The Effects of Body Composition on Female Softball Pitching Biomechanics

by

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A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
December 12, 2020

Keywords: biomechanics, softball, body composition, performance, pitching

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Abstract

Additional mass is often considered beneficial for softball pitching performance; however, there may be adverse effects of increased body mass and body fat on softball pitching biomechanics. The purpose of this project was to identify the effects of segmental and whole body fat percentage (BF%) on softball pitchers' kinematics, kinetics, and pitch velocity. High school and collegiate softball pitchers were recruited to participate. Pitchers completed all consent and health history forms, then underwent a full-body dual-energy x-ray absorptiometry scan. Pitchers then completed ten full effort fastball pitches; the first three fastest strikes were averaged and used for analysis. Kinematic and kinetic data were captured using an electromagnetic system and an in-ground force plate synced with motion analysis software, The MotionMonitor (Innovative Sports Training, Chicago, IL). Pitchers were grouped into healthy-fat% (<32 BF%) and high-fat% (>=32 BF%) categories. Results indicated healthy-fat% pitchers displayed increased peak medial GRF ($p < .05$) during pitch propulsion. Additionally, whole-body fat mass, whole-body lean mass, and throwing arm lean mass were associated with increased peak throwing shoulder distraction force ($p < .05$), and BF% was negatively associated with pitch velocity ($F_{4,42} = 4.23$, $p = .006$). Also, increased segmental girth was correlated with decreased shoulder plane of elevation at ball release ($p < .05$). Lastly, increased elbow and wrist flexion velocity were associated with increased pitch velocity ($p < .05$), while statistical parametric mapping revealed differences in time series segmental angular velocities between pitcher groups ($p < .05$). Biomechanical differences exist in the softball pitch according to pitcher body fat percentage. While attaining a healthy body composition is suggested for young softball pitchers, more research is necessary to develop how biomechanical alterations according to pitcher body composition may benefit or inhibit performance variables and injury risk factors.

Acknowledgments

I want to thank my mentor, Dr. Gretchen Oliver, who has continually pushed me to be better every day than I was the day before. Her constant support and guidance throughout the last few years have encouraged me to strive for more. I'd also like to thank each member of my dissertation committee, Dr. Wendi Weimar, Dr. Jaimie Roper, and Dr. David Shannon, for their assistance throughout my degree and dissertation. I have valued each committee member's expertise and commitment to sound research. I know that I am a better researcher because of their teachings and dedication to growing young scientists. I'd also like to thank Dr. Silvia Vilches for volunteering as my outside reader, as well as the Director of the School of Kinesiology, Dr. Mary Rudisill, for her continuous support.

I would also like to acknowledge each member of the Sports Medicine and Movement Laboratory, including Jessica Downs, Kyle Wasserberger, Kevin Giordano, Nicole Bordelon, Abby Brittain, and Anthony Fava. I am grateful for their assistance with data collections and for the experience of being teammates, research colleagues, and friends. I will always cherish the laughable moments and memories made in the lab.

Lastly, I would like to thank my wonderful family, who has offered support and encouragement throughout the last 8.5 years of college. Although I was geographically far from home, morning texts, prayers, and plenty of FaceTime calls with my loved ones helped me push through the most challenging days. Their constant reminder to "fix [my] eyes not on what is seen, but on what is unseen" has helped me remain grounded in love and truth.

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List of Abbreviations

BF%	Body Fat Percentage
BMI	Body Mass Index
GRF	Ground Reaction Force
NCAA	National Collegiate Athletic Association
BW	Body Weight
ROM	Range of Motion
iDXA	Dual-Energy X-Ray Absorptiometry
SEM	Standard Error of Measurement
RMS	Root Mean Square
MANOVA	Multivariate Analysis of Variance
MANCOVA	Multivariate Analysis of Covariance
SPM	Statistical Parametric Mapping
WB	Whole-body
TA	Throwing Arm
POE	Plane of Elevation
mph	Miles Per Hour
sd	Standard Deviation
EM	Event Mark
FC	Foot Contact
BR	Ball Release
RQ	Research Question

List of Symbols

Symbol	**Description (Unit)**
F	Force (N)
m	Mass (kg)
a	Linear Acceleration (m/s^2)
d	Distance (m)
r	Radius (m)
θ	Angle (º)
τ	Torque (Nm)
I	Mass Moment of Inertia (kgm^2)
k	Radius of Gyration (m)
M	Moment (Nm)
α	Angular Acceleration (rad/s^2)
p	Momentum (kgm/s)
v	Linear Velocity (m/s)
$\mathbf{L_s}$	Segmental Angular Momentum (kgm^2/s)
ω	Angular Velocity (rad/s)
Hz	Hertz (cycles/s)
n	Participant Sample
X2	SPM MANOVA
$\mathbf{V^{(s)}}$	Pillai's Trace
$\boldsymbol{\eta^2_p}$	Partial Eta-Squared
r	Correlation Coefficient

List of Symbols (continued)

Symbol	Description (Unit)
$\mathbf{R^2}$	Coefficient of Determination
SE	Standard Error
p	Alpha Level of Significance
B	Unstandardized Regression Coefficient
β	Standardized Regression Coefficient
SE_{skew}	Standard Error of Skewness
SE_{kurt}	Standard Error of Kurtosis

CHAPTER I

INTRODUCTION

Obesity is a persistent problem among all age groups in North America, and trends of a sedentary and obese population are steadily increasing (Lobstein & Jackson-Leach, 2016; Lobstein & Jacskon-Leach, 2007; McGuire et al., 2011; Soloman, 2019). Data from the National Health and Nutrition Examination Survey show that during 2017-2018, the age-adjusted prevalence of obesity in adults was 42.4%. From 1999-2000 through 2017-2018, the prevalence of obesity has continued to rise in adults (Hales et al., 2020). The prevalence of obesity in youth aged 12-19 years during 2015-2016 was 20.6% (Hales et al., 2017; Hales et al., 2018). While the effects of obesity create widespread health concerns, obesity is also cause for concern from a sports medicine perspective.

With the high prevalence of obesity among youth and young adults, obesity also gives rise to an increased risk of sport injury among athletes (Emery, 2003; Rose et al., 2008). Research shows a curvilinear relationship between body mass index (BMI) and sports-related injury (Rose et al., 2008). Specifically, inadequate body strength has been related to injury susceptibility in overweight individuals. Sufficient strength is required, mainly during weight-bearing activities, to control the body mass safely through the sport motion (McHugh, 2010). Additionally, BMI has been suggested to be a risk factor in overuse injuries due to the higher relative strain on the musculoskeletal system during repetitious tasks (Heir & Eide, 1996).

Softball pitching is already a highly repetitive and strenuous movement (Skillington et al., 2017). In response to the demanding nature of pitching, musculoskeletal and range of motion adaptations are regularly reported (Ellenbecker et al., 2007; Robb et al., 2010; Scher et al., 2010; Shanley et al., 2011). Specific to softball pitching, research has found pitchers with increased BMI display decreased internal rotational hip range of motion (Friesen et al., 2020). While the whole body is required to sequentially transfer energy from the lower extremity to the upper extremity, lack of range of motion of the hips may inhibit this proximodistal pattern of energy transfer and therefore place additional stress on the more distal components of the kinetic chain (Kibler & Sciascia, 2016).

Efficient use of the kinetic chain is essential in the full-body windmill softball pitch. As is the case with both the tennis serve (Kibler, 1995) and the baseball pitch (Hirashima et al., 2002), there is a general pattern of force development from the ground, through the core, and to the most distal segments including the wrist, hand, and ball (Kibler et al., 2006; Oliver et al., 2010). Softball research has noted that segmental sequencing is more prevalent within elite pitchers than youth (Oliver et al., 2010). This finding highlights elite softball pitchers' ability to effectively use proximal to distal sequencing, specifically by using the lower extremity to generate force and transfer energy up through the kinetic chain. The summation of speed principle highlights this phenomenon and explains why the most distal segments within the kinetic chain are the fastest-moving (Bunn, 1972). As a result, force generation via ground reaction force (GRF) plays an important role in softball pitching.

The majority of studies examining GRF in softball pitchers have identified traits upon foot contact, noting pitchers exhibit an immediate peak in landing foot GRF in the vertical, medial, and posterior directions which dissipates throughout the acceleration and delivery phases of the pitch (Guido et al., 2009; Oliver & Plummer, 2011). Little research to date has focused on the push leg during the propulsive phase of the windmill pitch. However, a recent report shows magnitude and timing of GRF in softball pitching propulsion corresponds to pitch velocity (Nimphius et al., 2016). Therefore, the force-time curve during the propulsion of the pitch is important to understand and may offer insight to pitchers' injury susceptibility and performance.

With the windmill pitch being of intense nature and involving a high mechanical load, the upper extremity is especially vulnerable to injury. During pitching, the throwing arm shoulder has been reported to withstand distraction forces near 100% of body weight (Barrentine et al., 1998; Werner et al., 2006). Understandably so, the upper extremity is commonly injured in softball pitchers (Loosli et al., 1992; Oliver et al., 2019; Smith et al., 2015; Valier et al., 2020), with overuse being cited as an overriding factor related to injury (Hill et al., 2004).

Due to the high-injury rates reported among softball pitchers, recent efforts have been made to understand the relationship between pitch biomechanics and injury. Trunk kinematics during foot contact and ball release are associated with upper extremity pain, as well as having a posteriorly shifted center of mass and greater throwing arm horizontal abduction at foot contact (Oliver et al., 2019; Oliver et al., 2018). Likewise, an examination of kinetics and pain suggests that increased throwing shoulder distraction force is related to increased upper extremity pain (Oliver et al., 2018). Further, specific pitching biomechanics associated with injury are more prevalent in those pitchers with a high BMI (Friesen et al., 2020). With softball pitching already placing the body at excessive risk of overuse injury (Hill et al., 2004), increased BMI and body weight may further exacerbate softball pitchers' injury risk.

Although BMI may lead to an increased risk of injury, an anecdotal observation notes many of the best softball pitchers are of larger stature. A recent study showed that pitchers exhibited the highest body fat percentages on collegiate softball teams (Czeck et al., 2019) and were the only players to increase body fat percentage throughout the season (Peart et al., 2018).

Though this is likely not intentional, the question remains, does increased body weight and body fat positively influence pitching performance? While baseball has been deemed ‘America’s past-time’ (Szymanski & Zimbalist, 2006), it has also been referred to as ‘a fat man’s game’ (Levitan, 2014). With the increasing prevalence of obesity in America, it may be no wonder we continually see some of the largest athletes becoming successful baseball and softball pitchers. Likewise, the rising rates of obesity may also contribute to the high injury rates noted among pitchers. Understanding the risks and rewards of additional mass and body fat on softball pitching biomechanics may provide athletes, coaches, and clinicians with information regarding training and coaching strategy to ideally decrease injury risk and increase sport performance.

