The Effect of Throwing Intensity on Overhand Throwing Mechanics

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Implications for Throwing Rehabilitation

by

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Abstract

Overhead throwing is a dynamic and demanding movement that places great amounts of stress on the throwing arm. Current consensus attributes most throwing-related injuries to repeated microtrauma of the musculoskeletal structures surrounding the shoulder and elbow. After sustaining an injury to the shoulder or elbow, overhead athletes complete an interval throwing program as part of the rehabilitation process. Interval throwing programs gradually increase throwing intensity over several weeks by manipulating throwing volume and distance to produce successively more throws at successively longer distances. Recently, there has been an increased call for objective methods of quantifying how and when to progress through the interval throwing program, including monitoring throwing intensity with a calibrated radar gun. Although objective methods of throwing intensity quantification are beneficial to the rehabilitation process, how the demands placed on the throwing arm change throughout the intensity range typically seen in throwing rehabilitation programs is not well understood. Therefore, the purpose of this research was to model changes in throwing arm joint loads as pitchers progressed from low to high intensity throwing.

Thirty-two skilled throwing athletes were recruited to participate (21 ± 2 yrs; 1.86 ± 0.08 m; 89.0 ± 10.2 kg). Once participants completed their typical non-throwing warm up, 50 reflective markers were placed at relevant anatomical locations and participants had their throwing mechanics recorded during their throwing warm up using a passive optical motion capture system. The primary findings of this project were two fold: first, the intra-participant relationship between throwing arm joint loading and throwing speed appears to be nonlinear in form. Specifically, the form of this relationship is quadratic linear concave up indicating that, as throwing arm joint loading increases, corresponding increases in throwing speed become successively smaller and smaller. Second, as body mass and height increase, the slope estimating the relationship between throwing arm joint loading and throwing speed decreases. In addition to providing novel insight into the intra and inter-participant relationships between throwing arm joint loading and throwing speed, these findings also serve as an initial exploration of, and

proof-of-concept for, the use of multilevel modeling strategies in sports biomechanics research.

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Abbreviations

BR Ball Release. 7, 10, 12, 24, *Glossary:* ball release

EET Elbow Energy Transfer. 28, 40, 41, 43–47, 49–51, 65, 67, 69, *Glossary:* elbow energy transfer

EVT Elbow Varus Torque. 25, 40, 41, 43–47, 49, 64, 66, 68, *Glossary:* elbow varus torque

FWE Familywise Error. 33, *Glossary:* familywise error rate

GIRD Glenohumeral Internal Rotation Deficit. 9, *Glossary:* glenohumeral internal rotation deficit

ITP Interval Throwing Program. 2, 3, 6, 15–18, 46, 48, *Glossary:* interval throwing program

JFP Joint Force Power. 26–28, 71, *Glossary:* joint force power

MER Maximum External Rotation. 7, 8, 23, 28, *Glossary:* maximum external rotation

MIR Maximum Internal Rotation. 7, 23, *Glossary:* maximum internal rotation

PKH Peak Knee Height. 6, 10, *Glossary:* peak knee height

RMSE Root Mean Squared Error. 40, 43, 46, 47, 50, 51, *Glossary:* root mean squared error

ROM Range of Motion. 8, 9, 11, 14, 15, *Glossary:* range of motion

RPE Rating of Perceived Exertion. 17, 18, 49, *Glossary:* rating of perceived exertion

SET Shoulder Energy Transfer. 28, 40, 41, 43–47, 49, 51, 65, 67, 69, *Glossary:* shoulder energy transfer

SFC Stride Foot Contact. 6, 7, 10, 11, 13, 23, 28, *Glossary:* stride foot contact

SRT Shoulder Rotation Torque. 25, 40, 41, 43–47, 49–54, 64, 66, 68, *Glossary:* shoulder rotation torque

STP Segment Torque Power. 26–28, 71, *Glossary:* segment torque power

UCL Ulnar Collateral Ligament. 1, 8, 32, *Glossary:* ulnar collateral ligament

Symbols

Symbol	Description	Unit
F	force	N
JFP	joint force power	W
SP	segment power	W
STP	segment torque power	W
$\cdot$	multiplication (scalars) or dot product (vectors)	
ω	angular velocity	$\mathrm{rad} \cdot \mathrm{s}^{-1}$
τ	torque	$\mathrm{N} \cdot \mathrm{m}$
v	linear velocity	$\mathrm{m} \cdot \mathrm{s}^{-1}$

1 Introduction

Overhead throwing is a dynamic and demanding movement that places great amounts of stress on the throwing arm.[29,79] To perform optimally, overhead athletes must generate energy in the lower extremities and trunk before funneling this energy distally through the shoulder and into the throwing arm.[3,5,37] In baseball, players repeat this motion thousands of times each competitive season, resulting in high injury incidences to the shoulder and elbow.[18,84] These injuries, even in their mildest forms, can cost players weeks of playing time. In more severe cases, surgical intervention and months of rehabilitation are required before returning to competition.

Current consensus attributes most throwing-related injuries to repeated microtrauma of the musculoskeletal structures surrounding the shoulder and elbow.[1,23,65] Overtime, microtrauma can compromise tissue integrity, eventually leading to traumatic tissue failure.[10,23,39] The structures of greatest interest to sports medicine professionals include the ulnar collateral ligament (UCL) at the elbow and the glenoid labrum and rotator cuff at the shoulder. The UCL helps produce the varus torque responsible for resisting the valgus torque exerted at the elbow by the inertia of the forearm while the glenoid labrum and rotator cuff maintain normal arthrokinematics between the humeral head and glenoid fossa. Injury to any of these tissues is likely severe and can result in substantial time missed from competition.[18] High throwing volumes combined with poor throwing technique can accumulate microtrauma within these vulnerable tissues and lead to tissue dysfunction and pathomechanic adjustments as athletes attempt to maintain a competitive edge.[39]

The varus torque at the elbow and rotation torque at the shoulder have received much attention in previous throwing biomechanics research because of their relevance to the UCL, glenoid labrum, and rotator cuff musculature.[20] Both torques have been shown to peak near maximum throwing shoulder external rotation during the transition from arm cocking to arm acceleration and have been hypothesized to influence a thrower's injury risk.[29] Independently, these measures have shown limited usefulness for evaluating injury risk and predicting future injury,[1,7] leading some researchers to look for other potentially complementary evaluation methods. Less frequently examined biomechanical measures such as segmental powers and energies are gaining in popularity and may offer additional insight into the relationships between throwing mechanics, performance, and injury. Segmental powers and energies may also improve collaboration between researchers and coaches given the prevalence of energy-centered coaching rhetoric in amateur and professional baseball.[13,35]

After sustaining an injury to the shoulder or elbow, overhead athletes complete an interval throwing program (ITP) as part of the rehabilitation process.[9,21,51,73,86] ITPs gradually increase throwing intensity over several weeks as pitchers retrain injured tissues to tolerate the stresses experienced during overhead throwing. Increases in throwing intensity are accomplished by manipulating throwing volume and distance to produce successively more throws at successively longer distances.[9] Under most circumstances, ITPs outline progressions in throwing volume and distance at the onset of the ITP and only deviate from these progressions when the athlete experiences some sort of setback (i.e., pain, tenderness, or excessive soreness).[9] While this approach may work for some, it may not be optimal for many attempting to return to competition. Indeed, current evidence suggests almost 50% of professional pitchers who undergo a rehabilitation program for a throwing-related injury will reinjure their throwing arm.[54,55,57] This percentage is likely even higher for youth and amateur overhead athletes who do not always have access to the same caliber rehabilitation facilities and personnel.

Although injury results from many factors, insufficient or inappropriate ITP protocols may be a contributing factor. If athletes are progressed too quickly or tissues surrounding the injured area are not adequately conditioned, reinjury risk can increase. Accordingly, successful progression from low to high intensity throwing requires an understanding of how the demands of the throwing motion change with intensity. While it is evident that the loads placed on the shoulder and elbow will increase with increasing throwing intensity,[32,46,61,73,74] it is unknown whether the rate of joint load increase differs between athletes. This is problematic since the complexity of the throwing motion implies that responses to increased throwing intensity are likely to be unique to the individual athlete's anatomy and technique as well as injury location and severity.

The progression from low to high intensity throwing is a complex phenomenon comprising both intra-individual growth patterns and inter-individual growth pattern variation. Typical repeated measures analysis is not well suited to simultaneously model this hierarchical structure given the rigidity of its assumptions and its treatment of inter-individual variation as error. In contrast, multilevel modeling is much more flexible in its assumptions and can explain variance at the intra and inter-individual levels. Additionally, multilevel modeling allows researchers to explore the functional form of the relationship between variables of interest. Multilevel modeling has the potential to improve the statistical rigor and expand the applicability of throwing biomechanics research by modeling both intra and inter-individual phenomena.

The majority of overhead throwing biomechanics research has focused on group averages during maximal intensity throwing. Only a select number of studies have examined mechanics during sub-maximal throwing[32,46,51,61,73] or considered within-athlete variation.[46,61,74,77,78] Additionally, much of the prior research into sub-maximal throwing is limited to a handful of biomechanical measures collected from one commercially available inertial sensor.[46,50,51,61] Together, these factors limit the applicability of overhead throwing biomechanics research in rehabilitation settings since neither group averages nor maximal intensity mechanics reflect the progressive and individualized nature of throwing rehabilitation. Modeling how pitchers respond to increases in throwing intensity will benefit the sports medicine community by informing the design, implementation, and modification of throwing rehabilitation protocols. In turn, more objective and individualized ITPs could improve the percentage of pitchers who are able to recover from injury and return to–or even surpass–their previous level of play. Therefore, the purpose of this project is to model changes in throwing arm joint loading as pitchers progress from low to high intensity throwing. The project specific aims, research questions, and hypotheses are outlined below.

1.1 Specific Aims and Research Questions

Aim 1: Model the intra-participant relationship between throwing arm joint loading and throwing speed as participants progress from low intensity to high intensity throwing

- $RQ_{1.1}$: How is the relationship between elbow varus torque and throwing speed better modeled as participants increase throw intensity?
  - H_0: The relationship between elbow varus torque and throwing speed will be better modeled using a quadratic relationship.
- $RQ_{1.2}$: How is the relationship between shoulder rotation torque and throwing speed better modeled as participants increase throw intensity?
  - H_0: The relationship between shoulder rotation torque and throwing speed will be better modeled using a quadratic relationship.
- $RQ_{1.3}$: How is the relationship between upper arm-to-forearm energy flow and throwing speed better modeled as participants increase throw intensity?
  - H_0: The relationship between upper arm-to-forearm energy flow and throwing speed will be better modeled using a quadratic relationship.
- $RQ_{1.4}$: How is the relationship between trunk-to-upper arm energy flow and throwing speed better modeled as participants increase throw intensity?

- H_0: The relationship between trunk-to-upper arm energy flow and throwing speed will be better modeled using a quadratic relationship.

Aim 2: Model inter-participant differences in responses to increased throwing intensity

- $RQ_{2.1}$: Does allowing differing rates of increase (random slopes) in Model 1.1 improve model fit? If so, do second level explanatory variables help explain the rate of increase (cross-level interaction)?
  - H_0: The rate of increase in variables from Model 1.1 will differ between participants. Variance in the rate of increase will be explained by pitcher anthropometrics and max throwing speed.
- $RQ_{2.2}$: Does allowing differing rates of increase (random slopes) in Model 1.2 improve model fit? If so, do second level explanatory variables help explain the rate of increase (cross-level interaction)?
  - H_0: The rate of increase in variables from Model 1.2 will differ between participants. Variance in the rate of increase will be explained by pitcher anthropometrics and max throwing speed.
- $RQ_{2.3}$: Does allowing differing rates of increase (random slopes) in Model 1.3 improve model fit? If so, do second level explanatory variables help explain the rate of increase (cross-level interaction)?
  - H_0: The rate of increase in variables from Model 1.3 will differ between participants. Variance in the rate of increase will be explained by pitcher anthropometrics and max throwing speed.
- $RQ_{2.4}$: Does allowing differing rates of increase (random slopes) in Model 1.4 improve model fit? If so, do second level explanatory variables help explain the rate of increase (cross-level interaction)?
  - H_0: The rate of increase in variables from Model 1.4 will differ between participants. Variance in the rate of increase will be explained by pitcher anthropometrics and max throwing speed.

1.2 Limitations

- Participant age range (14 – 25 years old)
- Controlled laboratory setting
- Intensity subjectivity

1.3 Delimitations

- Age range representative of majority of pitchers in need of optimized throwing rehabilitation programs

- Kinematic data collected using a calibrated 3D motion capture system
- Subjective intensity replaced with throwing speed

2 Review of Literature

This project models how throwing mechanics change as baseball players progress from low intensity to high intensity throwing. This chapter reviews key aspects of the study including overhead throwing biomechanics, throwing-related injuries, and overhead athlete rehabilitation practices. Section 2.1 provides a biomechanical overview of the overhand throwing motion with attention to common injury mechanisms. Section 2.2 discusses the importance of the kinetic chain in overhead throwing. Energy flow during overhead throwing is discussed in Section 2.3. Section 2.4 outlines ITPs and other common rehabilitation practices for overhead throwing athletes. Lastly, Section 2.5 explores subjective and objective measures of throwing intensity and their roles in throwing rehabilitation.

2.1 Biomechanics and injury mechanisms during the overhand throw

When performed at high intensity, the overhand throw is one of the most dynamic movements in all of sport. As a result, overhead throwing (in particular baseball pitching) has received much attention in sport biomechanics research. Preliminary examinations of baseball pitchers emerged in the 1980's and 90's with the seminal works of Feltner, Fleisig, and others describing the kinematics and kinetics of the pitch and establishing a foundation for future research.[24, 26–30] Since these works, research has sought to identify mechanical determinants of pitching performance and injury risk in baseball players of all ages and ability levels. However, despite the progress made in describing the mechanics of the pitch and quantifying the loads placed on the upper extremity, pitchers continue to injure their shoulders and elbows at alarming rates.[18]

The overhand throwing motion is most commonly divided into six distinct phases separated by five key events (Figure 2.1). The wind-up phase starts when the athlete first initiates movement and ends when the contralateral knee reaches its peak vertical position [peak knee height; (PKH)]. This phase raises the body's center of mass, increasing the body's potential energy, and prepares the athlete for the stride. During the wind-up, the torso counter-rotates and the upper extremities remain relatively still. The stride phase begins at PKH and ends when the contralateral foot first makes contact with the ground [stride foot contact; (SFC)]. To initiate the stride, the athlete extends and abducts their contralateral hip, extends their contralateral knee, and shifts their center of mass laterally in the direction of the throw to create linear momentum.[48, 66, 67] In synch with this shift, the athlete lowers and separates their hands and positions the throwing arm in preparation for the cocking phase. At SFC, the throwing arm is in approximately 90 degrees of abduction and 90 degrees of elbow flexion.[30]

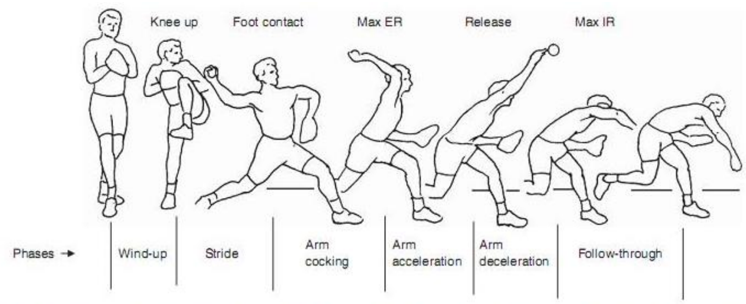

Figure 2.1: The Phases of the Baseball Pitch. Adapted from Fleisig et al.[30]

Cocking starts at SFC and is the first phase to place substantial loads on the throwing arm. Following SFC, the athlete rotates their torso towards the target while horizontally abducting their throwing arm. This causes the throwing arm to lag behind the torso, allowing the torso to increase its mechanical energy before transferring energy to the throwing arm. As the humerus begins to rotate towards the target, the orientation and inertia of the forearm causes it to lag even further, externally rotating the humerus and creating a powerful pre-stretch of the internal rotation musculature. Once the internal rotation musculature is maximally stretched, the humerus transitions from external rotation to internal rotation. This moment of inflection is termed [maximum external rotation; (MER)] and separates the cocking phase from the acceleration phase. The valgus torque at the elbow and the external rotation torque at the shoulder reach their peak near this time at approximately 3-7% of a pitcher's bodyweight*height.[30,74]

Acceleration begins at MER and ends when the ball leaves the athlete's hand [ball release; (BR)]. During acceleration, the athlete's torso continues to rotate towards the target and flexes forward over the contralateral leg. Elastic recoil of the internal rotation musculature internally rotates the humerus and extends the elbow. During the baseball pitch, humeral internal rotation and elbow extension can approach speeds of up to 7,000 and 2,300 degrees per second, respectively.[30] Rapid elbow extension produces a large centrifugal force between the humerus and forearm which is countered by a compression force upwards of 1,000 N produced primarily by the triceps and wrist flexors to maintain joint integrity.[31,79,85] Following BR, the rotator cuff and posterior shoulder musculature are responsible for slowing humeral internal rotation and horizontal adduction as well as resisting glenohumeral distraction during the deceleration phase. Once the humerus reaches its maximally internally rotated position [maximum internal rotation (MIR)], the follow through phase begins which lasts until the athlete finishes the throwing motion. Much like the wind up and stride phases, shoulder and elbow joint loading are minimal during the follow through.

Of these six phases, the shoulder and elbow are exposed to the greatest amounts of stress during the cocking, acceleration, and deceleration phases. Once cocking begins, the orientation and inertia of the forearm relative to the humerus exert a valgus torque on the elbow, placing compression stress on the lateral elbow and tensile stress on the medial elbow.[7, 29] Lateral compression stress is largely countered by the bony stop between the radial head and the capitellum of the humerus.[15] Excessive compression between the radius and humerus can increase the risk of bony pathologies such as Panner's disease and osteochondritis dissecans, particularly in youth athletes with immature boney anatomy.[15, 43] Medially, the flexor pronator mass and UCL are the main structures responsible for supplying a varus torque to resist the tensile stress placed on the medial elbow.[15] When the demands of the throwing motion exceed the capacity of the flexor pronator mass to resist the valgus torque, increased stress can be placed on the UCL. Over time, excessive stress applied to the UCL can accumulate microtrauma within the ligament, eventually leading to compromised tissue integrity and injury. In severe cases, the UCL tears and reconstructive surgery is required. Colloquially referred to as Tommy John surgery, this procedure requires athletes to complete several months of rehabilitation and miss approximately 12 – 18 months from competition.[6, 54]

Coincident with the increase of valgus torque at the elbow is an increase of external rotation torque at the shoulder; both of which peak close to MER.[29] Much like its valgus counterpart at the elbow, the rotational torque at the shoulder is caused by the inertia and orientation of the forearm and stresses important yet vulnerable tissues surrounding the shoulder joint capsule. The glenoid labrum, in particular, experiences great amounts of stress as the humerus undergoes large range of motion (ROM) during cocking and acceleration. This rapid progression through external and internal rotation is facilitated by translation of the humeral head on the glenoid fossa. Under normal conditions, the rotator cuff musculature maintain the humeral head within an anatomically acceptable range on the surface of the glenoid. With fatigue or pathology, the rotator cuff's ability to center the humeral head can be hampered, resulting in increased translation beyond anatomically safe limits.[53, 70] Increased humeral head translation can place undue shear stress on the glenoid labrum leading to tissue damage. Repetitive microtrauma to the glenoid labrum can result in injury to the labral complex, rotator cuff musculature, and the proximal biceps tendon.[10, 17] Once again, injury to these tissues often requires reconstructive surgery, forcing athletes to miss months of practice and complete extensive rehabilitation protocols.

Arm deceleration eccentrically loads the posterior shoulder girdle musculature as the throwing arm horizontally adducts across the body.[10, 17] Repetitive eccentric loading has been hypothesized to hypertrophy and stiffen the posteroinferior shoulder capsule and induce microtrauma into the glenohumeral and scapular stabilizing musculature.[10, 17, 39] Capsular contracture has, in turn, been hypothesized to constrain glenohumeral internal rotation, presenting clinically as glenohumeral internal rotation deficit (GIRD). Several studies have examined the association between glenohumeral internal rotation deficit (GIRD) and injury in baseball pitchers and found evidence that reductions in throwing arm internal rotation ROM of approximately 20 degrees or more compared to the non-throwing arm may place athletes at increased risk of injury.[1,87–89]

2.2 The kinetic chain in overhead throwing

Overhead throwing performance is predicated on the sequential transmission of energy starting with the more proximal lower extremities and torso and finishing with the distal throwing hand. Because the body segments are "linked" together, this proximal-to-distal flow of energy is often referred to as a kinematic or kinetic chain. Credit for adapting the concept of the kinetic chain from engineering to human movement is commonly given to von Baeyer whose work in the 1930's focused on synergistic muscle actions in the limbs.[75] Following von Baeyer, Steindler popularized the concept of the kinetic chain to human movement performance and rehabilitation and further differentiated between *open* and *closed* kinetic chains.[76] Steindler defined an open kinetic chain as "a combination of successively arranged joints in which the terminal segment can move freely" and a closed kinetic chain as a similarly constructed combination of successively arranged joints in which "…the distal segment meets considerable external resistance that prohibits or restrains its free motion".[76]

Rooted within the idea of the open kinetic chain is the summation of speed principle which states that, to produce the largest possible speed at the endpoint of an open kinetic chain, motion should start with the more proximal segments and then proceed sequentially to the more distal segments once the proximal segment reaches its peak speed.[16,58] Starting the motion proximally allows the more massive pelvis and torso musculature to act as the primary energy *generators*. As the task proceeds, energy that is generated proximally is funneled to the less massive distal segments. In the case of lower extremity open kinetic chain tasks such as kicking, energy is funneled from pelvis and torso to the thigh, shank, and foot. In the case of upper extremity open kinetic chain tasks like overhead throwing, energy is funneled to the upper arm, forearm, and hand. In both lower and upper extremity open kinetic chain tasks, segments become less massive as the task proceeds distally. This reduction in mass allows each successive segment in the kinetic chain to achieve faster speeds than its predecessor. Eventually, maximal speed is achieved in the terminal segment in the chain.[16,62,71,72]

In the case of overhead throwing, the athlete's ultimate goal is to achieve maximal speed of the most distal segment, the throwing hand, to release the baseball as fast as possible towards home plate. For baseball pitchers, releasing the baseball with as much speed as possible provides a competitive edge by reducing the time available to the hitter to identify the type of pitch and decide whether or not to swing. For position players, increased throwing speed is also desirable as it allows increased time to field the batted ball and still make a defensive out. The athlete starts the process of achieving maximal speed of the throwing hand by building linear kinetic energy during the stride phase.[48,66,67] Following PKH, the athlete translates their center of mass towards home plate and down the pitching mound. This process converts gravitational potential energy into kinetic energy while the pitcher generates additional kinetic energy by actively pushing off the pitching mound with the ipsilateral leg. At SFC the contralateral leg applies a breaking ground reaction force as the pitcher starts the conversion of linear kinetic energy into angular kinetic energy.

