedTracX, EMG Companies, Inc., Prescott, WI) was used to capture ball speed.

Procedures

Participants began the study by reporting to a university laboratory. Upon arrival, participants and their parent/guardian were administered a questionnaire containing general information about age, injury history and pain. Maturation stage was collected as a potential covariate by the Pubertal Development Scale (PDS), which is a non-invasive, valid, and reliable questionnaire for predicting Tanner staging (Carskadon & Acebo, 1993). An investigator measured height and weight following survey completion. After the demographic data were collected, Velcro bases for the retroreflective marker set, which included markers on the trunk (suprasternal notch, xiphoid process, C7 spinous process, and T8 spinous process), dominant arm (acromion process, medial epicondyle, lateral epicondyle, ulnar styloid process, radial styloid process, and dorsal 3rd metacarpal), and non-dominant foot (distal 3rd metatarsal on shoe) were secured by tape adherent to ensure that they remained in

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place while the pitcher was throwing. The participant was then instructed to warm up in exactly the same manner as they normally would before a bullpen session, with the Velcro bases on to become accustomed to the set-up. Warm-up was self-selected and consisted of a mixture of light throwing, stretching, calisthenics, and light resistance training work depending on participant preference. Participants told an investigator when they were ready to throw off of the mound at full velocity. The retroreflective markers were then fixed to the Velcro bases to begin the motion capture trials. To create accurate measures of trunk length and width, three additional markers, one at the non-dominant AC joint and two on the anterior superior iliac spine of each hip were added for a one second static trail. This trial also served the purpose of providing an accurate model for the data analysis. After the static standing trial, the three static markers were removed, and participants performed at least two pitches off an indoor pitching mound, placed at proper distance from the home plate (18.5m) to accommodate to the testing setting. Pitchers then completed 10 fastball pitches off of the indoor mound towards a target spanning the strike zone for an average sized high school player (Aguinaldo & Chambers, 2009; Oyama et al., 2014). These pitches were recorded via the motion capture system (Figure 14), and the radar gun was used to collect the velocity of each pitch. If three strikes were thrown within the 10 pitches, data collection was stopped. If a pitcher failed to throw three strikes, he had an additional 5 pitches to complete the testing. No pitcher needed more than 12 pitches to complete the protocol. Pitchers were allowed as much rest time as needed between pitches.

Data Analysis

The 3 fastest pitches thrown for strikes were analyzed, and the results from those trials were averaged (Oyama et al., 2014). The coordinate system for the each part of the upper extremity was constructed via recommendations from the International Society of Biomechanics (Wu & Cavanagh, 1995). Kinematic and kinetic variables were calculated using Visual3D based on a 3D, 6-degrees-of-freedom model of the upper extremity that has been previously used to calculate joint moments during pitching (Hurd, Kaufman, & Murthy, 2011). The ball was added as a 142g point mass immediately anterior to the 3rd metacarpal marker (Hurd et al., 2011) and was removed from the model at ball release. All data were low-pass filtered at 13.4 Hz with a fourth-order, zero-lag Butterworth filter (Escamilla et al., 2007; Fleisig et al., 1996). Shoulder kinematic variables were calculated using the Y-X-Y Euler angle rotation sequence and elbow variables with the Z-X-Y sequence recommended by the International Society for Biomechanics (Wu et al., 2005). Trunk kinematic variables were calculated in a X-Y-Z Euler angle sequence compared to the laboratory coordinate system. Kinematic variables were analyzed at five different points of the pitching motion: SFC, maximum external rotation, and ball release, maximum elbow varus moment, and maximum shoulder distraction force. These data points correspond to phases of the pitching motion and have been used in previous literature on upper extremity joint loading (Escamilla et al., 2007; Fleisig et al., 1995; Sabick et al., 2004; Werner et al., 2002). Maximum external rotation, elbow varus moment, and shoulder distraction force were defined as the frame in which each variable reached its largest

value. Ball release was defined as the point at which the hand marker reached its maximum velocity (Ramsey & Crotin, 2016). SFC was defined as the point at which the foot marker on the stride foot reaches a threshold that equaled its vertical minimum plus three times its standard deviation between maximum external rotation to ball release. Kinetic variables were calculated using inverse dynamics in the arm's local coordinate systems (Feltner & Dapena, 1986). Shoulder and elbow kinetics were defined as the forces and torques applied to the distal segment by the proximal segment (Fleisig et al., 1996). One athlete was removed from the analysis because the Velcro bases were not remaining adhered to the skin.

Statistical Analysis

Data were analyzed using JMP (SAS Institute, Cary, NC) and the Statistical Package for Social Sciences (SPSS, Chicago, IL). The PDS score was not significantly correlated to any variable, so it was not included as a covariate in the analysis. Co-linearity was expected between pitching variables, so binary recursive partitioning was performed in JMP to screen variables for the logistic regression analysis. Binary logistic regression analysis in SPSS was used to evaluate how well the dependent variables from the three dimensional pitching mechanics predicted injury history (NON, INJ). An *a priori* alpha level of .05 was used to determine statistical significance.

Results

A history of injury resulting from throwing was reported by 16 athletes, and 26 reported no previous injury history. All injured athletes reported either a specific diagnosis or had missed at least one week of competition as a result of the reported injury. Athletes threw at a speed of 29.99 ± 2.63 meters per second (67.1 ± 5.9 miles per hour). Binary recursive partitioning identified four variables that were able to improve the confusion matrix, which compares group prediction to the actual group identification. Those variables were shoulder abduction at stride foot contact, lateral trunk tilt at maximum internal varus moment, shoulder abduction at maximum external rotation, and shoulder horizontal abduction at ball release. Any further splitting of the data did not impact the confusion matrix. The results of the binary logistic regression showed that the four explanatory-variable model provided a statistically significant improvement over the constant-only model ($\chi^2 = 10.563$, df = 4, $p = .032$). The Hosmer-Lemeshow goodness-of-fit test showed a satisfactory model of fit with the data ($p = .259$). The Nagelkerke R^2 indicated that the model accounted for 30.2% of the variance. The R^2 was converted to Cohen's f^2 statistic (Cohen, 1988). The obtained f^2 (.432) suggested a large effect size for the predictors as a set in discriminating between pitchers with and without previous injury.

Predictive success was evaluated for cases used in the development of the model. Overall classification accuracy was 78.6% (Table 9). Sensitivity was moderate (68.8%) and specificity was high (84.6%).

Table 12 presents regression coefficients (*B*), Wald statistics, significance levels, odds ratios, and 95% confidence limits for the odds ratio for each predictor. The Wald test was statically significant for one predictor: shoulder abduction at maximum external rotation (p = .026). Specifically, athletes who displayed less abduction at the time point of maximum external rotation were more likely to be placed into the injured group (Figure 14).

Discussion

The purpose of this study was to examine whether previous injury could be predicted from a three dimensional analysis of pitching mechanics. While normal variability does exist between pitchers despite injury history, we found that athletes who have suffered a previous injury exhibit different biomechanical patterns than those with no injury history, even though the athletes had returned to full participation. Many of the observed upper extremity angles were similar between groups, but 30.2% of the variance can be predicted by four variables. Our model was able to accurately predict 11/16 (68.8%) of the pitchers that had an injury history and 22/26 (84.6%) of pitchers that had no injury history. Furthermore, only one variable of the 28 examined, shoulder abduction at maximum external rotation was a significant factor in the model (Figure 15, Figure 16). Anecdotally, this biomechanical pattern is referred to as "dropping the elbow" by people in the baseball community. It is important to note that 16 of the 42 pitchers in this study with complete data (38%) had experienced an injury to the pitching arm which removed them from competition at some point during their

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little league or high school careers. Six of the injuries occurred to the growth plate, six to the muscle, and four were reported as general discomfort. Even though no athlete had undergone surgery, 11 of the 16 injured pitchers were instructed by medical professionals to refrain from, or drastically alter, overhead activity for at least three months following the injury.

Pitching Mechanics and Injury History

The results from our study begin the process of determining the effect of injury on pitching mechanics in high school baseball pitchers, which has been limited in previous research. The results of this study differ from previous literature on professional athletes, which found that pitchers with previous superior labrum anterior-posterior (SLAP) repairs have horizontal abduction and external rotation deficits, while those with previous ulnar collateral ligament (UCL) reconstructions exhibit no differences compared to pitchers who had not undergone the surgery (Fleisig et al., 2015; Laughlin et al., 2014). We did find that the normal variability in pitching mechanics offsets most of the differences between previously injured and uninjured pitchers. However, our high school athletes, who had experienced injury but had not undergone surgery, did exhibit abduction deficits at the end of the cocking phase of the pitching motion.

It is also interesting to note that shoulder abduction at the end of the cocking phase of throwing was the only variable related to injury history. Previous investigations have found relationships between medial elbow load and maximum

external rotation, horizontal abduction, elbow flexion, and trunk lateral flexion (Aguinaldo & Chambers, 2009; Oyama et al., 2013; Werner et al., 2002). In the context of previous research (Aguinaldo & Chambers, 2009; Oyama et al., 2013; Werner et al., 2002), our results may indicate that shoulder and elbow loads may not have as direct of a relationship to injury in high school pitchers as previously thought. Another potential reason for the differences observed in our study compared to previous research may be the age difference in the athletes studied. Healthy youth and adult pitchers differ in abduction and elbow flexion angles at SFC (Escamilla et al., 2007; Fleisig et al., 1999; Ishida, Murata, & Hirano, 2006), so it is reasonable that injury could affect these populations differently.

Reduced abduction at the point of maximum external rotation may be a predisposition for elbow injury, as it has been previously related to increases in medial elbow load (Aguinaldo & Chambers, 2009; Matsuo & Fleisig, 2006). If a pitcher's mechanics remained consistent over time, a continued excessive load may be placed on the elbow. That load could then have contributed to the injury, and the abduction deficits could have remained present in previously injured pitchers' biomechanics that were observed in our laboratory. Since joint angles, arm velocity, and various other factors can influence loading rates, the timing of internal varus moments or elbow position at those positions may be more indicative of previous injury than only elbow load. Future investigations that explore the relationship between maximum internal varus moment, timing of that moment, elbow position, and injury are also needed.

The biomechanical differences exhibited by pitchers in this study may be related to lingering pain or biomechanical adaptations to reduce injury symptoms. During the cocking position, the humerus slides anteriorly to help produce external rotation (Meister & Seroyer, 2003), and the rotator cuff must contract to maintain congruency with the glenoid (Wilk, Andrews, Cain, & Devine, 2009). In people with shoulder pain, excessive anterior translation of the humerus, alteration in deltoid activation, and decreased rotator cuff activity occurs when abducting the arm past 90° (Diederichsen, Winther, Dyhre-Poulsen, Krogsgaard, & Norregaard, 2009; Lawrence, Braman, Staker, Laprade, & Ludewig, 2014). To remain in a non-painful arc of motion, previously injured pitchers may have adopted a delivery that limits abduction. That range of motion restriction during the pitch would limit subsequent anterior translation, resulting in increased stability and reduced strain on the inferior glenohumeral ligament (Karduna, Williams, Williams, & Iannotti, 1996). These throwing biomechanics may have become "normal" for when our pitchers who returned to competition and led to the differences we observed between injured and uninjured pitchers.

Reduced shoulder abduction angles at the point of maximum external rotation may also be a result of limited flexibility. Glenohumeral internal rotation deficit (GIRD) has been linked to epiphyseal plate injuries and other musculoskeletal pathologies in adolescent athletes (Byram et al., 2010; Heyworth et al., 2016). Tightness in the posterior shoulder, which is a direct consequence of GIRD (Burkhart et al., 2003), can present clinically as a deficit in abduction (J. J. Lin, Lim, & Yang,

2006). Moreover, posterior shoulder tightness leads to a humeral head position nearer to the rotator cuff tendons, which increases the chances of impingement and subsequent pain (Harryman et al., 1990). Improper flexibility in the posterior structures could then create a protective biomechanical pattern where athletes reduce abduction to reduce that rotator cuff tendon impingement and related pain. Therefore, the presence of GIRD would help explain why pitchers with previous injury present with limited abduction at the point of maximum external rotation.

Like deficits in flexibility, underdeveloped musculature may be another reason for a variety of injuries in youth athletes (Ireland & Hutchinson, 1995). Global muscular fatigue of the shoulder, as produced by pitching a simulated game, can produce voluntary activation deficits in the infraspinatus (Gandhi, ElAttrache, Kaufman, & Hurd, 2012). Those deficits may lead to abnormal humeral head translation, which may cause a pitcher to alter biomechanics as a protective mechanics to reduce injury risk (Murray, Cook, Werner, Schlegel, & Hawkins, 2001). Furthermore, reductions in glenohumeral strength in flexion/extension, abduction/adduction, and internal/external rotation are limited after high school aged pitchers throw 100 pitches (Pei-Hsi Chou et al., 2015). These deficits in strength appear to affect biomechanics. Previous authors have indicated that throwing multiple simulated innings can lead to decreased abduction and horizontal abduction throughout the pitching cycle (Barrentine, Takada, Fleisig, & et al, 1997). Therefore, potential strength deficits in our previously injured athletes, although not directly measured in this study, could have led to the development of a new motor control

pattern that mimicked fatigue and led to the observed reduction in abduction at maximal external rotation. Further research is needed to determine the relationship between strength and pitching biomechanics in previously injured high school pitchers, but the results of this study provide a foundation for those investigations.

Limitations

The main limitation of this study is that the data are not prospective. A wide variety of biomechanical strategies are used by pitchers, and the result that shoulder abduction at maximum external rotation differentiates between groups does not indicate future risk of injury. Instead, our model can only identify if injury had previously occurred. It is possible that pitchers may have exhibited similar biomechanical patterns before the injury occurred, but it is not guaranteed. Future investigations should prospectively examine the relationship between shoulder abduction and injury risk in high school baseball pitchers. Another limitation of this study was that elbow and shoulder injuries were grouped together. Pitchers with previous shoulder injury may throw differently than those with previous elbow injury, but the relatively small sample size necessitated that we combine the groups. Finally, the sample of pitchers collected exhibited a selection bias. While the recruitment for this study ranged across all local high school teams, the athletes who chose participate may have been more knowledgeable about their pitching mechanics. Therefore, the sample may not be representative of the entire high school pitching population.