Purpose, Significance, and Hypotheses

Purpose

The purpose of this project was to identify the influence of whole-body and segmental composition on softball pitchers' kinematics, kinetics, and pitch velocity. Specifically, this project aimed to examine the relationship of body fat percentage with propulsive phase force production, peak throwing shoulder distraction force, segmental sequencing, and pitch velocity. Upper arm, chest, waist, and hip girth were also compared with trunk and throwing arm positioning at ball release of the pitch.

Significance

Understanding the effects of body composition on softball pitching biomechanics is pertinent in helping softball pitchers maintain health, athletic longevity and improve performance while decreasing the risk of injury. Results will also have implications regarding the effects of body composition in athletes across a variety of sports.

Research Questions

RQ1: Do pitchers with a high-fat% display a force-time curve during the propulsive phase different from pitchers who have a healthy-fat%?

RQ2: Is pitcher whole-body composition and throwing arm segmental composition correlated with peak throwing shoulder distraction force during the acceleration phase of the pitch?

RQ3: Are whole-body composition measures associated with pitch velocity?

RQ4: Do pitchers' upper arm, chest, waist, and hip girth correlate with trunk and throwing arm position at ball release of the pitch?

RQ5: Do peak angular velocity trunk rotation, shoulder flexion, elbow flexion, and wrist flexion correlate with pitch velocity, and do time series plots of segmental angular velocities differ between pitchers who have a high-fat% and a healthy-fat%?

Hypotheses

H1: Pitchers with a high-fat% will display higher peak vertical GRF and a longer time of force development during the propulsive phase of the pitch.

H2: Whole-body fat mass and throwing arm segmental fat mass will both be positively correlated with peak throwing shoulder distraction force during the acceleration phase of the pitch.

H3: Whole-body composition measures will be positively correlated with pitch velocity.

H4: Increased pitchers' upper arm, chest, waist, and hip girth will be correlated with decreased trunk rotation, increased trunk flexion, and increased lateral flexion towards the throwing arm side, as well as increased shoulder plane of elevation and increased elevation at ball release of the pitch.

H5: Peak segmental angular velocities will be positively correlated with pitch velocity. Pitcher body-fat percentage groups will display altered segmental angular velocities during the pitch.

Limitations

The limitations of this study include:

1) Identification of bony landmarks is more difficult on individuals with large amounts of adipose tissue.

2) Study design excludes participant recruitment according to pitchers' body composition and size.

3) There is typically high variation between pitching style and skill within high school and collegiate pitchers.

4) Injury outcomes were not assessed.

Delimitations

The delimitations of this study include:

1) All data collections were executed in a controlled laboratory setting in the Auburn University Sports Medicine and Movement Laboratory.

2) Pitchers began the pitch with their push foot on the front edge of the force plate and it was required that the pitchers keep their stride foot off of the force plate.

3) Kinetics were calculated using inverse dynamics.

4) The sample demographic included female pitchers aged 14-23 years.

CHAPTER II

REVIEW OF LITERATURE

The purpose of this project was to identify the influence of whole-body and segmental composition on softball pitchers' kinematics, kinetics, and pitch velocity. The project objective was to understand how body mass and body fat may benefit or inhibit performance variables such as force generation capabilities and pitch velocity, as well as provide information regarding injury risk-factors. The following section gives an overview of the current available literature regarding softball pitchers' body composition, injury prevalence, risk factors, as well as general pitching biomechanics and performance indicators. The literature review is divided into seven sections, including: 1) Softball Origin and Participation, 2) Overuse and Fatigue, 3) Injury Incidence, 4) Softball Kinematics, 5) Softball Kinetics, 6) Body Composition in Softball, and 7) a Summary.

Softball Origin and Participation

The sport of softball first began in 1887 in Chicago, Illinois (Briskin, 2012). Fast-forward to the 1930s, softball's first organized governing body was formed, the Amateur Softball Association. In 1972, when Title IX was passed, softball was further expanded into the collegiate setting, and not long after, softball was introduced into the 1996 Olympic games in Atlanta, Georgia (Hill et al., 2004; Nutt, 1998). Consequently, the sport gained respect and popularity thus helping to grow the game. As a result, softball remains a popular sport today.

The number of softball athletes has reportedly doubled in the last two decades (Axe et al., 2002; Werner et al., 2006). In 2010, the Amateur Softball Association was comprised of 1.2 million female softball athletes (Krajnik et al., 2010). For children aged 6-12 years old, there was a reported 359,000 kids regularly competing in softball (Soloman, 2019). At the high school level, there was an estimated 362,000 athlete participants during the 2018-2019 school year in the United States (NFHS, 2019). Despite other sports experiencing a decline in team sport participation, softball participation continues to grow (Soloman, 2019).

Other sports experiencing a decrease in sport participation may result from sports specialization and athletes choosing to pursue one sport at the expense of others. Sport specialization has become a recent craze as Americans have caught hold of a recently published idea called the '10,000-hour rule.' The '10,000-hour rule' states that one needs to practice 10,000 hours to become an expert in a particular skill (Gladwell, 2008). This rule has been demonstrated by well-known athletes such as Tiger Woods and the Williams sisters. These athletes' success stories began with a strong childhood work ethic involving many hours dedicated to one specific sport, propelling them into world-renowned and successful athletes. These mantras and success stories of young, famous athletes have caught the eye of big-dreaming kids and wishful parents. Like many other sports, softball now has year-round participation, with the sport returning to its roots as an indoor game during the colder months of the year (Briskin, 2012). The increase in year-round sport participation creates issues surrounding overuse and lack of a real off-season and rest period for softball athletes.

With softball participation taking place year-round, it makes sense that some of the most skilled athletes would become accustomed to one sport and one position. Pitchers are especially susceptible to becoming one-dimensional athletes, as the best pitchers are often encouraged to focus only on pitching. With such great emphasis placed solely on pitching, pitchers often lose the notion that well-rounded athletic development is beneficial. Additionally, it is common for the pitchers on a softball or baseball team to be the largest and least physically fit. A recent study shows that pitchers have the highest body fat percentage on collegiate softball teams (Czeck et al., 2019).

Overuse and Fatigue

Unlike many pitch count restrictions in place throughout baseball leagues, only one governing body within softball has implemented pitch count limits, this being the Little League of Softball (Briskin, 2012). Within this league, pitchers are mandated rest days, and number of innings pitched is restricted. These pitch count restrictions are contrary to the majority of leagues that do not impose such limits. Consequently, it is common for pitchers to pitch multiple games in a day and to regularly pitch back-to-back days (Lear & Patel, 2016; Skillington et al., 2017; Werner et al., 2005). While most baseball teams carry a roster of at least ten pitchers, softball teams have much fewer pitchers, usually no more than five, and many softball teams rely heavily on one or two of those pitchers to throw the majority of a season's innings (Oliver et al., 2019; Skillington et al., 2017; Werner et al., 2006). Besides increased specialization of sport, softball pitchers also tend to play across several leagues at a time, often with high school and travel ball leagues intertwining season of play. Multiple league play further increases the risk to softball pitchers in not acquiring the adequate rest and recovery that should partner such a highly-ballistic skill.

Understandably so, fatigue and overuse are common threats to many of the best pitchers. Some prior studies have examined the effects of single-game effort and fatigue. While minimal results have shown single-game exposure affects fatigue (Oliver et al., 2019; Yang et al., 2016), whole season effort has been highly correlated with fatigue in terms of strength measures of the upper extremity (Yang et al., 2016). Similarly, pain ratings also increase throughout a season (Yang et al., 2016). Comparably, others have found fatigue and pain to increase even over a day of tournament play (Skillington et al., 2017). Although these prior studies did not link body mass index (BMI) with pain or fatigue ratings, it is common for athletes with a higher body fat percentage to be considered less conditioned and potentially more susceptible to fatigue.

Injury Incidence

Although much of the upper extremity sports literature has focused on the injury rates in baseball, softball has more recently come into the spotlight. Understanding the nature of the game of softball, and the high demand placed on softball pitchers, the sport of softball has acquired current interest. Reports have noted injury rates among softball players are comparable to those reported within baseball players (Knowles et al., 2006).

An initial report to stir interest was completed during the 1989 Women's National Collegiate Athletics Association (NCAA) Division I College World Series tournament. Loosli et al. (1992) reported 26 injuries and complaints in 20 of 24 pitchers included in their sample of collegiate pitchers. Seventeen of the above injuries involved the upper extremity, while 9 of the 11 time-loss injuries were specific to the shoulder (Loosli et al., 1992). This preliminary report jump-started a cascade of injury prevalence research in softball, with subsequent reports adding to the growing research supporting the high prevalence of upper extremity injury. A broad consensus has reported that pitchers' most common time loss injuries involved the throwing shoulder (Meyers et al., 2001; Sauers et al., 2011; Smith et al., 2015; Valier et al., 2020).

Specifically, Smith et al. (2015) found that of 18 youth pitchers who were injured, 61% of injuries involved the shoulder (Smith et al., 2015) while Sauers et al. (2011) reported the most common site of arm-time loss injury (81%) was the shoulder (Sauers et al., 2011). These examples reveal the high rate of shoulder injury among softball pitchers.

Injury rate studies which include all team members, including positional players, also report considerably high injury rates. Within a sample of NCAA softball players, there was a reported overall injury rate near 4.3 injuries per 1000 athlete exposures (Marshall et al., 2007), and within a sample of high school softball players there was an overall injury rate of 7.56 injuries per 1000 athlete exposures (Valier et al., 2020). When examining upper extremity injury rate within a sample of collegiate softball athletes, upper extremity injuries represented approximately 33% of all injuries (Marshall et al., 2007), while a similar report noted 27.4% of all softball-related injuries involved the upper extremity (Valier et al., 2020). A recent study revealed the shoulder injury rate for high school softball players between 2005-2006 and 2016-2017 was 1.14 injuries per 10,000 athlete exposures (Oliver et al., 2019).

Of interest is the reason behind the high-injury rates. Most injuries sustained by specifically softball pitchers involved strains and muscular injury (Lear & Patel, 2016; Valier et al., 2020). While the ballistic motion of the windmill pitch is recognized for placing a large amount of stress on the shoulder, some reports have stated overuse plays a large role in the etiology of injury (Hill et al., 2004; Oliver et al., 2019; Olsen et al., 2006). Hill (2004) examined collegiate softball pitchers and noted that 92 of 131 injuries were considered chronic, having developed from overuse. Of the injuries recorded to be from overuse, 33 involved the shoulder, and 9 involved the elbow (Hill et al., 2004). Another report showed that of 181 NCAA softball pitchers surveyed in 2007, 25% of their injuries were categorized as being chronic and due to overuse (Marshall et al., 2007). Most recently, half of the shoulder and elbow injuries recorded within high school softball players between 2005-06 and 2015-17 were due to a chronic and overuse mechanism (Oliver et al., 2019). Thus, more attention and research is needed to decrease injury prevalence and susceptibility among softball athletes, especially as it pertains to overuse.