The summation of segmental speeds starts with the pelvis which reaches its peak angular velocity of $600 - 700\ deg \cdot s^{-1}$ shortly after SFC.[30] Once pelvis angular velocity peaks, pelvis rotation slows, and energy funnels through the kinetic chain to the trunk. The trunk receives additional energy generated from contraction of the abdominal muscles as they rotate and flex the trunk over the contralateral leg.[5,63] Trunk angular velocity builds upon the angular velocity of the pelvis and peaks between $1{,}100 - 1{,}200\ deg \cdot s^{-1}$, approximately half way between SFC and BR.[30] Just as with the pelvis, trunk rotation slows after peaking and energy is directed distally through the shoulder girdle to the pitching arm.

Once the kinetic chain progresses to the throwing arm, evidence suggests pitchers do not necessarily adhere to a strict proximal-to-distal sequencing pattern.[71] Scarborough et al examined proximal-to-distal sequencing during 8 – 10 fastball trials in 22 experienced baseball pitchers and found that no pitcher displayed a perfectly sequenced kinetic chain from the pelvis to the pitching hand.[71] Most commonly, hand angular velocity peaked before forearm angular velocity indicating that a "textbook" definition of proximal-to-distal sequencing may not be employed by skilled pitchers when pitching at or near maximum effort. Deviation from a true proximal-to-distal sequence during open kinetic chain upper extremity sport movements is corroborated by other studies of the baseball pitch showing peak internal rotation velocity of the humerus occurring after peak elbow extension angular velocity[26,30] and studies of the squash serve showing "long-axis" rotations of the upper extremity (i.e. internal/external rotation of the shoulder and pronation/supination of the forearm) to be the last links in the kinetic chain.[62] This has led some researchers to conclude that, although proximal-to-distal sequencing may be adequate to explain open kinetic chain tasks in the lower extremity, the apparent importance of "long-axis" rotations during upper extremity open kinetic chain indicates that textbook proximal-to-distal sequencing may not be sufficient to accurately describe the complex segment interactions during overhead throwing.[62]

Whether the result of fatigue or poor technique, deficient proximal kinetic chain mechanics are hypothesized to interfere with the flow of energy to distal segments. As the pitcher fatigues and energy flow through the kinetic chain diminishes, research suggest one of two things can happen. First, pitchers can experience decreased pitch speed as less energy is delivered to the hand and funneled to the baseball. Conversely, pitchers can continue to deliver adequate amounts of energy to the end of the kinetic chain, but increased demands are placed on more distal segments to make up for limitations or breakdowns in proximal segments. The latter case is known as the *catch-up phenomenon* and is hypothesized to be especially problematic as it overloads the vulnerable tissues surrounding the shoulder and elbow.[39, 80] Common kinetic chain breakdowns that are hypothesized to increase the demands on the pitching arm include premature forward motion during the wind up and stride, excessively closed or open contralateral foot at SFC, premature trunk rotation towards home plate, diminished forward trunk tilt during cocking and acceleration, increased contralateral knee flexion following SFC, diminished glenohumeral external rotation ROM during cocking, and scapular dyskinesis.[4, 20, 72] Whether these mechanical deficiencies are due to poor technique, underdeveloped neuromuscular control, or secondary to inadequate physical conditioning (muscular strength, endurance, flexibility, etc. . .) is often difficult to determine.

2.3 Energy flow and overhead throwing

Due to the sustained rise in injury incidence to the pitching shoulder and elbow, researchers continue to search for additional analysis methods to complement traditional examination of overhead throwing mechanics. One method that has recently gained popularity is energy flow analysis. Rather than focusing on individual orthogonal components of a net joint force or moment, energy flow analysis examines how mechanical energy moves through the body during movement. Originally used to examine energy exchange among the lower extremity segments during gait,[69, 93] energy flow analysis and its variants (segment power analysis, joint power analysis, etc. . .) have recently been adapted in baseball biomechanics research to examine how overhead athletes move mechanical energy between body segments during the throw.[2, 3, 5, 36, 37, 40, 41, 63]

Energetic analyses can complement traditional biomechanical examinations of the overhead throwing motion. Quantification of energy generation, transfer and absorption allows researchers to determine the direction and method of energy flow as well as the efficiency by which pitchers use their kinetic chains.[37, 92] Furthermore, the breakdown of energy flow into its individual joint force and joint moment components may be particularly beneficial for the analysis of motions involving both linear and angular motion such as the overhead throw.[37] Perhaps most importantly, energy-based analyses allow researchers to better address questions relevant to coaches and clinicians. Coaches frequently instruct using rhetoric centered around energy and momentum transfer through the kinetic chain.[13,35] Despite widespread use of this rhetoric, research into the energetics of the throwing motion has only recently increased in popularity.

The first English examination of baseball pitching energetics was conducted by Naito, Takagi, and Maruyama in 2011[i]. They recorded the pitching mechanics of eight collegiate baseball pitchers and calculated the mechanical energy produced by the individual joint moments and forces during arm cocking and arm acceleration.[63] Additionally, they decomposed the joint moments into their muscular and non-muscular interactive moments to further understand how segmental energy is generated and transferred through the kinetic chain. They found that the kinetic energy of the of the pitching hand and ball at BR largely resulted from the trunk flexion and rotation moments during arm cocking and that the contribution of the shoulder axial rotation moment to pitching hand kinetic energy was comparingly small. They also found that the centrifugal force was an important factor in transferring energy distally through the pitching arm during arm acceleration. These findings reinforced clinical and coaching philosophies that the pitching arm acts primarily as an energy funnel and that most of the energy needed for pitching originates proximally in the trunk and lower extremities.

Several studies on the energetics of the overhead throw have since followed the work of Naito et al., the majority of which have examined baseball pitchers and have been published in the last three years. These studies include those of Aguinaldo,[2,3,5] Howenstein,[36,37] and Kimura.[40,41] Aguinaldo and Escamilla examined how trunk segment power influenced elbow valgus moment and pitch speed in a sample of 15 high school and 16 professional pitchers.[3] They reported that peak trunk power positively predicted both peak elbow valgus moment and pitch speed. Furthermore, when analyzed as one group instead of two, trunk rotation timing significantly predicted elbow valgus moment and pitch speed, indicating that the between group differences in timing of energy flow into the trunk was also important for pitching performance. Specifically, high school pitchers initiated trunk rotation earlier in the pitching motion compared to professional pitchers. Earlier initiation of trunk rotation coupled with similar amounts of normalized elbow valgus moments and slower pitch speeds in high school pitchers suggest early trunk rotation may prematurely transfer energy through the trunk and decrease kinetic chain efficiency. In a follow-up paper examining ten professional pitchers, Aguinaldo and Escamilla performed an induced power analysis to elucidate the mechanism of energy flow from the trunk to the pitching arm. Their results reinforced those of Naito et al[63] that trunk flexion and rotation contributed the greatest to pitching arm energy flow.

While Naito and Aguinaldo focused on older pitchers, Howenstein et al examined energy flow through

[i] as is common in baseball biomechanics, earlier works do exist (i.e. Shimada, 2000 and Shimada, 2004) but are written in Japanese which I, regretfully, am not able to read

the kinetic chain in a sample of 24 youth pitchers.[37] The goals were to relate the total magnitude of energy flow along with its linear and rotational components to both pitch speed and joint load efficiency. They reported strong correlations between the magnitudes of energy flow from the pelvis, trunk, and arm segments and pitch speed. They also reported that the linear component of energy flow into the trunk from the pelvis was correlated with measures of shoulder and elbow joint load efficiency. In a follow up study on the same youth sample, Howenstein et al further investigated energy flow through the kinetic chain by examining the relationship between horizontal ground reaction force and energy flow.[36] Their results showed that ipsilateral leg propulsion during the stride plays a role in transferring linear power through the pelvis and trunk segments whereas contralateral leg braking following SFC helps facilitate rotational power that is transferred from the trunk to the pitching arm. The importance of the ipsilateral leg for linear power and contralateral leg for rotational power reinforces the coaching philosophy that the ipsilateral leg should propel the athlete forward and generate kinetic energy while the contralateral is responsible for converting that kinetic energy from linear motion to angular motion following SFC.[13,35]

Supporting the opposing but complementary roles of the lower extremities during the throwing motion, Kimura et al used energetic analyses to examine in greater detail the mechanisms behind pelvis and torso rotation.[40,41] When examining pelvis rotation, their results indicated that the external rotation moment of the ipsilateral leg and the adduction moment of the contralateral leg transferred and generated the most energy from the lower extremities to the pelvis. Working up the kinetic chain, Kimura et al also examined the sources of torso rotation and demonstrated that the torsional moment between the pelvis and torso was responsible for the majority of energy transfer from the pelvis to the torso.

Researchers have now described the flow of mechanical energy through the kinetic chain,[37,40,41] investigated the associations between energetic measures and traditional measures of shoulder and elbow joint loads,[2,3,5,37] and established relationships between various energetic measures and pitch speed.[3,37] Taken together, the current body of literature investigating the energetics of the throwing motion reinforces the importance of energy transfer through the kinetic chain, particularly through the pelvis and torso segments as they have been shown to contribute heavily to the energy flow through the pitching arm. Unfortunately, given the relatively recent emergence of energy-based overhead throwing research, we still know little about whether energy flow analysis and its derivatives can be used to provide additional insight into an athlete's injury risk. We also do not know whether insights gained from energetic analyses can be used to inform clinical practice or guide training decisions. No studies have yet examined energy flow variability within individual pitchers and whether variability (or lack thereof) is associated with increases in shoulder and elbow joint loads or pitching performance. Longitudinal studies are also needed to examine whether aspects of energy flow through the kinetic chain are predictive of future injury.

2.4 Overhead throwing rehabilitation and interval throwing programs

Following injury to the shoulder or elbow, overhead athletes undergo extensive rehabilitation before returning to competition. Wilk separates the rehabilitation process for overhead athletes into four distinct phases: acute, intermediate, advanced strengthening, and return to activity (Table 2.1).[86] The acute phase starts immediately after injury and is designed to restore normal day-to-day upper extremity function. During this portion of the rehabilitation program pain and inflammation are reduced, joint motion and muscle balance are normalized, postural adaptations are corrected, proper muscle activation is restored, a baseline of dynamic joint stability is re-established.[86] Therapy modalities during the acute phase consist largely of manual therapies such as active assisted ROM, light manual stretching, and grade 1 and 2 joint mobilizations, as well as low intensity strengthening and stabilization exercises. Other passive modalities such as ice, heat, ultrasound, and electrical stimulation are also used to promote tissue healing. Strengthening and stabilization exercises are focused to the injured area and immediately surrounding tissues.

	Goals	Exercises and Modalities
Phase 1: Acute	Diminish pain and inflammation Normalize motion Delay muscular atrophy Re-establish dynamic stability (muscular balance) Control functional stress/strain	Cryotherapy Ultrasound Electrical Stimulation Flexibility/Stretching Rotator cuff and scapula stabilizer strengthening Dynamic stabilization Proprioception training Weight-bearing Abstain from throwing
Phase 2: Intermediate	Progress strengthening Restore muscular balance Enhance dynamic flexibility Control flexibility and stretches	Continued stretching and flexibility Progress isotonic strengthening Thrower's ten Rhythmic stabilization Core/lumbopelvic strengthening Lower extremity strengthening
Phase 3: Advanced Strengthening	Aggressive strengthening Progress neuromuscular control Improve strength, power, and endurance	Flexibility and stretching Rhythmic stabilization Advanced thrower's ten Plyometric drills Endurance drills Initiate short-distance throwing program
Phase 4: Return to Activity	Progress throwing program Return to competitive throwing Continue strengthening and flexibility	Stretching and flexibility drills Thrower's ten Plyometric program Progress interval throwing program to competitive throwing

Table 2.1: The Four Phases of Throwing Rehabilitation (adapted from Wilk et al[86])

The second phase of overhead throwing rehabilitation is the intermediate phase. The goals of the intermediate phase are to continue the progress made in the acute phase while enhancing the athlete's strength, stability, endurance, and neuromuscular control. Strengthening and stabilization exercises progress to full joint ROM and emphasis is placed on conditioning the core, lumbopelvic hip complex, and lower extremities to promote complete kinetic chain training. Additionally, it is this phase that sports medicine professionals typically introduce the Thrower's Ten, a series of upper extremity rehabilitation exercises designed specifically for overhead throwing athletes, and sport-specific conditioning.[91] Mobility and flexibility continue to be trained through passive and active ROM exercises and passive modalities such as heat and electrical stimulation can continue if deemed beneficial.

Graduation to the advanced strengthening phase is marked by the inclusion of plyometric exercises in addition to the progression of the strengthening, stabilization, and endurance exercises from Phase 2. Plyometric exercises designed to mimic the rapid eccentric pre-stretch experienced during the throwing motion are incorporated to further recondition injured tissues and increase the specificity of rehabilitation exercises.[90] Using medicine balls of various weights, athletes progress from two-handed plyometrics, such as the chest past, soccer throw, and rotational throw, to one-handed sport-specific plyometrics such as the reverse throw and plyoball wall throw.[90] The Thrower's Ten progresses to the Advanced Thrower's Ten which modifies exercises from the original program to further challenge the athlete's ability to use their kinetic chain to maintain stability of the upper extremity. Examples of this progression include performing external rotation exercises from a side plank position instead of standing, and weight-bearing exercises on unstable surfaces. Short distance ITPs can also be introduced during this phase as the athlete completes plyometric exercises without issue.

Once shoulder and/or elbow joint function has been restored and injured tissues have been sufficiently reconditioned, the overhead athlete begins an ITP. The ITP is a staple in all overhead throwing athlete rehabilitation protocols and gradually retrains the injured tissues to tolerate the stresses incurred during the throwing motion. Figure 2.2 outlines the long-toss and flat ground portions of a sample ITP for baseball pitchers. Pitchers begin throwing at short distances (approximately 30-45 feet) and complete a certain number of throwing sessions before proceeding to the next step of the program. Various strategies are employed to progress athletes through the ITP. Throw number is typically increased at a certain distance before the athlete increases throw distance. When distance increases, throw number temporarily decreases so as to not increase overall throwing intensity too abruptly. This process repeats as the athlete proceeds to incrementally longer distances and completes incrementally more throws. This portion of the ITP is sometimes referred to as the long-toss portion and results in an athlete who can comfortably complete a pre-determined number of throws at a pre-determined distance without experiencing soreness or pain. If the athlete experiences any pain or excessive soreness, they are typically instructed to abstain from throwing until symptoms resolve and then resume the ITP at the last program stage that did not elicit any symptoms (i.e., one stage prior to the stage that elicited symptoms).[9] If, after regressing one stage in the ITP, the athlete continues to experience symptoms with throwing, extended breaks from throwing and more drastic regressions in the ITP may be employed.

TABLE 2. Interval throwing program for baseball players: phase 1*

45-Ft Phase	60-Ft Phase	90-Ft Phase	120-Ft Phase
Step 1: A) Warm-up throwing B) 45 ft, 25 throws C) Rest 5–10 min D) Warm-up throwing E) 45 ft, 25 throws	Step 3: A) Warm-up throwing B) 60 ft, 25 throws C) Rest 5–10 min D) Warm-up throwing E) 60 ft, 25 throws	Step 5: A) Warm-up throwing B) 90 ft, 25 throws C) Rest 5–10 min D) Warm-up throwing E) 90 ft, 25 throws	Step 7: A) Warm-up throwing B) 120 ft, 25 throws C) Rest 5–10 min D) Warm-up throwing E) 120 ft, 25 throws
Step 2: A) Warm-up throwing B) 45 ft, 25 throws C) Rest 5–10 min D) Warm-up throwing E) 45 ft, 25 throws F) Rest 5–10 min G) Warm-up throwing H) 45 ft, 25 throws	Step 4: A) Warm-up throwing B) 60 ft, 25 throws C) Rest 5–10 min D) Warm-up throwing E) 60 ft, 25 throws F) Rest 5–10 min G) Warm-up throwing H) 60 ft, 25 throws	Step 6: A) Warm-up throwing B) 90 ft, 25 throws C) Rest 5–10 min D) Warm-up throwing E) 90 ft, 25 throws F) Rest 5–10 min G) Warm-up throwing H) 90 ft, 25 throws	Step 8: A) Warm-up throwing B) 120 ft, 25 throws C) Rest 5–10 min D) Warm-up throwing E) 120 ft, 25 throws F) Rest 5–10 min G) Warm-up throwing H) 120 ft, 25 throws

150-Ft Phase	180-Ft Phase		
Step 9: A) Warm-up throwing B) 150 ft, 25 throws C) Rest 5–10 min D) Warm-up throwing E) 150 ft, 25 throws	Step 11: A) Warm-up throwing B) 180 ft, 25 throws C) Rest 5–10 min D) Warm-up throwing E) 180 ft, 25 throws	Step 13: A) Warm-up throwing B) 180 ft, 25 throws C) Rest 5–10 min D) Warm-up throwing E) 180 ft, 25 throws F) Rest 5–10 min G) Warm-up throwing H) 180 ft, 20 throws I) Rest 5–10 min J) Warm-up throwing K) 15 throws, progressing from 120 to 90 ft	Note: All throws should be on an arc with a crow hop. Warm-up throws consist of 10 to 20 throws at approximately 30 ft. Throwing program should be performed every other day, 3 times per week unless otherwise specified by a physician or rehabilitation specialist. Perform each step ______ times before progressing to next step.
Step 10: A) Warm-up throwing B) 150 ft, 25 throws C) Rest 5–10 min D) Warm-up throwing E) 150 ft, 25 throws F) Rest 5–10 min G) Warm-up throwing H) 150 ft, 25 throws	Step 12: A) Warm-up throwing B) 180 ft, 25 throws C) Rest 5–10 min D) Warm-up throwing E) 180 ft, 25 throws F) Rest 5–10 min G) Warm-up throwing H) 180 ft, 25 throws	Step 14: Return to respective position or progress to step 14 below.	

Flat-Ground Throwing for Baseball Pitchers	
Step 14: A) Warm-up throwing B) 60 ft, 10–15 throws C) 90 ft, 10 throws D) 120 ft, 10 throws E) 60 ft (flat-ground) using pitching mechanics, 20–30 throws	Step 15: A) Warm-up throwing B) 60 ft, 10–15 throws C) 90 ft, 10 throws D) 120 ft, 10 throws E) 60 ft (flat-ground) using pitching mechanics, 20–30 throws F) 60–90 ft, 10–15 throws G) 60 ft (flat-ground) using pitching mechanics, 20 throws
Progress to phase 2: throwing off the mound	

* 45 ft = 13.7 m; 60 ft = 18.3 m; 90 ft = 27.4 m; 120 ft = 36.6 m; 150 ft = 45.7 m; 180 ft = 54.8 m.

Figure 2.2: Sample Interval Throwing Program (adapted from Reinold et al.[68])

After long-toss criteria are reached, the athlete progresses to partial-effort pitching from flat ground (i.e., not off of a pitching mound). Just as in the long-toss portion of the ITP, the athlete completes a certain number of throws at various distances to warm up the arm. Once the athlete is ready, the throwing session concludes with a pre-determined number of sub-maximal pitches from a regulation pitching distance. Here, because throw distance is fixed during pitching, throwing intensity is manipulated rather than throw distance. ITPs typically increase the number of pitches performed at a given intensity level before increasing pitch intensity. This portion of the ITP is commonly referred to as the flat ground portion because the athlete does not perform any throws from an elevated pitching mound. Following the flat ground portion of the ITP the athlete proceeds to pitching from the pitching mound. As intensity increases, emphasis is placed on reproducing in-game pitching mechanics, re-establishing the athlete's "feel", and re-developing the athlete's other pitches.

The threshold distance for completing the long-toss portion of the ITP is typically 180 feet although many athletes prefer progressing to further distances to increase arm strength and endurance. The threshold for completing the flat ground portion varies depending on what is expected of the athlete during competition. For example, relief pitchers may achieve adequate volume at a lower number of pitches compared to starting pitchers. Regardless of the exact criteria for progressing through the ITP, the general framework of controlled and gradual increases in throw number, distance, or intensity monitored by reporting of soreness or pain holds true across all commonly implemented programs.

2.5 Subjective vs. objective measures of throwing intensity

Sports medicine professionals overseeing throwing rehabilitation take caution to not stress recovering tissues unnecessarily during the ITP protocol. Quantifying and monitoring throwing intensity is, therefore, critical to the success of the ITP and the rehabilitation program as a whole. Typically, athletes are instructed to subjectively control throwing intensity by throwing at certain levels of exertion (rating of perceived exertion (RPE)). While RPE is a simple and practical means of controlling throwing intensity, it requires the athlete to accurately gauge their own effort. Gauging ones own effort may be difficult in some cases, particularly for younger athletes who lack the throwing experience of older athletes and for those rehabilitating from more severe injuries where psychological hurdles such as guarding, hesitation, and fear of re-injury may influence RPE perception.[8,45] Recently, radar guns have been suggested as a means of monitoring throwing intensity to help increase the objectivity of ITPs.[51] Radar guns are most convenient when rehabilitation professionals have access to a pitcher's pre-injury maximum throwing speed. In this case, ITP throws can be prescribed as a percentage of this–presumably–healthy benchmark, or some other reference speed.

Recommendations to include objective measures of throwing intensity during the ITP stem from a growing body of research that indicates pitchers tend to over-exert themselves at sub-maximal intensities, producing disproportionately large joint loads.[32,51,61,73] The first examination showing disproportionately large joint loads at sub-maximal throwing intensities was done in 1996 by Fleisig et al.[32] They recorded the pitching mechanics of 27 healthy college baseball pitchers while pitching at 100%, 75%, and 50% RPE. Their results showed that, at 75% RPE, pitchers still produced 90% of their maximal pitch speed (73 miles per hour at 75% vs. 79 miles per hour at 100%) and experienced 84% of their maximal shoulder rotation torque (46 $N \cdot m$ at 75% vs. 55 $N \cdot m$ at 100%) and 81% of their maximal elbow valgus torque (44 $N \cdot m$ at 75% vs. 54 $N \cdot m$ at 100%). At 50% RPE pitchers still produced 86% of their maximum pitch speed and 76% of their maximum shoulder rotation and elbow valgus torques.

The pattern of smaller-than-expected decreases in joint loads for a given decrease in RPE shown by Fleisig et al has been echoed and extended to flat ground throwing in recent literature.[46,51,61,73] Slenker et al examined throwing mechanics during maximal effort pitching, sub-maximal effort pitching, and flat ground long-toss in 29 healthy collegiate baseball pitchers.[73] When pitching with 80% RPE, pitchers threw with 91% of their maximum pitch speed and experienced 82% and 94% of their maximum shoulder rotation torque and elbow valgus torque, respectively. At 60% RPE, pitch speed, shoulder rotation torque, and elbow valgus torque decreased to 85%, 78%, and 77% of their maximum effort values. When comparing flat ground long-toss throws at 18 m (60 ft), 27 m (90 ft), 37 m (120 ft), and 55 m (180 ft) to maximal effort pitching, pitchers experienced similar shoulder rotation and elbow valgus torques across all conditions. However, this was expected as pitchers were asked to make all flat ground throws at full effort. Lizzio,[51] and Melugin[61] also examined sub-maximal intensity throwing in high school and collegiate pitchers and found similarly disproportionate decreases in RPE and upper extremity joint loads. However, these studies collected data using a single inertial sensor and were restricted to only examining elbow valgus torque.