Conclusion

We observed that shoulder abduction at maximum external rotation successfully grouped athletes with and without previous injury history in high school baseball pitchers. Shoulder external rotation and horizontal abduction, elbow flexion, and lateral trunk flexion were not able to differentiate between groups at any time point during the cocking, acceleration, or deceleration phase. Height, weight, and ball velocity also did not accurately identify injury group. While future injury risk is still not identifiable in these athletes, our results indicate athletes who have suffered a previous injury pitch differently than those with no injury history, even after they had been cleared to play. Therefore, clinicians, coaches, and parents should be aware of youth pitchers who throw with a reduced shoulder abduction angle. They also may want to begin conversations about pain or injury history in athletes who exhibit those pitching biomechanics in an attempt to provide early intervention for a potential injury.

Chapter 5

TWO-DIMENSIONAL ANALYSIS IS VALID BUT DOES NOT IDENTIFY INJURY HISTORY IN HIGH SCHOOL PITCHERS

Introduction

Baseball pitching is a complex movement requiring coordination along the kinetic chain to produce velocity, while maintaining accuracy of a projectile. Anecdotal data suggest that many of those working with high school pitchers believe that they can identify pathomechanics that impact joint loading and subsequent. A variety of visible qualitative cues have been used in attempts to limit injuries; these include not leading the movement into the acceleration phase with the elbow, avoiding the inverted "W", and pitchers removing the baseball from the glove with their hands on top of it. However, shoulder rotation occurs at speeds of 7000°/second in youth and high school pitchers (Fleisig et al., 1999), so the naked eye may struggle to accurately identify what is truly occurring during pitching. The 58% injury rate increase in baseball pitchers from 2005-2008 and previous research indicate also indicates that these qualitative instructions may not be entirely successful (Aguinaldo & Chambers, 2009; Berra, ; Douoguih, Dolce, & Lincoln, 2015; Posner, Cameron, Wolf, Belmont, & Owens, 2011). Relatively inexpensive and valid two-dimensional (2D) analysis may

help improve the cues given to young pitchers and improve the clinical tools available for those working with these athletes.

Instead of qualitative cues, researchers have examined quantitative kinematic variables throughout the pitching motion that relate to high upper extremity loading. The trunk is one area that has been investigated because it creates power for the pitch, after stride foot contact. Previous research has determined that exaggerated lateral trunk flexion away from the pitching arm creates separation between the axis of rotation and the ball, allowing pitchers to produce higher arm velocities (Oyama, Hibberd, & Myers, 2013; Solomito, Garibay, Woods, Ounpuu, & Nissen, 2015). Despite the velocity increases, this lateral trunk flexion strategy may be detrimental to arm health. Solomito et al. (2015) noted that elbow varus moment increases by 3.7 Nm and shoulder internal rotation moment increases by 2.5 Nm for every 10° of lateral flexion away from the dominant side. The relative increase in that upper extremity loading was more than double the comparative velocity gains (Solomito et al., 2015). While the trunk is an important factor in UE loading, other joints have an impact as well. Matsuo et al. (2006) conducted computer simulations to manipulate both trunk tilt and shoulder abduction angle at ball release in baseball pitchers. These simulations found that releasing the ball with shoulder abduction angles in a middle range (between 90-100°) limited medial elbow torque despite the angle of the trunk (Matsuo & Fleisig, 2006). Finally, elbow flexion angles have been associated with both shoulder and elbow kinetics (Aguinaldo & Chambers, 2009; Werner et al., 2002; Werner et al., 2007), but there remains a lack of understanding of the consequences of

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these high upper extremity loads. While kinematics that produce higher upper extremity forces and torques are thought to be an injury risk factor, limited literature exists on how joint angles differ in pitchers who have suffered a previous injury and those who have not.

The previous research on biomechanics has added greatly to our understanding of shoulder and elbow forces during the pitching motion, but these analyses present with two major problems. First, most of the previous research has used three-dimensional (3D) motion capture techniques to examine pitching mechanics. These 3D methods are prohibitively expensive for sports medicine professionals and also require a expertise in data analysis and interpretation. Therefore, translation of this laboratory research to on-field settings is lacking. The technological advances in the portability, resolution, and frame rate of two-dimensional cameras have created the potential for a relatively affordable examination of pitching mechanics, in the field, that may be valid compared to data captured in a laboratory setting. This type of analysis could produce kinematic variables related to injury history and joint loading that are able to be collected via 2D methodology, making them measurable for people working with youth pitchers. However, little research has examined the validity of these 2D techniques (Oyama, Sosa, Campbell, & Correa, 2017).

The second issue with these previous analyses in determining the factors associated with high joint loading is the use of correlation and regression analyses or direct group comparison (Matsuo, Escamilla, Fleisig, Barrentine, & Andrews, 2001; Matsuo & Fleisig, 2006; Oyama et al., 2013; Werner et al., 2002). These types of

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statistical models are only able to determine whether upper extremity loading in pitchers is associated with higher or lower trunk, shoulder, and elbow angles. Instead, the impact of kinematics on joint forces and torques indicates pitchers who exhibit non-normative upper extremity joint angles, whether they are extremely high or low, during pitching may experience higher loads than those who throw with relatively normative joint angles (Aguinaldo & Chambers, 2009; Matsuo et al., 2001; Matsuo & Fleisig, 2006; Oyama et al., 2013; Werner et al., 2002). Dividing pitchers by normative and non-normative values in a parabolic type of design based on individual variables may be a better method for determining joint loading than using a linear type of analysis. Furthermore, adding together the number of pitching mechanics performed in non-normative ranges could provide a more comprehensive analysis of the kinematics associated with high shoulder forces and elbow torques.

The current study aimed to address the current limitations in translation of research into a clinically applicable setting by using 2D analysis. We also attempted use a direct comparison of objective normative and non-normative pitching mechanics to see if those who throw with excessively high or low upper extremity angles experience higher shoulder force and elbow moments. The first aim was to examine concurrent validity of the 2D analysis in measuring kinematics, which have been previously linked to loading rate, by comparing them to the 3D data collected simultaneously. The second aim attempted to determine if injury history could be predicted from the 2D analysis. The final aim investigated whether internal elbow varus moments and shoulder distraction force were greater in pitchers who display

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non-normative pitching kinematics. We hypothesized that the 2D angles evaluated with mobile software applications will produce angles and predict injury group similarly to the 3D analysis. We also hypothesized that injury history could be predicted from the 2D analysis and that joint loads would be higher in pitchers who display lateral trunk tilt, shoulder abduction, and elbow flexion angles outside of normative values.

Dissertation Aim Description and Results

Aim 3: To determine if injury history, shoulder distraction force, elbow varus torques are greater in pitchers who display non-normative pitching kinematics measured by 2D analysis

H3.1 A The 2-dimensional pitching analysis evaluated with mobile software applications will produce angles and predict injury group similarly to 3-dimensional analysis.

> The 2-dimensional pitching analysis was valid for 3 of the 5 variables examined. However, those variables did not accurately predict injury history. Therefore, the 2D analysis did not predict injury history group similarly to the 3D analysis

H3.2: Shoulder distraction forces and elbow varus moments will be higher in pitchers who display lateral trunk tilt, shoulder abduction, and elbow flexion angles outside of normative values.

Upper extremity loads were similar between pitchers who presented with normative and non-normative pitching mechanics. The only value that differed was shoulder distraction force, which was greater in pitchers who performed lateral trunk flexion within a normative range.

Methods

Experimental Design

This study used a post-test only design. The independent variables were lateral trunk tilt at ball release, shoulder abduction at stride foot contact (SFC), shoulder abduction at ball release, and elbow flexion at SFC, and elbow flexion at ball release. 3D analysis was used to examine validity of the 2D data and collect the dependent variables of maximum shoulder distraction force and internal varus moment. Injury history was also collected as a dependent variable. Testing took place on a single day, with the experiment lasting approximately one hour.

Participants

Thirty eight high school aged baseball pitchers were analyzed in this study (Table 13). Injury group assignment was completed based on the results of a questionnaire completed by a combined effort from both the participant and his parent/guardian. That questionnaire included open-ended questions about all potential injuries to the shoulder or elbow. Participants were specifically asked whether they had missed practice/competition as a result of an arm injury. They were also asked to

describe the injury in as much detail as possible, including information about date of onset, specific diagnosis, restrictions placed on activity, and length of time that those restrictions lasted. Participants who did not report any previous shoulder or elbow injury were classified as un-injured. Those athletes that a reported shoulder or elbow injury that caused them to miss at least one day of scheduled practices/games were placed into the injury group (Kerr et al., 2014). Baseball pitcher was defined as currently playing the position of pitcher on a competitive team and having maintained this status for at least two consecutive seasons (Oyama et al., 2013). Participants were excluded from the study if they had undergone a shoulder or elbow surgery within the last year or had a current injury that prevents them from throwing with full velocity from a mound.

Instrumentation

Kinematic variables were measured with a combination of a 2 dimensional video player (Kinovea, Kinovea organization, France) and Image J software (National Institutes of Health, Bethesda, MD). Still frames at SFC and ball release from the Kinovea player were transferred into Image J, where the measurements were acquired. A 12 camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA) was used to record 3-dimensional coordinate data. Data were collected at 240 Hz. Commercially available video cameras (Sony X1000V 4K Action Cam, Sony Corporation, Tokyo, Japan) collected 2D data at the same time as the 3D data. A radar

gun (SpeedTracX, EMG Companies, Inc., Prescott, WI) was used to measure ball speed.

Procedures

After reporting to the laboratory, participants and their parents/guardians completed informed consent documents and a questionnaire providing information about injury history. Following the completion of those documents, demographic data of height and weight were collected by the primary investigator. Velcro bases for the retroreflective marker set, which included markers on the trunk (suprasternal notch, xiphoid process, C7 spinous process, and T8 spinous process), dominant arm (acromion process, medial epicondyle, lateral epicondyle, ulnar styloid process, radial styloid process, and dorsal 3rd metacarpal), and non-dominant foot (distal 3rd metatarsal on shoe) were secured by tape adherent to ensure that they remained in place while the pitcher was throwing. They were then instructed to warm up as if they were completing a bullpen session. After the pitchers reported they were prepared to throw off of the mound at maximum velocity, the retroreflective markers were fixed to the Velcro bases and pitching trials were initiated. Each pitcher received at least two practice pitches off of an indoor mound to a target placed 18.5 meters (60.6 feet) from the pitching rubber. These practice pitches allowed participants to become accustomed to the marker set and camera proximity. In addition to the 3D cameras, two 2D cameras were set up to record the throwing motion. One camera was placed to the side of the mound, which corresponded to the pitcher's dominant arm, to capture a frontal

plane view of the mound (Oyama et al., 2017). Another camera was placed in front of the mound to capture a sagittal plane view (Oyama et al., 2017). Once pitchers had accommodated to the testing environment, they threw 10 fastball pitches to a target strike zone spanning an average sized high school player (Aguinaldo & Chambers, 2009). These pitches were recorded by both the 3D and 2D camera systems simultaneously. Testing was completed if a pitcher achieved three strikes within the 10 pitches. However, if a pitcher did not achieve that goal, he was given additional trials to complete the testing protocol. No participant in this investigation threw more than 12 pitches to complete testing. Time between pitches was self-selected with the investigator suggesting a time frame that matched what the pitcher would normally do in a game situation.

Data Analysis

The fastest three pitches thrown for strikes were analyzed in this study (Fleisig et al., 1999). The mean of each variable was taken across trials for both the 2D and 3D data. For 3D analysis, the coordinate system for each segment of the upper extremity was constructed via recommendations from the International Society of Biomechanics (Wu & Cavanagh, 1995). A 6-degrees-of-freedom model created in Visual3D (C-Motion Inc, Germantown, MD) calculated joint kinematics and kinetics (Hurd et al., 2011). In that model, the ball was added as a 142g point mass immediately anterior to the 3rd metacarpal marker (Hurd et al., 2011). All 3D data were low-pass filtered at 13.4 Hz with a fourth-order, zero-lag Butterworth filter (Escamilla et al., 2007; Fleisig

et al., 1996). Shoulder kinematic variables were calculated using the Y-X-Y Euler angle rotation sequence and elbow variables with the Z-X-Y sequence recommended by the International Society for Biomechanics (Wu et al., 2005). Trunk kinematic variables were calculated in a X-Y-Z Euler angle sequence compared to the laboratory coordinate system. Kinetic variables were calculated as force and torque applied by the proximal segment to the distal segment (Fleisig et al., 1995). Elbow internal varus moment was normalized by body weight and height while shoulder distraction force was normalized to body weight. Ball release was defined as the point at which the hand marker reached its maximum velocity (Ramsey & Crotin, 2016). SFC was defined as the point at which the foot marker on the stride foot reached a threshold that equaled its vertical minimum plus three times its standard deviation from maximum external rotation to ball release.

The primary investigator, who has previous experience working with baseball teams and communicates regularly with baseball coaches, examined and calculated kinematics from all the 2D videos. He was blind to the 3D data during 2D analysis. This researcher identified SFC in the 2D videos as the point at which the foot became flat on the ground. Time of ball release on the 2D videos was marked as the frame at which the ball became separated from the hand. Manually digitized landmarks were used to calculate joint angles for all the independent variables.

Statistical Analysis

Data were analyzed using the Statistical Package for Social Sciences (SPSS, Chicago, IL). Validity of the 2D data was calculated via an intra-class correlation (ICC $_{(3,k)}$) that assessed absolute agreement. Variables that achieved an ICC $_{(3,k)}$ of greater than .80 were then included in the statistical analyses to examine differences between pitchers with and without injury history as well as those who had biomechanics inside and outside normative ranges. The use of only variables which produced an acceptable ICC $_{(3,k)}$ value helped eliminate the influence of invalid data. Binary logistic regression analysis was used to determine how well the 2D model could predict injury history.

To create normative and non-normative groups based on pitching mechanics, results for each independent variable were separated into quartiles (Table 14). These quartiles were then used to divide pitchers into groups, with the normative group encompassing the middle 50% of the data, and the non-normative group consisting of the highest and lowest 25% of the values for each independent variable. Therefore, the group of pitchers was divided in half for direct comparison, with each pitcher receiving one group identification for each of the valid variables. This parabolic type design was examined using t-tests to determine the differences in internal elbow varus moment and shoulder distraction force between groups. Then, the number of parameters performed incorrectly were added together (Davis et al., 2009), giving each pitcher a group identification value from 0 to the number for valid 2D variables (up to 5 total). Subsequently, that group value indicated the total number of parameters non-normative performed by the pitcher. Two, one-way ANOVAs were used to

determine whether elbow moments and shoulder forces could be differentiated by the performance of multiple parameters outside of normative values. An *a priori* alpha level of .05 was used to determine statistical significance for the binary logistic regression, t-tests, and ANOVAs.