Timing of injury is also of interest. Previous reports have shown that 78% of the pitching-related injuries occurred during the first six weeks of the season, possibly lending to deconditioning or perhaps a sudden and substantial increase in pitching volume as the cause of injury (Smith et al., 2015). Similarly, another study showed 71% of injuries during practice occurred during the pre-season (Meyers et al., 2001). Early-season injury has been a notable trend within the literature with other authors mentioning that more attention is warranted to conditioning pitchers primarily during the pre-season portion of the year (Lear & Patel, 2016; Marshall et al., 2007; Shanley et al., 2011; Smith et al., 2015). While pre-season is designated to prepare the athletes for the long, grueling game schedule, perhaps pre-season workouts are too much and too soon for these younger and less-elite level athletes. More elite athletes may prioritize conditioning throughout the off-season, while less elite and younger athletes likely do not emphasize training during this time.

The high rate of injury during pre-season activities and potential lack of preparation prior to the season may provide evidence that softball pitchers do not emphasize conditioning and regular exercise out of season. Some reports even mention softball pitchers tend to increase body fat percentage throughout the season (Peart et al., 2018). While pitching is becoming a more specialized position, with pitchers rarely playing other positions, overall fitness and physical ability outside of pitching may not be prioritized. As a result, pitchers tend to be the largest and carry the greatest percent of body fat on collegiate women's softball teams (Czeck et al., 2019).

Kinematics

Windmill softball pitch mechanics have been described in a few foundational papers (Barrentine et al., 1998; Guido et al., 2009; Oliver et al., 2010; Oliver & Plummer, 2011; Oliver et al., 2011; Werner et al., 2005; Werner et al., 2006). The windmill pitching motion is a full-body dynamic movement involving sequential sequencing of body segments. The throwing arm undergoes total circumduction of approximately 485 degrees. This large range in upper extremity movement requires several phases to fully break down the different joint actions occurring throughout the motion (Barrentine et al., 1998). The softball pitch is traditionally broken into four main phases. These include: 1) wind-up phase: from the start of the pitch/initial movement to push foot toe-off, 2) stride phase: from push foot toe-off to stride foot contact (foot flat), 3) delivery phase: stride foot contact to ball release, and 4) follow-through: ball release to end of forward movement (Barrentine et al., 1998) (Figure 2.1). Follow-through has also been defined as ten frames or 100 ms following ball release (Friesen et al., 2019; Oliver et al., 2010; Oliver, Plummer, et al., 2018). The pitch has also been broken into phases representing hands on a clock (Maffet et al., 1997; Rojas et al., 2009) (Figure 2.2). With these definitions in mind, kinematics are defined accordingly.

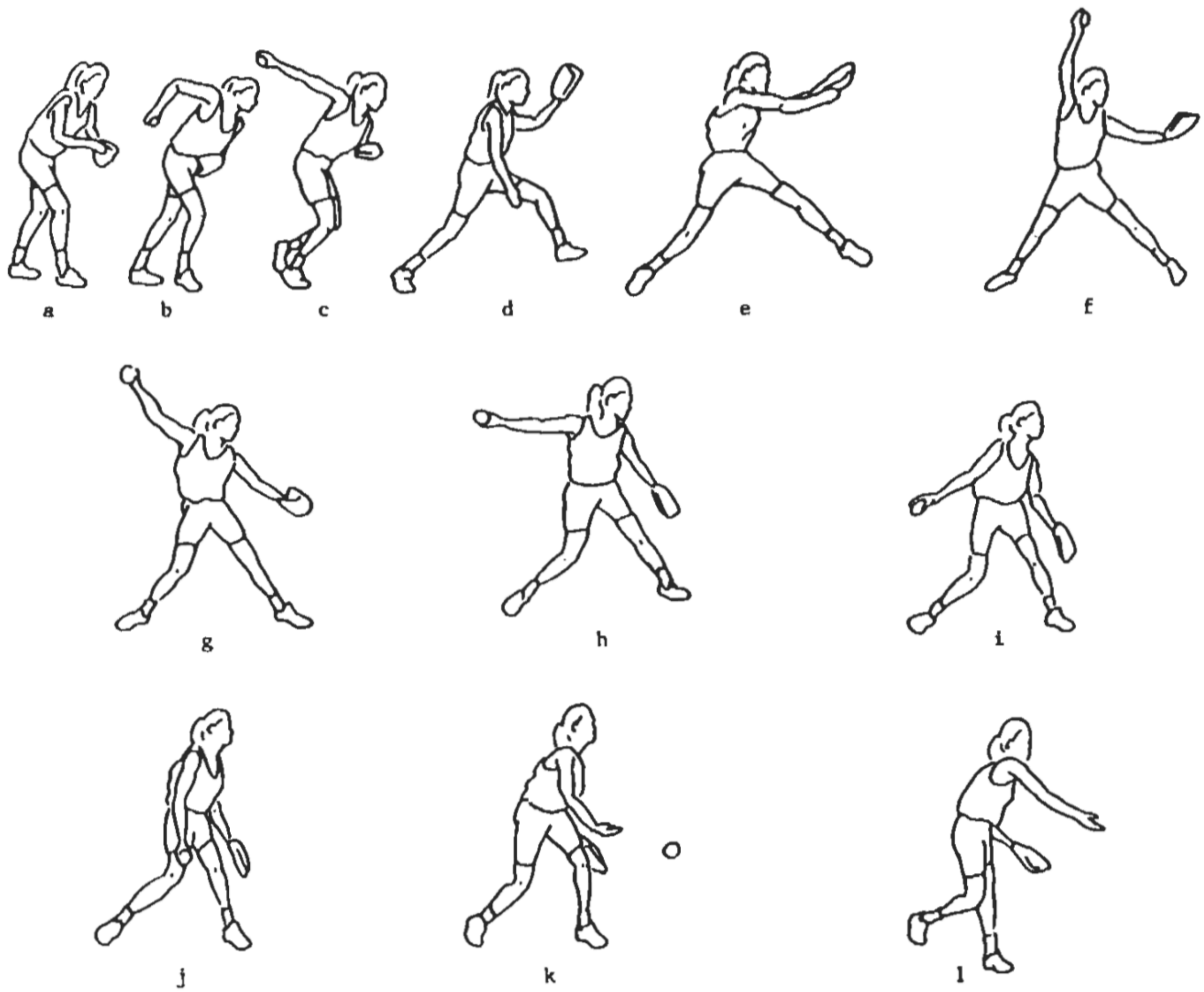

Figure 2.1. Sequence of motion in windmill pitching: a-c) wind up, d-f) stride, g-j) delivery, k-l) follow-through.

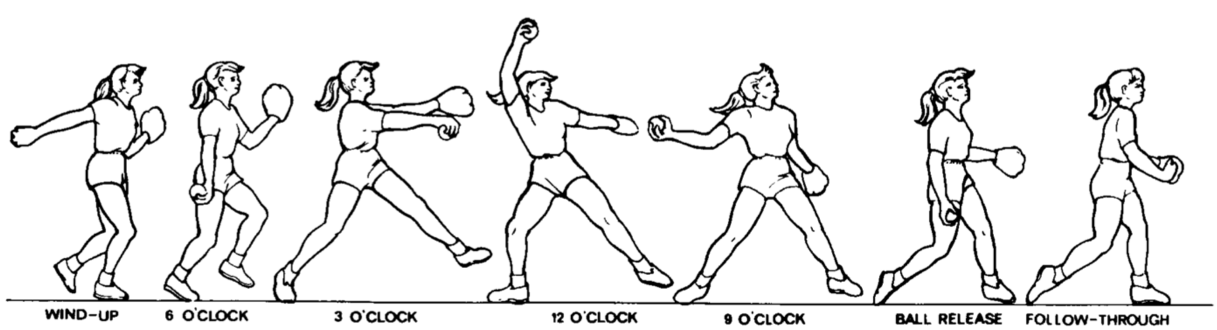

Figure 2.2. Windmill pitching phases according to the face of a clock.

The pitch normally begins with the heel of the throwing side foot (push foot) touching the front of the pitching rubber and the glove-side foot (stride foot) touching the back side of the rubber; although, a recent rule change now allows pitchers to not have the stride foot touching the rubber (WSBC, 2017). From this position, pitchers have a wide variety of preparatory movements, similar to the individualistic style of the preliminary motions in hitting. This preparation phase is ideally described as a loading period where pitchers shift weight onto their stride foot (Nimphius et al., 2016). Some pitchers choose to extend the throwing arm behind the frontal plane of their body. In contrast, other pitchers choose to keep the ball in the glove, often limiting the range of their counter-movement, and concealing the ball from the batter for a longer period. After this loading period, the pitcher drives off the mound and strides out with their stride leg. During this phase, the throwing arm shoulder flexes until the arm reaches peak elevation. The trunk and pelvis are also rotated towards the throwing arm side during this phase. This is commonly referred to as the 'stride.' From the top of backswing (where the throwing arm is mostly perpendicular to the ground) until the point of ball release is frequently referred to as the 'acceleration phase.' Once the stride foot makes ground contact, the trunk rotates back towards the catcher, while the arm is accelerating through to ball release. During this time, the throwing arm shoulder adducts, flexes, and internally rotates across the body towards home plate (Barrentine et al., 1998; Maffet et al., 1997). It is during this phase that the throwing arm shoulder experiences the largest stress. Ball release occurs near the hip and is adjusted very slightly depending on the type of pitch thrown and the intended trajectory. While the majority of the pitching motion is completed with the elbow mostly extended, literature shows the elbow flexes to approximately 18-24º near ball release (Barrentine et al., 1998; Werner et al., 2006).

Elbow flexion velocity is reportedly 1,248 ± 431 °/s at ball release (Werner et al., 2006) and 880 ± 360 °/s at follow-through (Barrentine et al., 1998).

Trunk motion has been shown to depend greatly on the expertise of the athlete, with younger pitchers exhibiting significantly more trunk flexion at foot contact (68 ± 17°) versus elite players (17 ± 16°) (Friesen et al., 2019; Oliver et al., 2018). Trunk rotation range of motion relative to the global axis reaches a peak near foot contact, as the trunk is rotated towards the throwing arm. Following foot contact, the trunk then rotates back towards the target for ball release. Stride length is usually determined as a percentage of body height and has been shown to range from approximately 62% body height in youth pitchers to about 89% body height in elite pitchers (Guido et al., 2009; Oliver et al., 2018; Werner et al., 2005; Werner et al., 2006).