Recent research into the mechanics and demands of sub-maximal throwing has largely been limited to a few shoulder kinematic parameters and one elbow kinetic parameter extracted from one inertial sensor[46,51,61] and only two studies[32,73] have used full body motion capture to study sub-maximal throwing mechanics. Additional examination of sub-maximal throwing mechanics, throwing techniques, and comparison of subjective and objective measures of throwing intensity could assist the design, implementation, and modification of ITPs and increase the percentage of pitchers who are able to complete the rehabilitation process successfully.

3 Methods

3.1 Experimental Protocol

Participants reported to the laboratory prior to engaging in any strenuous physical activity on the day of testing. A verbal overview of all experimental procedures was given and written informed consent was obtained prior to any testing. In the case of underage participants, informed assent and parental consent was obtained. Following informed consent, participants performed their typical non-throwing dynamic warm up to prepare for full effort throwing. Non-throwing warm up modalities included jogging, sprinting, static and dynamic stretches, and resistance band exercises. Non-throwing warm up protocols were not standardized so that each participant could prepare in the manner and to the extent they needed to prepare for game effort throwing.[81] Once they indicated they were ready, participants performed their throwing warm up as if they were preparing to throw with game effort. Instruction to "perform as many throws as needed to prepare for game effort throwing" were standardized and given to all participants. Participants threw from flat ground towards a stationary 3.16 m^2 (1.78 m x 1.78 m square) target placed 45 ft away (Figure 3.1). Crow-hopping and leg kicks were not allowed to reduce the confounding effects of different lower body mechanics.

Figure 3.1: Motion Capture Camera Arrangement (image courtesy of Driveline Baseball)

Motion capture and throwing speed data were collected on as many trials as possible during the throwing warm up without interfering with the participant's natural warm up pace. Motion capture data were collected using a calibrated 3D motion capture system consisting of 17 Optitrak Pime17 cameras arranged symmetrically around the throwing volume (Section 3.2). Throwing speed data were collected using a calibrated radar gun. Three criteria constituted a good trial. First, all motion capture reflective markers must have remained affixed to the participant's skin for the entire duration of the throwing motion. Second, the radar gun must have registered the throwing speed. Third, the throw must have hit the stationary target. Failure to meet any one of these criteria resulted in an invalid trial which was discarded and not used in subsequent analyses.

3.2 Motion Capture Setup

Prior to throwing, participants were equipped with fifty reflective markers were attached bilaterally on the third distal phalanx, lateral and medial malleolus, calcaneus, tibia, lateral and medial femoral epicondyle, femur, anterior and posterior iliac spine, iliac crest, inferior angle of scapula, medial scapular spine, acromial joint, midpoint of the humerus, lateral and medial humeral epicondyle, midpoint of the ulna, radial styloid, ulnar styloid, distal end of index metacarpal, parietal bone, and frontal bone, as well as on the cervicothoracic (C7/T1) and thoracolumbar (T12/L1) vertebral junctions, the jugular notch, and the xiphoid process (Figures 3.2 and 3.3). Marker positions were collected at 360 Hz using an optical motion capture system (Natural Motion/Optitrak; Corvallis, Oregon, USA). Throwing speed was collected by a calibrated radar gun positioned behind the participant in line with the direction of the throw (Stalker Radar; Applied Concepts, Richardson, TX, USA).

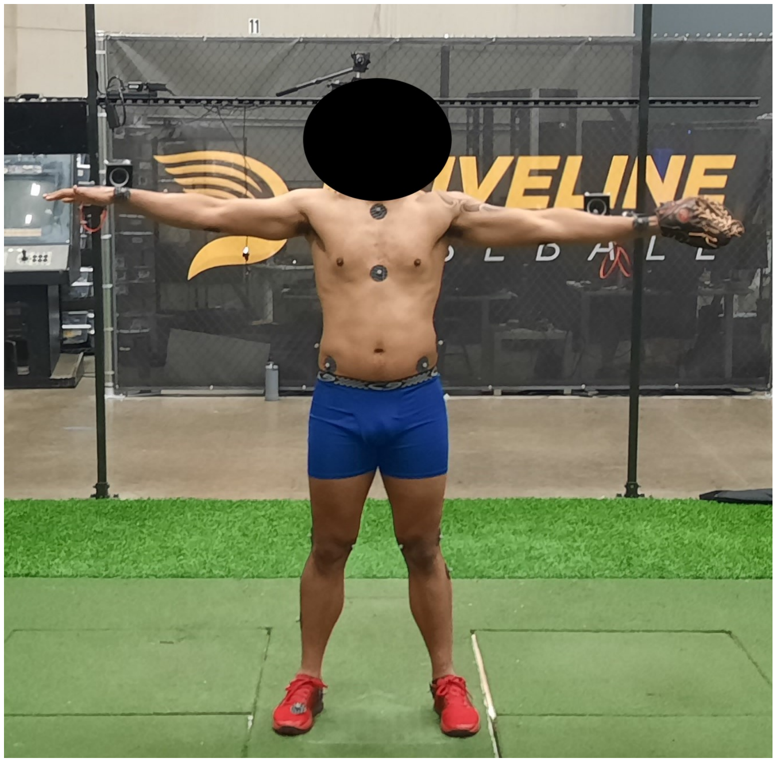

Figure 3.2: Reflective Marker Setup (Front) (image courtesy of Driveline Baseball)

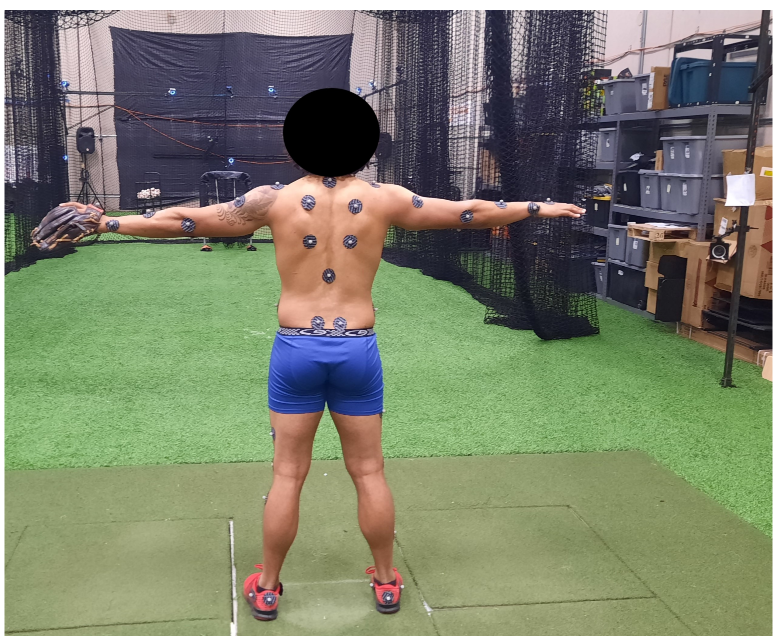

Figure 3.3: Reflective Marker Setup (Back) (image courtesy of Driveline Baseball)

3.3 Linked-segment biomechanical model

The linked-segment biomechanical model consisted of twelve segments: the bilateral shank (1-2), thigh (3-4), upper arm (5-6), and forearm (7-8) as well as the throwing hand (9), pelvis (10), lumbar spine (11), and thoracic spine (12). The bony landmarks and corresponding palpated anatomical location used for marker placement are presented in Table 3.1.

Bony Landmark	Palpated Anatomical Location
Pelvis	
Anterior Superior Iliac Spine	Most prominent aspect of the anterior superior iliac spines
Posterior Superior Iliac Spine	Most prominent aspect of the posterior superior iliac spines
Thorax	
C7	Most prominent aspect of the seventh cervical spinous process
Suprasternal Notch	Most superior aspect of the sternum
T12	Most prominent aspect of the twelfth thoracic spinous process
Xiphoid Process	Most inferior aspect of the sternum
Upper Arm	
Lateral Elbow	Most distal aspect of the lateral humeral epicondyle
Medial Elbow	Most distal aspect of the medial humeral epicondyle
Forearm	
Lateral Wrist	Most distal aspect of the radial styloid
Medial Wrist	Most distal aspect of the ulnar styloid
Hand	
First Knuckle	Most distal end of index metacarpal
Thigh	
Lateral Knee	Most distal aspect of the lateral femoral condyle
Medial Knee	Most distal aspect of the medial femoral condyle
Shank	
Lateral Ankle	Most distal aspect of the lateral malleolus
Medial Ankle	Most distal aspect of the medial malleolus

Table 3.1: Bony Landmarks and Digitized Bony Processes

Joint	Definition
Ankle	Midpoint between lateral and medial malleoli
Knee	Midpoint between lateral and medial femoral epicondyles
Hip	Bell method[12]
Lumbosacral junction	Midpoint between LASIS & RPSIS markers[12]
Thoracolumbar junction	Offset from thoracolumber marker position[19]
Cervicothoracic junction	Offset from cervicothoracic marker position[19]
Shoulder	Offset from acromial marker[56]
Elbow	Midpoint between lateral medial humeral epicondyles
Wrist	Midpoint between radial and ulnar styloids

Table 3.2: Joint Center Definitions

Joint centers for the ankles, knees, elbows, and wrists were defined as the midpoint between the lateral and medial segment endpoints.[94,95] Shoulder joint centers were estimated using established offsets from the acromial joint marker.[56] Hip and spinal column joint centers were estimated using established offsets from bony landmarks as described by Bell[12] and Chaffin.[19] Joint center definitions and supporting citations are presented in Table 3.2.

Local coordinate systems were defined for each segment in the model consistent with International Society of Biomechanics recommendations.[94,95] Euler angle rotation sequences that were used to describe joint motion are presented in Table 3.3.

Segment	Rotation Sequence	Anatomical Meaning
	Z	Anterior/Posterior tilt
Pelvis	X’	Left/right lateral rotation
	Y”	Left/right axial rotation
	Z	Flexion/Extension
Thorax	X’	Left/right lateral flexion
	Y”	Left/right axial rotation
	Y	Plane of elevation
Upper Arm	X’	Elevation/depression
	Y”	Internal/external axial rotation
	Z	Flexion/extension
Forearm	X’	Varus/valgus
	Y”	Pronation/supination

Table 3.3: Euler Angle Rotation Sequences

3.4 Data processing

Marker positions were filtered using a fourth-order Butterworth filter with a cutoff frequency of 15.2 Hz.[83,96] Since the focus of this study was on the shoulder and elbow, only data for the thorax, throwing arm humerus, and throwing arm forearm were extracted for analysis. Relevant linear and angular velocities as well as joint forces and torques were calculated in ***The MotionMonitor*** (Section 3.5.1) and then exported for further processing in MATLAB (2020a; Mathworks Corp., Natick, MA, USA) to calculate energy flow across the shoulder and elbow (Section 3.5.2).

Four events were identified in each throwing trial consistent with previously published overhead throwing research.[29,60,81] The first event was SFC which was defined as the first frame in which the contralateral ankle joint center linear velocity was less than 1.5 $m \cdot s^{-1}$ in the global reference frame.[60] Throwing shoulder MER and MIR were identified as the local minimum and maximum (for right-handed throwers) or the local maximum and minimum (for left-handed throwers) of the humeral Y” rotation relative to the thorax (Table 3.3).[95] BR was defined to be coincident with maximal hand angular velocity in the global reference frame.[64]

3.5 Calculations

Below are the kinematic, kinetic, and energetic calculations that were performed in this project. Throughout, the subscripts p and d refer to proximal and distal, respectively. The meaning of other symbols can be found in the symbol glossary.

3.5.1 Upper Extremity Kinetics

Joint forces and torques for shoulder and elbow were estimated in a linked chain model using top-down inverse dynamics equations as described by Gagnon and Gagnon.[33] The general equations of motion are outlined below. This process, starting the hand, was repeated to calculate the forces and torques at the wrist, elbow, and shoulder.

The sum of all force vectors acting on segment n equals the product of the segment's mass and its linear acceleration vector:

$$\sum \vec{F} = m\vec{a} \tag{1}$$

The expansion of Equation 1 yields the following three scalar equations to solve for the spatial translational equilibrium of the n^{th} segment:

$$F_{px} + F_{dx} = ma_x \tag{2}$$

$$F_{py} + F_{dy} - mg = ma_y \tag{3}$$

$$F_{pz} + F_{dz} = ma_z \tag{4}$$

The sum of all the torque vectors about the n^{th} segment's center of mass equals the rate of change of the angular momentum vector of the segment.

$$\sum \vec{\tau} = \dot{\vec{H}} \tag{5}$$

The expansion of Equation 5 yields the following three scalar equations to solve for the spatial rotational equilibrium of the n^{th} segment:

$$\tau_{px} + \tau_{dx} + r_{py}F_{pz} - r_{pz}F_{py} + r_{dy}F_{dz} - r_{dz}F_{dy} = I_x\alpha_x - (I_y - I_z)\omega_y\omega_z \tag{6}$$

$$\tau_{py} + \tau_{dy} + r_{pz}F_{px} - r_{px}F_{pz} + r_{dz}F_{dx} - r_{dx}F_{dz} = I_y\alpha_y - (I_z - I_x)\omega_z\omega_x \tag{7}$$

$$\tau_{pz} + \tau_{dz} + r_{px}F_{py} - r_{py}F_{px} + r_{dx}F_{dy} - r_{dy}F_{dx} = I_z\alpha_z - (I_x - I_y)\omega_x\omega_y \tag{8}$$

The solutions to Equations 2-8 were obtained by sequentially solving for the unknown forces and torques for each axis at each time sample. Once solved, the proximal net forces and torques on the n^{th} segment became the distal reaction components of the $(n+1)^{th}$ segment. Net force and torque vectors were then be transformed from the global coordinate system to the local coordinate system using the appropriate 3D segment rotation matrix (Equation 10).

$$\begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = \mathbf{R} \begin{bmatrix} \tau_X \\ \tau_Y \\ \tau_Z \end{bmatrix} \tag{9}$$

where x, y, z correspond to the components of the net joint torque about the orthogonal local coordinate system basis vectors, X, Y, Z correspond to the components of the net joint torque about the global coordinate system basis vectors, and $\mathbf{R}$ is the $3x3$ rotation matrix relating the basis vectors of the global and local coordinate systems (Equation 10).[33, 92]

$$\mathbf{R} = \begin{bmatrix} r_{x.x} & r_{y.x} & r_{z.x} \\ r_{x.y} & r_{y.y} & r_{z.y} \\ r_{x.z} & r_{y.z} & r_{z.z} \end{bmatrix} \tag{10}$$

Elbow varus torque (EVT) was defined as the torque exerted by the upper arm on forearm about the forearm anteroposterior axis.[25] Shoulder rotation torque (SRT) was defined as the torque exerted by the thorax on the upper arm about the upper arm longitudinal axis.[4] Upper extremity torques for left-handed pitchers were scaled by -1 to simplify analysis.[83] Normative anthropometric values were taken from Zatsiorsky.[97] All kinetic calculations were conducted in ***The MotionMonitor*** software.

3.5.2 Segment Powers

Power is the rate at which work is performed. Instantaneous power was calculated at each end point for each segment in the kinetic chain.[69, 92] Joint force power (JFP) quantified the rate of work performed on (or performed by) a segment at its endpoint via its net joint force and was equal to the dot product of the net joint force and the joint linear velocity vectors (Equation 11). Positive JFP values indicated energy entering (or work being done on) the segment via its joint force. Negative JFP values indicated energy leaving (or work being done by) the segment via its joint force. Likewise, segment torque power (STP) quantified the rate of work performed on (or performed by) a segment at its endpoint via its net joint torque and was equal to the dot product of the net joint torque and the segment angular velocity vectors (Equation 12). Positive STP values indicated energy entering (or work being done on) the segment via its joint torque. Negative STP values indicated energy leaving (or work being done by) the segment via its joint torque.

$$JFP = \vec{F} \cdot \vec{v} \tag{11}$$

$$STP = \vec{\tau} \cdot \vec{\omega} \tag{12}$$

where $\vec{F}$, $\vec{v}$, $\vec{\tau}$, and $\vec{\omega}$ are in the global reference frame.

A segment's instantaneous power (hereafter referred to simply as *segment power*; SP) equaled the sum of the instantaneous powers at its end points. For a segment with a proximal and distal endpoint (i.e., two endpoints):

$$SP = JFP_p + JFP_d + STP_p + STP_d \tag{13}$$

Alternatively, proximal and distal JFPs and STPs may be summed separately to isolate the segment's endpoint powers.

$$SP_p = JFP_p + STP_p \tag{14}$$

$$SP_d = JFP_d + STP_d \tag{15}$$

For segments typically modeled with more than two endpoints, such as the thorax or pelvis, Equation 13 was generalized to segments with n endpoints:

$$SP = \sum_{i=1}^{n} JFP_i + STP_i \tag{16}$$

3.5.3 Energy generation, absorption, and transfer across joints

Equation 16 is theoretically equivalent to taking the time derivative of the segment's mechanical energy. However, two benefits of calculating segment powers from the net joint forces and torques instead of from the segment's mechanical energy time derivative is that it allows differentiation of segment endpoint powers (Equations 14 and 15) and partitioning of energy flow into energy generation, absorption, and transfer across the segment's joints (Table 3.4).[69, 83, 92] Together, these benefits provide deeper insight into the direction and mode of energy flow through the kinetic chain, potentially increasing the value of throwing biomechanics research.

If no joint translation is assumed, JFPs only transfer (redistribute) energy between body segments.[69, 92] JFPs are limited to energy transfer because adjoining segments share the linear velocity of their common joint center and the net force acting on each segment is equal and opposite by Newton's third law. Therefore, adjacent JFPs will also be equal and opposite and no additional energy generation or absorption can take place. Unlike JFPs, STPs are not necessarily equal and opposite due to differing angular velocities of adjacent segments. Therefore, depending on their sign and magnitude, STPs can indicate additional energy generation or absorption by the structures surrounding the joint (Table 3.4).

	Generation	Absorption	Transfer
Same Sign			
Both +	STP_p TO proximal segment STP_d TO distal segment	0	0
Both -	0	STP_p FROM proximal segment STP_d FROM distal segment	0
Opposite Sign $\lvert STP_p\rvert > \lvert STP_d\rvert$			
STP_p + STP_d -	$STP_p + STP_d$ TO proximal segment	0	STP_d TO proximal segment
STP_p - STP_d + $\lvert STP_d\rvert > \lvert STP_p\rvert$	0	$STP_p + STP_d$ FROM proximal segment	STP_d TO distal segment
STP_p + STP_d -	0	$STP_p + STP_d$ FROM distal segment	STP_p TO proximal segment
STP_p - STP_d +	$STP_p + STP_d$ TO distal segment	0	STP_p TO distal segment

Table 3.4: Partitioning of Energy Flow via STP (adapted from Robertson et al[69]). STP_p = proximal segment torque power. STP_d = distal segment torque power

JFP and STP time series were exported from ***The MotionMonitor*** into MATLAB for further partitioning into energy generation, absorption and transfer.[83] At each instant in time, the proximal upper arm JFP represented the rate of energy transfer across the shoulder by the shoulder joint force. Positive proximal upper arm JFP values represented distal energy transfer across the shoulder from the thorax to the upper arm. Negative upper arm JFP values represented proximal energy transfer across the shoulder from the upper arm to the thorax. Likewise, the proximal forearm JFP represented the rate of energy transfer across the elbow by the elbow joint force with positive and negative values indicating distal and proximal energy transfer, respectively.

Depending on their signs and magnitudes, the rate of energy flow across the shoulder and elbow via adjacent STPs were partitioned into a mixture of generation, absorption, or transfer as described by Robertson and Winter (Table 3.4; Section 8). The first step in separating energy flow via STP was to consider the sign of adjacent STPs (STP_p and STP_d, respectively). If both STP_p and STP_d have the same sign (i.e., both are positive or negative) then only energy generation (if positive) or absorption (if negative) took place and there was no energy transfer. When both STPs are positive the structures surrounding the joint were generating energy to both segments and their mechanical energies were both increasing. When both STPs are negative, the structures surrounding the joint were absorbing energy from both segments and their mechanical energies were both decreasing. More often, adjacent STPs had opposite signs (i.e., one was positive, and one was negative). In this case, the next step was to consider their absolute values. The STP of smaller absolute value quantified the rate of energy transfer across the joint and its sign indicated the direction of transfer across the joint. STP_p and STP_d were then added together to quantify the remaining power that was either absorbed or generated across the joint with the sign again differentiating between generation or absorption. For an example of partitioning energy flow via STP from Winter,[92] please see Section 9.

Net rate of energy transfer (hereafter referred to simply as *rate of energy transfer*) across the shoulder and elbow was defined as the sum of the energy transfer via JFP and STP ($trans_{jfp}$ and $trans_{stp}$, respectively). Isolation of energy transfer across the shoulder and elbow resulted in new time-series data which were then analyzed during the throwing motion. Shoulder energy transfer (SET) and Elbow energy transfer (EET) were defined as the total amounts of energy transfer (in Joules) across the shoulder and elbow during the arm cocking phase ($trans_{total}$) and were estimated by integrating the rate of energy transfer curves between SFC and MER:

$$trans_{total} = \int_{t_1}^{t_2} (trans_{JFP} + trans_{STP}) \tag{17}$$

3.6 Statistical Analysis

The statistical approach of this project was centered around hierarchical data (throws within participants) and multilevel modeling. Despite their popularity in the political and educational sciences, multilevel models have received less attention in the sport biomechanics literature. Because of the scarcity of multilevel modeling in overhead throwing research, a brief introduction to the topic and its potential benefits to biomechanics research is given below. For more thorough coverage of multilevel modeling, readers are directed to Introducing Multilevel Modeling by Kreft[44] and Multilevel Analysis: Techniques and Applications by Hox.[38]

3.6.1 The Assumption of Observational Independence

Standard statistical techniques such as analysis of variance (ANOVA), ordinary least-squares regression, or even the simple *t*-test rely on the assumption that individual observations are independent. In biomechanics, this is not the case if more than one trial from each participant is analyzed since trials from the same participant will tend to be more closely associated than trials from different participants (commonly known as the *intra-class correlation* or *cluster correlation*). This causes the biomechanist to either 1) only analyze one trial from each participant or 2) aggregate multiple trials into one *representative* trial for each participant (i.e., ensemble average). Option 1 throws away the majority of collected data, resulting in wasted time and resources. Option 2 removes intra-participant variability which, if left intact, could be modeled to provide richer insight. There is a third option of using all trials from each participant and treating them as independent; however, this constitutes a grave error because it ignores the implicit hierarchical structure of the data. Option 3 overestimates the true sample size and, consequently, underestimates model standard errors. Underestimated standard errors inflate test statistics and increase the risk of erroneously rejecting null hypotheses, potentially leading to inappropriate conclusions. Barcikowski illustrated the consequences of not accounting for hierarchical data structures, particularly when the number of samples within a cluster is large. Through traditional ANOVA simulation using 100 samples per cluster, a significance level of .05, and an intra-class correlation of .01, he showed an increase in false positive rate from 5% to 17%. With an intra-class correlation of .20, a sample size of 10 per cluster increased the false positive rate to .28.[11]

One way to combat inflated false positive rates, reduce the amount of discarded data, and avoid removing intra-participant variability is to use multilevel modeling techniques. Under the multilevel framework, the data's hierarchical structure is accounted for and fewer statistical constraints are made. These differences allow the multilevel model to handle partially missing data and unbalanced designs, incorporate time-variant or time-invariant covariates to model conditional outcomes, and deal with nonlinear relationships between predictor and explanatory variables.[38]

3.6.2 Multilevel Models for Repeated Measures

Multilevel models in the political or educational sciences typically contain individuals at the lowest level grouped within second level social contexts such as congressional districts or schools. More relevant to the biomechanist is the multilevel model that places individuals at the second level and repeated measures from each individual at the lowest level, equating the multilevel model to traditional repeated measures ANOVA. This makes the multilevel framework well suited for examining inter-individual variability in intra-individual patterns of change over time, particularly in cases where theorized relationships are nonlinear and when experimental conditions result in partially missing data or unbalanced designs.[22] Modeling inter and intra-individual patterns of change over time is sometimes referred to as *multilevel growth modeling* or *growth curve modeling*.[34] Growth models can be used to assess acute change within a single data collection session, as it will be used in this project, or chronic change over many sessions in more traditional longitudinal designs.