Results

Concurrent Validity

Trunk lateral flexion values exhibited strong concurrent validity ($ICC_{(3,k)}$ = .950) between 2D and 3D biomechanics. Two other variables, shoulder abduction at SFC ($ICC_{(3,k)}$ = .837) and elbow flexion at SFC ($ICC_{(3,k)}$ = .909) were also valid. Elbow flexion ($ICC_{(3,k)}$ = .624) and shoulder abduction ($ICC_{(3,k)}$ = .611) at ball release did not show good validity. Therefore, only trunk lateral flexion, shoulder abduction at SFC, and elbow flexion at SFC were used for group analyses.

Injury History

History of throwing injury was reported in 14 athletes, with 24 reporting no previous injury history. All injured athletes reported either a specific diagnosis or had missed at least one week of competition as a result of the reported injury. The results of binary logistic regression showed that the three independent variables: trunk lateral flexion at ball release, shoulder abduction at SFC, and elbow flexion at SFC, did not produce a statistically significant improvement over the constant-only model (χ^2 = 2.323, df = 3, p = .508) (Table 15). The Nagelkerke R^2 indicated that the model only

accounted for 8.1% of the variance between injury groups. The primary problem with the model was that it did not accurately predict those with injury history, as only 21.4% of those athletes were accurately identified. Overall 68.4% of participants were accurately placed into the proper group, primarily due to the fact that the model correctly identified 95.8% of those reported no previous injury. Table 16 presents regression coefficients (B), Wald statistics, significance levels, odds ratios, and 95% confidence limits for the odds ratio for each predictor and indicates that the Wald test was not statistically significant for any of the predictors.

Elbow Varus Moment

No significant differences in normalized internal elbow varus moment existed when comparing the normative groups trunk lateral flexion at ball release ($t = -.07$, $p = .946$) and shoulder abduction at SFC ($t = 1.03$, $p = .310$) with the respective non-normative groups. Pitchers with normative elbow flexion values at SFC ($.167 \pm .032$ Nm/kgm) did display lower varus moments than those outside normative values ($.173 \pm .016$ Nm/kgm), but that difference was not significant ($t = -.649$, $p = .520$). Finally, when adding together the number of non-normative pitching mechanics, no differences were observed between those who exhibited 0, 1, 2, or 3 of the kinematic angles outside of the normative values ($F_{34,3} = 1.459$, $p = .243$) (Figure 17)

Distraction Force

A significant difference in normalized shoulder distraction force existed between pitchers who threw with differing lateral trunk flexion angles ($t = 2.01$, $p = $

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.043). Interestingly, the athletes who displayed normative trunk lateral flexion (.574 ± .073 Nm/kg) exhibited higher shoulder distraction forces than those who threw outside of the normative values (.520 ± .083). No significant differences existed in normalized shoulder distraction force when comparing pitchers with normative shoulder abduction angles (t = -.476, p = .638) and elbow flexion angles (t = -1.049, p = .305) at SFC to those with non-normative values. When combining the number of non-normative pitching mechanics, no differences were observed between those who exhibited 0,1,2, or 3 of the kinematic angles outside of the normative values ($F_{34,3}$ = .780, p = .514) (Figure 18)

Discussion

This study examined the concurrent validity of 2D kinematic analysis to determine whether those on-field professionals working with high school baseball pitchers could use commercially available tools to differentiate athletes who have a history of injury and experience higher shoulder and elbow joint loads. We found that some angles measured by 2D analysis, namely trunk lateral flexion at ball release, shoulder abduction at SFC, and elbow flexion at SFC were valid in comparison to 3D measures. While these values may be valid, they do not accurately differentiate whether a pitcher has a history of injury or not. Furthermore, throwing outside of normative values for these valid variables did not lead to higher loads on the shoulder and elbow. Instead, throwing within a middle range of values actually led to higher shoulder distraction forces in the pitchers who participated in this study.

Concurrent Validity

Our data support the findings of Oyama et al. (2017) that shoulder abduction angle at SFC can be identified accurately via 2D analysis. In addition, we found that measures of elbow flexion at SFC are also valid compared to 3D analysis. The reason that these values are valid is likely related to camera position. Angle measurement accuracy increases as angle between the body segments and the 2D video cameras approach 90˚ (Elliott, Alderson, & Denver, 2007). At SFC, the torso is aligned parallel to the direction of the throw and has not yet begun to rotate (Oyama et al., 2017). The elbow has typically reached a vertical position by this time point as well. Therefore, the camera that captured the frontal plane view, which was placed to the side of the mound corresponding to the pitchers' dominant arm, was able to accurately capture an in-plane measurement of the proposed variables at SFC. From that view, the direct relationships between the torso, humerus, and forearm could then be measured at that time point.

The accuracy of the 2D measurements was also excellent for one variable at ball release: trunk lateral flexion. While the trunk was rotated past the sagittally positioned camera at ball release, center of the pelvis, which acts as the joint center for the trunk during lateral flexion, was still orthogonally directed towards the camera. Even though the distal segment rotation may have slightly altered bony landmark position, it may not have been enough to drastically influence the measurement. Trunk rotation did appear to affect the validity of the shoulder and elbow angles at ball release, matching previous literature (Oyama et al., 2017). That rotation would then

have created a poor reference for movement of the upper arm and forearm in the sagittal plane and led to the inaccurate measurement. An improvement in the validity of shoulder and elbow angles could likely occur if the trunk rotation were accounted for by camera position. Then shoulder and elbow angles could be tracked in an appropriate orthogonal 2D plane. However, this technique would require individualized camera placement for each pitcher, as trunk rotation at ball release varies based on the pitcher. For clinicians with a limited population of athletes or time to conduct the assessments, finding the camera angles that are best for each pitcher may be useful. However, using individualized camera positions has not been validated with 3D data. Ultimately, if clinicians consider using 2D techniques to measure upper extremity joint positions, they should use angles that have been proven valid by this study and in previous literature (Oyama et al., 2017).

Pitching Kinematics and Injury History

The three 2D pitching kinematics shown to be valid in comparison with 3D analysis were used to predict injury history in high school pitchers. Biomechanical analyses have been conducted on pitchers using 2D analysis, but those investigations examined the effects qualitative instruction on joint load and the influence of kinematics on ball velocity (Davis et al., 2009; Sgroi et al., 2015). Providing a clinically relevant 2D assessment would be useful for those who work with high school pitchers because they could identify previously injured athletes, which may lead to earlier intervention techniques or modified rehabilitation in those athletes.

However, we did not find that any of our 2D variables were useful in predicting injury history in this population. That finding is similar to studies which also found no differences in lateral trunk tilt, abduction, or elbow flexion in athletes who had previously undergone superior labral repair or UCL reconstruction (Fleisig et al., 2015; Laughlin et al., 2014).

When we examined previously injured high school pitchers who had not undergone surgery, 3D kinematic analysis identified shoulder abduction at maximum external rotation as the only variable which could differentiate whether pitchers had suffered a previous injury (Chapter 4). This point of maximum external rotation in the pitching motion is extremely close in time to the maximum elbow varus moment (Wight et al., 2004). Therefore, arm position during times of high joint load may be more indicative of previous injury than arbitrary points of the pitching motion such as SFC and ball release. While adequate 2D measurements of upper extremity angles at the instant of maximal external rotation could be valid because the trunk and shoulder are nearly orthogonal to a sagittal plane camera (Oyama et al., 2017), those measures were not included in this study because they are likely harder for those working with youth athletes to identify and had not been validated in previous literature. Also, the position of the humerus and forearm at the point of maximum external rotation makes measurement of elbow angle impossible from only sagittal and frontal plane cameras. Future research should be conducted to determine whether 2D angles at maximum external rotation are able to identify injury history in high school pitchers.

Pitching Kinematics and Joint Loading

Injury history is important, but it may not provide much insight into joint forces present at the upper extremity. This investigation used an innovative 2D video and statistical analysis to determine if pitchers who exhibited abnormally high or low upper extremity angles at specific time points during the pitching motion produced higher elbow internal varus moments than those whose values were in the middle range. Our analysis found that elbow varus moments did not differ between athletes who were placed into normative and non-normative groups based on specific upper extremity angles during pitching. This finding is contrary to previous literature, which has found shoulder abduction and trunk lateral tilt influences varus moments in pitchers of various age groups (Matsuo & Fleisig, 2006; Oyama et al., 2013; Werner et al., 2002). Therefore, a 3D laboratory analysis, and not 2D cameras or naked eye observations, are likely needed to identify pitchers who exhibit high medial elbow moments.

Our grouping of pitchers based on elbow and shoulder kinematics provided a similar result for shoulder loading as for elbow moments. We found that shoulder distraction force was not different between groups when only defined by elbow flexion and shoulder abduction values at SFC. Those results contrast with previous studies that found a more flexed elbow at SFC was associated with reduced shoulder distraction force (Werner et al., 2001), suggesting again that 3D analysis is likely more useful in predicting shoulder forces from elbow angles. However, trunk tilt values did differentiate shoulder loading between groups. Unexpectedly, pitchers who threw

within a normative range of trunk tilt experienced normalized shoulder distraction forces almost 10% higher than those who exhibited trunk angles outside that normative range. This finding may be a result of the mean trunk tilt observed in our population. Overall, our pitchers presented with similar lateral flexion on average (30.7˚) at ball release as those that have been previously identified as presenting with "excessive" trunk tilt (30.3˚) (Oyama et al., 2013). Since higher amounts of trunk lateral flexion is associated with higher shoulder joint loading (Oyama et al., 2013; Solomito et al., 2015), it is possible that the high normative values observed in this study may have impacted our analysis of shoulder distraction forces. Based on our results, more research should be completed on the degree of lateral trunk flexion angles that are normal in athletes of various ages and how they relate to shoulder joint loading.

Differences between the pitching mechanics of adult and youth athletes may have led to the inconsistences in this study. Many high school pitchers are skeletally immature, so their pitching mechanics may be constantly adapting to meet the changing demands of their musculoskeletal growth and physical activity. Previous investigations have determined that youth and adolescent pitchers exhibit reduced shoulder abduction and elbow flexion at SFC (Escamilla et al., 2007; Fleisig et al., 1999; Ishida et al., 2006). Older pitchers also display higher elbow moments and shoulder forces than youth, even when controlling for body weight and height (Fleisig et al., 1999). The slight variability in joint angles while pitching, combined with lower shoulder forces and elbow torques, may indicate that the relationships between

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kinematics and kinetics differ between age groups. Since none of the 2D variables measured in this study significantly related to upper extremity loading, different 2D variables should be examined and more 3D analyses should be completed to determine these relationships in young, developing athletes.

Even though athletes in our study who presented with non-normative biomechanics on individual 2D parameters did not present with higher upper extremity loads, a combination of these abnormal values may better differentiate pitchers who experience high shoulder distraction forces and elbow torques. Since the body works as a kinetic chain, improper position of multiple upper extremity joints may have created an additive loading effect as shown by computer simulations from Matsuo et al (2006). Therefore, non-normative pitching mechanics across the trunk, shoulder, and elbow forces may cause forces to accumulate on one body part and create high forces on that joint. However, our results indicated that shoulder distraction force and internal varus moments were not different when allocating groups based on the combination of the three valid 2D variables. This finding also differs from Davis et al. (2009), who found that young pitchers who performed multiple qualitative parameters "incorrectly" exhibited higher normalized humeral internal rotation torques and elbow varus loads than those who performed them "correctly." Combined with our previous data on individual 2D variables, it appears that the measurements and statistical analyses used in this study do not accurately identify athletes who experience higher joint loads during pitching. Therefore, 3D analysis, which is current gold standard for

measuring pitching biomechanics, is currently the only way to accurately identify high joint loading.

Limitations

This study had a few limitations. The raw values of shoulder distraction force and internal varus moment were slightly lower than previous literature on youth and high school aged pitchers, while the velocity was similar (Fleisig et al., 1999). Slight variations in the processing of our data may have led to those differences. Furthermore, our testing took place in a laboratory setting during the late fall and winter. At that time of year, pitchers may not have been conditioned to throw as they would in a competitive game. Although we allowed a period for familiarization to the lab setting and marker set-up, pitchers may have still felt uncomfortable and not thrown at maximal effort. Finally, the sample of pitchers collected exhibited a selection bias. While the recruitment for this study ranged across all local high school teams, the athletes who chose participate may have been more knowledgeable about their pitching mechanics. Therefore, the sample may not be representative of the entire high school pitching population.

Conclusion

We found that two-dimensional measures of shoulder abduction and elbow flexion angles at stride foot contact, as well as trunk lateral flexion at ball release, were valid compared to traditional three-dimensional laboratory techniques. However,

those 2D valid measures do not differentiate between pitchers with and without previous injury history. Also, shoulder and elbow joint loading are not lower in pitchers who throw with normative pitching mechanics compared to those with non-normative values, based on those 3 valid variables. These data suggest that 3D techniques are still needed to identify pitchers with an injury history or high upper extremity joint loading. Much more research is needed to identify clinically applicable, quantitative tools that are useful for those working with high school pitchers.

Chapter 6

**DISCUSSION AND CONCLUSION: SPORT AND AGE INFLUENCE UPPER
EXTREMITY TISSUE CHARACTERISTICS WHILE THREE-
DIMENSIONAL BIOMECHANICS PREDICT INJURY HISTORY IN
OVERHEAD ATHLETES**

Discussion

Repetitive, joint loads over an athlete's career can create excessive stress on
upper extremity anatomical structures and lead to abnormal UE tissue proliferation
(Astolfi et al., 2015; M. G. Ciccotti et al., 2014; Nazarian et al., 2003; Thomas et al.,
2011; Thomas et al., 2012). Data on youth baseball players promote this theory, as
they present with bilateral differences in range of motion, humeral retrotorsion,
posterior capsule thickening, and UCL thickening (Astolfi et al., 2015; A. Atanda et
al., 2016). Those anatomical changes have been related to injury and altered joint
arthrokinematics in a physiologically vulnerable population (M. C. Ciccotti et al.,
2014; Huffman et al., 2006; Thomas et al., 2011; Thomas et al., 2012). To date,
literature on bilateral differences has been primarily limited to baseball athletes, but
other overhead athletes, specifically softball and tennis players, may also experience
upper extremity alterations because of the biomechanical similarities among overhead
sports (Reid et al., 2015; Ryu et al., 1988). The variances between sports may alter the
scope of these bilateral differences. Early specialization and year-round sport

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participation could also exacerbate these tissue features, but little data exist to identify factors which relate to unilateral anatomical changes in young athletes. Therefore, the first purpose of this dissertation was to investigate how age, sport, and degree of specialization relate to a variety of upper extremity tissue characteristics.