Though there are few reports describing lower extremity kinematics, some studies have described the stride knee. Upon stride foot contact, the stride knee is generally flexed near 27-33° with elite pitchers exhibiting slightly more extension (Guido et al., 2009; 2018; Werner et al., 2005; Werner et al., 2006). Position of stride foot contact can vary, although it is typically positioned slightly lateral of the midline between the pitcher and catcher towards the stride leg side (Werner et al., 2006). Stride foot orientation is generally about 35 degrees clockwise from the anterior direction of motion (for a right-handed pitcher) (Werner et al., 2005).

While kinematics of windmill pitching are overall less studied than in baseball pitching, certain kinematics have been associated with upper extremity pain, demonstrating the importance of body positioning throughout the pitch. Research has shown that greater throwing arm horizontal abduction relative to the thorax at foot contact and decreased trunk lateral flexion towards the throwing arm side at ball release are associated with pitchers who experience upper extremity pain (Oliver et al., 2018). Similarly, it has also been suggested that increased trunk rotation towards the throwing arm side and center of mass positioned further back at foot contact, as well as increased stride length, is associated with those pitchers who are currently experiencing upper extremity pain (Oliver et al., 2019). These positions are hypothesized to negatively affect the kinetic chain's efficiency, potentially placing additional stress on the upper extremity (Kibler & Sciascia, 2016). While the upper extremity already endures high-stress, body positioning may be particularly essential throughout the windmill pitch.

Segmental Sequencing

Proximal to distal sequencing is defined as the successive temporal pattern of joints and segments ordered from the lower extremity proximal segments to the upper extremity distal segments (Herring & Chapman, 1992). Proper sequencing of segments and slowing down of more proximal segments provides a lever to allow optimal velocity at the distal end of segments (Alexander & Haddow, 1982). A prominent example of this within the softball pitch is while the throwing arm is nearing ball release. As the upper arm maintains a position near perpendicular to the ground, the forearm completes a rapid whipping motion to prepare for the wrist and hand to release the ball with maximal velocity near the hip. For the ball to be thrown with maximal velocity, the whole body is required to sequentially transfer energy in a way that safely generates the most distal end velocity.

The summation of speed principle states that sequential involvement from each link within a kinetic chain helps to generate optimal distal end velocity (Bunn, 1972). This is completed through the summation and transfer of energy from more proximal segments to distal segments (Bunn, 1972; Kibler, 1995). A majority of these forces originate as ground reaction forces, and thus the large leg and trunk muscles are essential to the overall velocity of the throw.

Research studying the tennis serve has shown the leg and trunk muscles combine to contribute over 50% of the total kinetic energy during the tennis serve (Kibler, 1995). Although the relationship of GRF and total kinetic energy has not yet been studied in softball, the sequential nature and distal whipping of segments are shared with both overhand pitching and windmill pitching. The two pitching styles are often compared as both tasks involve full-body sequential movement ending with distal segment peak velocity. Baseball research has shown that a 20% decrease in kinetic energy transfer from the hip and trunk to the throwing arm requires an increase of 34% of the rotational velocity of the throwing shoulder to impart the same amount of resultant force to the hand (Kibler & Sciascia, 2016). This is considered inefficient energy transfer, and many researchers have acknowledged the importance of total kinetic chain involvement to reduce the kinetic contributions of the shoulder joint (Kibler & Chandler, 1995; Stodden et al., 2005; Werner et al., 2008).

With such large amounts of force being funneled through the shoulder, scapular stability is vital in centralizing the humeral head to provide stability for force to smoothly accelerate the arm in the plane of the pitch (Kibler, 1995). A scapula stabilized by trapezius and rhomboid muscles allows for over a 20% increase in maximal rotator cuff muscle activity (Kibler et al., 2006). This emphasizes the need for all links within the kinetic chain to properly work in sequence to develop a high amount of force safely and optimally for high pitch velocity.

Previous literature has investigated the difference in segmental sequencing among softball pitchers of varying levels of expertise. More elite pitchers portrayed a proximal to distal sequencing of segments, whereas novice pitchers did not (Oliver et al., 2010). Similarly, novice pitchers have demonstrated more dependence on the upper extremity during throwing, whereas elite pitchers depend more on the force generation from proximal segments (Oliver et al., 2010).

Development of power from musculature surrounding the trunk has shown to be vital; therefore, emphasis has been placed on the development of gluteal muscle groups to generate a portion of the force requirement (Oliver & Plummer, 2011; Oliver et al., 2011). Although throwing emphasizes the upper extremity, namely the shoulder, dysfunction proximally throughout the kinetic chain can lead to altered kinetics in the more distal segments, exposing these segments to pathomechanics and potential injury (Kibler & Sciascia, 2016; Putnam, 1993).

Proximal stability is necessary for distal mobility (Kibler, 1998). While the hip and trunk contribute a large portion of force to the throwing motion (Kibler, 1995), thoracolumbar fascia connects the lower limbs to the upper limbs via core musculature. The gluteus maximus and the latissimus dorsi are particularly crucial in transferring force (Kibler & Sciascia, 2016). Similarly, the trunk transverse and oblique muscle groups are essential to trunk rotation, while the stable pelvis allows for such rapid movement. This lower body to upper body connection helps to transfer energy distally to the upper extremity. Additionally, proximal segments must provide a secure and stable base to allow for greater force production of distal segments' musculature. The mechanism referred to as the stretch-shortening cycle, which is present within the windmill softball pitch, also helps remove slack from muscles to aid in proper force generation.

During the windmill pitch, the segmental sequence allows angular momentum from a proximal segment to be transferred to a distal segment. This pattern is more efficient via the stretch-shortening cycle if a distal segment can delay movement, thus creating a stretch on the agonist muscle. This stretch generates muscular excitement of the muscle spindles to eventually cause a more forceful muscle contraction (Alexander & Haddow, 1982). Throughout the windmill pitch, throwing arm motion illustrates the stretch-shortening cycle. During the initial push off of the ground, the throwing arm flexes forward and moves up and behind the body's frontal plane. Anterior shoulder muscles that aid in shoulder flexion (such as the pectoralis major) are placed under great stretch while the throwing arm is extended behind the body. As the arm once again begins flexing forward during the acceleration phase, the previously stretched muscles can now contract more forcefully, according to the stretch-shortening cycle theory. Besides increased muscle spindle activity, this eccentric loading and amortization phase prior to the concentric contraction can lead to the storage of potential energy to create more kinetic energy upon contraction, thereby increasing segment velocity (Alexander & Haddow, 1982).

Range of Motion

An adequate range of motion is imperative to the kinetic chain's mechanical efficiency in transferring energy among body segments. Musculoskeletal adaptations in hip and shoulder range of motion (ROM) have been reported within baseball and softball literature. Previous literature has shown that both hip and shoulder ROM adaptations occur over time and correspond to both players' ages and defensive positions (Friesen et al., 2019). With ROM adaptations analogous to position, sport, and BMI, implications of functional musculoskeletal changes may result from high repetition accrued over many years of the sport. As the number of repetitions increases throughout a pitcher's career, these high-demand positions and sports stimulate physical adaptation in the hip and shoulder (Greenberg et al., 2017; Kettunen et al., 2000; Li et al., 2015; Picha et al., 2016; Robb et al., 2010; Zeppieri Jr et al., 2015). This is problematic as previous work has found decreased hip external ROM throughout a competitive season has been associated with a history of shoulder (Scher et al., 2010), and elbow pain (Saito et al., 2014). Similarly, decreased hip internal rotation ROM has been associated with an increased risk of lower extremity injury, such as anterior cruciate ligament tear (Bedi et al., 2016; Tainaka et al., 2014; VandenBerg et al., 2017), and groin pain (Li et al., 2015). This is a concern as decreased hip range of motion throughout the season is widely reported in throwing literature (Camp et al., 2018; Zeppieri Jr et al., 2015). Also widely reported is the above-average size of softball pitchers (Czeck et al., 2019), which could pose more problems as evidence shows decreased ROM could be further exacerbated by athletes who possess an increased BMI.

Retrospective studies have acknowledged there is decreased hip ROM within retired elite athletes who had a higher BMI (Kettunen et al., 2000). Furthermore, data by Friesen et al. (2020) demonstrated pitchers with higher BMI had decreased internal hip ROM, which could pose problems with force generation and transfer along the kinetic chain (Friesen et al., 2020). While research alludes to both decreased range of motion and increased BMI being associated with an increased risk of injury, it can be theorized that the additional adipose tissue may be the culprit of impingement and decreased range of motion issues. While the softball pitch requires many rotational and linear aspects of movement, it is plausible to assume pitchers with higher levels of fatty tissue and potentially decreased range of motion may present altered biomechanics during the windmill pitch. Altered kinematics may change kinetics to result in an altered pattern of movement.

Kinetics

Force generation from the ground up is an essential aspect of the softball pitch. The lower extremity is important in generating force to be transferred up through the kinetic chain to create high velocity of the throwing arm, wrist, and ball. Understanding the propulsive forces near the beginning of the pitch provides information regarding body segments' angular accelerations and the subsequent impact on pitch velocity. The acceleration of proximal segments allows for transfer of momentum to distal segments (Nimphius et al., 2016; Putnam, 1993). Baseball pitchers who develop the most force during the propulsion phase reportedly throw the fastest, verifying that leg drive strongly influences pitch velocity (MacWilliams et al., 1998). Furthermore, Kibler et al. (1995) explained that the legs developed 54% of the total force during the tennis serve (Kibler, 1995), a sport task comparable to the upper extremity throwing motion of both baseball and softball pitchers. It is assumed that greater proximal force generation can allow for increased amounts of energy to be transferred up the kinetic chain to affect pitch velocity.

Not only does the magnitude of force generation impact pitch velocity, but so does the timing of force generation. Softball literature has reported that both the magnitude and timing of ground reaction forces during the propulsion of the pitch can influence pitch velocity. Nimphius et al. (2016) found that more time between vertical GRF peaks and greater peak magnitude of vertical GRF during the propulsive phase were both associated with increased pitch velocity (Nimphius et al., 2016). Of note, this study was completed with pitchers beginning with both feet on the force plate, resulting in numerous peaks within each directional force component (Figure 2.3). As a result, it is hypothesized that a longer duration of propulsion can generate increased amounts of force, possibly leading to increased pitch velocities. Overall, the magnitude and timing of the peak GRFs explained 83% of the variance in pitch velocity, with pitcher height not being a significant covariate (Nimphius et al., 2016).