3.6.3 Model Notation

In traditional regression, a predicted outcome, $\hat{y}$, is modeled as a function of an intercept, β_0, an explanatory variable, x_1, and some residual error, ϵ:

$$\hat{y} = \beta_0 + \beta_1 x_1 + \epsilon \tag{18}$$

In the multilevel model with repeated measures at the lowest level and individuals at the second level, a separate regression equation for each individual can be constructed as follows:

$$\hat{y}_{ij} = \beta_{0j} + \beta_{1j} x_{1ij} + \epsilon_{ij} \tag{19}$$

In Equation 19, β_{0j} is the intercept, β_{1j} is the regression coefficient (slope) for explanatory variable x_1, and ϵ_{ij} is the residual error. The subscript j differentiates between second level elements (individuals) and the subscript i differentiates between first level elements (repeated measures). For example, $\hat{y}_{ij}$ can be described as *"the predicted outcome of trial i from individual j"*. Like traditional regression, β_{0j} represents the predicted outcome for individual j when x_1 equals zero and β_{1j} can be thought of as the estimated increase in $\hat{y}$ for a one unit increase in x for individual j.

The introduction of the i and j subscripts represents the difference between traditional and multilevel regression: that individuals can be modeled to have different intercepts, slope(s), or both. When we allow model coefficients to vary between individuals (or whatever grouping structure is used at the second level), we refer to them as *random* coefficients. If we allow only some of the intercept and slope(s) to vary and constrain others to be equal between individuals, we refer to the constrained coefficients as *fixed* coefficients. The next step in the multilevel framework is to (attempt to) explain variation in the coefficients from Equation 19 by introducing a second level explanatory variable, z. This can be done for the model intercept (β_{0j}), slope (β_{1j}), or both:

$$\beta_{0j} = \gamma_{00} + \gamma_{01} z_j + \mu_{0j} \tag{20}$$

$$\beta_{1j} = \gamma_{10} + \gamma_{11} z_j + \mu_{1j} \tag{21}$$

Just as with Equation 19, the right sides of Equations 20 and 21 each contain three terms with the first representing the respective model intercept, γ_{00} or γ_{10}, the second representing a second level explanatory variable, z_j, and its corresponding slope, γ_{01} or γ_{11}, and the third representing residual variance in the intercept (μ_{0j}) and slope (μ_{1j}). Level one random coefficients are assumed to be multivariate normal with means, γ, and (co)variances, τ:

$$\begin{bmatrix} \beta_{0j} \\ \beta_{1j} \end{bmatrix} \sim N(\begin{bmatrix} \gamma_{00} \\ \gamma_{10} \end{bmatrix}, \begin{bmatrix} \tau_{00} & \tau_{01} \\ \tau_{10} & \tau_{11} \end{bmatrix}) \tag{22}$$

Equations 20 and 21 can then be substituted in place of the coefficients in Equation 19 to obtain the full multilevel model:

$$\hat{y}_{ij} = \overbrace{\gamma_{00} + \gamma_{01} z_j + \mu_{0j}}^{\beta_{0j}} + \overbrace{(\gamma_{10} + \gamma_{11} z_j + \mu_{1j})}^{\beta_{1j}} x_{1ij} + \epsilon_{ij} \tag{23}$$

Finally, we distribute x_{1ij} and arrange like terms to delineate the fixed and random parts of the model:

$$\hat{y}_{ij} = \overbrace{\gamma_{00} + \gamma_{01} z_j + \gamma_{10} x_{ij} + \gamma_{11} x_{ij} z_j}^{fixed} + \overbrace{\mu_{1j} x_{ij} + \mu_{0j} + \epsilon_{ij}}^{random} \tag{24}$$

Equation 24 combines Equations 19, 20, and 21 and concisely represents in one equation a multilevel model with one level one explanatory variable and one level two explanatory variable accounting for variance in the model intercept and slope. If a level two explanatory variable is only used to account for variance in model slope and variance in model intercept is of no concern (as will be the case in Specific Aim 2) then the final equation becomes:

$$\hat{y}_{ij} = \overbrace{\gamma_{00} + \gamma_{10}x_{ij} + \gamma_{11}x_{ij}z_j}^{fixed} + \overbrace{\mu_{1j}x_{ij} + \mu_{0j} + \epsilon_{ij}}^{random} \tag{25}$$

Equation 25 contains three fixed effects: the overall model intercept (γ_{00}), the overall model slope (γ_{10}), and the overall cross-level interaction effect between x_{ij} and z_j (γ_{11}). Equation 25 also contains three random effects: the residual slope variance ($\mu_{1j}x_{1ij}$), the residual intercept variance (μ_{0j}), and the residual level-1 variance (ϵ_{ij})

3.6.4 Modeling Throwing Speed as a Function of Throwing Arm Joint Loads

Specific Aim 1 addressed the intra-individual relationship between throwing mechanics and throwing speed. Of particular interest was whether the functional form of this relationship was linear or nonlinear. For $RQ_{1.1}$ and $RQ_{1.2}$, the explanatory variables were the varus torque at the elbow and the rotation torque at the shoulder. For $RQ_{1.3}$ and $RQ_{1.4}$, the explanatory variables were thorax-to-upper arm energy transfer and upper arm-to-forearm energy transfer. These four measures consisted of two traditional measures of throwing arm joint loads (elbow varus and shoulder rotation torques) and two less frequently examined joint load measures (total energy transfer across the shoulder and elbow). These measures were chosen because of their relevance to the health of the UCL, glenoid labrum, and rotator cuff musculature; often injured anatomical structures surrounding the shoulder and elbow.

To test whether the relationship between throwing arm joint loading and throwing speed is nonlinear a hypothesis test was constructed comparing a linear model predicting throwing speed from throwing arm joint loads to a quadratic model doing the same.[34] The null hypothesis was that the linear model fit the data *at least as well* as the quadratic model (i.e. that no model fit improvement would be observed when introducing the quadratic term). In Specific Aim 1, the model intercepts were allowed to vary between participants, but the model slopes were not. Random slopes and cross-level interactions will be addressed in Specific Aim 2.

$$M_r : \hat{y}_{ij} = \beta_{0j} + \beta_1 x_{ij} + \epsilon_{ij} \tag{26}$$

$$M_a : \hat{y}_{ij} = \beta_{0j} + \beta_1 x_{ij} + \beta_2 x_{ij}^2 + \epsilon_{ij} \tag{27}$$

or, in words…

$$M_r : throw\hat{s}peed_{ij} = intercept_{0j} + slope_1 * torque_{ij} + error_{ij} \tag{28}$$

$$M_a : throw\hat{s}peed_{ij} = intercept_{0j} + slope_1 * torque_{ij} + slope_2 * torque_{ij}^2 + error_{ij} \tag{29}$$

Some texts refer to the simpler model as the *restricted* model (M_r) and to the more complex model as the *alternative model* (M_a). Because M_r is nested within M_a, they can be compared using the likelihood ratio test which compares model deviances.[34] The difference in deviances between two nested models follows a Chi-squared (χ^2) distribution with degrees of freedom equal to the number of additional parameters in M_a.[38] Because M_a contains only one additional parameter (the quadratic term) the significance test for $RQ_{1.1}$ and $RQ_{1.2}$ will be a χ^2 test with one degree of freedom ($\chi^2_{crit} = 3.841$). A statistically significant χ^2 test (i.e., $\chi^2_{obs} > \chi^2_{crit}$) rejects the null hypothesis that relationship between throwing arm joint loads and throwing speed is linear and provides evidence for including the quadratic term. $RQ_{1.3}$ and $RQ_{1.4}$ followed the same format with energy flow across the shoulder and elbow in place of elbow varus torque and shoulder rotation torque.

Because separate models were constructed for each of the four dependent variables in Specific Aim 1, the Holmes-Šidák correction for multiple comparisons was used to control familywise error rate (FWE).[42, 52, 82] To perform the Holmes-Šidák procedure an iterative correction was applied to each p-value obtained from the original statistical test, starting with the smallest p-value. For a study with n comparisons, the original p-value is adjusted such that: $p' = 1 - (1 - p)^n$. The formula then proceeds to next smallest p-value which is adjusted such that $p' = 1 - (1 - p)^{n-1}$. The exponential term reduces by 1 for each test until the correction results in a non-significant result at the original α level, at which point the procedure stops.

Specific Aim 2 addressed inter-individual differences in the relationship between throwing arm joint loads and throwing speed established in Specific Aim 1. Of particular interest were the differences between harder and slower throwers, taller and shorter throwers, and heavier and lighter throwers. To examine these differences, the participant-level explanatory variables maximum throwing speed, participant height, and participant weight were introduced to the models. In the first part of $RQ_{2.1}$ through $RQ_{2.4}$, the instantaneous rate of change in joint load (linear term slope) was allowed to vary between individuals. In the second part of $RQ_{2.1}$ through $RQ_{2.4}$, a cross-level interaction between participant-level explanatory variables and the linear term slope was introduced. A summary of statistical tests for Specific Aims 1 and 2 can be found in Table 3.5.

RQ	Purpose	DV(s)	IV(s)	Event/Phase	M_r	M_a
1.1 1.2 1.3 1.4	model intra-participant growth trajectories	throwing speed	elbow varus torque shoulder rotation torque	peak btwn FC and BR	$\beta_{0j} + \beta_1 x_{ij}$ $(1\|ID)$	$M_r + \beta_2 x_{ij}^2$
			thorax-upper arm energy transfer upper arm-forearm energy transfer	total btwn FC and BR		
2.1 2.2 2.3 2.4	model inter-participant growth differences	same as 1.1-1.4	max speed height weight	same as 1.1-1.4	final models from 1.1-1.4	$M_r + (\beta_{1j}\|ID)$ $M_r + (\beta_{1j}\|IV)$

Table 3.5: Summary of Statistical Tests. BR = ball release; FC = foot contact; ID = participant; IV = independent variable

3.6.5 Power Analysis

Statistical power is the likelihood of rejecting a false null hypothesis and is dependent on numerous situation-specific factors such as sample size, effect size, and measurement reliability.[14, 59] Also of note in multilevel designs is the intraclass-correlation, which quantifies the proportion of total outcome variance is explained by the hierarchical structure of the data. Low intra-class correlations indicate much of the outcome variance resides at the intra-participant level. Conversely, a high intra-class correlation indicates most of the variability in the outcome resides at the inter-participant level.

Statistical power in multilevel designs is most readily estimated through data simulation where the appropriate effect sizes, sample sizes, parameter estimates, and variable (co)variances are used to simulate data to which the multilevel model is fit.[59] This process is then repeated many times, each time simulating new data and seeing whether the model detects the effect of interest. Power is then defined as the proportion of models that detect the true effect correctly. When previous research does not provide appropriate values necessary for simulation, a pilot study is often necessary to obtain rough estimates of all necessary parameters. The power analysis for this study was, therefore, based off simulation from a pilot study of healthy and active overhead throwing athletes.

3.6.6 Power Analysis Results

Six skilled throwing athletes who were active and healthy at the time of data collection participated in the pilot study. Participants performed between 25 and 30 throws using the previously outlined protocol of gradual, self-directed increases in throwing intensity. Self-directed throwing resulted in joint load growth curves wherein the stresses experienced by the throwing arm gradually increased as throwing speed increased. Figures 3.4 and 3.5 show the progression in shoulder rotation torque for each of the six pilot study participants. Elbow varus torque progressed in a similar manner but is not visualized here for brevity.

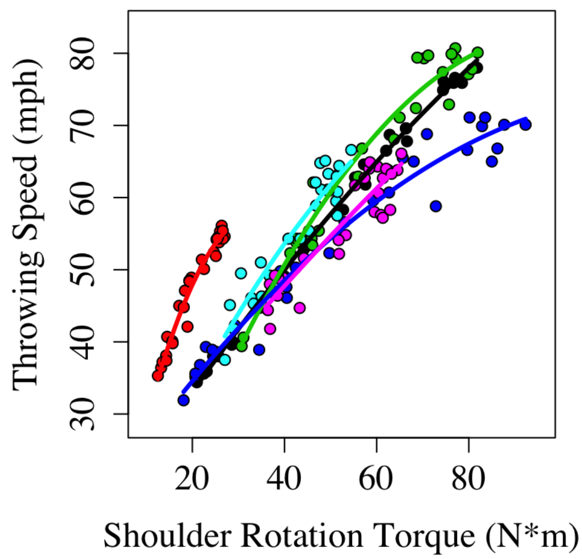

Figure 3.4: Pilot Study Joint Load vs. Throwing Speed Growth Curves

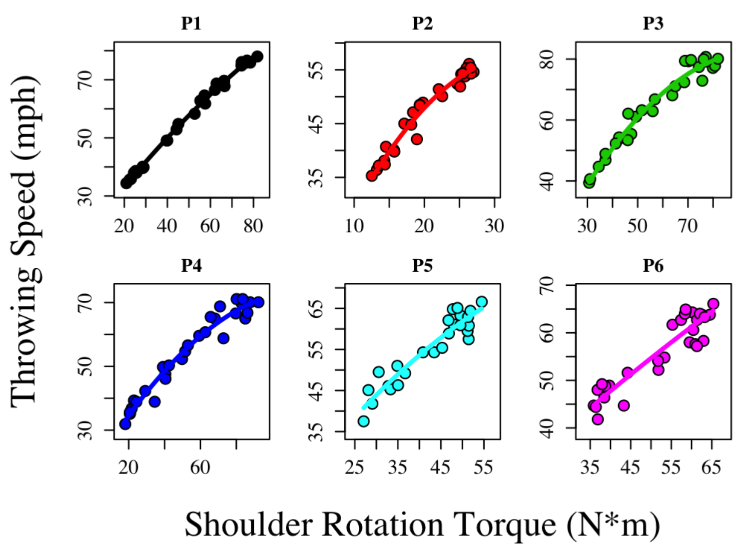

Figure 3.5: Pilot Study Joint Load vs. Throwing Speed Growth Curves

Pilot study results demonstrated that introduction of the quadratic term improved model fit statistics and reduced unexplained variance at both the intra and inter-participant levels, providing evidence in favor of its inclusion in the model (Table 3.6). Because of the large magnitude that comes with squaring joint torques, model result tables are extended to three digits. Isolation of the quadratic term revealed an effect of -0.006 ± 0.001 (Table 3.6). This effect size was then input into our power simulation to determine how our ability to detect a quadratic effect of that magnitude varied as a function of level one and level two sample sizes (Figure 3.6).

	Linear	Quadratic
Intercept	24.920 (2.326)***	12.329 (3.278)***
SRT	0.667 (0.017)***	1.244 (0.083)***
SRT^2		-0.006 (0.001)***
AIC	963.231	935.042
BIC	975.844	950.808
Log Likelihood	-477.615	-462.521
Num. obs.	173	173
Num. groups: pid	6	6
Var: pid (Intercept)	28.357	42.185
Var: Residual	12.594	9.686

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

Table 3.6: Comparison of linear and quadratic regression models. AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; SRT = Shoulder Rotation Torque

Approximately 35 participants each throwing between 30 and 40 throws were needed to obtain ~0.80 power to detect an effect of similar size to the one observed in our pilot data.

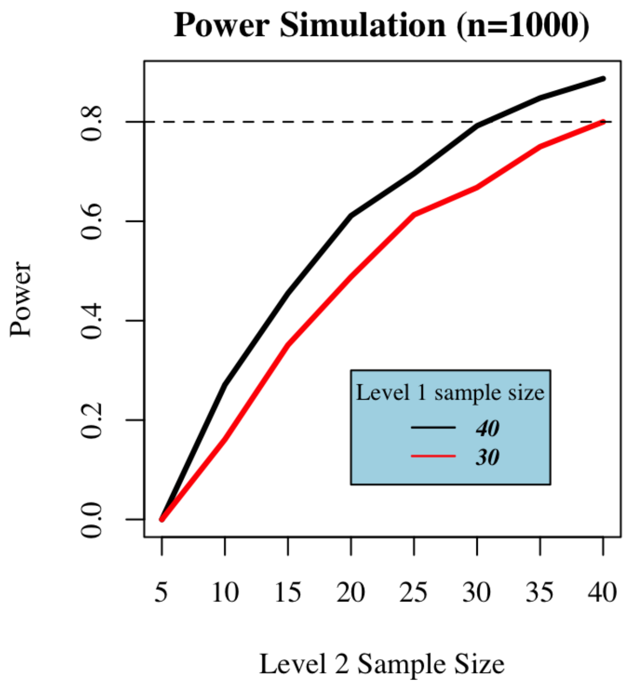

Figure 3.6: Pilot Study Power Simulation

4 Results

4.1 Descriptive Data

Thirty-six skilled throwing athletes were recruited to participate in the study. Thirty-two participants met all inclusion criteria and were included for final analysis. The mean age, height, and weight of participants who met all inclusion criteria were 21 ± 2 yrs (range: 14 - 25), 1.86 ± 0.08 meters (range: 1.68 - 2.03), and 89.0 ± 10.2 kg (range: 61.9 - 107.1). The other four participants failed to meet the age range criteria and were excluded.

On average, participants performed 36 throws. The minimum number of throws performed by any participant was 20, while the maximum number of throws performed was 52 (Figure 4.1). Twenty-two out of thirty-two participants achieved a maximum throwing speed between 75 and 85 mph (33.5 - 38.0 m/s). The fastest maximum throwing speed was 85.6 mph while the slowest was 65.8 mph (Figure 4.2). In total, 1,152 throws were included for analysis. Of those 1,152 throws, nine were removed prior to model comparison due to missing data. Of the nine throws missing data, six throws were missing throw speed data and three throws were missing biomechanical data. Missing throw speed data were due to investigators forgetting to turn on the radar gun prior to the start of data collection or occasional misreads from the radar gun itself. Missing biomechanical data were primarily due to markers falling off resulting in being unable to perform inverse dynamics calculations. After removing trials with missing data, the final sample size was 1,143 throws from 32 participants.

The mean peak elbow varus torque was 59.4 Nm and the mean peak shoulder rotation torque was 68.8 Nm. Expressed as a percent of participants' bodyweight*height, the mean peak elbow varus torque was 3.7% while the mean peak shoulder rotation torque was 4.2%. On average, participants transferred a maximum of 238 Joules of energy from their thorax to their humerus and 175 Joules of energy from their humerus to their forearm during the arm cocking phase of the throwing motion. Expressed as Joules of energy per kilogram of body mass, on average participants transferred a maximum 2.66 J/kg from their thorax to their humerus and 1.96 J/kg from their humerus to their forearm.

4.2 The Null Model

	Mass	Height	Throw Speed	EVT	SRT	SET	EET	$\bar{X}$	SD
Mass	-	-	-	-	-	-	-	89	10.2
Height	0.767	-	-	-	-	-	-	1.9	0.1
Throw Speed	0.046	0.129	-	-	-	-	-	63.1	13.3
EVT	0.342	0.307	0.868	-	-	-	-	386.1	162.5
SRT	0.364	0.342	0.830	0.917	-	-	-	457.9	188.2
SET	0.297	0.327	0.902	0.861	0.784	-	-	1597.1	697.3
EET	0.285	0.314	0.909	0.858	0.786	0.984	-	1178.8	485.3

All correlations based on a sample size of 1,143 throws. EET = Elbow Energy Transfer; EVT = Elbow Varus Torque; SET = Shoulder Energy Transfer; SRT = Shoulder Rotation Torque. Table generated using TexReg[47]

Table 4.1: Data Correlation Matrix

To quantify the proportion of outcome variance accounted for by the nested nature of the data (i.e. throws nested within participants) and to provide a baseline fit to which models from Specific Aims 1 and 2 can be compared, a null model (sometimes known as an *intercept-only model*)[38] was constructed. For this study, the null model predicted the throw speed for any given trial from only each participant's average throw speed across all trials (`throw speed ~ 1 + (1|pID)`). The null model revealed approximately 12% ($\frac{s^2(\beta_0)}{s^2(\beta_0)+s^2(e)}$) of the total outcome variance was accounted for by the nested nature of the data, providing evidence in favor of the multilevel approach to the research questions. Detailed null model results may be found in Table 4.2.

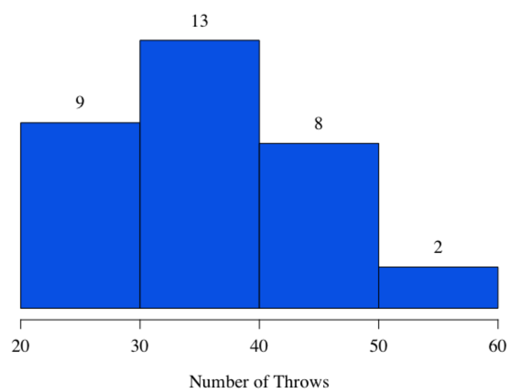

Figure 4.1: Throw Counts by Participant

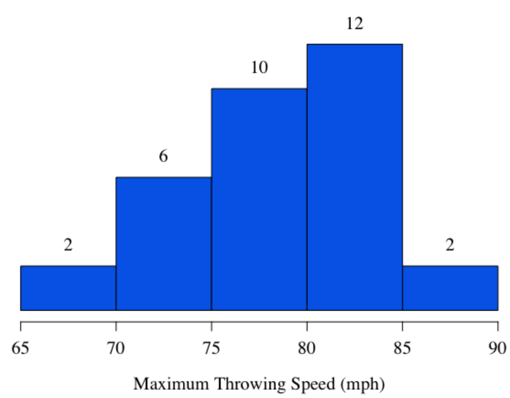

Figure 4.2: Maximum Throwing Speed by Participant

	Null
Intercept	63.085 (0.897)***
AIC	9075.196
BIC	9090.320
Log Likelihood	-4534.598
N_{throws}	1143
$N_{subjects}$	32
$s^2(\beta_0)$	21.194
$s^2(e)$	155.653

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$. AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion. Table generated using TexReg[47]

Table 4.2: Null Model

4.3 Specific Aim 1

Specific Aim 1 sought to model the intra-participant relationship between throwing mechanics and throw speed as participants progressed from low effort to high effort throwing. The main hypothesis for Specific Aim 1 was that the intra-participant relationship between throwing mechanics and throw speed was nonlinear in form. This hypothesis was tested using a model comparison approach where a linear model predicting throw speed from throwing mechanics was compared to a quadratic model doing the same. Equations 28 and 29 specified the linear and quadratic models, respectively. Because the linear model is nested within the quadratic model, model comparison was performed using a Chi-Squared test on the difference in model deviances with degrees of freedom equal to the number of additional parameters in the quadratic model (1). This comparison process was repeated four times: twice for traditional measures of throwing arm joint loading commonly found in the literature (EVT and SRT) and twice for the total amounts of energy transferred across the shoulder and elbow during the arm cocking phase of the throwing motion (EET and SET).