Individual biomechanical differences among athletes who participate in the same sport can also increase joint forces and subsequent tissue proliferation. Pitchers who exhibit excessive shoulder abduction and trunk lateral flexion away from the throwing arm, as well as reduced elbow flexion, experience higher the shoulder forces and elbow joint (Oyama et al., 2013; Werner et al., 2002). These joint loads could theoretically account for bilateral differences in anatomical tissue characteristics and injury history in elite pitchers (M. G. Ciccotti et al., 2014; Nazarian et al., 2003; Thomas et al., 2011; Thomas et al., 2012), but no current research has examined these theories. Furthermore, the three-dimensional (3D) methods currently used to analyze pitching mechanics are prohibitively expensive for sports medicine professionals, so translation of this laboratory research to field setting is lacking. The technological advances in the portability, resolution, and frame rate of commercially available video cameras have created the potential for a relatively affordable examination of pitching mechanics in the field that may be valid compared to data captured in a laboratory setting. This type of analysis could produce kinematic variables related to joint loading and injury that are able to be collected via 2D methodology, making them measurable for people working with youth pitchers. The second purpose of this dissertation aimed to address the limitations in previous research by examining how pitching mechanics,

measured by both 2D and 3D analyses, relate to tissue adaptation, injury history, and upper extremity joint loading.

Influence of age, sport, and specialization on Upper Extremity Characteristics

The results of this study provide new insights into age differences in upper extremity tissue characteristics. Humeral retrotorsion differences of approximately 6-10° were observed in both youth (11-14 years old) and collegiate unilateral overhead athletes participating in baseball, softball, and tennis. These bony features were similar in magnitude to glenohumeral external rotation gain and loss experienced by these athletes in the dominant arm, indicating that they are likely related. Despite similar bilateral disparities in glenohumeral range of motion and humeral retrotorsion across athletes of varying ages, soft tissue differences in the posterior capsule and ulnar collateral ligament between the dominant and non-dominant arm were greater in collegiate athletes. Since the youth athletes in this study likely had not reached skeletal maturity (Kwong et al., 2014; Patel & Lyne, 2009), these findings suggest that some stress from overhead sport is primarily absorbed by bony structures at a young age. As skeletal maturity is reached, a larger majority of that load may then be transferred to the soft tissue structures, creating tissue proliferation in older athletes.

While age does impact the presence of upper extremity tissue characteristics, specific sport and degree of specialization do not appear to have as much effect. Baseball players in these age groups do present with significantly more posterior capsule thickness, but the small difference (.06mm) limits clinical relevance. Baseball

athletes in these age groups also exhibit double the amount of bilateral ulnar collateral ligament thickness difference when compared to tennis or softball players, but that comparison did not reach significance in our statistical analysis. Degree of sport specialization had no impact on upper extremity tissue characteristics. However, our statistical models for this variable were limited because only 5% of athletes had met the, self-reported, high sport specialization criteria by 11 years old and only 21% were highly specialized by age 14. These data indicate that baseball may be more stressful on the soft tissue structures than softball or tennis and that sport specialization does not exacerbate upper extremity musculoskeletal tissue differences. However, more research is needed on youth and adult populations that play unilateral overhead sport to confirm those conclusions.

Influence of pitching biomechanics on tissue adaptation, injury history, and joint loading

The effect of baseball on upper extremity tissue characteristics was thought to be exacerbated by pitching with poor mechanics. Examination of a population of high school baseball pitchers indicated that biomechanics do not seem to have a large influence on tissue proliferation. Data indicated that bilateral differences in humeral retrotorsion and ulnar collateral ligament thickening did not significantly correlate to any of the 25 kinematic variables that were investigated. Posterior capsule thickness was correlated to horizontal abduction at the points of maximum external rotation ($r = .306$, $p = .041$) and distraction force ($r = .309$, $p = .047$). Bilateral ulnohumeral joint space differences were also correlated to horizontal abduction at the points of

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maximum valgus torque ($r = .437$, $p = .004$), maximum external rotation ($r = .419$, $p = .006$), ball release ($r = .341$, $p = .027$), and maximum distraction force ($r = .329$, $p = .033$). Horizontal adduction, known colloquially as "leading with the elbow," has been associated in previous research with higher valgus torques on the elbow (Fleisig et al., 1995). Therefore, these correlations could indicate that excessive horizontal adduction during acceleration, and after release, may create stress on the shoulder and elbow that leads to tissue adaptations. However, these correlations were weak, with no value reaching $r = 0.5$. The number of correlations run, in addition to the weak nature of those values and co-linearity of the variables, more likely indicates that current pitching mechanics are not indicative of differences between tissue characteristics on the dominant and non-dominant arm in high school pitchers. Biomechanics may also change slightly with age (Fleisig et al., 1999), leading to stress on different anatomical structures and less adaptation of an individual structure over time.

Even though kinematic variables measured by three-dimensional analysis may not be related to tissue characteristics, these biomechanics do appear to differentiate between previously injured and uninjured pitchers. Shoulder abduction at maximum external rotation was able to successfully group high school pitchers with and without injury history. This reduction in abduction when the humerus is translating anteriorly at the end of the cocking phase may be a result of learned biomechanical strategies in these athletes, possibly developed to reduce pain (Diederichsen et al., 2009; Lawrence et al., 2014) or compensate for limited range of motion and strength (Gandhi et al., 2012; J. J. Lin et al., 2006; Murray et al., 2001). External rotation, horizontal

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abduction, elbow flexion, and trunk lateral flexion have all been linked to shoulder and elbow loads (Aguinaldo & Chambers, 2009; Oyama et al., 2013; Werner et al., 2002), but they were not indicative of previous injury in this study. These results may indicate that joint loading may not have as direct of a relationship to injury as previously thought.

Our study indicates that two-dimensional analysis does show some promise, compared to conventional three-dimensional measures, for accurately identifying upper extremity angles during pitching. We found that elbow flexion and shoulder abduction at stride foot contact, as well as trunk lateral flexion angle at ball release, exhibited strong validity (ICC $_{(3,k)}$ > 0.80) when comparing two-dimensional videos to the current gold standard of three-dimensional techniques. However, elbow flexion and shoulder abduction at ball release did not exhibit high validity, likely as a result of trunk rotation creating a non-orthogonal relationship of the upper extremity to a camera positioned in the sagittal plane (Oyama et al., 2017). Analyses using only the valid two-dimensional angles did not differentiate between pitchers with and without injury history or identify athletes with higher upper extremity joint loading. Combined with our three-dimensional data, these results suggest that the position of the upper extremity joints near maximal loading (ex. maximum external rotation) likely provides a better understanding of injury and joint stress than collecting variables at arbitrary points during the pitching motion.

Conclusion

The overall results of this study indicate that the normal stresses of sport lead to bilateral differences in tissue characteristics in youth athletes. Distinctions in bony features and range of motion are most likely to be develop at an early age and be present throughout an athlete's career. Conversely, variance in soft tissue structures, such as the posterior shoulder capsule and ulnar collateral ligament, appear only in collegiate-aged athletes. Factors other than age do not appear to have as big of an impact on the bilateral differences in tissue characteristics. For the average athlete, general overhead sport participation, not specialization or biomechanics, appears to have more of an effect on bony and soft tissue structures. An analysis of biomechanics, as measured by three-dimensional techniques, was able to determine previous injury history in high school-aged pitchers, indicating that pitching biomechanics may change in response to injury. Since pitching biomechanics only relates to injury history and not bilateral tissue characteristics, the impact of those musculoskeletal features on pain/injury is still not yet understood.

Research Implications

The results of this study provide areas of future research so that clinicians and researchers can better understand tissue development and pitching mechanics. While we did see differing tissue characteristics among groups, the impact of many of these features on pain and injury is still unknown. Prospective, longitudinal investigations are also needed to determine if a cut-off point exists for these tissue characteristics, which may identify risk for pathology. After the impact is determined, longitudinal

analysis of tissue adaptations, as a result of playing various overhead sports, are needed to examine how early or how many seasons it takes for bilateral bony and soft tissue differences to appear. Then, clinicians may be able to identify which adaptations are negative and develop targeted interventions to limit them. Furthermore, the analysis of pitching biomechanics in this study was cross-sectional. Since a large amount of individual variability exists, a longitudinal investigation of pitching mechanics is needed to determine how they change over time and what leads to injury, especially in youth athletes. These analyses should begin to incorporate clinically applicable tools so that people working with youth pitchers can understand the results and translate the research into the field. Finally, tissue characteristics and pitching biomechanics are only some of the variables related to upper extremity injury risk. Future investigations should use other dependent measures, such as strength, stiffness, or neuromuscular control, to determine the effects of overhead load on young athletes.

Clinical Implications

The results of this dissertation indicate that clinicians can use two-dimensional tools for accurately measuring shoulder abduction and elbow flexion at stride foot contact, as well as trunk lateral flexion at ball release. While these angles may not link to injury history and/or high joint loads, they do provide those working with high school pitchers a foundation for beginning to look at quantitative data during pitching. Clinicians should also be aware of high school pitchers who "drop their elbow", or have reduced shoulder abduction, when they reach the maximum external rotation.

While we cannot claim that identification of that joint angle is accurate via two-dimensional analysis or will prospectively lead to injury, a recognition of this potential biomechanical pattern can allow clinicians to begin conversations with high school pitchers about pain or injury history. Those conversations may then lead to earlier intervention programs for athletes who have been injured. Finally, the differing bilateral characteristics among groups in this dissertation suggest that age is the primary factor in the development of upper extremity tissue proliferation. Sport selection may be a small factor, and early specialization, although it was self-reported in only 5% of our participants, does not seem to have any impact on shoulder or elbow tissue characteristics. Since specific bony characteristics appear at an early age without the appearance of soft tissue features, clinicians should be cognizant of growth plate injuries in a young population. Our results promote age and sport specific prevention and rehabilitation programs which address the underlying anatomical differences associated with each population. Implementing these programs may improve their efficacy and help with the prevention and treatment of upper extremity athletes of various sports and ages.

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Appendix A

TABLES

Table 1   **Sport by age group demographics**

Sport	Age	n	Age (years)	Height (cm)	Weight (kg)
Baseball	Youth	24	13.2 ± 1.1	166.0 ± 12.7	58.1 ± 15.1
	Adult	30	20.2 ± 1.2	183.6 ± 6.4	87.5 ± 9.5
Softball	Youth	21	13.1 ± 1.3	159.7 ± 6.9	52.7 ± 13.9
	Adult	25	19.1 ± 1.5	166.8 ± 6.3	69.0 ± 12.9
Tennis	Youth	11	13.1 ± 1.0	162.4 ± 10.1	48.7 ± 10.7
	Adult	21	19.9 ± 1.4	173.9 ± 9.8	71.0 ± 9.8

Table 2   **Sport and Age Differences in Range of Motion Values**

		Baseball	Softball	Tennis
Internal Rotation (˚)	Youth	-9.8 ± 5.8	-9.9 ± 6.4	-6.7 ± 6.6
	Adult	-9.9 ± 3.4	-6.9 ± 5.2	-10.3 ± 3.8
External Rotation (˚)	Youth	12.4 ± 6.8	6.5 ± 9.3	11.0 ± 8.1
	Adult	10.7 ± 8.1	9.5 ± 7.9	9.4 ± 8.8
Total Range of Motion (Internal + External, ˚)	Youth	2.6 ± 7.2	-3.4 ± 8.6*	1.9 ± 6.4
	Adult	0.8 ± 7.6	2.6 ± 7.0*	-0.9 ± 6.4

All values equal dominant minus non-dominant arm
*- significant difference between youth and adult athletes of same sport

Table 3   **Regression analysis summary for high specialization: clinical measurements**

Variable	B	SE B	b	pr^2	f^2
External Rotation					
Middle (11-14)	5.577	5.18	0.229	0.016	0.023
High (15+)	6.056	4.839	0.270	0.022	0.031
Internal Rotation					
Middle (11-14)	5.133	3.192	0.339	0.036	0.052
High (15+)	2.271	2.982	0.163	0.008	0.012
Posterior Shoulder Tightness					
Middle (11-14)	2.159	2.846	0.116	0.008	0.010
High (15+)	3.051	2.668	0.255	0.018	0.023

Note: R^2 for External Rotation = .286, R^2 for Internal Rotation = .307, R^2 for Posterior Shoulder Tightness = .185, pr^2 = squared semi-partial coefficient, f^2 = Cohen's effect size statistic for multiple regression analyses.

Table 4   <u>**Regression analysis summary for high specialization: shoulder ultrasound measurements**</u>

Variable	B	SE B	b	pr^2	f^2
Posterior Capsule Thickness					
Middle (11-14)	0.006	0.006	0.197	0.012	0.015
High (15+)	0.004	0.006	0.158	0.007	0.010
Humeral Retrotorsion					
Middle (11-14)	-2.240	2.993	-0.156	0.008	0.012
High (15+)	0.859	2.796	0.065	0.001	0.002

Note: R^2 for Posterior Capsule Thickness = .240, R^2 for Humeral Retrotorsion = .347, pr^2 = squared semi-partial coefficient, f^2 = Cohen's effect size statistic for multiple regression analyses.

Table 5   **Regression analysis summary for high specialization: elbow
ultrasound measurements**

Variable	B	SE B	b	pr^2	f^2
UCL Thickness					
Middle (11-14)	0.014	0.031	0.095	0.003	0.004
High (15+)	0.021	0.029	0.155	0.007	0.011
Ulnohumeral Joint Space					
Middle (11-14)	0.001	0.019	0.015	<0.001	<0.001
High (15+)	-0.008	0.018	-0.102	0.003	0.004

Note: UCL= Ulnar Collateral Ligament; R^2 for UCL Thickness = .302, R^2 for Ulnohumeral Joint Space = .192, pr^2 = squared semi-partial coefficient, f^2 = Cohen's effect size statistic for multiple regression analyses.