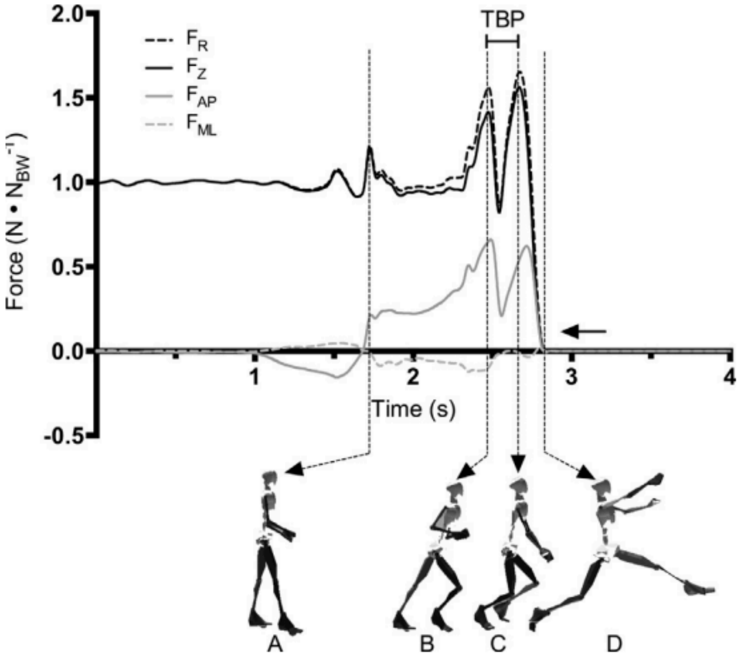

Figure 2.3. Ground reaction forces as published via Nimphius et al. (Nimphius et al., 2016). Note: GRF [Vertical (F_Z), Resultant (F_R), Anterior-Posterior (F_{AP}) and Medio-lateral (F_{ML})] during the windmill pitching motion of a representative pitcher. (A) Preparation phase, (B) Initial drive, (C) An explosive drive, (D) Foot dragging from the mound.

Studies that examined stride foot contact GRF revealed the magnitude of the body weight normalized GRF positively correlated with pitch velocity (Guido et al., 2009; Oliver & Plummer, 2011). Therefore, it was concluded that the more force the pitcher impacts the ground with at foot contact, the faster the pitch. As a result, the stride leg has been noted as an important feature in softball and baseball pitching. The stride leg can provide an ‘anchor’ or a post of resistance around which the linear translation of the body can be stopped, while the hips and upper arm finish their rotation towards home plate (Guido et al., 2009; MacWilliams et al., 1998; Nimphius et al., 2016; Werner et al., 2006). While a study has not yet examined both push and stride foot GRF in softball pitchers, it can be hypothesized that there is a strong relationship between the force generated during push-off and the force measured at foot contact. Nimphius et al. (2016)

stated that the pitching motion relies heavily on the momentum gained from the push of the pitch. This early pitch momentum combined with a quick brake on the stride leg, allows for the transfer of stored potential energy from the push phase of the pitch to kinetic energy upon stride foot contact (Nimphius et al., 2016). Momentum is then transferred finally into the softball during the acceleration phase of the pitch (Nimphius et al., 2016).

In softball pitching, a braking force peaks quickly after foot contact to a mean magnitude of 115 ± 46% BW and then reverses direction, becoming an anterior force near ball release and peaking shortly after near 24% BW (Oliver & Plummer, 2011; Werner et al., 2005). Putnam (1993) states that the braking force seen throughout foot contact and ball release is necessary to slow the lower body segments as energy is transferred to the distal portions of the kinetic chain (Putnam, 1993). Medial GRF peaks just after stride foot contact (42 ± 27% BW) to slow rotation and changes to a lateral force after ball release. Maximum vertical GRF has been shown to average 139 ± 43% BW approximately 300 ms after foot contact (Guido et al., 2009) (Figure 2.4). Vertical GRF has been reported to have a more gradual increase with a peak magnitude being achieved right before ball release in baseball pitchers. In contrast, softball pitchers' vertical GRF peaks soon after foot contact and dissipates shortly after (MacWilliams et al., 1998; Werner et al., 2005). The steep slope in force application indicates softball pitchers depend heavily on the front leg as a pivot point, particularly while the body rotates back towards home plate during the acceleration phase. Anecdotally, softball pitching coaches will refer to this phenomenon as having a strong front side to throw 'against.' Although upper extremity injuries are more commonly reported, the lower leg may be susceptible to injury because of the quick and high loading rate upon foot contact.

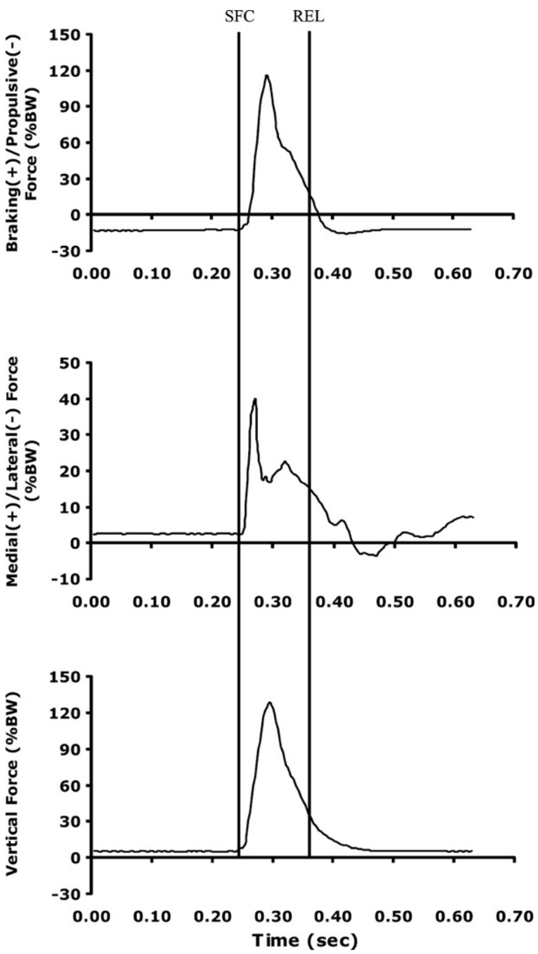

Figure 2.4. Ground reaction forces as published via Guido et al (Guido et al., 2009).

Shoulder Distraction Forces

The windmill pitch, though still an upper extremity throwing motion, differs from the baseball pitch. The windmill softball pitch requires that the throwing arm undergo full circumduction (Barrentine et al., 1998), causing a different primary type of stress on the throwing arm than during baseball pitching. While the actions prior to the true ‘acceleration’ phase of the softball pitch are purposed to create high angular velocity of the throwing arm, hand, and ball, this action occurs with the throwing arm mostly extended. Barrentine et al. reported that the elbow’s extended position helps to accentuate the centrifugal distraction force placed upon the glenohumeral joint (Barrentine et al., 1998).

High distraction forces have been noted within softball literature and made comparable to those within the baseball pitch. The peak shoulder distraction forces occur during the softball pitch’s acceleration phase while the arm is overhead and behind the body. While in this position, the anterior capsule of the glenohumeral joint is under great stress. The pectoralis major is a dominant muscle that contributes to the high-velocity adduction and internal rotation of the throwing arm during the acceleration phase. Simultaneously, the subscapularis supports the anterior capsule of the glenohumeral joint (Maffet et al., 1997). While anterior shoulder pain is commonly reported, the exact mechanism is not well understood, although prior research has alluded to the high distraction forces being a potential cause for injury within softball pitchers (Barrentine et al., 1998; Werner et al., 2006). Prior work by Oliver et al. (2018) has associated greater throwing shoulder distraction force at ball release with upper extremity pain (Oliver et al., 2018). While the shoulder is experiencing a large distraction force, the biceps brachii provides an important protective mechanism (Barrentine et al., 1998).

The biceps labral complex functions to aid in resisting humeral head distraction and providing an elbow flexion moment while the elbow flexes near ball release (Rojas et al., 2009; Werner et al., 2006). The reported elbow flexion angle is near 18º - 28º at ball release, despite a majority of the arm circle taking place with the elbow more extended (Rojas et al., 2009; Werner et al., 2006). Because of the high shoulder distraction stress and the elbow extension torque present during the acceleration phase of the pitch, researchers have focused on this phase in attempt to identify possible injury risk factors (Rojas et al., 2009). Prior work has shown that the biceps tendon increases in cross-sectional area following an acute bout of pitching, providing evidence that the windmill pitch stresses the biceps complex which could lead to fatigue and injury throughout a heavy pitching season (Barfield et al., 2018).

Influence of Body Mass Index on Ground Reaction Forces

Pitcher height is not regularly associated with pitch velocity (Nimphius et al., 2016); however, pitcher mass is positively associated with pitch velocity (Werner et al., 2008). Larger pitchers innately have larger GRFs; therefore, understanding how propulsion is affected by body mass may elicit implications for force generation. As a result, it is hypothesized that pitcher size will affect ground reaction forces during the propulsion phase of the pitch. However, with greater force comes greater responsibility, and there must be proper transfer of energy from the lower extremity to the upper extremity in an attempt to prevent injury (Kibler, 1998).

Ground reaction force is the force directed from the ground into the pitcher. Acceleration due to gravity is equal to 9.81 m/s^2. A person's weight can then be calculated as their mass multiplied by the acceleration due to gravity. Therefore, a person of larger mass exerts more force on the ground, and directly proportionate, the ground returns an equal and opposite force. If a pitcher weighs 600 N and another weighs 700 N, the pitcher who weighs more will have a greater ground reaction force equal and opposite to the force of their body weight.

Newton's 2^{nd} law states that force (F) is equal to mass (*m*) multiplied by acceleration (a) (Equation I).

$$\text{Equation I.} \quad F = ma$$

If two people of varying mass set out to pitch with maximal effort, the pitcher that generates more force (relative to body weight) will achieve greater acceleration during the pitch. Previously, GRF and pitch velocity have been related (MacWilliams et al., 1998; Nimphius et al., 2016), thus suggesting that pitchers who generate greater weight-normalized GRFs will also achieve faster pitch velocities. While larger pitchers are often successful in softball pitching, it is hypothesized that larger pitchers may generate additional force relative to body weight to aid in propulsion during the pitch, which may ultimately lead to an increased pitch velocity.