In all four models, inclusion of a quadratic term significantly improved model fit (Table 4.3). With respect to model accuracy, inclusion of a quadratic term improved EVT model root mean squared error (RMSE) from 3.5 mph to 2.5 mph. Similar improvements in RMSE were observed for the other models (SRT: 4.0 mph to 2.3 mph; EET: 3.3 mph to 2.4 mph; SET: 3.2 mph to 2.1 mph). Detailed model comparison results are found in Tables 7.1 through 7.4. Model fit improvements are visualized in the scatter plots with model fixed effects regression lines (Figures 4.3 through 4.6).

	Deviance	χ^2	*df*	p	p'
RQ 1.1 (EVT)					
Linear	6313	-	-	-	-
Quadratic	5502	811	1	2.32e-178	2.32e-178
RQ 1.2 (SRT)					
Linear	6577	-	-	-	
Quadratic	5340	1236	1	8.41e-271	8.41e-271
RQ 1.3 (EET)					
Linear	6138	-	-	-	-
Quadratic	5427	711	1	1.06e-156	1.06e-156
RQ 1.4 (SET)					
Linear	6052	-	-	-	-
Quadratic	5147	906	1	5.75e-199	5.75e-199

EET = Elbow Energy Transfer; EVT = Elbow Varus Torque; SET = Shoulder Energy Transfer; SRT = Shoulder Rotation Torque. Table generated using TexReg[47]

Table 4.3: Chi-Square Test Results (Specific Aim 1)

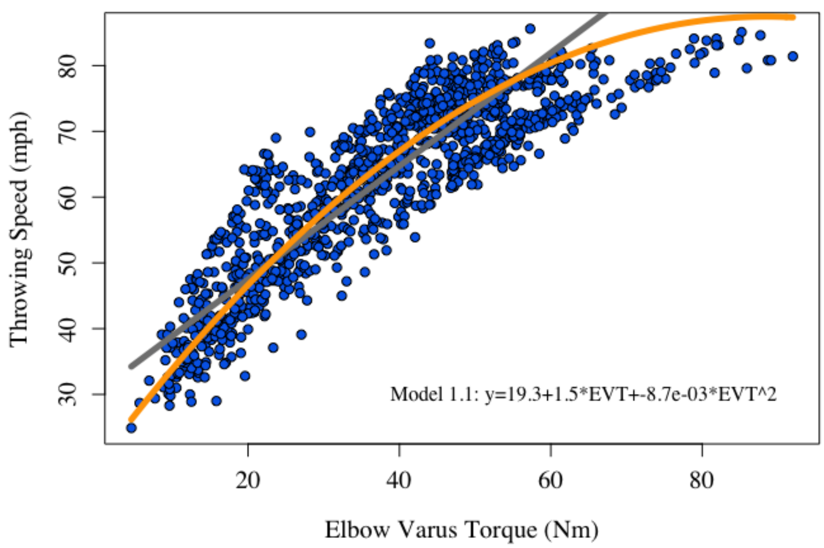

Figure 4.3: Elbow Varus Torque Model Comparison. Grey line = linear model; Yellow line = quadratic model.

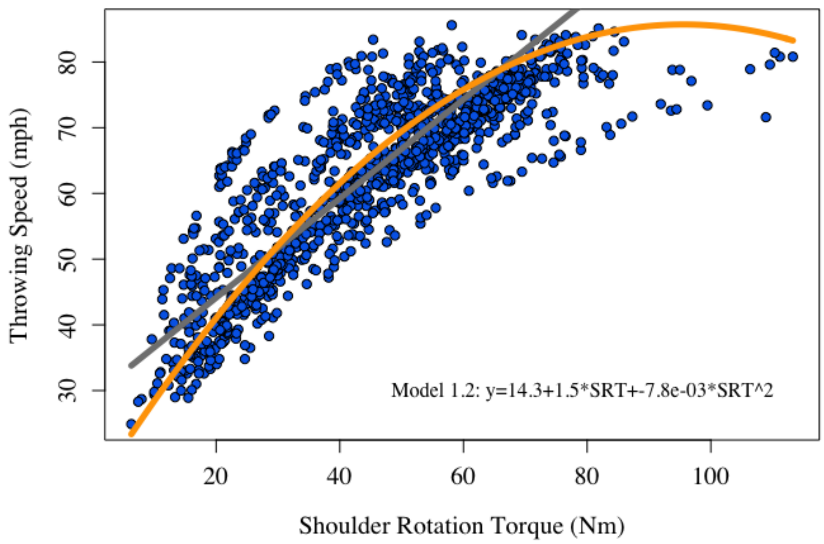

Figure 4.4: Shoulder Rotation Torque Model Comparison. Grey line = linear model; Yellow line = quadratic model.

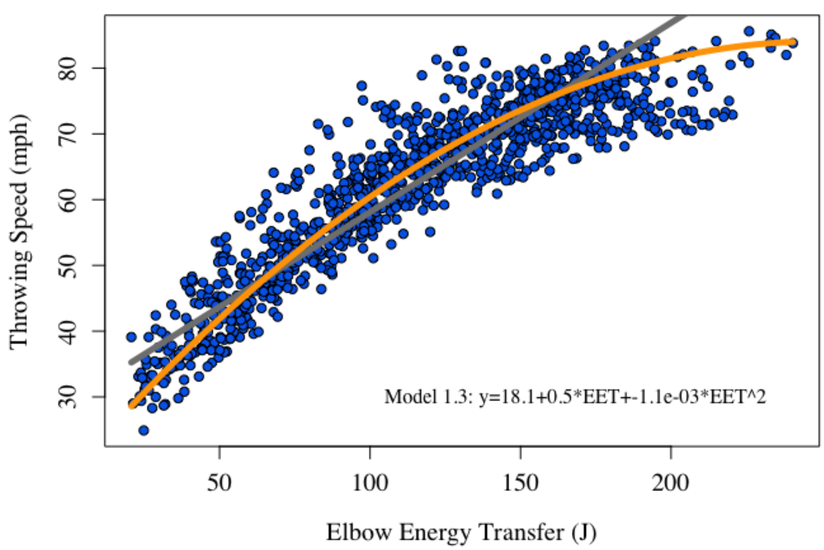

Figure 4.5: Elbow Energy Transfer Model Comparison. Grey line = linear model; Yellow line = quadratic model.

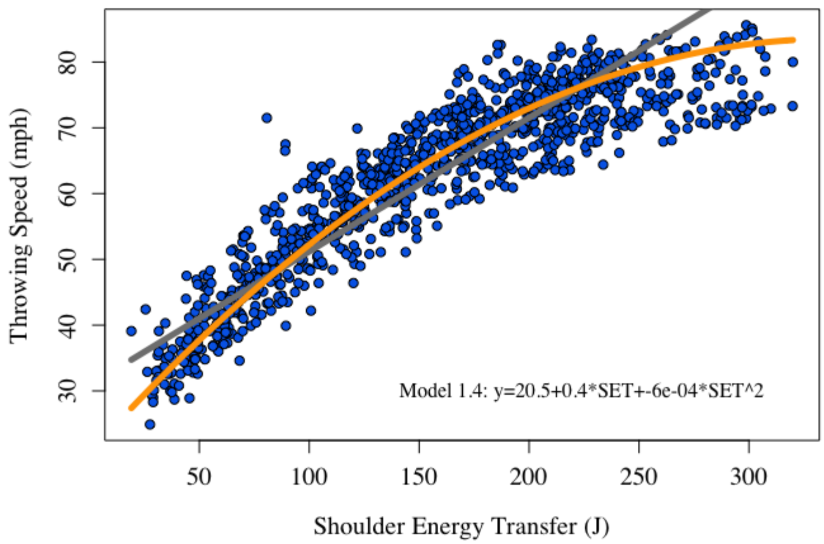

Figure 4.6: Shoulder Energy Transfer Model Comparison. Grey line = linear model; Yellow line = quadratic model.

4.4 Specific Aim 2

The goal of Specific Aim 2 was to determine whether allowing different model slopes for each participant (random slopes) improved model fits and, if so, whether participant-level characteristics (i.e. participant anthropometrics and max throwing speed) helped explain slope variance in Models 1.1-1.4. The main hypotheses for Specific Aim 2 were 1) that allowing random slopes would improve model fits and 2) that participant anthropometrics (i.e. height and mass) and maximum throwing speed would help explain variance in model slopes. The first hypothesis was tested using a model comparison approach similar to Specific Aim 1. Instead of comparing linear model and quadratic models, a quadratic model with a fixed slope across participants was compared to a quadratic model that allowed slopes to vary between participants. The second hypothesis was tested by comparing the random slopes model to a model containing a cross level interaction between the linear level-1 term (i.e. one of EVT, SRT, EET, or SET) and the level-2 term of interest (i.e. mass, height, or max throwing speed).

Similar to Specific Aim 1, all four models were improved by allowing random slopes across participants (Table 4.4). However, improvements in model prediction accuracy from the inclusion of random slopes were smaller than the accuracy improvements gained from the introduction of the quadratic term in Specific Aim 1. For example, RMSE in the EVT model improved from 2.5 mph to 2.1 mph. Similar magnitude improvements were observed for the other models (SRT: 2.3 mph to 1.8 mph; EET: 2.4 mph to 2.1 mph; SET: 2.1 mph to 1.8 mph). Detailed model comparison results are found in Tables 7.5 through 7.8.

	Deviance	χ^2	*df*	p	p'
RQ 2.1 (EVT)					
Quadratic	5502	-	-	-	-
RS	5280	222	2	5.72e-49	5.72e-49
RQ 2.2 (SRT)					
Quadratic	6577	-	-	-	-
RS	4916	424	2	7.52e-93	7.52e-93
RQ 2.3 (EET)					
Quadratic	6138	-	-	-	-
RS	5132	295	2	7.79e-65	7.79e-65
RQ 2.4 (SET)					
Quadratic	6052	-	-	-	-
RS	4925	222	2	6.67e-49	6.67e-49

EET = Elbow Energy Transfer; EVT = Elbow Varus Torque; SET = Shoulder Energy Transfer; SRT = Shoulder Rotation Torque. Table generated using TexReg[47]

Table 4.4: Chi-Square Test Results (Specific Aim 2)

Inclusion of participant-level explanatory variables in the random slope models from earlier in Specific Aim 2 revealed body mass and height influenced the relationship between throwing speed and throwing arm joint loading (Table 4.5). Specifically, body mass influenced the relationship between throwing speed and throwing arm joint loading in the SRT, EET, SET random slope models while height influenced the relationship between throwing speed and throwing arm joint loading only in the EET, SET random slope models. Body mass did not influence the relationship between EVT and throwing speed and height did not influence the relationship between EVT or SRT and throwing speed. Additionally, maximum throwing speed did not influence the relationship between throwing arm joint loading and throwing speed in any of the random slope models. In all cases, cross-level interaction terms were negative, indicating that as body mass (or height) increased the predicted slope of the regression line between throwing speed and throwing arm joint loading would decrease (Tables 7.9 to 7.12).

	Deviance	χ^2	*df*	*p*	*p'*
RQ 2.1 (EVT)					
RS	5502	-	-	-	-
:Mass	5273	7.16	1	0.007	0.051
:Height	5280	0.55	1	0.459	-
:Speed	5280	0.24	1	0.621	-
RQ 2.2 (SRT)					
RS	5340	-	-	-	-
:Mass	4905	11.22	1	8.09e-04	0.008
:Height	4911	4.86	1	0.027	0.151
:Speed	4916	0.11	1	0.741	-
RQ 2.3 (EET)					
RS	5427	-	-	-	-
:Mass	5117	14.79	1	1.2e-04	0.001
:Height	5124	7.55	1	0.006	0.047
:Speed	5132	0	1	1	-
RQ 2.4 (SET)					
RS	5147	-	-	-	-
:Mass	4913	12.12	1	4.98e-04	0.005
:Height	4917	8.06	1	0.005	0.044
:Speed	4925	0	1	1	-

EET = Elbow Energy Transfer; EVT = Elbow Varus Torque; SET = Shoulder Energy Transfer; SRT = Shoulder Rotation Torque. Table generated using TexReg[47]

Table 4.5: Chi-Square Test Results [Specific Aim 2 (Part 2)]

5 Discussion

The purpose of this research was to model changes in throwing arm joint loads as pitchers progressed from low to high intensity throwing. Modeling how loads on the shoulder and elbow change as a function of throwing intensity may help inform more objective and individualized ITPs and, in turn, help improve the success rate of throwing rehabilitation protocols. This chapter discusses the results from this study, places these results in the context of the current body of literature, and addresses potential limitations and future directions for this line of research.

5.1 Specific Aim 1

The goal of Specific Aim 1 was to model the intra-participant relationship between throwing arm joint loading and throwing speed as participants progressed from low to high intensity throwing. The intra-participant mechanics-speed relationship was examined using four measures of throwing arm joint loading: elbow varus torque (EVT), shoulder rotation torque (SRT), elbow energy transfer (EET), and shoulder energy transfer (SET). Each measure of throwing arm joint loading was used to predict throwing speed and, in each case, it was hypothesized that the intra-participant mechanics-speed relationship would be better explained using a quadratic model compared to a linear model. For all four measures of throwing arm joint loading, this hypothesis was supported by the data. Therefore, the primary finding from Specific Aim 1 is that the relationship between throwing arm joint loading and throwing speed is better modeled using a quadratic relationship.

$RQ_{1.1}$: How is the relationship between elbow varus torque (EVT) and throwing speed best modeled as participants increase throwing intensity?

The hypothesis that the relationship between EVT and throw speed would be better modeled using a quadratic relationship was supported (Table 4.3). Inclusion of a quadratic term in the improved model RMSE from 3.5 mph to 2.5 mph, reducing model error by approximately 30%.

$RQ_{1.2}$: How is the relationship between shoulder rotation torque (SRT) and throwing speed best modeled as participants increase throwing intensity?

The hypothesis that the relationship between SRT and throw speed would be better modeled using a quadratic relationship was supported (Table 4.3). Inclusion of a quadratic term in the improved model RMSE from 4.0 mph to 2.3 mph, resulting in a reducing model error by approximately 43%.

$RQ_{1.3}$: How is the relationship between upper arm-to-forearm energy flow (EET) and throwing speed better modeled as participants increase throw intensity?

The hypothesis that the relationship between EET and throw speed would be better modeled using a quadratic relationship was supported (Table 4.3). Inclusion of a quadratic term in the improved model RMSE from 3.3 mph to 2.4 mph, reducing model error by approximately 27%.

$RQ_{1.4}$: How is the relationship between trunk-to-upper arm energy flow (SET) and throwing speed better modeled as participants increase throw intensity?

The hypothesis that the relationship between SET and throw speed would be better modeled using a quadratic relationship was supported (Table 4.3). Inclusion of a quadratic term in the improved model RMSE from 3.2 mph to 2.1 mph, reducing model error by approximately 33%.

Previous research analyzing intra-participant relationship between throwing arm joint loading and throwing speed using multilevel techniques has been limited to one study examining game-effort pitching from a pitching mound.[74] The results from the present study indicating improvements in model fits with the inclusion of a quadratic term differ from those of Slowik et. al., who showed a strong linear relationship between EVT and throwing speed ($R^2 = 0.957$)[ii]. It is hypothesized that the apparent contradiction between the present study's results and those of Slowik et. al. are likely due to the increased range of throwing speeds in the present study. If the present study had isolated only the fastest throws from each participant, as was done in the Slowik study, it is possible that the relationship between throwing arm joint loading and throwing speed would be better described by a linear model. However, when each participant's entire throwing speed range is considered, it appears that the relationship between throwing arm joint loading and throwing speed can become nonlinear.

Not only is the intra-participant relationship between throwing arm joint loading and throwing speed nonlinear, but it also has a consistent functional form. Specifically, it is quadratic linear concave up (Figure

[ii] It should be noted that Slowik et. al. did not compare linear and quadratic models in their study so these results aren't in contradiction *per se*, but rather the already large R^2 value indicates minimal, if any, improvement would be possible by including a quadratic term.

5.1). To better picture a functional form of this shape, consider the regression equation using one of the measures of throwing arm joint loading to predict the throwing speed of throw i from participant j:

$$thro\hat{w}speed_{ij} = \beta_{0j} + \beta_{1j}jointload_{ij} + \beta_{2}jointload_{ij}^{2}$$

When β_{1j} is positive and β_2 is negative, the resulting regression line will have an initial positive slope that becomes incrementally less positive as x increases. This results in the quadratic linear concave up shape seen in the scatter plots in Figures 4.3 through 4.6 and in the middle right panel of Figure 5.1. In the context of throwing rehabilitation protocols, this shape suggests that a certain magnitude increase in throwing arm joint loading will result in greater increases in throwing speed at slower throwing speeds than at faster throwing speeds. Stated alternatively, as throwers increase their throwing intensity, they will experience diminishing increases in throwing speed as they increase intensity and deliver more and more energy to the baseball.

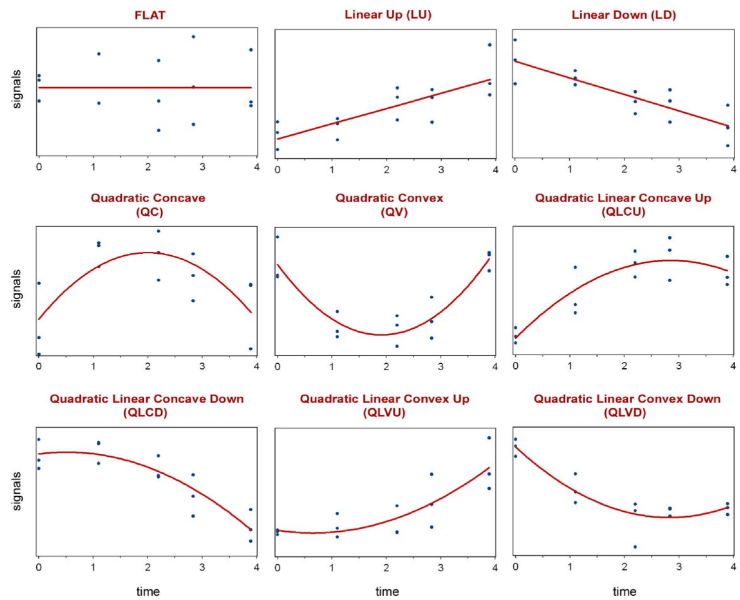

Figure 5.1: Regression Types (adapted from Liu et al.[49])

Inclusion of each participant's entire range of throwing speeds when modeling the relationship between throwing arm joint loading and throwing speed has the potential to guide the development of more objective and individualized ITPs. Most current throwing rehabilitation protocols involve performing a predetermined number of throws at a predetermined distance multiple times per week, guided by subjective feedback from the athlete themselves (for further information on throwing rehabilitation protocols, see Section 2.4). Although this approach will work for many overhead athletes returning from injury, many others will fail to return to their previous ability level or will re-injure their throwing arm,[54,55,57] begging the question of whether these return-to-play programs can be improved. The desire for improved efficacy of throwing rehabilitation programs has led researchers and clinicians to search for ways to quantify critical variables such as throwing intensity and workload objectively. One proposed way to improve quantification of throwing intensity is to replace subjective athlete-reported intensity levels with throwing speeds from a calibrated radar gun.[51]

Despite increased adoption of objective throwing intensity measures like throwing speed, how the loads placed on the throwing arm change through the entire throwing speed range used in throwing rehabilitation programs is still not well understood. The present study serves as a first step towards better understanding of throwing rehabilitation programs and is the first to provide data regarding the loads placed on the shoulder and elbow throughout a thrower's entire throwing speed range. The present study is also the first to treat throwing intensity as a continuous measure instead of using discrete perceived intensity levels. For example, previous studies examining sub-maximal throwing have employed a finite number of intensity "conditions" such as 50%, 75%, and 100% of an athlete's RPE or maximum throwing speed. While discrete intensity levels simplify experimental design and statistical analysis, they also decrease the applicability of study results to real-world rehabilitation scenarios where athletes may not be instructed to throw at specific intensities or where athletes are not able to consistently reproduce similar RPE level on different training days. Therefore, understanding how the loads placed on the throwing arm change throughout the entire throwing speed range is crucial in individualizing throwing rehabilitation protocols. The present study expands on the initial multilevel findings of Slowik et. al.[74] and can serve as an initial exploration and proof-of-concept for using multilevel regression modeling techniques to understand the complex relationships between throwing arm joint loads and throwing speed within and across multiple athletes.

5.2 Specific Aim 2

The goal of Specific Aim 2 was to model the inter-participant differences in responses to increased throwing intensity. Specific Aim 2 built upon the final models from Specific Aim 1 and examined whether participants varied in their rate of increase in throwing speed for a given increase in throwing arm joint loading (i.e. introducing random slopes) and whether participant-level characteristics (i.e. body mass, height, and maximum throwing speed) helped explain random slope variance (i.e. cross-level interactions). Just as in Specific Aim 1, this process was repeated on four models predicting throwing speed from one of EVT, SRT, EET, or SET and it was hypothesized that both random slopes and cross-level interactions would improve model fits. Each model fit was improved by allowing random slopes (Table 4.4) and each model fit except for the EVT model was improved by introducing participant-level characteristics.

$RQ_{2.1}$: Does allowing differing rates of increase (random slopes) in Model 1.1 improve

model fit? If so, do participant-level explanatory variables help explain the rate of increase (cross-level interaction)?

The hypothesis that introducing random slopes to Model 1.1 would improve model fit was supported (Table 4.4). Allowing random slopes improved model RMSE from 2.5 mph to 2.1 mph. The hypothesis that introducing a cross-level interaction between participant-level explanatory variables and the linear term slope would improve model fit was not supported (Table 4.5).

$RQ_{2.2}$: Does allowing differing rates of increase (random slopes) in Model 1.2 improve model fit? If so, do participant-level explanatory variables help explain the rate of increase (cross-level interaction)?

The hypothesis that introducing random slopes to Model 1.2 would improve model fit was supported (Table 4.4). Allowing random slopes improved model RMSE from 2.3 mph to 1.8 mph. The hypothesis that introducing a cross-level interaction between participant-level explanatory variables and the linear term slope would improve model fit was partially supported (Table 4.5). Body mass influenced the relationship between throwing arm joint loading and throwing such that as body mass increased, the slope estimating the relationship between SRT and throwing speed decreased. Introducing a body mass by SRT interaction explained approximately 19% of the random slope variance (Table 7.10).

$RQ_{2.3}$: Does allowing differing rates of increase (random slopes) in Model 1.3 improve model fit? If so, do participant-level explanatory variables help explain the rate of increase (cross-level interaction)?

The hypothesis that introducing random slopes to Model 1.3 would improve model fit was supported (Table 4.4). Allowing random slopes improved model RMSE from 2.4 mph to 2.0 mph. The hypothesis that introducing a cross-level interaction between participant-level explanatory variables and the linear term slope would improve model fit was partially supported (Table 4.5). Both body mass and height influenced the relationship between throwing arm joint loading and throwing speed such that as body mass and height increased, the slope estimating the relationship between EET and throwing speed decreased. Introducing a body mass by EET interaction explained approximately 1% of the random slope variance whereas introducing a height by EET interaction explained approximately 8% of the random slope variance (Table 7.11).

$RQ_{2.4}$: Does allowing differing rates of increase (random slopes) in Model 1.4 improve

model fit? If so, do participant-level explanatory variables help explain the rate of increase (cross-level interaction)?