Table 6   **Regression analysis summary for playing more than 8 months out of the year: clinical measurements**

Variable	B	SE B	b	pr^2	f^2
External Rotation					
Middle (11-14)	0.275	2.969	0.013	<0.001	<0.001
High (15+)	-2.290	3.267	-0.106	0.006	0.009
Internal Rotation					
Middle (11-14)	1.978	1.838	0.151	0.016	0.023
High (15+)	2.817	2.022	0.210	0.027	0.037
Posterior Shoulder Tightness					
Middle (11-14)	-1.031	1.611	-0.092	0.006	0.008
High (15+)	2.258	1.762	0.195	0.023	0.032

Note: R^2 for External Rotation = .269, R^2 for Internal Rotation = .277, R^2 for Posterior Shoulder Tightness = .272, pr^2 = squared semi-partial coefficient, f^2 = Cohen's effect size statistic for multiple regression analyses.

Table 7   **Regression analysis summary for playing more than 8 months out of the year: shoulder ultrasound measurements**

Variable	B	SE B	b	pr^2	f^2
Posterior Capsule Thickness					
Middle (11-14)	-0.003	0.003	-0.103	0.008	0.010
High (15+)	0.002	0.004	0.076	0.004	0.005
Humeral Retrotorsion					
Middle (11-14)	2.227	1.712	0.179	0.024	0.036
High (15+)	2.859	1.884	0.224	0.032	0.048

Note: R^2 for Posterior Capsule Thickness = .263, R^2 for Humeral Retrotorsion = .339, pr^2 = squared semi-partial coefficient, f^2 = Cohen's effect size statistic for multiple regression analyses.

Table 8   **Regression analysis summary for playing more than 8 months out of the year: elbow ultrasound measurements**

Variable	B	SE B	b	pr^2	f^2
UCL Thickness					
Middle (11-14)	0.024	0.017	0.191	0.027	0.040
High (15+)	0.016	0.019	0.127	0.010	0.016
Ulnohumeral Joint Space					
Middle (11-14)	0.005	0.011	0.068	0.003	0.004
High (15+)	-0.009	0.012	-0.117	0.008	0.011

Note: UCL= Ulnar Collateral Ligament; R^2 for UCL Thickness = .329, R^2 for Ulnohumeral Joint Space = .223, pr^2 = squared semi-partial coefficient, f^2 = Cohen's effect size statistic for multiple regression analyses.

Table 9   <u>**Confusion matrix differentiating injured and uninjured pitchers**</u>

	Predicted		
Observed	Uninjured	Injured	Percentage Correct
Uninjured	22	4	84.6
Injured	5	11	68.8
		Overall Percentage	78.6

Table 10   Variables included in pitching analysis

Variable
Height (m)
Weight (kg)
Ball velocity (m/s)
Stride foot contact
Shoulder abduction
Shoulder external rotation
Shoulder horizontal abduction
Elbow flexion
Lateral trunk tilt
Maximum internal varus moment
Shoulder abduction
Shoulder external rotation
Shoulder horizontal abduction
Elbow flexion
Lateral trunk tilt
Maximum external rotation
Shoulder abduction
Shoulder external rotation
Shoulder horizontal abduction
Elbow flexion
Lateral trunk tilt
Ball release
Shoulder abduction
Shoulder external rotation
Shoulder horizontal abduction
Elbow flexion
Lateral trunk tilt
Maximum shoulder distraction force
Shoulder abduction
Shoulder external rotation
Shoulder horizontal abduction
Elbow flexion
Lateral trunk tilt

Table 11   <u>Demographic Data for Pitchers in Three-dimensional analysis</u>

	Uninjured	Previous Injury History
Number	27	16
Age (years)	15.8 ± 1.1	15.6 ± 1.5
Height (cm)	179.8 ± 4.4	177.6 ± 8.0
Weight (kg)	74.4 ± 11.6	72.7 ± 14.1
Velocity (m/s)	30.5 ± 2.3	29.1 ± 2.9

Table 12   **Regression analysis summary for three dimensional variables predicting injury history**

Predictor	Time Point	B	Wald	p	Odds Ratio	95% CI for Odds Ratio	
						Lower	Upper
Shoulder ABD	SFC	-.013	.106	.745	.987	.913	1.067
	Max ER	-.139	4.95	.026	.870	.770	.984
Shoulder H_ABD	Ball Release	.022	.205	.650	1.023	.928	1.127
Trunk Lat FLEX	Max Valgus	.035	.712	.399	1.035	.955	1.122
Constant		11.463	5.64				

B = unstandardized coefficient, N = 42
ABD = Abduction
H_ABD = Horizontal Abduction
SFC = Stride foot contact
Max = Maximum
ER = External Rotation
Lat FLEX = Lateral flexion

Table 13   **Demographic data for pitchers participating in 2-dimensional analysis**

	Uninjured	Previous Injury History
Number	24	14
Age (years)	15.7 ± 1.1	15.8 ± 1.6
Height (cm)	179.9 ± 4.5	177.8 ± 8.6
Weight (kg)	74.5 ± 11.8	70.7 ± 12.4
Velocity (m/s)	30.6 ± 2.3	29.5 ± 2.8

Table 14   **Quartile division for normative and non-normative pitching mechanics**

Variable	Time point	25%	50%	75%
Elbow Flexion	SFC	84.5	96.0	112.6
Shoulder Abduction	SFC	75.5	81.4	87.8
Trunk Lateral Flexion	Release	21.8	31.8	37.6

SFC = stride foot contact

Values between 25% and 75% for each variable were placed into the normative group

Values below 25% and above 75% for each variable were placed into the non-normative group

50% represents the mean value for the population investigated

Table 15 **Regression analysis summary for two dimensional variables**
predicting injury history

Predictor	Time Point	B	Wald	p	Odds Ratio	95% CI for Odds Ratio	
						Lower	Upper
Elbow FLEX	SFC	.010	.197	.658	1.010	.965	1.058
Shoulder ABD	SFC	-.027	.379	.538	.974	.894	1.060
Trunk Lateral FLEX	Release	.059	1.913	.167	1.060	.976	1.152
Constant		-1.191	.057				

B = unstandardized coefficient, N = 38
FLEX= Flexion
ABD = Abduction
SFC = Stride foot contact

Appendix B

FIGURES

Sport	Age of 1st participation	Age participation stopped	Total Years
Baseball			
Basketball			
Cross-country			
Diving			
Football			
Golf			
Gymnastics			
Hockey (Field)			
Hockey (Ice)			
Lacrosse			
Rowing			
Soccer			
Softball			
Swimming			
Tennis			
Track and Field			
Volleyball			
Water Polo			
Wrestling			
Other			

Can you pick a main sport? If so, what is it?

_____

Did you quit other sports to focus on a main sport?   YES   NO
If so, at what age?   _____

Do you train for more than 8 months per year in an sport?   YES   NO
If so, which sport?   _____
At what age did you start training for more than 8 months per year?
_____

Figure 1   Sport history form

Figure 2   *Posterior shoulder tightness measurement*
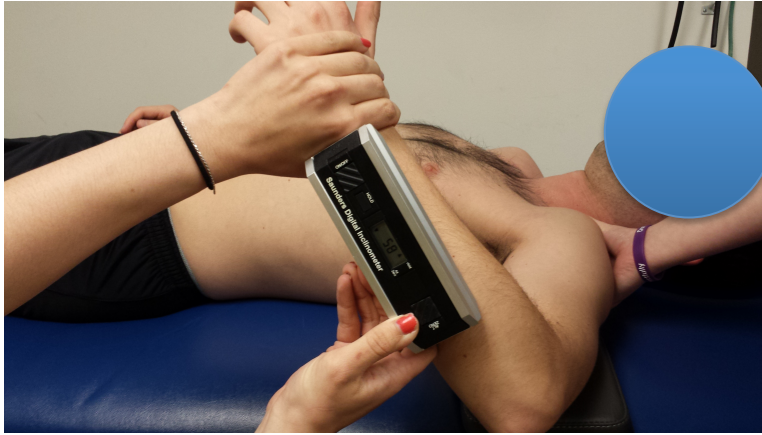
Figure 3   ***Glenohumeral range of motion measurement***
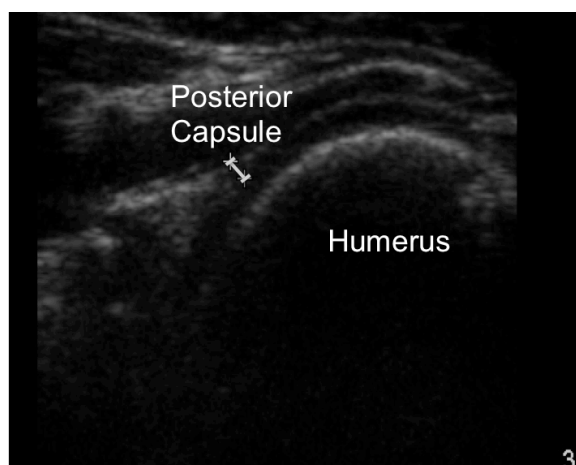
Figure 4   Posterior capsule measurement on ultrasound
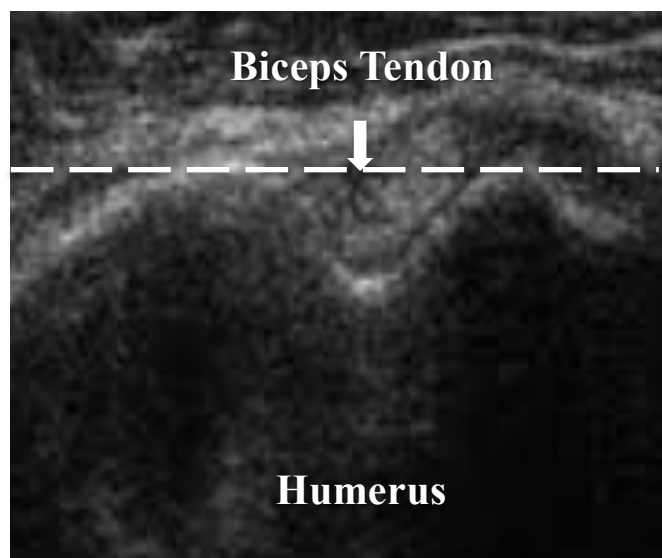
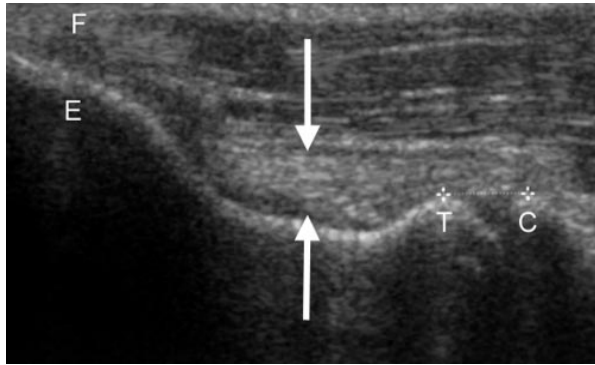*Figure 5   Humeral retrotorsion on ultrasound*

Figure 6   Ultrasound scan of UCL and ulnohumeral joint space

From Nazarian '03:
Bony landmarks include the medial humeral epicondyle (E), trochlea of the humerus
(T), and coronoid process of the ulna (C). The arrows indicate the thickness of the
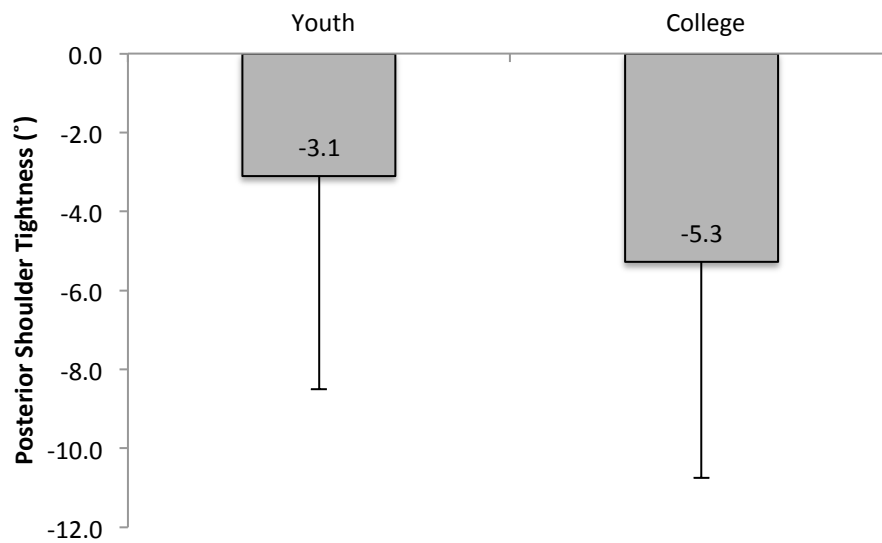UCL, and the cursors indicate the ulnohumeral joint

Figure 7   *Posterior shoulder tightness between ages*

A significant difference (p<.05) existed between groups
Values represent combined data across sports and are presented in degrees
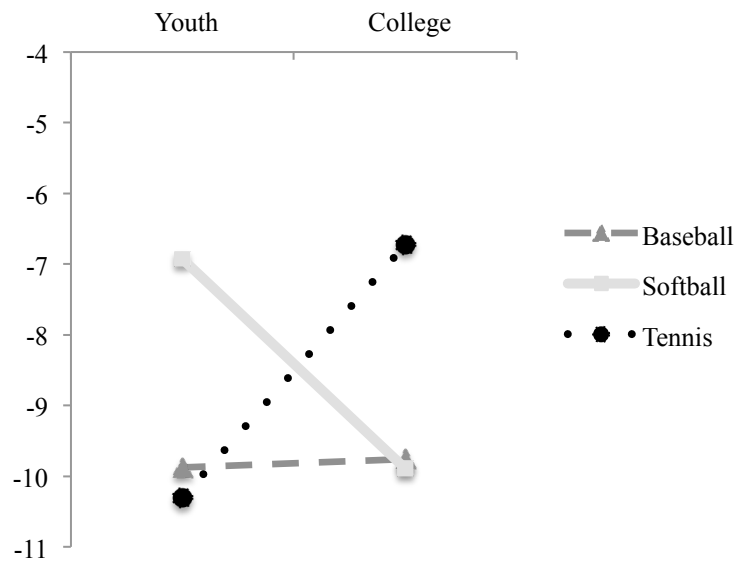 (-) values indicated more tightness on the dominant arm compared to the non-dominant arm