Body Composition in Softball

Baseball has been referred to as 'a fat man's game' (Szymanski & Zimbalist, 2006), alluding to the above-average size of players, and specifically pitchers, compared to athletes of other sports. Similar statements are made in softball, with people aware that bigger may sometimes be better when it comes to softball performance. However, research has shown that bigger may only be better up to a certain point. In terms of injury, bigger may not be better (Chalmers et al., 2015). A 10-inch increase in height was associated with a 20% increase in injury history of baseball pitchers. Similarly, a 10-mph increase in pitch velocity was associated with a 12% increase in the likelihood of injury (Chalmers et al., 2015). Several studies have acknowledged that injury rate amongst baseball and softball players increased with additional body weight, and pitchers who were in pain were on average heavier, taller, and had a higher BMI (Chalmers et al., 2015; Greenberg et al., 2017; Hill et al., 2004; Oliver et al., 2019). Because of the higher load larger players experience per pitch, researchers have emphasized quality over quantity to decrease overuse and risk of injury (Hill et al., 2004).

Research shows that as baseball pitchers mature, the kinetic chain experiences increased forces and moments, concomitant to an increase in pitch velocity (Bushnell et al., 2010; Fleisig & Escamilla, 1996; Werner et al., 2008). Furthermore, taller participants have been shown to exert more force through the upper extremity due to the longer lever arm (Aguinaldo & Chambers, 2009). Lever arm, also commonly referred to as moment arm (d), is the perpendicular distance (r) from the axis of rotation to the force line of action (Equation II).

Equation II. $d = r\sin\theta$

Additionally, torque (τ) (also known as the moment of force) is equal to the product of force (F) and the moment arm (d) (Equation III).

Equation III. $\tau = Fd$

Therefore, throwers who are taller and have longer limbs (specifically increased throwing arm length), may have both favorable and unfavorable consequences. Performance-wise, longer limbs may be beneficial in generating more torque for faster pitch velocity; but, injury-wise, longer limbs may predispose the athlete to more injury-prone biomechanical factors.

Mass moment of inertia (I) is the measure of a segment to resist change in angular velocity. Mass moment of inertia (I) is calculated as the product of the mass of a segment in kilograms (m) and the radius of gyration (k) squared (Equation IV). Therefore, as taller and heavier pitchers exhibit longer and heavier arms, the mass moment of inertia is increased.

Equation IV. $I = m\mathrm{k}^2$

The moments experienced at joints will also increase with an increase in mass moment of inertia (I), given that the angular acceleration (α) of segments remains consistent. This principle is expressed in Equation V.

Equation V. $\mathrm{M} = I\,\alpha$

Therefore, the hypothesized main link between injury risk and increased body mass is hypothesized to be a result of greater joint moments potentially present in those individuals with increased mass.

Larger absolute joint moments are typically present in those who possess increased segmental mass moment of inertia due to both the increased mass moment of inertia, and the increased angular accelerations older pitchers can achieve (Fleisig et al., 1999). Therefore, Fleisig et al. (1999) hypothesized increases in joint forces and moments were likely due to the increased strength and mass of older athletes (Fleisig et al., 1999). Smaller youth pitchers have been shown to experience less distraction forces at the elbow than elite and older baseball pitchers (Fleisig et al., 1999), likely a product of smaller mass and shorter moment arms. Likewise, research has shown that absolute elbow varus moment was most strongly associated with body weight (Sabick et al., 2004).

In studying specifically body fat and body composition effects on throwing, Garner et al. (2011) found that body composition and segmental mass in overweight individuals negatively impacts throwing biomechanics in youth baseball players. The increased body composition in pitchers corresponded to increased throwing arm moments previously associated with throwing arm injury (Garner et al., 2011). Specifically, increased total mass, fat mass, arm length, segmental mass, and segmental fat mass all corresponded to increased joint moments of the throwing arm (varus, valgus, internal rotation, external rotation, horizontal ab/adduction), independent of height. While many body composition measures were related to joint moments, lean mass related to only a few of the throwing arm moments (valgus, external rotation moment, and horizontal adduction). This finding supports the belief that additional stress is placed on the upper extremity from specifically fat mass, not just total body mass. Of similar nature, the regression equation used to determine the effects of body composition measures on joint moments was mostly unaltered when using only segmental values, indicating that joint moments may be susceptible to segmental composition more than overall body composition (Garner et al., 2011).

While some literature has acknowledged a positive correlation between joint moments, pitch velocity, and age (Fleisig et al., 1999), a study to counteract this showed that weight-normalized throwing arm joint moments were larger in high school-aged baseball pitchers compared to larger professional pitchers (Luera et al., 2018). Specifically, Luera et al. (2018) found that professional pitchers had less weight-normalized elbow varus torque at maximum external rotation compared to high school baseball pitchers. However, the study also noted significant kinematic differences between the two groups of pitchers. The professional pitchers displayed better proximal to distal segmental sequencing, which may explain how the professional pitchers could throw the ball with higher velocities while also experiencing less weight-normalized elbow varus torque. The authors hypothesized that these younger pitchers were less capable of using the force generated from the proximal segments and resorted to the throwing arm to create the force necessary for peak pitch velocity (Luera et al., 2018). This study highlights the potential impact of kinematics and kinetic chain usage in decreasing the kinetics associated with injury in the upper extremity.

With increased adipose tissue in some pitchers, kinematics may unintentionally change throughout the windmill pitch. Research shows regular kinematic alterations for those individuals who are obese, even within low-velocity activities of daily living (Bollinger, 2017). While larger and older athletes are innately predisposed to higher velocities and higher forces, they may also be predisposed to injurious positions as impingement issues may arise, limiting the full range of motion and typical kinematic positioning during the pitch. In pitchers who are overweight, the trunk segment typically exhibits the greatest mass and thus requires additional force to accelerate compared to someone of smaller mass. If appropriate sequential timing of the trunk is not achieved, the arm may be predisposed to altered kinematics. Previously it has been reported that certain kinematics throughout the windmill pitch are associated with upper extremity pain. Specifically, increased throwing arm horizontal abduction, increased trunk rotation towards the throwing arm side, and a more posteriorly shifted center of mass at foot contact, as well as decreased trunk lateral flexion towards the glove arm side at ball release, were all associated with increased upper extremity pain (Oliver et al., 2018; Oliver et al., 2019). If pitchers with greater adipose tissue around their trunk approach impingement problems, they may not be able to adduct their throwing arm properly for ball release. Therefore, those pitchers with a larger trunk girth may be predisposed to altered kinematics at the trunk and throwing arm.

BMI and Performance

While larger pitchers may be more susceptible to injury, anecdotally, the high number of pitchers who appear overweight are also high performers, possibly indicating an injury/performance tradeoff. The increased body mass may be linked to performance from a biomechanical perspective. Force is generated through the kinetic chain, originating largely from the lower extremity. Previous studies have shown that in individuals who are obese, lower-extremity and weight-bearing muscles portrayed increased absolute muscle mass (Forbes, 1987), muscle strength, and muscle power (Lafortuna et al., 2005; Rolland et al., 2004), compared to non-obese individuals. The reason for this increase in absolute muscle mass is theorized to be a response to an overload effect. Individuals who carry excess adipose tissue and a greater load will adapt and develop increased muscle mass (Bollinger, 2017). However, when normalizing muscle strength and power to total body mass, many studies allude to an obese population reporting decreased weight-normalized muscle strength (Hulens et al., 2001; Maffiuletti et al., 2007). This is especially important among softball pitchers, as pitchers need to move their own bodies forcefully towards home plate. Therefore, reports suggesting obese individuals have less weight-normalized muscle strength is problematic.

Research has also revealed a decreased intrinsic ability of muscle force within those individuals who are obese (Maffiuletti et al., 2007). Consequently, there has also been reports that there is increased volitional fatigue of muscles within obese individuals, potentially leading to altered kinematics (Bollinger, 2017; Maffiuletti et al., 2007). Therefore, while pitchers who are considered obese may create higher absolute muscle power, these pitchers may have a decreased ability to accelerate their own body weight towards the target sufficiently, with reported decreased weight-normalized muscle strength.

In prior work, it has been shown that both baseball and softball pitchers who develop the highest absolute GRF threw the fastest (MacWilliams et al., 1998; Nimphius et al., 2016; Oliver & Plummer, 2011). While a majority of pitch velocity is a product of lower extremity work, larger pitchers may be able to generate increased force due to increased muscle strength hypothesized to be present among more obese populations (Hulens et al., 2001; Maffiuletti et al., 2007). Newton's 3rd law states that every action will have an equal and opposite reaction. This law highlights the importance of the large force placed on the ground, and the equal and opposite force of the ground on the body, commonly referred to as the ground reaction force (GRF). Depending on the pitcher's direction pushing off the plate with the push foot (right foot for right-handed pitchers), the pitcher will move in the opposite direction with the amount of force initiated during the pitch (normalized to body mass).

Likewise, momentum (p) also plays a crucial role especially in differentiating larger pitchers from smaller pitchers. Total body momentum is the sum of the body's segmental momenta, where each segmental mass (*m*) is multiplied by the velocity vector (v) of the segment center (Equation VI).

Equation VI. $p = mv$

Angular momentum is also important in helping the body rotate segments in order for the body to translate explosively towards the catcher. Angular momentum of the arm segment (L_s) is a product of the moment of inertia and angular velocity in radians/second (ω) of the arm (Equation VII). Therefore, increased moment of inertia and increased angular velocity leads to a segment having greater momentum. This greater momentum could be another potential mechanism leading to an increased pitch velocity among those pitchers larger in stature. However, it's important to note, larger pitchers with a larger mass moment of inertia will have greater difficulty overcoming inertia to achieve a greater angular velocity.

Equation VII. $L_s = I\,\omega$

Between-Pitch Variability

Research has suggested an increase in a pitcher's ability to reproduce consistent pitching form leads to improved ball location consistency (Glanzer et al., 2019). Furthermore, research shows higher-level baseball pitchers have more consistent release points (Whiteside et al., 2016). Consequently, there is a notable increase in variability as fatigue ensues throughout the duration of a game (Escamilla et al., 2007; Keeley et al., 2014). While variability has been suggested to be a measure of fatigue and poor performance, it has also been suggested as a means to offset injurious repetitive patterns (Bartlett et al., 2007; Fleisig et al., 2009). Due to the increased mass moment of inertia (especially within the trunk that already possesses a large portion of the body's mass), bigger pitchers may have decreased variability in their mechanics, due to increased difficulty in manipulating body segments. This again could be a potential cause for bigger pitchers experiencing both increased performance and higher injury rates.

Summary

While there may be advantages for a softball pitcher carrying extra adipose tissue, there may also be disadvantages related to injury and performance. Although this project seeks to understand the possible benefit and burden of additional mass and body fat percentage of softball pitch biomechanics, it is vital to keep in mind the full spectrum of issues that come with being overweight. Obesity induces various complications that can deter health and lead to physical disability (Bollinger, 2017). Altered kinematic and kinetic variables, as well as increased loading, can increase the likelihood of developing osteoarthritis and other physical disabilities (Bollinger, 2017; Chaudhari et al., 2008). Therefore, although this project seeks to identify the potential advantages and disadvantages of increased mass, an overarching goal of this research is to provide the best information to inform pitchers on how body composition can influence injury susceptibility and performance. Ideally, we can learn from the best pitchers, regardless of body size, and apply those biomechanics to all pitchers using a safe approach while emphasizing healthy decisions for improved quantity and quality of life.