The hypothesis that introducing random slopes to Model 1.4 would improve model fit was supported (Table 4.4). Allowing random slopes improved model RMSE from 2.1 mph to 1.8 mph. The hypothesis that introducing a cross-level interaction between participant-level explanatory variables and the linear term slope would improve model fit was partially supported (Table 4.5). Both body mass and height influenced the relationship between throwing arm joint loading and throwing speed such that as body mass and height increased, the slope estimating the relationship between SET and throwing speed decreased. Introducing a body mass by SET interaction explained approximately 6% of the random slope variance whereas introducing a height by SET interaction explained approximately 18% of the random slope variance (Table 7.12).

To the author's knowledge, the present study is the first in the throwing biomechanics literature to use the multilevel regression modeling framework to examine inter-participant differences in intra-participant patterns of change. This was accomplished by introducing random slopes and cross-level interactions into the models from Specific Aim 1. The results from Specific Aim 2 add novel insight to the literature regarding the influence of participant anthropometrics on the relationship between throwing arm joint loading and throwing speed. These results also offer an initial glimpse into the many potential applications of multilevel regression models in the sports biomechanics domain.

5.2.1 Understanding the Cross-Level Interaction

For three of the four models predicting throwing speed from measures of throwing arm joint loading, the inclusion of a cross-level interaction between participant-level explanatory variables and the linear term slope (β_{1j}) improved model fit (SRT, EET, and SET). In each case, increases in the participant-level explanatory variable (whether it was body mass or height) decreased the estimated slope of the relationship between throwing arm joint loading and throwing speed. To better understand what the cross-level interaction term is doing, let's revisit Equation 23 (without the participant-level explanatory variable being used to predict random slope variance):

$$\hat{y}_{ij} = \gamma_{00} + \mu_{0j} + (\gamma_{10} + \gamma_{11} z_j + \mu_{1j}) x_{1ij} + \epsilon_{ij}$$

Here, $\hat{y}_{ij}$ is the predicted throwing speed of throw i from participant j, γ_{00} is the overall model intercept (i.e. grand mean throwing speed across all participants), μ_{00} is the intercept variance, $(\gamma_{10} + \gamma_{11} z_j + \mu_{1j})$ is the participant-level equation being used to try to predict variance in the relationship between x_{1ij} and y_{ij}, and ϵ_{ij} is the residual level-1 variance. Distributing x_{1ij} across $(\gamma_{10} + \gamma_{11}z_j + \mu_{1j})$ produces the cross-level interaction term $(\gamma_{11}z_jx_{1ij})$:

$$\hat{y}_{ij} = \gamma_{00} + \mu_{0j} + \gamma_{10}x_{1ij} + \gamma_{11}z_jx_{1ij} + \mu_{1j}x_{1ij} + \epsilon_{ij}$$

Once x_{1ij} has been distributed, it can be understood that γ_{11} quantifies the cross-level interaction effect that z_j has on the relationship between x_{1ij} and $\hat{y_{ij}}$ (i.e. β_{1j}). Specifically, when γ_{11} is positive, increases in z_j would result in increases in β_{1j} and when γ_{11} is negative, increases in z_j would result in decreases in β_{1j}. It can also be seen that $(\gamma_{10} + \mu_{1j})$ represents the slope between x_{1ij} and $\hat{y_{ij}}$ for participant j when z is equal to 0.

Figure 5.2 provides an visual example of one of the observed cross-level interactions; in this case between body mass and SRT (Table 7.10; Column 2). In Figure 5.2, the SRT vs. throwing speed growth curves for three participants are emphasized and the predictions from the final model incorporating the cross-level interaction are overlaid as dashed regression lines. Each of the example participants achieved similar maximum throwing speeds; however, all participants had significantly different body masses. Using Figure 5.2, it can be seen that, as body mass increases, the predicted regression slope between SRT and throwing speed decreases. All other cross-level interactions followed this same pattern.

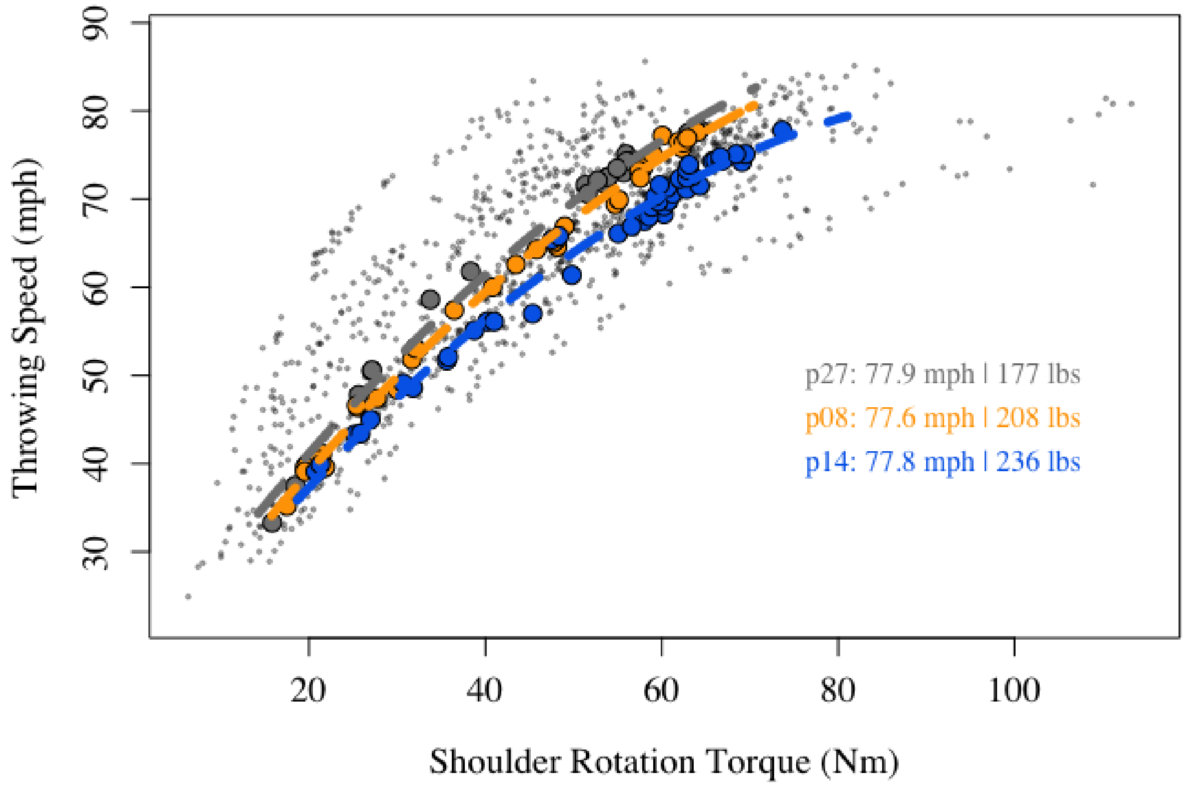

Figure 5.2: Example Cross-Level Interaction between SRT and body mass using three participants. Even though all participants achieved similar maximum throwing speeds, the slope of regression line decreases as participant body mass increases.

Including a cross-level interaction term also allows the model to predict what would happen to the relationship between throwing arm joint loading and throwing speed if an athlete's body mass changed. For example, how would the relationship between SRT and throwing speed change for participant 14 from Figure 5.3 if they lost ten pounds? Using the equation derived from the body mass by SRT cross-level interaction model (Table 7.10; Column 2), we can input a new mass value and plot how the prediction line changes:

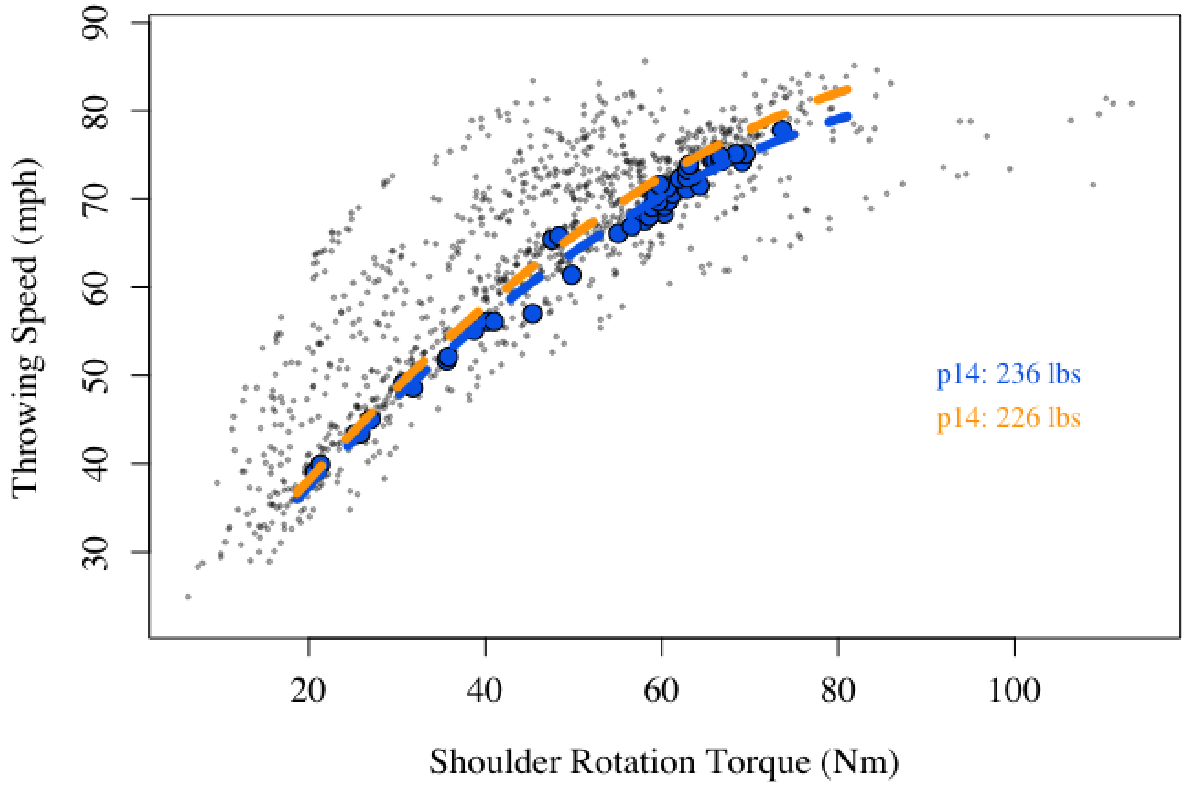

Figure 5.3: Theoretical Cross-Level Interaction between SRT and body mass for one participant. Hypothetically reducing body mass increases the slope between SRT and throwing speed.

6 Conclusions, Limitations, and Future Directions

This project aimed to model the intra and inter-participant relationships between throwing arm joint loading and throwing speed. The primary findings of this project were two-fold: first, the intra-participant relationship between throwing arm joint loading and throwing speed appears to be nonlinear in form. Specifically, the form of this relationship is quadratic linear concave down indicating that, as throwing arm joint loading increases, corresponding increases in throwing speed become successively smaller and smaller. Second, as body mass and height increase, the slope estimating the relationship between throwing arm joint loading and throwing speed tends to decrease.

In addition to providing novel insight into the intra and inter-participant relationships between throwing arm joint loading and throwing speed, this project also serves as an initial exploration of, and proof-of-concept for, the use of multilevel modeling strategies in sports biomechanics research. Although popular in other research fields, multilevel modeling techniques have received limited attention in the sports biomechanics literature. Through parallel examination of variance at both the intra and inter-participant levels, researchers can ask more profound and multilayered research questions in addition to employing more sophisticated and externally valid research protocols.

Although this project employed innovative data collection and analysis techniques, it is not without limitations. First, the relative homogeneity of the participant sample may have undercut some of the results, particularly when investigating the presence of cross-level interactions. 28 out of 32 participants who met all inclusion criteria were pitchers currently active at the collegiate level. Although there was some variability, most of these participants had similar anthropometric profiles and maximum throwing speeds. Only two participants were currently competitive at the high school level and one of those was a signed high school senior preparing for their freshman season. Additional sampling of high school and youth participants may have provided increased variability of participant-level explanatory variables and further elucidated the impact, or lack thereof, of potential cross-level interactions. Second, although every participant was instructed to eventually reach maximal throwing intensity, the project's controlled laboratory nature may have prevented some participants from truly reaching maximal intensity.

References

[1] Agresta, C. E., Krieg, K., and Freehill, M. T. Risk factors for baseball-related arm injuries: a systematic review. *Orthopaedic journal of sports medicine*, 7(2):2325967119825557, 2019.

[2] Aguinaldo, A. and Escamilla, R. Relationship of segmental energy flow and elbow valgus loading during baseball pitching. *ISBS Proceedings Archive*, 36(1):911, 2018.

[3] Aguinaldo, A. and Escamilla, R. Segmental power analysis of sequential body motion and elbow valgus loading during baseball pitching: comparison between professional and high school baseball players. *Orthopaedic journal of sports medicine*, 7(2):2325967119827924, 2019.

[4] Aguinaldo, A. L., Buttermore, J., and Chambers, H. Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various levels. *Journal of Applied Biomechanics*, 23(1):42–51, 2007.

[5] Aguinaldo, A. L. and Escamilla, R. F. Induced power analysis of sequential body motion and elbow valgus load during baseball pitching. *Sports Biomechanics*, pages 1–13, 2020.

[6] Andrews, J. R., Venkateswaran, V., Christensen, K. D., Plummer, H. A., Hart, K. M., Opitz, T. J., Wilk, K. E., Pinegar, C. O., Cain Jr, E. L., Dugas, J. R., Jordan, S. E., and Fleisig, G. S. Outcomes after ulnar collateral ligament revision reconstruction in baseball players. *The American Journal of Sports Medicine*, page 0363546520951529, 2020.

[7] Anz, A. W., Bushnell, B. D., Griffin, L. P., Noonan, T. J., Torry, M. R., and Hawkins, R. J. Correlation of torque and elbow injury in professional baseball pitchers. *The American journal of sports medicine*, 38(7):1368–1374, 2010.

[8] Appaneal, R. N., Levine, B. R., Perna, F. M., and Roh, J. L. Measuring postinjury depression among male and female competitive athletes. *Journal of Sport and Exercise Psychology*, 31(1):60–76, 2009.

[9] Axe, M., Hurd, W., and Snyder-Mackler, L. Data-based interval throwing programs for baseball players. *Sports Health*, 1(2):145–153, 2009.

[10] Bakshi, N. and Freehill, M. T. The overhead athletes shoulder. *Sports Medicine and Arthroscopy Review*, 26(3):88–94, 2018.

[11] Barcikowski, R. S. Statistical power with group mean as the unit of analysis. *Journal of Educational Statistics*, 6(3):267–285, 1981.

[12] Bell, A. L., Pedersen, D. R., and Brand, R. A. A comparison of the accuracy of several hip center location prediction methods. *Journal of biomechanics*, 23(6):617–621, 1990.

[13] Boddy, K. and Daniels, M. *Hacking the Kinetic Chain*. Driveline Baseball.

[14] Brandmaier, A. M., von Oertzen, T., Ghisletta, P., Lindenberger, U., and Hertzog, C. Precision, reliability, and effect size of slope variance in latent growth curve models: Implications for statistical power analysis. *Frontiers in psychology*, 9:294, 2018.

[15] Buffi, J. H., Werner, K., Kepple, T., and Murray, W. M. Computing muscle, ligament, and osseous contributions to the elbow varus moment during baseball pitching. *Annals of biomedical engineering*, 43(2):404–415, 2015.

[16] Bunn, J. W. *Scientific principles of coaching*. Prentice Hall, 1972.

[17] Burkhart, S. S., Morgan, C. D., and Kibler, W. B. The disabled throwing shoulder: spectrum of pathology part i: pathoanatomy and biomechanics. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 19(4):404–420, 2003.

[18] Camp, C. L., Dines, J. S., van der List, J. P., Conte, S., Conway, J., Altchek, D. W., Coleman, S. H., and Pearle, A. D. Summative report on time out of play for major and minor league baseball: an analysis of 49,955 injuries from 2011 through 2016. *The American journal of sports medicine*, 46(7):1727–1732, 2018.

[19] Chaffin, D. B., Andersson, G. B., and Martin, B. J. *Occupational biomechanics.* John Wiley & Sons, 2006.

[20] Chalmers, P. N., Wimmer, M. A., Verma, N. N., Cole, B. J., Romeo, A. A., Cvetanovich, G. L., and Pearl, M. L. The relationship between pitching mechanics and injury: a review of current concepts. *Sports Health*, 9(3):216–221, 2017.

[21] Cisco, S., Semon, M. M., Moraski, P., Smith, J., and Thorndike, C. Distance-based throwing programs for baseball players from little league to high school. *Pediatric Physical Therapy*, 31(3):297–300, 2019.

[22] Curran, P. J., Obeidat, K., and Losardo, D. Twelve frequently asked questions about growth curve modeling. *Journal of cognition and development*, 11(2):121–136, 2010.

[23] DeFroda, S. F., Goyal, D., Patel, N., Gupta, N., and Mulcahey, M. K. Shoulder instability in the overhead athlete. *Current Sports Medicine Reports*, 17(9):308–314, 2018.

[24] Dillman, C. J., Fleisig, G. S., and Andrews, J. R. Biomechanics of pitching with emphasis upon shoulder kinematics. *Journal of Orthopaedic & Sports Physical Therapy*, 18(2):402–408, 1993.

[25] Elliott, B., Fleisig, G., Nicholls, R., and Escamilia, R. Technique effects on upper limb loading in the tennis serve. *Journal of Science and Medicine in Sport*, 6(1):76–87, 2003.

[26] Feltner, M. and Dapena, J. Dynamics of the shoulder and elbow joints of the throwing arm during a baseball pitch. *Journal of Applied Biomechanics*, 2(4):235–259, 1986.

[27] Feltner, M. E. Three-dimensional interactions in a two-segment kinetic chain. part ii: Application to the throwing arm in baseball pitching. *Journal of Applied Biomechanics*, 5(4):420–450, 1989.

[28] Feltner, M. E. and Dapena, J. Three-dimensional interactions in a two-segment kinetic chain. part i: General model. *Journal of Applied Biomechanics*, 5(4):403–419, 1989.

[29] Fleisig, G. S., Andrews, J. R., Dillman, C. J., and Escamilla, R. F. Kinetics of baseball pitching with implications about injury mechanisms. *The American journal of sports medicine*, 23(2):233–239, 1995.

[30] Fleisig, G. S., Barrentine, S. W., Zheng, N., Escamilla, R. F., and Andrews, J. R. Kinematic and kinetic comparison of baseball pitching among various levels of development. *Journal of biomechanics*, 32(12):1371–1375, 1999.

[31] Fleisig, G. S. and Barrentine, S. W. Biomechanical aspects of the elbow in sports. *Sports Medicine and Arthroscopy Review*, 3(3):1–159, 1995.

[32] Fleisig, G., Zheng, N., Barrentine, S., Escamilla, R., Andrews, J., and Lemak, L. Kinematic and kinetic comparison of full-effort and partial-effort baseball pitching. In *20th Annual Meeting of the American Society of Biomechanics*, pages 151–152, 1996.

[33] Gagnon, D. and Gagnon, M. The influence of dynamic factors on triaxial net muscular moments at the l5s1 joint during asymmetrical lifting and lowering. *Journal of biomechanics*, 25(8):891–901, 1992.

[34] Holt, J. K. Modeling growth using multilevel and alternative approaches. *Multilevel modeling of educational data*, pages 111–159, 2008.

[35] House, T., Neil, G., and Johnson, S. *The Art and Science of Pitching.* Coaches Choise.

[36] Howenstein, J., Kipp, K., and Sabick, M. Peak horizontal ground reaction forces and impulse correlate with segmental energy flow in youth baseball pitchers. *Journal of Biomechanics*, 108:109909, 2020.

[37] Howenstein, J., Kipp, K., and Sabick, M. B. Energy flow analysis to investigate youth pitching velocity and efficiency. *Medicine & Science in Sports & Exercise*, 2018.

[38] Hox, J. J., Moerbeek, M., and Van de Schoot, R. *Multilevel analysis: Techniques and applications.* Routledge, 2017.

[39] Kibler, W. B., Wilkes, T., and Sciascia, A. Mechanics and pathomechanics in the overhead athlete. *Clinics in sports medicine*, 32(4):637–651, 2013.

[40] Kimura, A., Yoshioka, S., and Fukashiro, S. Contribution of hip joint kinetics to rotate the pelvis during baseball pitching. *International Journal of Sport and Health Science*, page 201920, 2020.

[41] Kimura, A., Yoshioka, S., Omura, L., and Fukashiro, S. Mechanical properties of upper torso rotation from the viewpoint of energetics during baseball pitching. *European journal of sport science*, 20(5):606–613, 2020.

[42] Knudson, D. Significant and meaningful effects in sports biomechanics research. *Sports Biomechanics*, 8(1):96–104, 2009.

[43] Kobayashi, K., Burton, K. J., Rodner, C., Smith, B., and Caputo, A. E. Lateral compression injuries in the pediatric elbow: Panner's disease and osteochondritis dissecans of the capitellum. *JAAOS-Journal of the American Academy of Orthopaedic Surgeons*, 12(4):246–254, 2004.

[44] Kreft, I. G., Kreft, I., and de Leeuw, J. *Introducing multilevel modeling.* Sage, 1998.

[45] Kvist, J., Ek, A., Sporrstedt, K., and Good, L. Fear of re-injury: a hindrance for returning to sports after anterior cruciate ligament reconstruction. *Knee surgery, sports traumatology, arthroscopy*, 13(5):393–397, 2005.

[46] Leafblad, N. D., Larson, D. R., Fleisig, G. S., Conte, S., Fealy, S. A., Dines, J. S., D'Angelo, J., and Camp, C. L. Variability in baseball throwing metrics during a structured long-toss program: Does one size fit all or should programs be individualized? *Sports health*, 11(6):535–542, 2019.

[47] Leifeld, P. texreg: Conversion of statistical model output in R to LaTeX and HTML tables. *Journal of Statistical Software*, 55(8):1–24, 2013.

[48] Lin, H.-T., Su, F.-C., Nakamura, M., and Chao, E. Y. Complex chain of momentum transfer of body segments in the baseball pitching motion. *Journal of the Chinese Institute of Engineers*, 26(6):861–868, 2003.

[49] Liu, H., Tarima, S., Borders, A. S., Getchell, T. V., Getchell, M. L., and Stromberg, A. J. Quadratic regression analysis for gene discovery and pattern recognition for non-cyclic short time-course microarray experiments. *BMC bioinformatics*, 6(1):1–17, 2005.

[50] Lizzio, V. A., Smith, D. G., Guo, E. W., Cross, A. G., Gulledge, C. M., Koolmees, D. S., Chalmers, P. N., and Makhni, E. C. The effect of the crow hop on elbow stress during an interval throwing program. *The American Journal of Sports Medicine*, page 0363546520976629, 2020.

[51] Lizzio, V. A., Smith, D. G., Jildeh, T. R., Gulledge, C. M., Swantek, A. J., Stephens, J. P., Schulz, B. M., and Makhni, E. C. Importance of radar gun inclusion during return-to-throwing rehabilitation following ulnar collateral ligament reconstruction in baseball pitchers: a simulation study. *Journal of shoulder and elbow surgery*, 29(3):587–592, 2020.