Figure 8   Internal rotation comparisons across sport and age

Significant interaction effect (p<.05) existed between variables
 (-) values indicate less internal rotation on the dominant arm compared to the non-dominant arm
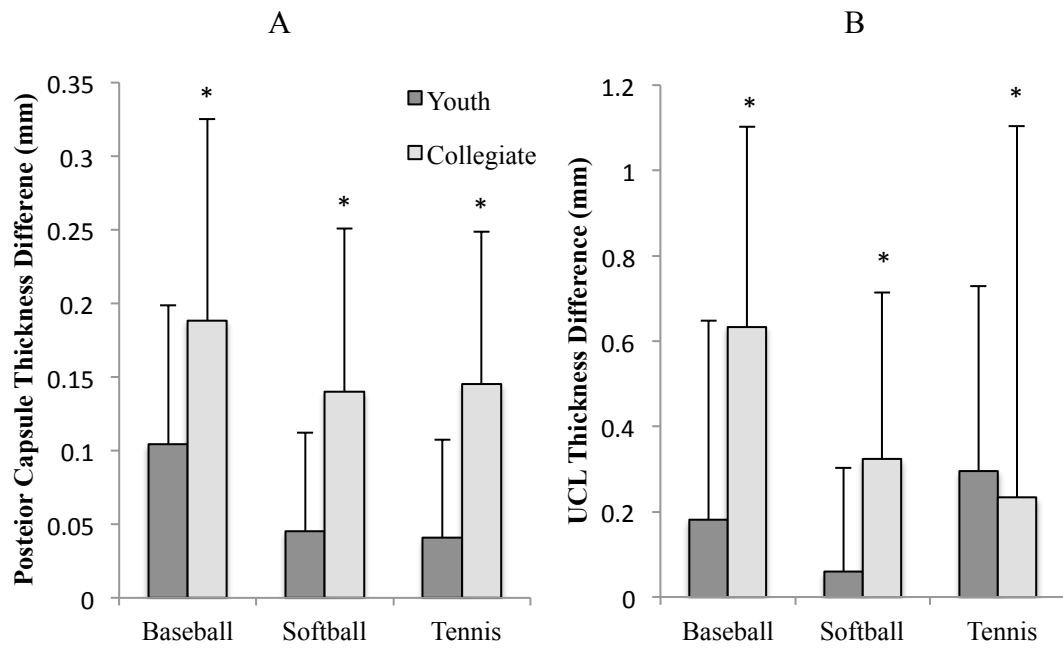Youth softball athletes displayed less bilateral difference than collegiate athletes

Figure 9   ***Soft tissue differences across age and sport***

A- Posterior capsule thickness differences
B- Ulnar collateral ligament (UCL) thickness difference
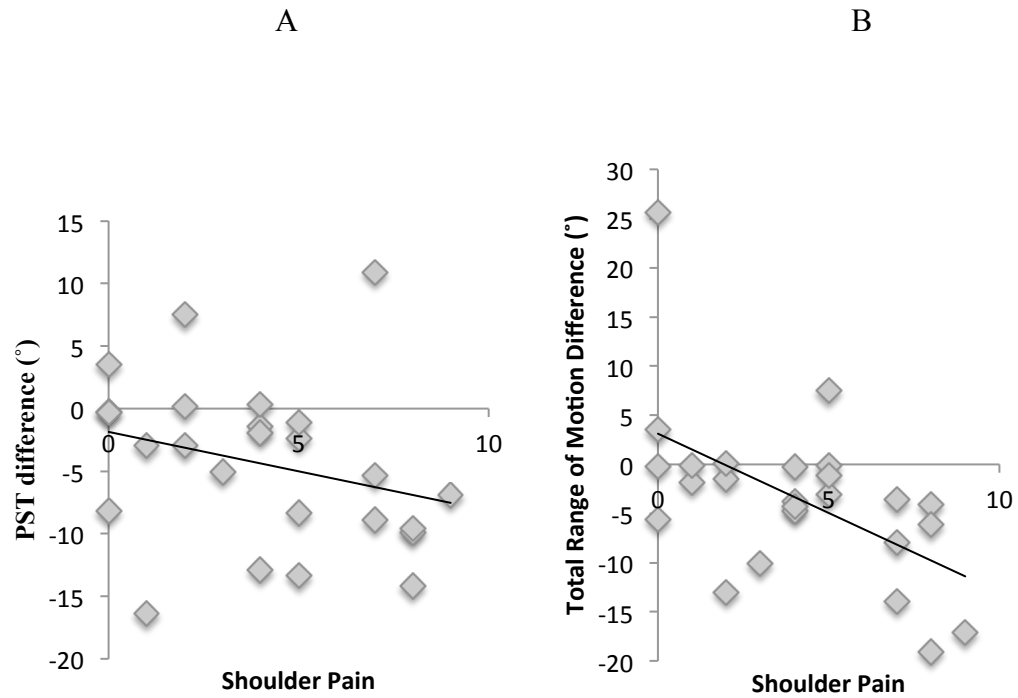*Significantly greater (p < 0.05) than youth athletes of the same sport

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Figure 10   Shoulder pain correlations in adult softball

PST = Posterior shoulder tightness

A- Correlation between posterior shoulder tightness and shoulder pain (p = -.495)

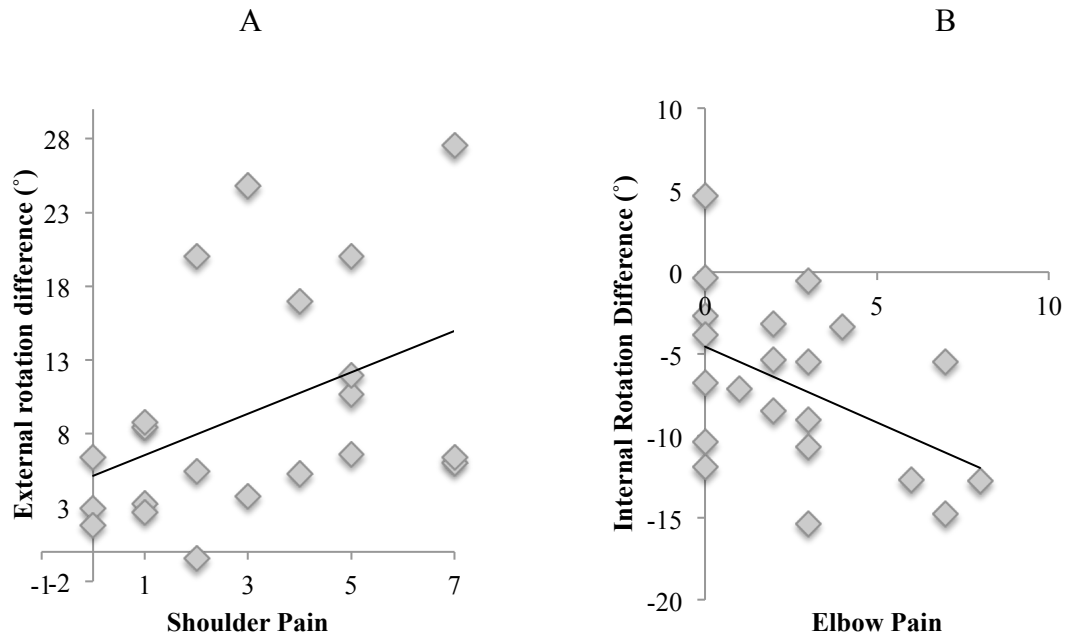B- Correlation between total range of motion and shoulder pain (p = -.525)

A

B

Figure 11   Pain correlations in youth softball

A- 'Correlation between external rotation and shoulder pain (r = .499)
B- Correlation between internal rotation and elbow pain (r = -.440)
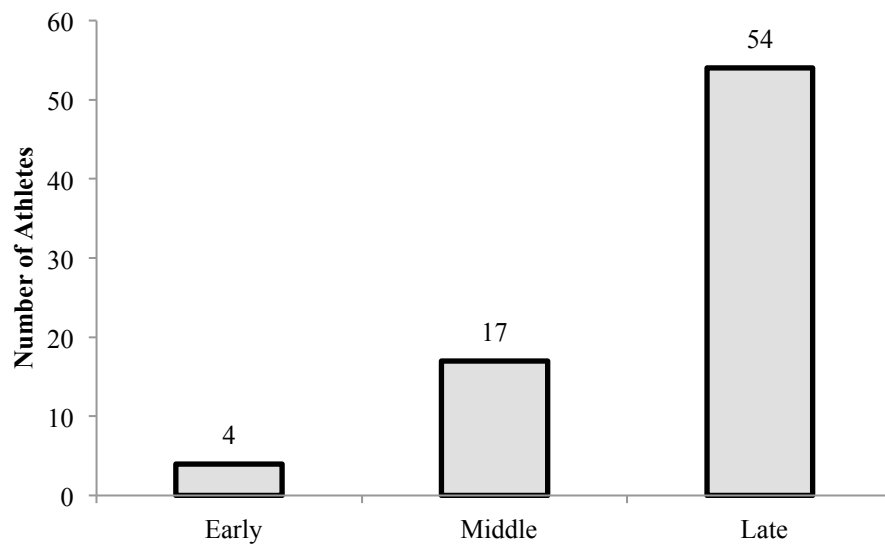
Figure 12   Numerical breakdown of high sport specialization

High sport specialization qualified as being able to pick a main sport, quitting other sports to play that main sport, and playing that main sport for more than 8 months per year
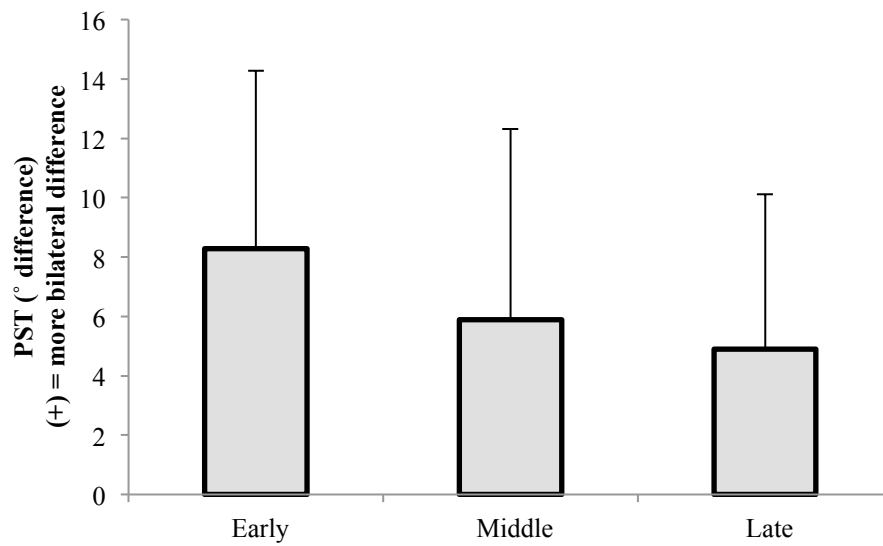
Figure 13   High specialization group differences in posterior shoulder tightness

PST= Posterior shoulder tightness

Figure 14   Laboratory set-up

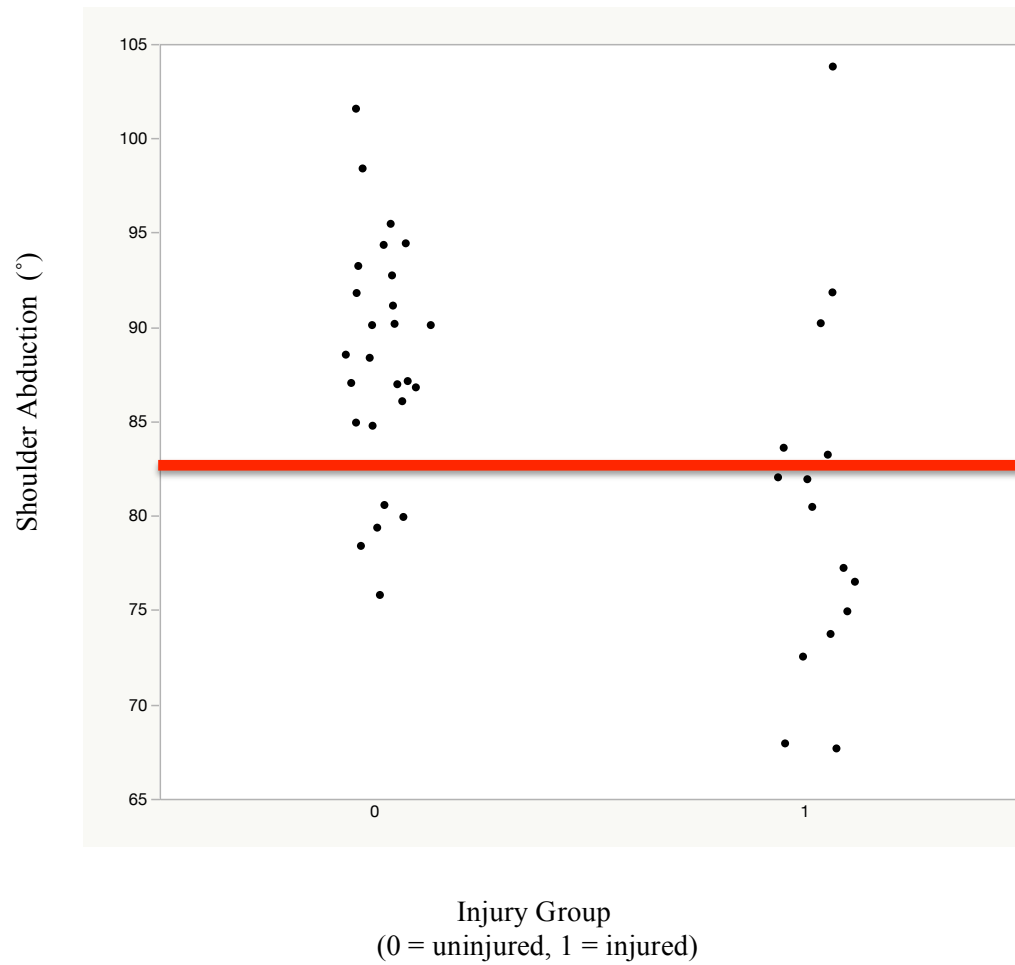***Figure 15***   ***Visual group comparison of shoulder abduction values at time of maximum external rotation***

A   B

Figure 16   *Visual representation of limited shoulder abduction at maximum*
                external rotation

A: Previously injured pitcher exhibits lower abduction at maximum external rotation

B: Pitcher with no injury history exhibits higher abduction at maximum external rotation

Figure 17: Normalized valgus moments in groups divided by total number of normative pitching values

Figure 17   Normalized valgus moments in groups divided by total number of normative pitching values

Number of non-normative values taken from valid two-dimensional pitching variables (elbow flexion at stride foot contact, shoulder abduction at stride foot contact, trunk lateral flexion at release).