CHAPTER III

METHODS

The purpose of this project was to identify the influence of segmental and total body composition on softball pitchers' kinematics, kinetics, and pitch velocity. This study utilized a cross-sectional design to examine the effects of body composition on softball pitching biomechanics. The research design was descriptive and attempted to understand how body mass and fat mass are associated with 1) the force-time curve during propulsion of the pitch, 2) peak throwing shoulder distraction force, 3) pitch velocity, as well as 4) how upper arm, chest, waist, and hip girth correlate with trunk and throwing arm position, and lastly, 5) how segmental angular velocities are affected by body fat. This chapter's purpose is to describe in detail the methods used in answering the above research questions.

Participants

*G*Power* software (version 3.1.9.4; Kiel, Germany) (Faul et al., 2007) was used *a priori* with an effect size of 0.25 and an alpha level set at $\alpha = .05$. The power analysis deemed a sample of 32 participants was necessary to attain a power of .80 for the first research question. A subsequent power analysis deemed a sample of 42 was necessary to attain a power of .80 for the fourth research question. Two separate power analyses were conducted to accommodate the varied design and analyses of the separate research questions.

Participants were recruited through use of an approved recruitment letter as well as through an approved social media script which were disseminated through various social media platforms (Appendix A). Selection criteria deemed participants eligible to participate given they were currently high school or college-aged softball pitchers (including ages 14-23 years) and were currently active as pitchers on a softball team roster. All participants needed to have pitched in a game within the past year and needed to have at least one year of experience to be considered eligible. Participants with an injury or who had undergone musculoskeletal surgery within the past six months were excluded from the study, as well as those who were currently pregnant.

Once participants arrived at the Sports Medicine and Movement Laboratory, they were instructed on the study procedures and were given time to ask any questions regarding the study and procedures. Participants and parents/guardians were provided with an informed consent document to be read and signed prior to any other procedures (Appendix B). For those participants who were 19 years of age or younger, an informed assent document was also signed (Appendix C). Both informed consent documents and all study procedures were approved by the Auburn University Institutional Review Board. Parents/guardians and participants were also given an information letter which described the procedures of the dual-energy x-ray absorptiometry (iDXA) scan (Appendix D). Use of iDXA was approved by the Auburn University Radiation Safety Committee and the Alabama Department of Public Health. Participants then completed a health history questionnaire to ensure participants were eligible to participate in the study (Appendix E).

A total of 44 softball pitchers volunteered to participate (1.697 ± .071 m, 76.09 ± 16.67 kg, 15 ± 2 years; 8 left-handed pitchers; 4 collegiate pitchers). A table representing the number of participants per research question is displayed in Table F1 (Appendix F).

Setting

All testing took place at the Auburn University School of Kinesiology building. Following the consenting process and completion of the health history questionnaire, participants completed the iDXA scan in room 125 of the School of Kinesiology building, then completed all other testing in laboratory 014. This is a controlled laboratory setting, where pitchers pitched off of a rubberized platform to a catcher located at regulation distance (43 ft).

Instrumentation

iDXA

Whole-body and segmental composition measurements including fat tissue, lean tissue, and bone mineral content, were collected through use of a dual-energy x-ray absorptiometry (iDXA) scan (GE Healthcare, Madison, WI, USA). Previous reports acknowledge certain sport athletes achieve muscular development well above the average population to where body mass index (BMI) is not an accurate representation of adipose tissue (McHugh, 2010). It is possible that softball athletes' BMI does not correlate to true body fat percentage; therefore, iDXA uses x-rays to yield precise body composition measurement. Participants underwent one whole-body iDXA scan, which took between 7-13 minutes, and was equal to .003 Sv of radiation. The annual regulatory limit for children under 18 years of age is 0.1 Sv. The standard error of estimate for the iDXA is ± 1.8%.

Measuring Tape

A measuring tape was used to measure participants' upper arm, chest, waist, and hip girth to the nearest .5 cm. Reliability testing was conducted to verify the primary researcher had good test-retest reliability reporting an ICC (3,1) of 0.860-.997 for all four measurements (SEM_{UA} = 1.0 cm, SEM_{chest} = 1.5 cm, SEM_{waist} = 1.0 cm, SEM_{hip} = 1.0 cm) (Portney & Watkins, 2009; Weir, 2005).

Kinematics and Kinetics

Kinematic data were collected through use of an electromagnetic tracking system (trakStar, Ascension Technologies Inc., Burlington, VT) synced with motion analysis software, The MotionMonitor (Innovative Sports Training, Chicago, IL). System distortion has been reported with an error of 5º in movement ranging further than 2 m from the extended range transmitter (Day et al., 2000), however increases in instrumental sensitivity have reduced this error following calibration to be less than 2º (Perie et al., 2002). Therefore, the electromagnetic system was calibrated prior to data collection, according to previously established techniques (Day et al., 2000; Keeley et al., 2012; Perie et al., 2002). Pilot testing prior to data collection determined magnitude of error in position and orientation of the electromagnetic sensors in relation to the lab/world axis system was .03 m and 4.01º, respectively. The measurement system has been previously validated in producing trial-by-trial interclass correlation coefficients for axial humeral rotation in both loaded and non-loaded conditions greater than 0.96 (Ludewig & Cook, 2000). A triangular plexiglass stylus was used to digitize bony landmarks. The stylus was also calibrated prior to data collection and produced an RMS error of .094 cm.

All kinematic data were sampled at a frequency of 240 Hz (Fleisig et al., 2013). The world axis was defined with the positive Y-axis in the upwards vertical direction, and with the positive X-axis anterior of the Y-axis and in the direction of the pitch. Orthogonal and to the right of the XY plane was the positive Z-axis. Raw data were transformed to a locally-based reference system for each segment based on Euler angle decomposition sequences described using the International Society of Biomechanics recommendations (Table 3.1) (Oliver & Plummer, 2011; Wu et al., 2002; Wu et al., 2005). The shoulder joint used the Euler decomposition sequence YX'Y" to represent humeral motion relative to the thorax (Wu et al., 2005). The pelvis, thorax, elbow, and wrist used the Euler decomposition sequence ZX'Y", and all other lower extremity joints used The MotionMonitor default anatomical axes with the axis fixed to the proximal end of each segment. The anatomical axis system was defined with the primary axis being the positive Y-axis and the secondary axis being the positive Z-axis.

Joint kinetics were measured in The MotionMonitor using inverse dynamics through a top to down approach and by use of validated anthropometric parameters (Zatsiorsky, 1983). Shoulder distraction (+) and compression (-) force was measured in the Y direction relative to the axis of the throwing shoulder. All data were synchronized by a data acquisition board and timestamped through The MotionMonitor.

Segmental angular velocities were gathered during the pitch. Angular velocity of the trunk included rotational velocity about the world Y-axis. For shoulder, elbow, and wrist angular flexion velocity, values were reported to occur about the Z-axis relative to the proximal segment. Therefore, shoulder flexion velocity was reported relative to the trunk, elbow flexion velocity was reported relative to the upper arm, and wrist flexion velocity was reported relative to the forearm (Table 3.2).

All ground reaction force (GRF) data were measured using an in-ground non-conductive force plate (Bertec 4060 NC; Bertec Corp.; Columbus, OH, USA) and reported as force applied by the force plate on the foot at the center of pressure of foot contact. Center of pressure was determined by the vertical force component, GRFy, as well as the moments about the *x*- and *z*-axes. The foot touching the force plate is referred to as the push foot (right foot on a right-handed pitcher), and the opposite foot is referred to as the stride foot. GRFs were normalized to pitcher body weight.

Table 3.1. Euler angle decomposition sequence per segment.

Segment	Axis of Rotation	Angle
Trunk		
Flexion/Extension	Z	Extension [+]/Flexion [-]
Lateral Flexion	X'	Right Flexion [+]/Left Flexion [-]
Axial Rotation	Y''	Left Rotation [+]/Right Rotation [-]
Right Shoulder		
Plane of Elevation	Y	Flexion [0º]/Abduction [90º]
Elevation	X'	Elevation [+]/Depression [-]
Rotation	Y''	External Rotation [+]/Internal Rotation [-]

Note: Prime (') and double prime ('') notations represent the subsequent axes orientations following previous axes rotations.

Table 3.2. Segmental angular velocity directions.

Segment	Axis of Rotation	Angular Velocity
Trunk		
Axial Rotation	Y	Glove Side Rotation [+]/Ball Side Rotation [-]
Right Shoulder		
Flexion/Extension	Z	Flexion [+]/Extension [-]
Right Elbow		
Flexion/Extension	Z	Flexion [+]/Extension [-]
Right Wrist		
Flexion/Extension	Z	Flexion [+]/Extension [-]

Note: Axial trunk rotation to the left side is rotation towards the glove arm side for those pitchers who are right-handed.

Design and Procedure

Participants were asked to arrive at the Sports Medicine and Movement Laboratory having fasted for at least two hours prior to arrival. They were also asked to refrain from physical activity for 24 hours prior to participation. Upon arrival, participants were asked to use the restroom if necessary, and change into shorts, a loose-fitting t-shirt, and shoes in which they would be comfortable pitching. Following the consenting process and health history questionnaire, participants were asked to remove all jewelry in order to ensure safety and accuracy of the iDXA scan. Participants also needed to verify that they were not pregnant (included in the health history questionnaire). Participants' height and mass were measured using the electromagnetic system and recorded on the data collection sheet (Appendix G). Participants were then led to the iDXA testing room and asked to lie still on the padded testing table. A strap was secured around the participants' ankles to ensure legs remained still during the entire examination. Participants were instructed to breathe normally while the iDXA scanner completed a whole-body composition scan and analysis. The duration of the scan was approximately 7-13 minutes, depending on the size of the individual. Immediately following the scanning procedures, participants' girth measurements were collected. All measurements were recorded to the nearest 0.5 cm. Upper arm girth was measured as the circumference of the arm halfway between the acromion and lateral epicondyle (Kaminsky, 2013). Chest circumference was measured at the maximum horizontal girth at bust level, under the armpits, over the shoulder blades, and across the nipples, with the subject breathing normally. Waist circumference was measured at the level immediately below the lowest rib and hip circumference was measured as the horizontal girth measured around the buttocks at the level of maximum circumference (Simmons, 2001).