[52] Ludbrook, J. Multiple comparison procedures updated. *Clinical and Experimental Pharmacology and Physiology*, 25(12):1032–1037, 1998.

[53] Ludewig, P. M. and Cook, T. M. Translations of the humerus in persons with shoulder impingement symptoms. *Journal of Orthopaedic & Sports Physical Therapy*, 32(6):248–259, 2002.

[54] Makhni, E. C., Lee, R. W., Morrow, Z. S., Gualtieri, A. P., Gorroochurn, P., and Ahmad, C. S. Performance, return to competition, and reinjury after tommy john surgery in major league baseball pitchers: a review of 147 cases. *The American journal of sports medicine*, 42(6):1323–1332, 2014.

[55] Makhni, E. C., Lee, R. W., Nwosu, E. O., Steinhaus, M. E., and Ahmad, C. S. Return to competition, re-injury, and impact on performance of preseason shoulder injuries in major league baseball pitchers. *The Physician and sportsmedicine*, 43(3):300–306, 2015.

[56] Marsh, J. A., Wagshol, M. I., Boddy, K. J., O'Connell, M. E., Briend, S. J., Lindley, K. E., and Caravan, A. Effects of a six-week weighted-implement throwing program on baseball pitching velocity, kinematics, arm stress, and arm range of motion. *PeerJ*, 6:e6003, 2018.

[57] Marshall, N. E., Jildeh, T. R., Okoroha, K. R., Patel, A., Moutzouros, V., and Makhni, E. C. Implications of core and hip injuries on major league baseball pitchers on the disabled list. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 34(2):473–478, 2018.

[58] Marshall, R. N. Proximal-to-distal sequencing research: Application to throwing. *International Research in Sports Biomechanics*, page 9, 2002.

[59] Mathieu, J. E., Aguinis, H., Culpepper, S. A., and Chen, G. Understanding and estimating the power to detect cross-level interaction effects in multilevel modeling. *Journal of applied psychology*, 97(5):951, 2012.

[60] Matsuo, T., Escamilla, R. F., Fleisig, G. S., Barrentine, S. W., and Andrews, J. R. Comparison of kinematic and temporal parameters between different pitch velocity groups. *Journal of Applied Biomechanics*, 17(1):1–13, 2001.

[61] Melugin, H. P., Larson, D. R., Fleisig, G. S., Conte, S., Fealy, S. A., Dines, J. S., D'Angelo, J., and Camp, C. L. Baseball pitchers' perceived effort does not match actual measured effort during a structured long-toss throwing program. *The American Journal of Sports Medicine*, 47(8):1949–1954, 2019.

[62] N. Marshall, R. and Elliott, B. Long-axis rotation: the missing link in proximal-to-distal segmental sequencing. *Journal of sports sciences*, 18(4):247–254, 2000.

[63] Naito, K., Takagi, H., and Maruyama, T. Mechanical work, efficiency and energy redistribution mechanisms in baseball pitching. *Sports Technology*, 4(1-2):48–64, 2011.

[64] Naito, K., Takagi, T., Kubota, H., and Maruyama, T. Relationship between shoulder forces, shoulder joint shear stress, and throwing velocity during baseball pitching. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 233(4):489–502, 2019.

[65] Popchak, A. J., Hogaboom, N. S., Vyas, D., Abt, J. P., Delitto, A., Irrgang, J. J., and Boninger, M. L. Acute response of the infraspinatus and biceps tendons to pitching in youth baseball. *Medicine and science in sports and exercise*, 49(6):1168–1175, 2017.

[66] Ramsey, D. K. and Crotin, R. L. Effect of stride length on overarm throwing delivery: Part ii: An angular momentum response. *Human movement science*, 46:30–38, 2016.

[67] Ramsey, D. K., Crotin, R. L., and White, S. Effect of stride length on overarm throwing delivery: A linear momentum response. *Human movement science*, 38:185–196, 2014.

[68] Reinold, M., Wilk, K., Reed, J. L., Crenshaw, K., and Andrews, J. Interval sport programs: guidelines for baseball, tennis, and golf. *The Journal of orthopaedic and sports physical therapy*, 32(6):293–8, 2002.

[69] Robertson, D. and Winter, D. A. Mechanical energy generation, absorption and transfer amongst segments during walking. *Journal of biomechanics*, 13(10):845–854, 1980.

[70] Royer, P. J., Kane, E. J., Parks, K. E., Morrow, J. C., Moravec, R. R., Christie, D. S., and Teyhen, D. S. Fluoroscopic assessment of rotator cuff fatigue on glenohumeral arthrokinematics in shoulder impingement syndrome. *Journal of shoulder and elbow surgery*, 18(6):968–975, 2009.

[71] Scarborough, D. M., Bassett, A. J., Mayer, L. W., and Berkson, E. M. Kinematic sequence patterns in the overhead baseball pitch. *Sports biomechanics*, 19(5):569–586, 2020.

[72] Seroyer, S. T., Nho, S. J., Bach, B. R., Bush-Joseph, C. A., Nicholson, G. P., and Romeo, A. A. The kinetic chain in overhand pitching: its potential role for performance enhancement and injury prevention. *Sports health*, 2(2):135–146, 2010.

[73] Slenker, N. R., Limpisvasti, O., Mohr, K., Aguinaldo, A., and ElAttrache, N. S. Biomechanical comparison of the interval throwing program and baseball pitching: upper extremity loads in training and rehabilitation. *The American Journal of Sports Medicine*, 42(5):1226–1232, 2014.

[74] Slowik, J. S., Aune, K. T., Diffendaffer, A. Z., Cain, E. L., Dugas, J. R., and Fleisig, G. S. Fastball velocity and elbow-varus torque in professional baseball pitchers. *Journal of athletic training*, 54(3):296–301, 2019.

[75] Steindler, A. A historical review of the studies and investigations made in relation to human gait. *JBJS*, 35(3):540–728, 1953.

[76] Steindler, A. *Kinesiology of the Human Body, Charles C*. 1955.

[77] Stodden, D. F., Fleisig, G. S., McLean, S. P., and Andrews, J. R. Relationship of biomechanical factors to baseball pitching velocity: within pitcher variation. *Journal of applied biomechanics*, 21(1):44–56, 2005.

[78] Stodden, D. F., Fleisig, G. S., McLean, S. P., Lyman, S. L., and Andrews, J. R. Relationship of pelvis and upper torso kinematics to pitched baseball velocity. *Journal of applied biomechanics*, 17(2):164–172, 2001.

[79] Van den Tillaar, R. The biomechanics of the elbow in overarm throwing sports. *International SportMed Journal*, 6(1):7–24, 2005.

[80] van der Hoeven, H. and Kibler, W. B. Shoulder injuries in tennis players. *British journal of sports medicine*, 40(5):435 – 440, 2006.

[81] Wasserberger, K. W., Barfield, J. W., Downs, J. L., and Oliver, G. D. Glenohumeral external rotation weakness partially accounts for increased humeral rotation torque in youth baseball pitchers. *Journal of Science and Medicine in Sport*, 23(4):361–365, 2020.

[82] Wasserberger, K. W., Friesen, K. B., Downs, J. L., Bordelon, N. M., and Oliver, G. D. Comparison of pelvis and trunk kinematics between youth and collegiate windmill softball pitchers. *Journal of Athletic Training*, 2021. In review.

[83] Wasserberger, K. W., Giordano, K. A., de Swart, A., Barfield, J. W., and Oliver, G. D. Energy generation, absorption, and transfer at the shoulder and elbow in youth baseball pitchers. *Journal of Sport Biomechanics*, 2021. In review.

[84] Wasserman, E. B., Sauers, E. L., Register-Mihalik, J. K., Pierpoint, L. A., Currie, D. W., Knowles, S. B., Dompier, T. P., Comstock, R. D., Marshall, S. W., and Kerr, Z. Y. The first decade of web-based sports injury surveillance: Descriptive epidemiology of injuries in us high school boys' baseball (2005–2006 through 2013–2014) and national collegiate athletic association men's baseball (2004–2005 through 2013–2014). *Journal of athletic training*, 54(2):198–211, 2019.

[85] Werner, S. L., Fleisig, G. S., Dillman, C. J., and Andrews, J. R. Biomechanics of the elbow during baseball pitching. *Journal of Orthopaedic & Sports Physical Therapy*, 17(6):274–278, 1993.

[86] Wilk, K. E., Arrigo, C. A., Hooks, T. R., and Andrews, J. R. Rehabilitation of the overhead throwing athlete: there is more to it than just external rotation/internal rotation strengthening. *Pm&r*, 8:S78–S90, 2016.

[87] Wilk, K. E., Macrina, L. C., Fleisig, G. S., Aune, K. T., Porterfield, R. A., Harker, P., Evans, T. J., and Andrews, J. R. Deficits in glenohumeral passive range of motion increase risk of elbow injury in professional baseball pitchers: a prospective study. *The American journal of sports medicine*, 42(9):2075–2081, 2014.

[88] Wilk, K. E., Macrina, L. C., Fleisig, G. S., Aune, K. T., Porterfield, R. A., Harker, P., Evans, T. J., and Andrews, J. R. Deficits in glenohumeral passive range of motion increase risk of shoulder injury in professional baseball pitchers: a prospective study. *The American journal of sports medicine*, 43(10):2379–2385, 2015.

[89] Wilk, K. E., Macrina, L. C., Fleisig, G. S., Porterfield, R., Simpson, C. D., Harker, P., Paparesta, N., and Andrews, J. R. Correlation of glenohumeral internal rotation deficit and total rotational motion to shoulder injuries in professional baseball pitchers. *The American Journal of Sports Medicine*, 39(2):329–335, 2011.

[90] Wilk, K. E., Voight, M. L., Keirns, M. A., Gambetta, V., Andrews, J. R., and Dillman, C. J. Stretch-shortening drills for the upper extremities: theory and clinical application. *Journal of Orthopaedic & Sports Physical Therapy*, 17(5):225–239, 1993.

[91] Wilk, K. E., Yenchak, A., Arrigo, C. A., and Andrews, J. R. The advanced throwers ten exercise program: a new exercise series for enhanced dynamic shoulder control in the overhead throwing athlete. *The Physician and sportsmedicine*, 39(4):90–97, 2011.

[92] Winter, D. A. *Biomechanics and motor control of human movement.* John Wiley & Sons, 2009.

[93] Winter, D. A. and Robertson, D. Joint torque and energy patterns in normal gait. *Biological cybernetics*, 29(3):137–142, 1978.

[94] Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., Whittle, M., D D'Lima, D., Cristofolini, L., Witte, H., et al. Isb recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part i: ankle, hip, and spine. *Journal of biomechanics*, 35(4):543–548, 2002.

[95] Wu, G., Van der Helm, F. C., Veeger, H. D., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A. R., McQuade, K., Wang, X., et al. Isb recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—part ii: shoulder, elbow, wrist and hand. *Journal of biomechanics*, 38(5):981–992, 2005.

[96] Yu, B., Gabriel, D., Noble, L., and An, K.-N. Estimate of the optimum cutoff frequency for the butterworth low-pass digital filter. *Journal of Applied Biomechanics*, 15(3):318–329, 1999.

[97] Zatsiorsky, V. The mass and inertia characteristics of the main segments of the human body. *Biomechanics*, pages 1152–1159, 1983.

Glossary

ball release the time at which the baseball first leaves the pitcher's hand. Identified using visual inspection. Separates the acceleration and deceleration phases of the pitching motion.

catch-up phenomenon the biomechanical process by which sub-optimal mechanics in the proximal kinetic chain result in increased demands placed on distal kinetic chain segments as pitchers maintain performance.

contralateral the side of the body opposite of the throwing arm. Sometimes referred to as the *non-throwing*, or *non-dominant* side when referring to the upper extremities and *stride* side when referring to the lower extremities.

elbow energy transfer the total amount of energy (in Joules) transferred from the upper arm to the forearm across the elbow during the arm cocking phase of the pitching motion.

elbow varus torque the torque exerted by the upper arm on the forearm about the forearm's anteroposterior axis.

familywise error rate the probability of a coming to at least one false conclusion in a series of hypothesis tests.

glenohumeral internal rotation deficit a clinical presentation common in overhead throwing athletes which presents as a reduction in glenohumeral internal rotation range of motion in the throwing arm compared to the non-throwing arm.

glenoid labrum a fibrocartilaginous rim attached around the margin of the glenoid cavity. Deepens the glenoid fossa.

gravitational potential energy the energy of an object due to its position above a reference frame.

interval throwing program the portion of a rehabilitation program during which athletes begin throwing again to reintroduce sport-specific demands to the injured tissues.

ipsilateral the same side of the body as the throwing arm. Sometimes referred to as the *throwing*, or *dominant* side when referring to the upper extremities and *drive* side when referring to the lower extremities.

joint force power the rate of work done on (done by) a segment by the net joint force at a segment's endpoint.

kinetic chain a coordinated sequence of segment motions where each segment reaches its peak angular velocity in a proximal-to-distal order to maximize velocity at the distal end.

kinetic energy the energy of an object due to its linear and/or angular motion.

maximum external rotation the time at which the pitcher's ipsilateral humerus transitions from external rotation to internal rotation. Identified using local minimum of YX'Y" Euler rotation sequence. Separates the cocking and acceleration phases of the pitching motion.

maximum internal rotation the time at which the pitcher's ipsilateral humerus reaches its maximal degree of internal rotation. Identified using local maximum of YX'Y" Euler rotation sequence. Separates the deceleration and follow through phases of the pitching motion.

peak knee height the time at which the pitcher's contralateral knee reaches its maximum vertical position in the laboratory reference frame. Separates the wind-up and stride phases of the pitching motion.

range of motion the extent of movement of a joint. Most often measured in degrees.

rating of perceived exertion a frequently used quantitative measure describing the difficulty of a task. Typically measured using a 6 - 20 (Borg) or a 1 - 10 (modified Borg) scale. Used interchangeably with *intensity* in this project.

root mean squared error the average error (±) in outcome prediction for a given regression model. Can also be thought of as the standard deviation of model residuals.

rotator cuff a group of four muscles responsible for maintaining normal glenohumeral arthrokinematics. Includes the infraspinatus, supraspinatus, teres minor, and subscapularis.

segment torque power the rate of work done on (done by) a segment by the net joint torque at a segment's endpoint.

shoulder energy transfer the total amount of energy (in Joules) transferred from the thorax to the upper arm across the shoulder during the arm cocking phase of the pitching motion.

shoulder rotation torque the torque exerted by the thorax on the upper arm about the upper arm's longitudinal axis.

stride foot contact the time at which the pitcher's contralateral foot first makes contact with the ground. Identified using an in-ground force plate. Separates the stride and cocking phases of the pitching motion.

ulnar collateral ligament a thick triangular ligament at the medial aspect of the elbow connecting the distal aspect of the humerus to the proximal aspect of the ulna.

7 Appendix A: Supporting material

7.1 Model Comparison Results (Linear vs. Quadratic)

	Null	Linear	Quadratic
Intercept	63.09 (0.90)***	30.30 (1.10)***	19.31 (1.04)***
EVT		8.61 (0.08)***	15.41 (0.20)***
EVT^2			-0.87 (0.03)***
AIC	9075.20	6321.38	5512.50
BIC	9090.32	6341.55	5537.70
Log Likelihood	-4534.60	-3156.69	-2751.25
N_{throws}	1143	1143	1143
$N_{subjects}$	32	32	32
$s^2(\beta_0)$	21.19	35.55	29.52
$s^2(e)$	155.65	12.90	6.25

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$. Torques presented as 10's of Nm to improve model coefficient readability. AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; EVT = Elbow Varus Torque. Table generated using TexReg[47]

Table 7.1: Elbow Varus Torque Model Comparison

	Null	Linear	Quadratic
Intercept	63.09 (0.90)***	29.05 (1.27)***	14.26 (1.27)***
SRT		7.55 (0.08)***	14.95 (0.16)***
SRT^2			-0.78 (0.02)***
AIC	9075.20	6584.57	5350.40
BIC	9090.32	6604.73	5375.60
Log Likelihood	-4534.60	-3288.28	-2670.20
N_{throws}	1143	1143	1143
$N_{subjects}$	32	32	32
$s^2(\beta_0)$	21.19	46.85	47.30
$s^2(e)$	155.65	16.22	5.33

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$. Torques presented as 10's of Nm to improve model coefficient readability. AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; SRT = Shoulder Rotation Torque. Table generated using TexReg[47]

Table 7.2: Shoulder Rotation Torque Model Comparison

	Null	Linear	Quadratic
Intercept	63.09 (0.90)***	29.28 (0.90)***	18.10 (0.85)***
EET		2.88 (0.02)***	5.29 (0.08)***
EET^2			-0.11 (0.00)***
AIC	9075.20	6146.05	5436.79
BIC	9090.32	6166.22	5461.99
Log Likelihood	-4534.60	-3069.03	-2713.39
N_{throws}	1143	1143	1143
$N_{subjects}$	32	32	32
$s^2(\beta_0)$	21.19	23.18	17.75
$s^2(e)$	155.65	11.16	5.93

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$. Energy Transfers presented as 10's of J to improve model coefficient readability. AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; EET = Elbow Energy Transfer. Table generated using TexReg[47]

Table 7.3: Elbow Energy Transfer Model Comparison

	Null	Linear	Quadratic
Intercept	63.09 (0.90)***	30.84 (0.93)***	20.46 (0.83)***
SET		2.03 (0.02)***	3.73 (0.05)***
SET^2			-0.06 (0.00)***
AIC	9075.20	6060.35	5156.68
BIC	9090.32	6080.52	5181.89
Log Likelihood	-4534.60	-3026.18	-2573.34
N_{throws}	1143	1143	1143
$N_{subjects}$	32	32	32
$s^2(\beta_0)$	21.19	25.47	18.31
$s^2(e)$	155.65	10.30	4.60

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$. Energy Transfers presented as 10's of J to improve model coefficient readability. AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; SET = Shoulder Energy Transfer. Table generated using TexReg[47]

Table 7.4: Shoulder Energy Transfer Model Comparison

7.2 Model Comparison Results (Fixed vs. Random Slope)

	Quadratic	RS
Intercept	19.31 (1.04)***	18.97 (1.10)***
EVT	15.41 (0.20)***	15.29 (0.31)***
EVT^2	-0.87 (0.03)***	-0.82 (0.03)***
AIC	5512.50	5294.33
BIC	5537.70	5329.62
Log Likelihood	-2751.25	-2640.16
N_{throws}	1143	1143
$N_{subjects}$	32	32
$s^2(\beta_0)$	29.52	33.28
$s^2(e)$	6.25	4.73
$s^2(\beta_1)$		1.25
$cov(\beta_0, \beta_1)$		-2.10

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$. Torques presented as 10's of Nm to improve model coefficient readability. AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; EVT = Elbow Varus Torque; RS = Random Slopes. Table generated using TexReg[47]

Table 7.5: Elbow Varus Torque Model Comparison (Random Slopes)

	Quadratic	RS
Intercept	14.26 (1.27)***	15.38 (1.16)***
SRT	14.95 (0.16)***	14.11 (0.27)***
SRT^2	-0.78 (0.02)***	-0.64 (0.02)***
AIC	5350.40	4930.15
BIC	5375.60	4965.44
Log Likelihood	-2670.20	-2458.07
N_{throws}	1143	1143
$N_{subjects}$	32	32
$s^2(\beta_0)$	47.30	38.60
$s^2(e)$	5.33	3.32
$s^2(\beta_1)$		1.47
$cov(\beta_0, \beta_1)$		0.50

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$. Torques presented as 10's of Nm to improve model coefficient readability. AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; RS = Random Slopes; SRT = Shoulder Rotation Torque. Table generated using TexReg[47]

Table 7.6: Shoulder Rotation Torque Model Comparison (Random Slopes)

	Quadratic	RS
Intercept	18.10 (0.85)***	18.08 (0.82)***
EET	5.29 (0.08)***	5.21 (0.10)***
EET^2	-0.11 (0.00)***	-0.10 (0.00)***
AIC	5436.79	5145.56
BIC	5461.99	5180.85
Log Likelihood	-2713.39	-2565.78
N_{throws}	1143	1143
$N_{subjects}$	32	32
$s^2(\beta_0)$	17.75	15.52
$s^2(e)$	5.93	4.24
$s^2(\beta_1)$		0.10
$cov(\beta_0, \beta_1)$		-0.31

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$. Energy transfers presented as 10's of J to improve model coefficient readability. AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; EET = Elbow Energy Transfer; RS = Random Slopes. Table generated using TexReg[47]

Table 7.7: Elbow Energy Transfer Model Comparison (Random Slopes)

	Quadratic	RS
Intercept	20.46 (0.83)***	21.17 (0.74)***
SET	3.73 (0.05)***	3.57 (0.06)***
SET^2	-0.06 (0.00)***	-0.05 (0.00)***
AIC	5156.68	4938.83
BIC	5181.89	4974.12
Log Likelihood	-2573.34	-2462.41
N_{throws}	1143	1143
$N_{subjects}$	32	32
$s^2(\beta_0)$	18.31	13.02
$s^2(e)$	4.60	3.54
$s^2(\beta_1)$		0.04
$cov(\beta_0, \beta_1)$		-0.05

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$. Energy transfers presented as 10's of J to improve model coefficient readability. AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; RS = Random Slopes; SET = Shoulder Energy Transfer. Table generated using TexReg[47]

Table 7.8: Shoulder Energy Transfer Model Comparison (Random Slopes)

7.3 Model Comparison Results (Random Slope vs. Random Slope + Cross-Level Interaction)

	RS	RS + Mass	RS + Height	RS + Speed
Intercept	18.97 (1.10)***	18.99 (1.10)***	18.97 (1.10)***	18.95 (1.11)***
EVT	15.29 (0.31)***	15.22 (0.33)***	15.27 (0.31)***	15.30 (0.30)***
EVT^2	−0.82 (0.03)***	−0.81 (0.03)***	−0.82 (0.03)***	−0.82 (0.03)***
EVT:mass		−0.03 (0.01)***		
EVT:height			−0.05 (0.06)	
EVT:speed				0.02 (0.04)
AIC	5294.33	5289.17	5295.78	5296.09
BIC	5329.62	5329.50	5336.11	5336.42
Log Likelihood	−2640.16	−2636.58	−2639.89	−2640.04
N_{throws}	1143	1143	1143	1143
$N_{subjects}$	32	32	32	32
$s^2(\beta_0)$	33.28	32.80	33.17	33.41
$s^2(\beta_1)$	1.25	1.58	1.31	1.21
$cov(\beta_0, \beta_1)$	−2.10	−4.55	−2.54	−1.98
$s^2(e)$	4.73	4.73	4.73	4.73

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$. Torques presented as 10's of Nm to improve model coefficient readability. Level 2 variables centered around the sample mean. AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; EVT = Elbow Varus Torque; RS = Random Slopes. Table generated using TexReg.[47]

Table 7.9: Level 2 Model Comparison (Elbow Varus Torque)