0= performed all pitching mechanics within normative range (n= 7)
1= one value performed outside normative range (n= 13)
2= two values performed outside of normative range (n=13)
3= all three values performed outside of normative range (n=5)

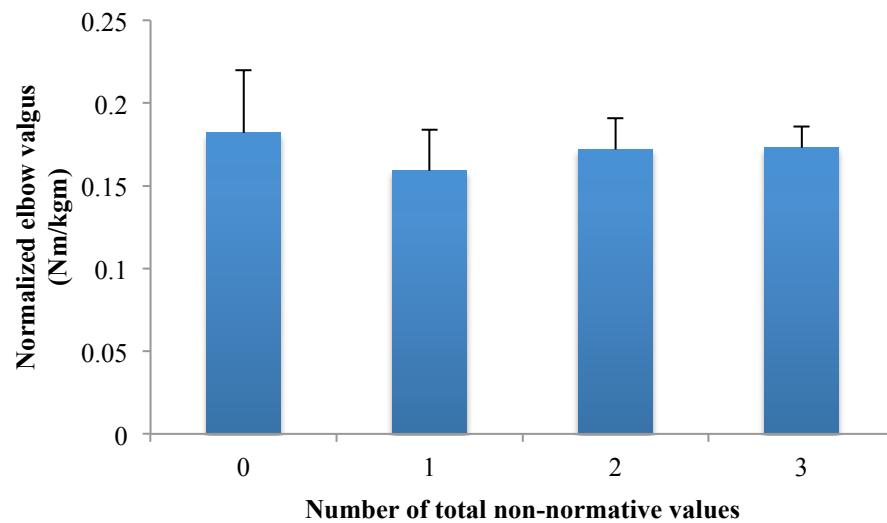*Figure 18   Normalized shoulder distraction forces in groups divided by total number of normative pitching values*

Number of non-normative values taken from valid two-dimensional pitching variables (elbow flexion at stride foot contact, shoulder abduction at stride foot contact, trunk lateral flexion at release).

0= performed all pitching mechanics within normative range (n= 7)
1= one value performed outside normative range (n= 13)
2= two values performed outside of normative range (n=13)
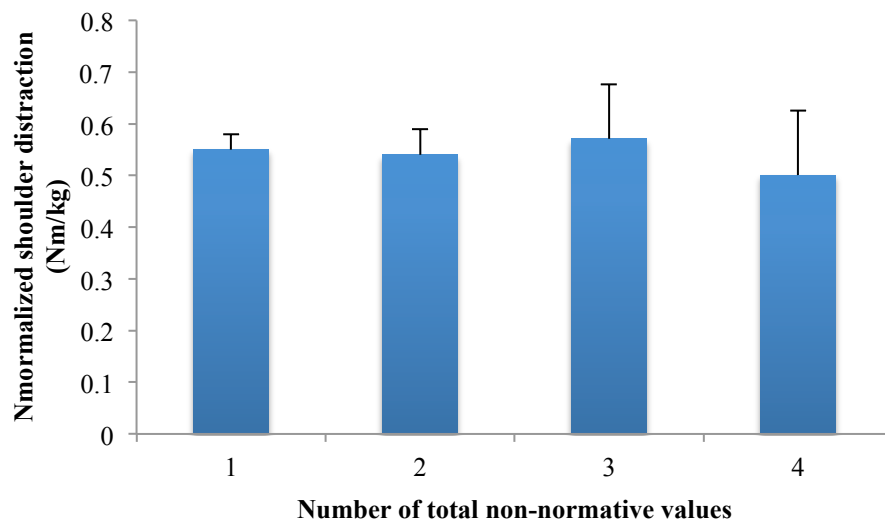3= all three values performed outside of normative range (n=5)

Appendix C

INFORMED CONSENTS TO PARTICIPATE IN RESEARCH

Title of Project: **Biomechanical adaptations to the shoulder and elbow in youth and collegiate overhead athletes**

Principal Investigator (s): Aaron Struminger, MA, ATC

Other Investigators: Charles "Buz" Swanik, PhD., ATC

You are being asked to participate in a research study. This form tells you about the study including its purpose, what you will do if you decide to participate, and any risks and benefits of being in the study. Please read the information below and ask the research team questions about anything you do not understand before you decide whether to participate. Your participation is voluntary and you can refuse to participate or withdraw at anytime without penalty or loss of benefits to which you are otherwise entitled. If you decide to participate, you will be asked to sign this form and a copy will be given to you to keep for your reference.

WHAT IS THE PURPOSE OF THIS STUDY?
The purpose of this study is to learn about soft tissue and bone changes that overhead athletes develop in the shoulder and elbow due to sport participation and whether these adaptations are linked to pain. A secondary purpose is to compare data among athletes participating different sports and at different ages to determine whether certain sports cause greater changes.

You are being asked to participate in this study because you are a collegiate athlete between the ages of 18-25 who plays an overhead sport (baseball, softball, tennis, swimming, or volleyball).

If you choose to participate, you will be one of 350 subjects, 150 college-aged and 200 youth, who undergoes the testing protocol. You should not participate in this study if:
- you have undergone shoulder surgery within the past year

- you have any neurological disorder
- you have a musculoskeletal disorder that prevents you from unrestricted sports participation or produces abnormal muscle or bone development

WHAT WILL YOU BE ASKED TO DO?

You will be asked to come in for one session of testing that lasts about 30 minutes. All testing will be done at the University of Delaware in either the Human Performance Lab, Athletic Training rooms on campus, or playing fields/courts where you practice. To begin the study, you will fill out a questionnaire that includes general health history and pain scales in your shoulder and elbow.

During the testing session, the examiner will use an ultrasound machine to examine different parts of your shoulder and elbow. The examiner will also take range of motion measurements. For two of the ultrasound measures, you will be asked to sit upright while the investigator applies the ultrasound head with a coupling gel onto back of your shoulder or the inside of your elbow. The investigator will move the ultrasound head around until a proper image is displayed on the screen. The image on the screen will be frozen, and the measurement will be taken using a tool on the ultrasound unit. For the other ultrasound measure, you will lie on your back with your arm out to the side and your elbow bent while the examiner places the ultrasound head with a coupling gel onto the front of your shoulder. The investigator will then rotate your shoulder until the proper image is present on the screen. Once the image is observed, the investigator will measure the angle between your forearm and the table.

During the same testing session, the examiner will take range of motion measurements either before or after the ultrasound measurements. For two of these measurements, you will lie on your back with your shoulder out to the side and elbow bent. The examiner will then put a hand on your shoulder blade to make sure that it does not move during testing. Then, the examiner will rotate your arm backwards and forwards until you feel it cannot go any further or your shoulder blade comes off the table. At the end of the motion, the angle of your forearm to the table will be measured. For the last measurement, you will stand up straight and move your arm out to the side at an angle specified by the investigator. When you reach that angle, you will be asked to hold your arm in that spot until the angle of your shoulder blade is measured. Each range of motion measurement will be completed twice.

WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?

It is unlikely but you may experience slight muscle or joint soreness within the next 24 hours after range of motion testing. This soreness will be similar to soreness experienced after a stretching routine. There is minimal risk of muscle and/or joint injury (i.e. pulled muscle, joint sprain) as a result of testing. There is minimal risk associated with the ultrasound measurements. You may experience discomfort from the pressure of the ultrasound transducer on the skin in order to get a proper coupling.

To minimize any risks of injury, we will: (1) closely watch the testing, and talk with you prior to and during testing to reduce risk of harm. (2) You will be instructed to tell the investigator of any discomfort with measures. If you feel any discomfort, your position and position of the ultrasound can be adjusted.

WHAT ARE THE POTENTIAL BENEFITS?
You will not benefit directly from taking part in this research. However, the knowledge gained from this study may help our understanding of the shoulder in overhead athletes and how it is different between sports. This increased knowledge can lead to future research that develops prevention programs aimed at decreasing the occurrence of shoulder injuries in overhead athletes.

HOW WILL CONFIDENTIALITY BE MAINTAINED?
Although your coaches and teammates may see you participate in the study, your personal information will remain confidential. Anyone who sees you participate in the study will not see the data collected by the investigators. No names, photographs, or videos will be used in data analysis. Paper tests will be identified by randomly assigned subject codes, and all names and codes will be kept solely by the principal investigator or advisor in a locked cabinet. All data will be stored on paper in a locked cabinet, a computer that is encrypted and password-protected, or an encrypted and password-protected external hard-drive. Paper data will be kept in a locked cabinet for three years. Deidentified electronic data will be kept indefinitely. All personal identifiers will be destroyed after the study is complete. While the results of this research may be published and presented at conferences, subjects name or identity will not be revealed. Your research records may be viewed by the University of Delaware Institutional Review Board, but the confidentiality of your records will be protected to the extent permitted by law.

WILL THERE BE ANY COSTS RELATED TO THE RESEARCH?
There are no costs associated with participating in this study.

WILL THERE BE ANY COMPENSATION FOR PARTICIPATION?
There will be no compensation for participation in this study

WHAT IF YOU ARE INJURED BECAUSE OF THE STUDY?
If you are injured during research procedures, you will be offered first aid at no cost. If you require additional medical treatment, you will be responsible for the cost.

DO YOU HAVE TO TAKE PART IN THIS STUDY?
Taking part in this research study is entirely voluntary. You do not have to participate in this research. If you choose to take part, you have the right to stop at any time. If you decide not to participate or if you decide to stop taking part in the research at a later date, there will be no penalty or loss of benefits to which you are otherwise entitled. Your refusal will not influence current or future relationships with the University of Delaware. Your refusal will also not influence your status on the team, playing time, or relationship with coaches at the University of Delaware.

WHO SHOULD YOU CALL IF YOU HAVE QUESTIONS OR CONCERNS?
If you have any questions about this study, please contact the Principal Investigator, Aaron Struminger at astrum @udel.edu or 901-390-4624, C. Buz Swanik at cswanik@udel.edu or 302-831-2306. If you have any questions or concerns about your rights as a research participant, you may contact the University of Delaware Institutional Review Board at 302-831-2137.

_____

Your signature below indicates that you are agreeing to take part in this research study. You have been informed about the study's purpose, procedures, possible risks and benefits. You have been given the opportunity to ask questions about the research and those questions have been answered. You will be given a copy of this consent form to keep. By signing this consent form, you indicate that you voluntarily agree to participate in this study.

_____   _____
Signature of Participant   Date

_____
Printed Name of Participant

_____   _____
Signature of Investigator   Date

Title of Project: **Using Ultrasound to Identify the Effect of Pitching on the Structural and Functional Anatomy of the Shoulder and Elbow in Youth Baseball Pitchers**

Principal Investigator (s): Aaron Struminger, MA, ATC, Alfred Atanda Jr., MD

Other Investigators: Charles "Buz" Swanik, PhD., ATC

You are being asked to participate in a research study. This form tells you about the study including its purpose, what you will do if you decide to participate, and any risks and benefits of being in the study. Please read the information below and ask the research team questions about anything you do not understand before you decide whether to participate. Your participation is voluntary and you can refuse to participate or withdraw at anytime without penalty or loss of benefits to which you are otherwise entitled. If you decide to participate, you will be asked to sign this form and a copy will be given to you to keep for your reference.

WHAT IS THE PURPOSE OF THIS STUDY?
Overhand athletes place a lot of force on the elbow and shoulder during throwing. The number of overuse injuries in youth baseball has been steadily increasing over the past 10 years. Our work with adult baseball players shows that diagnostic ultrasound testing may be able to identify changes in elbow or shoulder anatomy in pitchers that do not have any pain. The purpose of this study is to determine normal values of elbow ligament thickness, looseness of the elbow joint, and shoulder tissue adaptations in youth baseball pitchers. Another purpose of this study is to determine whether pitching history and pitching mechanics are related to the tissue adaptations of the shoulder and elbow as measured by diagnostic ultrasound.

You are being asked to participate in this study because you are a baseball player within the ages of 12-18 who currently plays the position of pitcher on a competitive team (e.g. high school. Little League, travel baseball team, etc.)

If you choose to participate, you will be one of 105 subjects who undergoes the testing protocol. You should not participate in this study if:
- you have been playing the position of pitcher for less than one year
- you have a current injury that prevents you from throwing with full velocity off of a pitching mound
- you have undergone shoulder surgery within the past year
- you have any neurological or developmental disorder

WHAT WILL YOU BE ASKED TO DO?
You will be asked to come in for one session of testing that lasts about 60-75 minutes. You should wear a t-shirt and tennis shoes or cleats to testing. You should also bring your baseball glove. All testing will be done at the University of Delaware Biomechanics Laboratory in STAR campus or the Nemours/A.I. DuPont Children's hospital. The first part of the testing session will involve you filling out a questionnaire about your pitching habits and injury history. **You will also complete a maturational scale, which includes questions about height, body hair, growth, secondary sexual characteristics, and menstruation. You have the right to decline participation in this portion of the research study**.. It will also involve taking measurements of height, weight, arm length, and arm girth.

After completing the questionnaire and basic measurements, the examiner will use a diagnostic ultrasound machine to examine different parts of your shoulder and elbow. For two of the ultrasound measures, you will be asked to sit upright while the investigator applies the ultrasound head with a coupling gel onto back of your shoulder or the inside of your elbow. The investigator will move the ultrasound head around until a proper image is displayed on the screen. The image on the screen will be frozen, and the measurement will be taken using a tool on the ultrasound unit. For another ultrasound measure, you will remain in a seated position while a stress is applied to the inside of your elbow. This stress is much less than what you experience while pitching a baseball. Both before and after the stress, the investigator will move the ultrasound head around until a proper image is displayed on the screen. The proper image will be frozen, and another measurement will be taken on the screen. For the final ultrasound measure, you will lie on your back with your arm out to the side and your elbow flexed while the examiner places the ultrasound head with a coupling gel

onto the front of your shoulder. The investigator will then rotate your shoulder until the proper image is present on the screen. Once the image is observed, the investigator will measure the angle between your forearm and the table.