	RS	RS + Mass	RS + Height	RS + Speed
Intercept	15.38 (1.16)***	15.39 (1.16)***	15.39 (1.16)***	15.37 (1.16)***
SRT	14.11 (0.27)***	14.04 (0.26)***	14.06 (0.26)***	14.11 (0.27)***
SRT^2	−0.64 (0.02)***	−0.64 (0.02)***	−0.64 (0.02)***	−0.64 (0.02)***
SRT:mass		−0.04 (0.01)***		
SRT:height			−0.16 (0.07)*	
SRT:speed				0.02 (0.05)
AIC	4930.15	4920.93	4927.29	4932.04
BIC	4965.44	4961.26	4967.62	4972.37
Log Likelihood	−2458.07	−2452.47	−2455.64	−2458.02
N_{throws}	1143	1143	1143	1143
$N_{subjects}$	32	32	32	32
$s^2(\beta_0)$	38.60	38.37	38.44	38.68
$s^2(\beta_1)$	1.47	1.21	1.29	1.45
$cov(\beta_0, \beta_1)$	0.50	−2.31	−0.58	0.56
$s^2(e)$	3.32	3.31	3.32	3.32

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$. Torques presented as 10's of Nm to improve model coefficient readability. Level 2 variables centered around the sample mean. AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; RS = Random Slopes; SRT = Shoulder Rotation Torque. Table generated using TexReg.[47]

Table 7.10: Level 2 Model Comparison (Shoulder Rotation Torque)

	RS	RS + Mass	RS + Height	RS + Speed
Intercept	18.08 (0.82)***	18.11 (0.82)***	18.12 (0.82)***	18.00 (0.83)***
EET	5.21 (0.10)***	5.18 (0.10)***	5.19 (0.10)***	5.22 (0.10)***
EET^2	−0.10 (0.00)***	−0.10 (0.00)***	−0.10 (0.00)***	−0.10 (0.00)***
EET:mass		−0.01 (0.00)***		
EET:height			−0.05 (0.02)**	
EET:speed				0.02 (0.01)
AIC	5145.56	5132.77	5140.01	5144.91
BIC	5180.85	5173.10	5180.34	5185.24
Log Likelihood	−2565.78	−2558.38	−2562.00	−2564.45
N_{throws}	1143	1143	1143	1143
$N_{subjects}$	32	32	32	32
$s^2(\beta_0)$	15.52	15.27	15.20	15.88
$s^2(\beta_1)$	0.10	0.10	0.09	0.08
$cov(\beta_0, \beta_1)$	−0.31	−0.75	−0.49	−0.18
$s^2(e)$	4.24	4.24	4.24	4.24

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$. Energy transfers presented as 10's of J to improve model coefficient readability. Level 2 variables centered around the sample mean. AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; EET = Elbow Energy Transfer; RS = Random Slopes. Table generated using TexReg.[47]

Table 7.11: Level 2 Model Comparison (Elbow Energy Transfer)

	RS	RS + Mass	RS + Height	RS + Speed
Intercept	21.17 (0.74)***	21.22 (0.74)***	21.22 (0.73)***	21.10 (0.74)***
SET	3.57 (0.06)***	3.55 (0.06)***	3.55 (0.06)***	3.58 (0.06)***
SET^2	−0.05 (0.00)***	−0.05 (0.00)***	−0.05 (0.00)***	−0.05 (0.00)***
SET:mass		−0.01 (0.00)***		
SET:height			−0.03 (0.01)**	
SET:speed				0.01 (0.01)
AIC	4938.83	4928.71	4932.76	4938.73
BIC	4974.12	4969.04	4973.10	4979.06
Log Likelihood	−2462.41	−2456.35	−2458.38	−2461.37
N_{throws}	1143	1143	1143	1143
$N_{subjects}$	32	32	32	32
$s^2(\beta_0)$	13.02	12.92	12.79	13.21
$s^2(\beta_1)$	0.04	0.03	0.03	0.03
$cov(\beta_0, \beta_1)$	−0.05	−0.32	−0.15	−0.03
$s^2(e)$	3.54	3.54	3.54	3.55

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$. Energy transfers presented as 10's of J to improve model coefficient readability. Level 2 variables centered around the sample mean. AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; RS = Random Slopes; SET = Shoulder Energy Transfer. Table generated using TexReg.[47]

Table 7.12: Level 2 Model Comparison (Shoulder Energy Transfer)

8 Appendix B: Supporting code

All supporting code for this project may be found online at https://github.com/kww-22/diss.

9 Appendix C: Example Segment Torque Power Partition

An example to illustrate the role of energy flow via STP for energy transfer, generation, and absorption between the thigh and the shank is provided in Figure 9.1. In this example, energy is flowing from the distal thigh via the JFP and STP at a rate of 44.81 W and 23.08 W, respectively. All 44.81 W leaving the distal thigh via JFP is transferred to the proximal shank. However, only 7.19 W of the STP energy flow makes it across the knee to the shank. The other 15.89 W is absorbed by the structures surrounding the knee joint. If the knee is flexing, such as during the load acceptance phase during gait, this would represent eccentric energy absorption by the knee extensors. If the knee is extending, such as during the late swing phase during gait, this would represent eccentric energy absorption by the knee flexors.[69]

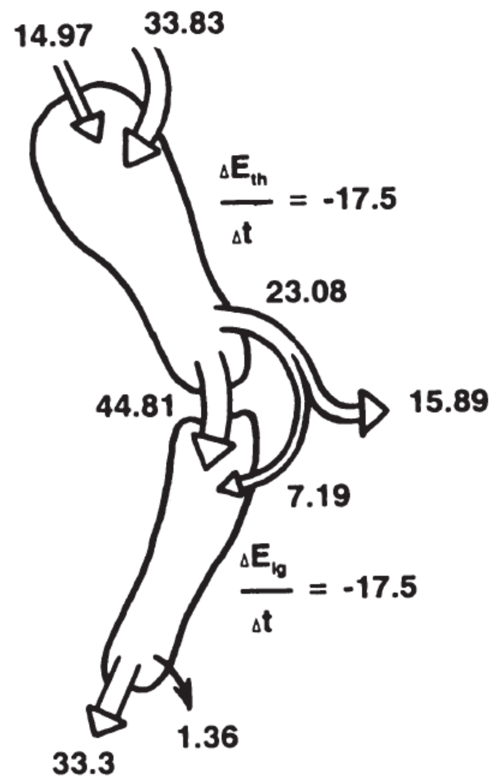

Figure 9.1: Example Energy Flow (adapted from Winter[92])

10 Appendix D: Supporting Documents

This section contains all IRB materials for this project.

SCHOOL OF
KINESIOLOGY
301 Wire Road
Auburn, AL 36849
(334) 884-4483

AUBURN UNIVERSITY

COLLEGE OF EDUCATION

(NOTE: DO NOT SIGN THIS DOCUMENT UNLESS AN IRB APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)

Auburn University
CONSENT TO PARTICIPATE IN RESEARCH
Title: The Effect of Throw Intensity of Overhead Throwing Mechanics

Explanation and Purpose of the Research
You are being asked to participate in a research study for the Sports Medicine & Movement Lab in the School of Kinesiology. Before agreeing to participate in this study, it is vital that you understand certain aspects of what might occur. This statement describes the purpose, methodology, benefits, risks, discomforts, and precautions of this research. This statement describes your right to confidentially and your right to discontinue your participation at any time during the course of this research without penalty or prejudice. No assurances or guarantees can be made concerning the results of this study.

This study is designed to examine the effects of throw intensity on overhead throwing mechanics in participants between the ages of 14 – 25 years old. Participants must be without surgery or injury for the past 6 months not currently be experiencing any ailment which would prevent them from throwing with 100% effort, and have played or be currently playing competitive baseball at the high school level.

Research Procedures
Testing for this research will require you to be dressed in compression shorts and tennis shoes. Your height, body mass, and age will be documented. Height and mass will be measured with a stadiometer and weight scale to the nearest tenth of a kilogram and centimeter. Age will be determined from this consent form and will be recorded to the nearest month.

Once these measurements have been collected, you will be allowed to perform any kind of non-throwing warm up you would typically do before throwing. After this non-throwing warm up, you will have motion capture markers placed on your legs, arms, torso, and neck with tape and allowed to complete your typical throwing warm up. Your throwing mechanics as you complete your throwing warm up will be recorded.

After you have completed your throwing warmed up, you will complete ten throws at 50% effort. Five of these throws will be performed with a crow-hop and five will be performed with a single step from standstill. You will then repeat this combination of five crow-hop and five single-step throws at 75% and 100% effort. Following the 100% effort throws, you will be offered an optional break of up to 10 minutes to minimize the risk of fatigue. During the break we will calculate your average max throw speed from the five 100% effort single-step throws. You will then complete five crow-hop and five single-step throws at 50% and 75% of your average max throw speed. You will be allowed a ±2.5% margin of error for these throws (i.e., if your average max speed was 80 miles per hour, your target for the 50% condition will be 38 – 42 miles per hour). This will take approximately two hours.

Participant Initials: _______

Potential Risks
As with any movement research, certain risks and discomforts may arise. The possible risks and discomforts associated with this study are no greater than those involved in competitive baseball and may include muscle strain, muscle soreness, ligament, labral, and tendon damage to the throwing arm. Every effort will be made to minimize these risks and discomforts by selecting participants who are currently playing the position of pitcher competitively. It is your responsibility, as a participant, to inform the investigators if you notice any indications of injury or fatigue or feel symptoms of any other possible complications that might occur during testing.

Due to the need for your physical presence at the research site, face to face interaction with the researcher or others, etc., there is a risk that your child may be exposed to COVID-19 and the possibility that your child may contract the virus. For most people, COVID-19 causes only mild or moderate symptoms. For some, especially older adults and people with existing health problems, it can cause more severe illness. Current information suggests that about 1-3% of people who are infected with COVID-19 might die as a result. Your child will need to review the Information on COVID-19 for Research Participants that is attached to this consent document. To minimize your child's risk of exposure any investigator who needs to come closer than 6 feet in contact with the participant will wear the appropriate personal protective equipment (PPE) of a face mask, eye protection, gloves (discarded after each participant), and lab coat (discarded after each participant). Additionally, all research equipment that will come in contact with the participant will be decontaminated BEFORE and AFTER each participant with EPA approved disinfectant. Participants will be required to wear a cloth mask while researchers are within 6 feet. These procedures will be enforced while the Human Research Protection Program requires additional safety measures due to COVID-19. To reduce the risk of injury, certain precautions will be taken. Ample warm-up and cool-down periods will be required of you, and water will be provided to you as needed.

Confidentiality
All information gathered in completing this study will remain confidential. Your individual performance will not be made available for public use and will not be disclosed to any person(s) outside of the research team. The results of this study may be published as scientific research. Your name or identity shall not be revealed should such publication occur. The researcher will try to prevent any problem that could happen because of this research. If at any time there is a problem you should let the researcher know and he or she will help you. Should an emergency arise, we will call 911 and follow our Emergency Action Plan. You are responsible for any cost associated with medical assistance.

Participation and Benefits
Participation in this research is strictly voluntary and refusal to participate will result in no penalty. If you change your mind about participating, you can withdraw at any time during the study. Your participation is completely voluntary. If you choose to withdraw, your data can be withdrawn as long as it is identifiable. Your decision about whether or not to participate or to stop participating will not jeopardize your future relations with Auburn University or the School of Kinesiology.

By participating in this study, you will receive information regarding appropriate age-related pitch counts that may help prevent injury. This will allow you the opportunity to alter your training programs in an effort to minimize injury resulting from fatigue. By receiving this information, you and your parent(s)/legal guardian(s) may be able to better determine the proper length of the pitching performance.

Participant Initials _________

Questions Regarding the Study
If you have questions about this study, please ask them now. If you have questions later you may contact Kyle Wasserberger by phone 616 502 4969, or email at kww0009@auburn.edu.

If you have any questions about your rights as a research participant, you may contact the Auburn University Office of Research Compliance or the Institutional Review Board by phone (334)-844-5966 or email at irbadmin@auburn.edu or IRBChair@auburn.edu.

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.

____ ________________
Printed Name of Participant Date of Birth

____ ________________
Signature of Participant Date

The above consent form was read, discussed, and signed in my presence. In my opinion, the person signing said consent form did so freely and with full knowledge of its contents.

____ ________________
Signature of Investigator Date

Information on COVID-19 For Research Participants

Auburn University recognizes the essential role of research participants in the advancement of science and innovation for our university, community, state, nation, and beyond. Therefore, protection of those who volunteer to participate in Auburn University research is of utmost importance to our institution.

As you are likely aware, COVID-19 references the Coronavirus that is being spread around the world including in our country, state, and community. It is important that we provide you with basic information about COVID-19 and the risks associated with the virus so that you can determine if you wish to participate or continue your participation in human research.

How is COVID-19 spread? COVID-19 is a respiratory virus that is spread by respiratory droplets, mainly from person-to person. This can happen between people who are in close contact with one another. It is also possible that a person can get COVID-19 by touching a surface or object (such as a doorknob or counter surface) that has the virus on it, then touching their mouth, nose, or eyes.

Can COVID-19 be prevented? Although there is no guarantee that infection from COVID-19 can be prevented and no vaccine is currently available, there are ways to minimize the risk of exposure to the virus. Examples include but are not limited to, "social distancing" where individuals physically distance themselves from others (a minimum of 6 feet is often used as a standard distance); using effective barriers between persons; wearing personal protective equipment like masks, gloves, etc.; washing hands with soap and water or sanitizing hands after touching objects; disinfecting objects touched by multiple individuals, etc.

What are the risks of COVID-19? For most people, COVID-19 causes only mild or moderate symptoms, such as fever and cough. For some, especially older adults and people with existing health problems, it can cause more severe illness. While everyone is still learning about this virus, current information suggests that about 1-3% of people who are infected with COVID-19 might die as a result.

Who is most at risk? Individuals over age 65 and those with chronic conditions such as cancer, diabetes, heart or lung or liver disease, severe obesity, and conditions that cause a person to be immunocompromised have the highest rates of severe disease and serious complications from infection.

What precautions should be taken? Based on the proposed research, precautions for the risk of COVID-19 will be addressed on a project by project basis. You will be provided with information about precautions for the project in which you may participate. Any site where research activities will occur that are not a part of Auburn University (offsite location) are expected to have standard procedures for addressing the risk of COVID-19. It is important for participants to follow any precautions or procedures outlined by Auburn University and, when applicable, offsite locations. Further, participants will need to determine how best to address the risk of COVID-19 when traveling to and from research locations. The US Center for Disease Control and Prevention has issued recommendations on types of prevention measures you can use to reduce your risk of exposure and the spread of COVID-19.

Auburn University is continuing to monitor the latest information on COVID-19 to protect our students, employees, visitors, and community. Our research study teams will update participants as appropriate. If you have specific questions or concerns about COVID-19 or your participation in research, please talk with your study team. The name and contact information for the study team leader, along with contact information for the Auburn University Institutional Review Board for Protection of Human Research Participants, can be found in the consent document provided to you by the study team.

SC H O O L O F K I N ESI O LO G Y
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AUBURN UNIVERSITY
COLLEGE OF EDUCATION

(NOTE: DO NOT SIGN THIS DOCUMENT UNLESS AN IRB APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)

PARENTAL PERMISSION & MINOR ASSENT for a Research Study entitled
"The Effect of Throw Intensity on Overhead Throwing Mechanics"

Explanation and Purpose of the Research

Your child is being asked to participate in a research study for the Sports Medicine & Movement Lab in the School of Kinesiology. Before agreeing to participate in this study, it is vital that you (and your child) understand certain aspects of what might occur. This statement describes the purpose, methodology, benefits, risks, discomforts, and precautions of this research. This statement describes your child's right to confidentially and your child's right to discontinue your child's participation at any time during the course of this research without penalty or prejudice. No assurances or guarantees can be made concerning the results of this study.

This study is designed to examine the effects of throw intensity on overhead throwing mechanics in participants between the ages of 14 – 25. Participants must be without surgery or injury for the past 6 months not currently be experiencing any ailment which would prevent them from throwing with 100% effort, and have played or be currently playing competitive baseball at the high school level.

Research Procedures

Testing for this research will require your child to be dressed in compression shorts and tennis shoes. Your child's height, body mass, and age will be documented. Height and mass will be measured with a stadiometer and weight scale and will be recorded to the nearest tenth of a kilogram and centimeter. Age will be determined from this consent form and will be recorded to the nearest month.

Once these measurements have been collected, your child will be allowed to perform any kind of non-throwing warm up they would typically do before throwing. After this non-throwing warm up, your child will have motion capture markers placed on your legs, arms, torso, and neck with tape and allowed to complete their typical throwing warm up. Your child's throwing mechanics as they complete their throwing warm up will be recorded.

Parent (Legal Guardian) Initials: _________

Participants Initials: _______

After your child has completed their throwing warmed up, they will complete ten throws at 50% effort. Five of these throws will be performed with a crow-hop and five will be performed with a single step from standstill. They will then repeat this combination of five crow-hop and five single-step throws at 75% and 100% effort. Following the 100% effort throws, they will be offered an optional break of up to 10 minutes to minimize the risk of fatigue. During the break we will calculate their average max throw speed from the five 100% effort single-step throws. They will then complete five crow-hop and five single-step throws at 50% and 75% of their average max throw speed. They will be allowed a ±2.5% margin of error for these throws (i.e., if the average max speed was 80 miles per hour, the target for the 50% condition will be 38 – 42 miles per hour). This will take approximately two hours.

Potential Risks

As with any movement research, certain risks and discomforts may arise. The possible risks and discomforts associated with this study are no greater than those involved in competitive baseball and may include muscle strain, muscle soreness, ligament, labral, and tendon damage to the throwing arm. Every effort will be made to minimize these risks and discomforts by selecting participants who are currently playing the position of pitcher competitively. It is your child's responsibility, as a participant, to inform the investigators if your child notices any indications of injury or fatigue or feel symptoms of any other possible complications that might occur during testing.

Due to the need for your child's physical presence at the research site, face to face interaction with the researcher or others, etc., there is a risk that your child may be exposed to COVID-19 and the possibility that your child may contract the virus. For most people, COVID-19 causes only mild or moderate symptoms. For some, especially older adults and people with existing health problems, it can cause more severe illness. Current information suggests that about 1-3% of people who are infected with COVID-19 might die as a result. Your child will need to review the Information on COVID-19 for Research Participants that is attached to this consent document. To minimize your child's risk of exposure any investigator who needs to come closer than 6 feet in contact with the participant will wear the appropriate personal protective equipment (PPE) of a face mask, eye protection, gloves (discarded after each participant), and lab coat (discarded after each participant). Additionally, all research equipment that will come in contact with the participant will be decontaminated BEFORE and AFTER each participant with EPA approved disinfectant. Participants will be required to wear a cloth mask while researchers are within 6 feet. These procedures will be enforced while the Human Research Protection Program requires additional safety measures due to COVID-19.

To reduce the risk of injury, certain precautions will be taken. Ample warm-up and cool-down periods will be required of your child, and water will be provided to your child as needed.

Parent (Legal Guardian) Initials: _________

Participants Initials: _______

Confidentiality

All information gathered in completing this study will remain confidential. Your child's individual performance will not be made available for public use and will not be disclosed to any person(s) outside of the research team. The results of this study may be published as scientific research. your child's name or identity shall not be revealed should such publication occur. The researcher will try to prevent any problem that could happen because of this research. If at any time there is a problem your child should let the researcher know and he or she will help Your child. Should an emergency arise, we will call 911 and follow our Emergency Action Plan. You are responsible for any cost associated with medical assistance.

Participation and Benefits

Participation in this research is strictly voluntary and refusal to participate will result in no penalty. Your child will be allowed to withdraw consent and discontinue their participation in this research at any time; without bias or prejudice from Auburn University Department of Kinesiology or the Sports Medicine and Movement group. In the unlikely event that you sustain an injury from participation in this study, the investigators have no current plans to provide funds for any medical expenses or other costs you may incur.

By participating in this study, your child will receive information regarding appropriate age-related pitch counts that may help prevent injury. This will allow you the opportunity to alter their training programs in an effort to minimize injury resulting from fatigue. By receiving this information, you may be able to better determine the proper length of the pitching performance.

Questions Regarding the Study

If you have questions about this study, please ask them now. If you have questions later, you may contact Kyle Wasserberger at 616 502 4969 or email at kww0009@auburn.edu

If you have any questions about your child's rights as a research participant, you may contact the Auburn University Office of Research Compliance or the Institutional Review Board by phone (334)-844-5966 or email at irbadmin@auburn.edu or IRBChair@auburn.edu

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOU SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.

____
Printed Name of Participant

______ yr. ______ mo.
Age of Participant

____
Printed Name of Parent of Participant

____
Date

____
Signature of Parent

The above consent form was read, discussed, and signed in my presence. In my opinion, the person signing said consent form did so freely and with full knowledge of its contents.

____
Signature of Investigator

____
Date

Information on COVID-19 For Research Participants

Auburn University recognizes the essential role of research participants in the advancement of science and innovation for our university, community, state, nation, and beyond. Therefore, protection of those who volunteer to participate in Auburn University research is of utmost importance to our institution.

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Can COVID-19 be prevented? Although there is no guarantee that infection from COVID-19 can be prevented and no vaccine is currently available, there are ways to minimize the risk of exposure to the virus. Examples include but are not limited to, “social distancing” where individuals physically distance themselves from others (a minimum of 6 feet is often used as a standard distance); using effective barriers between persons; wearing personal protective equipment like masks, gloves, etc.; washing hands with soap and water or sanitizing hands after touching objects; disinfecting objects touched by multiple individuals, etc.
What are the risks of COVID-19? For most people, COVID-19 causes only mild or moderate symptoms, such as fever and cough. For some, especially older adults and people with existing health problems, it can cause more severe illness. While everyone is still learning about this virus, current information suggests that about 1-3% of people who are infected with COVID-19 might die as a result.
Who is most at risk? Individuals over age 65 and those with chronic conditions such as cancer, diabetes, heart or lung or liver disease, severe obesity, and conditions that cause a person to be immunocompromised have the highest rates of severe disease and serious complications from infection.
What precautions should be taken? Based on the proposed research, precautions for the risk of COVID-19 will be addressed on a project by project basis. You will be provided with information about precautions for the project in which you may participate. Any site where research activities will occur that are not a part of Auburn University (offsite location) are expected to have standard procedures for addressing the risk of COVID-19. It is important for participants to follow any precautions or procedures outlined by Auburn University and, when applicable, offsite locations. Further, participants will need to determine how best to address the risk of COVID-19 when traveling to and from research locations. The US Center for Disease Control and Prevention has issued recommendations on types of prevention measures you can use to reduce your risk of exposure and the spread of COVID-19.

Auburn University is continuing to monitor the latest information on COVID-19 to protect our students, employees, visitors, and community. Our research study teams will update participants as appropriate. If you have specific questions or concerns about COVID-19 or your participation in research, please talk with your study team. The name and contact information for the study team leader, along with contact information for the Auburn University Institutional Review Board for Protection of Human Research Participants, can be found in the consent document provided to you by the study team.

Participant ID: ______________________ Date: ________ Mass (kg): ________ Height (m): _______

RMS ERROR: Lshldr: ______ ________ ________ ________ _______

Rshldr: ______ ________ ________ ________ _______

Max Speed from 100e condition: ______ Low V: ______ High V: ______ Throw Hand: L / R

Normal Warm Up

#	Velo (mph)	#	Velo (mph)
1		28	
2		29	
3		30	
4		31	
5		32	
6		33	
7		34	
8		35	
9		36	
10		37	
11		38	
12		39	
13		40	
14		41	
15		42	
16		43	
17		44	
18		45	
19		46	
20		47	
21		48	
22		49	
23		50	
24		51	
25		52	
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