After the ultrasound measures are taken, you will be asked to remove your shirt while the investigators put Velcro markers on your chest and pitching arm. Then, you will move your arm into 11 positions, as directed by the investigator, that are similar to activities of daily living such as reaching, brushing teeth, or combing hair. After the 11 motions, you will complete a warm-up like you normally would for a game or bullpen session. You can complete stretching, light throwing, jogging, or any other activity that helps you get ready to throw. When you feel like you are ready to throw at full velocity, you will let an examiner know. At this time, you will complete 10 pitches off an indoor mound at a pitching target. While you are pitching, 10 3-D motion cameras will record the position of the markers on your body. Also, one digital camera will be set up in front of you and the other will be placed to the side of the arm with which you throw. A radar gun will also be measuring speed of the pitch. If you throw at least 3 strikes during the first 10 pitches, you will stop pitching. If you do not throw 3 strikes, you will have 5 additional attempts to complete the goal of throwing 3 strikes. After 15 total pitches, you will be told to stop throwing.

WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?
There is a minimal risk of injury and soreness as a result of testing. This risk is similar to your normal sport activity and soreness may last 24-48 hours. There is also a minimal risk associated with the diagnostic ultrasound measurements. You may experience slight discomfort from the pressure of the ultrasound head on your skin. You may also experience slight discomfort when the stress is applied to the elbow by the device.

To minimize any risks of injury the following steps will be taken: (1) We will closely watch the testing and talk with you prior to and during testing to reduce risk of harm. (2) You will be instructed to tell the investigator of any discomfort with measures. If you feel any discomfort, your position and position of the ultrasound can be adjusted. (3) The joint stress applied to your elbow will be less than the stress that is present when pitching. (4) A pitch limit of 15 pitches will be used to make sure that you do not experience fatigue during the pitching protocol.

WHAT ARE THE POTENTIAL BENEFITS?

You will not benefit directly from taking part in this research. However, you will be provided with the handout "STOP Sports Injuries-Baseball Information Sheet." Also, the knowledge gained from this study may help clinicians and researchers learn about the changes in the elbow and shoulder that occur in youth baseball pitchers. The information could also help coaches and sports medicine professionals understand what causes tissue changes in baseball pitchers.

HOW WILL CONFIDENTIALITY BE MAINTAINED?
Although your coaches and teammates may see you participate in the study, your personal information will remain confidential. Anyone who sees you participate in the study will not see the data collected by the investigators. Paper tests will be identified by randomly assigned subject codes, and all names and codes will be kept solely by the principal investigator or advisor in a locked cabinet. **Data recorded from the maturational scale assessment will be placed in a folder by your child that will not be examined by the investigators until at least one week after testing.** Electronic video recordings will be stored on a secure computer that is password-protected or an external hard-drive that is encrypted-password protected. The video recordings will be saved by subject number and will not contain any personally identifiable information other than an image of your face. The video images will be stored by different subject codes than the other data collected, and the master list linking the code numbers will be kept on a password-protected and encrypted file to ensure that no one can link your identity to any of your data.

All data will be stored on paper in a locked cabinet, a computer that is encrypted and password-protected, or an encrypted and password-protected external hard-drive. Paper data will be kept in a locked cabinet for three years. Deidentified electronic data will be kept indefinitely. All personal identifiers will be destroyed after the study is complete. While the results of this research may be published and presented at conferences, subjects name or identity will not be revealed. Research records may be viewed by the Institutional Review Boards at the University of Delaware or Nemours/A.I. Dupont Children's Hospital, but the confidentiality of your records will be protected to the extent permitted by law.Research records may be viewed by the University of Delaware Institutional Review Board, but the confidentiality of your records will be protected to the extent permitted by law.

WILL THERE BE ANY COSTS RELATED TO THE RESEARCH?
There are no costs associated with participating in this study.

WILL THERE BE ANY COMPENSATION FOR PARTICIPATION?
There will be no compensation for participation in this study.

WHAT IF YOU ARE INJURED BECAUSE OF THE STUDY?
If you are injured during research procedures, you will be offered first aid at no cost. If you require additional medical treatment, you will be responsible for the cost.

DO YOU HAVE TO TAKE PART IN THIS STUDY?
Taking part in this research study is entirely voluntary. You do not have to participate in this research. If you choose to take part, you have the right to stop at any time. If you decide not to participate or if you decide to stop taking part in the research at a later date, there will be no penalty or loss of benefits to which you are otherwise entitled. Your refusal will not influence current or future relationships with the University of Delaware or any other teams/institutions associated with the research project. Your refusal will also not influence your status on the team, playing time, or relationship with coaches at the University of Delaware.

WHO SHOULD YOU CALL IF YOU HAVE QUESTIONS OR CONCERNS?
If you have any questions about this study, please contact the Principal Investigator, Aaron Struminger at astrum @udel.edu or 901-390-4624, C. Buz Swanik at cswanik@udel.edu or 302-831-2306.

If you have any questions or concerns about your rights as a research participant, you may contact the University of Delaware Institutional Review Board at 302-831-2137.

_____
Your signature below indicates that you are agreeing to take part in this research study. You have been informed about the study's purpose, procedures, possible risks and benefits. You have been given the opportunity to ask questions about the research and those questions have been answered. You will be given a copy of this consent form to keep.
By signing this consent form, you indicate that you voluntarily agree to participate in this study.

_____   _____
Signature of Participant   Date

_____
Printed Name of Participant

OPTIONAL **CONSENT TO BE CONTACTED FOR FUTURE STUDIES:**

Do we have your permission to contact you regarding participation in future studies? Please write your initials next to your preferred choice and include your email address.

_____ YES   _____ NO

Email Address: _____

Appendix D

INFORMED ASSENTS TO PARTICIPATE IN RESEARCH

Research Study: Biomechanical Adaptations to the Shoulder in Youth and Collegiate Overhead Athletes

Investigators: Aaron H. Struminger, MA, ATC, C. Buz Swanik, PhD, ATC
(Department of Kinesiology and Applied Physiology)
I am asking if you want to be part of a research study. This form tells you what the study is about, what you will be asked to do if you want to be in the study, and the possible bad and good things about this study. Please read this paper and ask us any questions you have.

WHAT IS THE PURPOSE OF THE STUDY?

This research study looks at changes to shoulders and elbows from overhead activity such as throwing, swimming, serving, and spiking. We are asking if you want to be in it because we want to learn how you shoulders and elbows are different from the shoulders and elbows of college athletes and athletes who play different sports.

WHAT WILL YOU BE ASKED TO DO?

If you want to participate we will ask you to wear a t-shirt or tank top to one test at our laboratory or your sports field, court, or pool. The testing should take about 30 minutes. To start the test, you will be asked questions about pain in your shoulder and elbow. Your parents will also be asked to answer questions about your age, the sports you play, and your general health that will be given to the researchers after testing. **You will be asked to answer questions about how your body is changing. If you do not want to answer those questions, you can skip them.**

We will start testing by looking at your shoulder flexibility and taking pictures of the inside of your shoulder and elbow. For one flexibility test, you will lie on your back while the tester moves your arm around to different positions. For the other flexibility

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test, you will stand and move your arm to different angles. To take pictures, we will use a safe, non-harmful ultrasound machine. The machine will allow us to look at the bones and muscles under your skin. A gel will be put on your shoulder and elbow to help the device work.

WHAT ARE THE POSSIBLE BAD THINGS ABOUT THIS RESEARCH?

A few things about this study may be uncomfortable or hurt you. By moving your arm around, you may feel a stretch or pain in your shoulder. However, it is very unlikely that it will hurt longer than one day. It is your responsibility to tell the researcher about any pain or funny feelings you get during the testing.

WHAT ARE THE POSSIBLE GOOD THINGS ABOUT THIS RESEARCH?

You will not directly benefit from being in this study. We hope to learn new things that would help stop shoulder and elbow pain from happening in other children.

WHO MAY KNOW THAT YOU PARTICIPATED IN THIS RESEARCH?

No one besides the investigators will know that you were in this study. Your coaches and teammates might see you participating if we are at the field, but they will not see any of your numbers. All of the surveys will not be seen by the researchers until one week after you finish testing. If we tell other people about the research we will not use your name.

WILL YOU RECEIVE ANY COMPENSATION FOR PARTICPATION?

You will receive no compensation for participating in this study.

CAN YOU CHANGE YOUR MIND ABOUT BEING IN THE STUDY?

You do not have to say yes. Taking part in this research study is up to you. If you choose to take part, you can change your mind and stop at any time. If you decide not to participate or if you decide to stop taking part in the research later, nothing bad will happen to you and no one will be upset with you. If, at any time, you decide to stop please let us know by telling one of the researchers. If you decide not to take part in this research, your choice will not affect your relationship with your coaches and will not affect your playing time.

WHO SHOULD YOU CALL IF YOU HAVE QUESTIONS OR CONCERNS?
If you have any questions about this study, please tell Aaron Struminger at (302) 831-8222 or astrum@udel.edu or C. Buz Swanik at (302) 831-2306 or cswanik@udel.edu.

If you have any questions or concerns about your rights as a research participant, you may contact the University of Delaware Institutional Review Board at hsrb-research@udel.edu or (302)831-2137.

If you want to participate, and we have answered all of your questions about it, please sign below.

_____	_____	_____
Printed Name of Participant	Signature of Participant	Date
_____	_____	_____
Person Obtaining Consent	Person Obtaining Consent	Date

Research Study: Using Ultrasound to Identify the Effect of Pitching on the Structural and Functional Anatomy of the Shoulder and Elbow in Youth Baseball Players

Investigators: Aaron H. Struminger, MA, ATC, Alfred Atanda Jr., MD, C. Buz Swanik, PhD, ATC (Department of Kinesiology and Applied Physiology)
I am asking if you want to be part of a research study. This form tells you what the study is about, what you will be asked to do if you want to be in the study, and the possible bad and good things about this study. Please read this paper and ask us any questions you have.

WHAT IS THE PURPOSE OF THE STUDY?

This research study is looking at changes to elbow and shoulder from pitching. The purpose of this study is to find out what the inside of the elbow and shoulder normally look like in pitchers. Another purpose is to find out whether pitching history and pitching mechanics are related to changes to the elbow and shoulder in pitching.

WHAT WILL YOU BE ASKED TO DO?

If you want to participate we will ask you to wear a t-shirt and tennis shoes or cleats to one test at our laboratory. You should also bring your glove to the testing session. The testing should take about 60-75 minutes. To start the test, you and your parent/guardian will be given questions how much you pitch, the types of pitches you throw, your health and other general information. **You will be asked to answer questions about how your body is changing. If you do not want to answer those questions, you can skip them.**

After you finish the questions, we will measure your height, weight, arm length, and arm thickness. Then, we will look inside your elbow and shoulder with diagnostic ultrasound. Diagnostic ultrasound is a type of test that uses sound waves to create a picture of the bones and ligaments inside your body. During one of the ultrasound tests, we will add pressure on the inside of your elbow to see how your bones and ligaments might look when you are pitching.

After we look inside your elbow and shoulder, we will put marker on different points of your body. Then, you will move your arm into 11 different positions that you do almost every day, like brushing your teeth or combing your hair. After you move into those positions, you will warm-up to get ready for pitching. You can do whatever you need to get ready including running, light throwing, or stretching. After you feel like you are ready to throw as hard as you can, you will let one of the examiners know. At this time, you will throw 10 pitches off an indoor mound at a pitching target. While you are pitching, 10 3D cameras will record where the markers are. Also, two digital cameras will record your motion, and a radar gun will be measuring how fast you throw. If you throw 3 strikes in the first 10 pitches, you will be done with testing. If you do not throw 3 strikes, you will throw 5 pitches with the goal of throwing 3 strikes. After these 5 extra pitches, you will stop throwing.

WHAT ARE THE POSSIBLE BAD THINGS ABOUT THIS RESEARCH?

A few things about this study may be uncomfortable or hurt you. When applying pressure to your elbow, you may feel a stretch or pain. You may also hurt yourself while you are pitching. However, it is very unlikely that your shoulder or elbow will hurt longer than it normally does after pitching. If your arm feels funny or hurts anytime during the testing, it is your responsibility to tell one of the researchers.

WHAT ARE THE POSSIBLE GOOD THINGS ABOUT THIS RESEARCH?

You will not directly benefit from being in this study. We hope to learn new things that would help stop elbow and shoulder pain from happening in other baseball players your age.

WHO MAY KNOW THAT YOU PARTICIPATED IN THIS RESEARCH?

No one besides the investigators will know that you were in this study. Your coaches and teammates might see you participating if we are at the field, but they will not see any of your numbers. All of the surveys will not be seen by the researchers until one week after you finish testing. We will also have a video that includes your face, but we will do everything possible to make sure that the video tape is not linked with any information of yours that we have. If we tell other people about the research we will not use your name.

WILL YOU RECEIVE ANY COMPENSATION FOR PARTICPATION?

You will receive no compensation for participating in this study.

CAN YOU CHANGE YOUR MIND ABOUT BEING IN THE STUDY?

You do not have to say yes. Taking part in this research study is up to you. If you choose to take part, you can change your mind and stop at any time. If you decide not to participate or if you decide to stop taking part in the research later, nothing bad will happen to you and no one will be upset with you. If, at any time, you decide to stop please let us know by telling one of the researchers. If you decide not to take part in this research, your choice will not affect your relationship with your coaches and will not affect your playing time.

WHO SHOULD YOU CALL IF YOU HAVE QUESTIONS OR CONCERNS?
If you have any questions about this study, please tell Aaron Struminger at (302) 831-8222 or astrum@udel.edu or C. Buz Swanik at (302) 831-2306 or cswanik@udel.edu.

If you have any questions or concerns about your rights as a research participant, you may contact the University of Delaware Institutional Review Board at hsrb-research@udel.edu or (302)831-2137.

If you want to participate, and we have answered all of your questions about it, please sign below.

_____   _____   _____
Printed Name of Participant   Signature of Participant   Date

_____   _____   _____
 Person Obtaining Consent   Person Obtaining Consent   Date