Following the iDXA scan and circumference measurements, participants were allotted time to complete a dynamic warm-up. Once participants indicated they were ready, fourteen electromagnetic sensors were affixed to the skin using double-sided tape, cover-roll tape, and PowerFlex tape (Andover Healthcare, Inc., Salisbury, MA). Sensors were attached to the following segments: [1] posterior aspect of the trunk at the first thoracic vertebrae (T1) spinous process; [2] posterior aspect of the pelvis at the first sacral vertebrae (S1); [3 and 4] flat, broad portion on the superior aspect of the acromion on bilateral scapula; [5 and 6] lateral aspect of the bilateral upper arm at the deltoid tuberosity; [7 and 8] posterior aspect of the bilateral distal forearm, centered between the radial and ulnar styloid processes; [9] dorsal aspect of the second metatarsal of the stride foot; [10 and 11] lateral aspect of bilateral upper leg, centered between the greater trochanter and the lateral condyle of the knee; [12 and 13] lateral aspect of bilateral lower leg, centered between the head of the fibula and lateral malleolus; and [14] dorsal aspect of the third metacarpal of the pitching hand. These sensor locations are pictured in Figure 3.1.

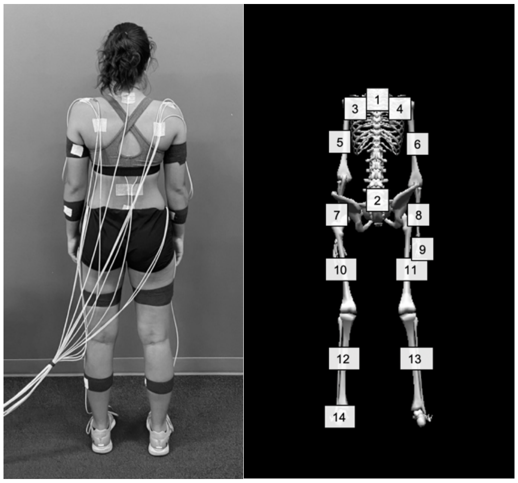

Figure 3.1. Posterior view of electromagnetic sensor placement for a right-handed pitcher. Left: Still picture of human participant with sensors affixed to body segments. Right: Still picture of digitized animated skeleton within The MotionMonitor and sensor positions labelled.

A 15th movable sensor was attached to a plexiglass stylus and used for the digitization of bony landmarks. A link segment model was developed by palpating and digitizing bony landmarks. Joint centers were calculated as the midpoint between two digitized points, except for the shoulder and hip. The shoulder joint center was determined through use of a rotation method previously validated (Veeger, 2000; Wu et al., 2002; Wu et al., 2005). Hip joint location was established using the Bell Method (Bell et al., 1989).

Digitization of segment endpoints were completed with the participant standing in a neutral position with arms at participants' sides and palms facing thighs to ensure accuracy of segment lengths upon digitization. Bony landmarks are described in Table 3.3. Two digitization points describe the longitudinal axis of each segment and a third point on the segment defined the plane of the segment.

Table 3.3. Description of body landmarks used to create the segment link model.

Bony Landmarks	Digitized Bony Process
Upper Extremity	
Medial elbow	Medial epicondyle
Lateral elbow	Lateral epicondyle
Medial wrist	Most distal aspect of radius
Lateral wrist	Most distal aspect of ulna
Third metacarpophalangeal joint	Dorsal, distal aspect of 3rd metacarpal
Middle distal phalanx	Most distal aspect of the 3rd phalanx
Trunk	
Seventh cervical vertebra (C7)	C7 Spinous process
Twelfth thoracic vertebra (T12)	T12 Spinous process
Eighth thoracic vertebra (T8)	T8 Spinous process
Suprasternal notch	Most cranial aspect of sternum
Xiphoid process	Most distal aspect of sternum
Lower Extremity	
Foot	Second phalange metacarpal joint
Lateral ankle	Lateral malleolus
Medial ankle	Medial malleolus
Lateral knee	Lateral femoral condyle
Medial knee	Medial femoral condyle
Pelvis	Bilateral anterior superior iliac crest Bilateral posterior superior iliac crest

Following digitization, participants were instructed to warm up according to how they normally would in preparing to throw a game with maximal effort. Warm-up time did not exceed 30 minutes. Participants threw fastballs with a regulation size softball (12 inches, ~ 6.25 oz) to a catcher located at regulation distance (43 ft). The participant was instructed to let the primary researcher know when they felt completely warm and game ready.

The participant was then asked to throw fastballs as maximal effort strikes to a catcher. Each trial that was considered a strike by the primary investigator was saved for analysis

(Barrentine et al., 1998; Nimphius et al., 2016; Werner et al., 2005). Participants threw as many pitches as was required to record ten acceptable trials. Total pitch count did not exceed 30, and pitchers were given a minimum of 20 seconds between pitches to rest. This is the maximum amount of time between pitches allotted during international softball competition (WSBC, 2017).

Participants were required to throw all trials with the front edge of their push foot originating on the back side of the front edge of the force plate (Figure 3.2). A researcher who held the flock of bird cords and the primary investigator visually observed that each trial began with the participants' push foot fully on the force plate. Additionally, it was visually observed that the participant's stride foot was behind and not touching the force plate. Accurate foot placement was required to ensure data included only the one point of contact of the push foot on the force plate. Participants were also asked to be still prior to initiation of a pitch, like game rules, to allow for easy identification of the first event mark: start of motion.

Figure 3.2. Push foot placement on the force plate for a right-handed pitcher.

The windmill pitch was broken into 5 events: 1) start of motion: first change in center of mass velocity in the posterior direction greater than .1 m/s, 2) foot off: participants' push foot net GRF was less than 20 N prior to leaving the force plate (Dai et al., 2012), 3) foot contact (FC): where the magnitude of velocity of the stride foot ankle decreased to less than 1.5 m/s (Escamilla et al., 1998), 4) ball release (BR): where the throwing arm wrist net acceleration begins to decrease following foot contact, 6) follow-through: defined as 24 frames following BR, which is equal to 100 ms (Oliver et al., 2018). According to these events, the following phases were of interest: 1) Propulsion phase: from start of motion to foot off, 2) Acceleration phase: from foot off to ball release (Figure 3.3) (Nimphius et al., 2016).

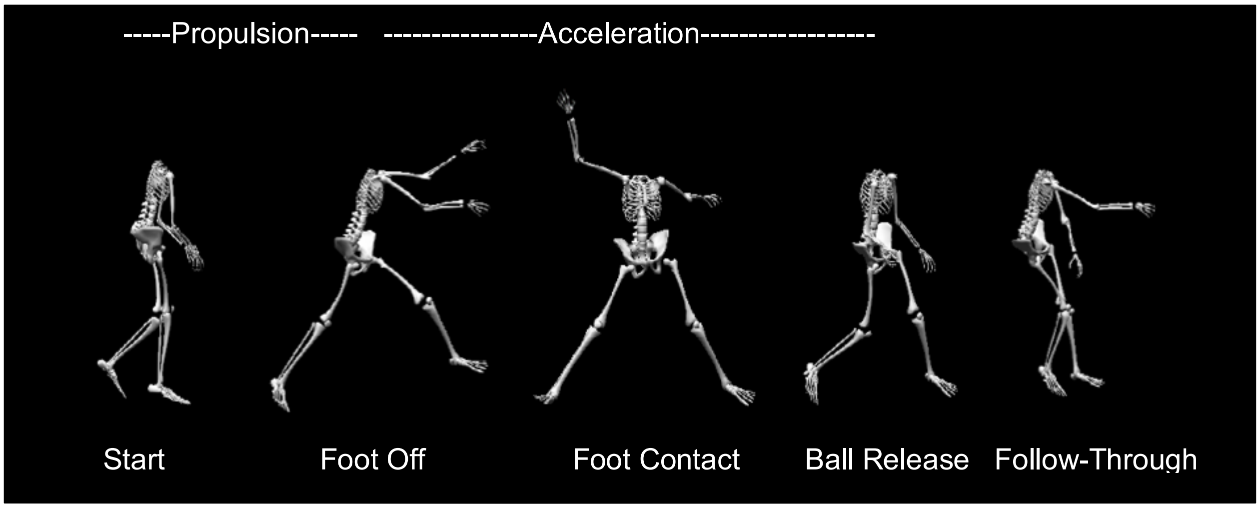

Figure 3.3. Phases (top) and events (bottom) throughout the windmill pitch.

Data Analysis

All data were filtered within The MotionMonitor (Innovative Sports Training, Chicago, IL). Raw data was independently filtered using a 4th order Butterworth filter with a cutoff frequency of 13.4 Hz (Darke et al., 2018; Fleisig et al., 1999; Matsuo et al., 2006; Zheng et al., 2004), deemed acceptable according to a pilot residual analysis of differently sized participants. Data were processed using customized MATLAB scripts (MATLAB R2020a, MathWorks, Natick, MA, USA) and analyzed using IBM SPSS Statistics 26 Software (IBM corp., Armonk, NY). The first three fastest pitch trials were averaged and analyzed (Werner et al., 2005), as previous reports have suggested there is little variability between pitches (Pappas et al., 1985), and that three trials are sufficient to analyze pitch motion (Bates et al., 1992). Prior to full analyses, data were analyzed for outliers, normality, and linearity. Histograms for each variable are presented in Figures H1-H36 (Appendix H). Alpha level was set *a priori* at $\alpha = .05$. Table 3.4 shows the variables, events analyzed, and statistical approaches used for each research question.

The American College of Sports Medicine criterion-based reports define 20-32% body fat as being satisfactory for health in women (Kaminsky 2013). Therefore, the cutoff value determining pitchers with high-fat% from pitchers with healthy-fat% was set at 32% body fat. Those pitchers with a body fat percentage below 32% were grouped into the healthy-fat% category, while those pitchers with 32% body fat or greater were grouped into the high-fat% category. Of note, none of the pitchers in the healthy-fat% group had less than 20% body fat.

Statistical Approach

Table 3.4. Description of the statistical approach for each research question.

Research Question (RQ)		Independent Variable	Dependent Variable	Pitch Event/ Phase	Statistical Analysis
RQ1	Do pitchers with a high-fat% display a force-time curve during the propulsive phase different from pitchers who have a healthy-fat%?	▪ Pitcher groups: high-fat% vs. healthy-fat%	▪ GRFx (% BW) ▪ GRFy (% BW) ▪ GRFz (% BW)	▪ Propul-sion phase ▪ 1000 ms prior to foot off	▪ MANOVA ▪ 2 SPM(X2)
RQ2	Is pitcher whole-body composition and throwing arm segmental composition correlated with peak throwing shoulder distraction force during the acceleration phase of the pitch?	▪ Whole-body lean mass ▪ Whole-body fat mass ▪ Arm fat mass ▪ Arm lean mass ▪ Arm length	▪ Peak throwing shoulder distraction force	▪ Accel-eration phase	▪ 2 Backwards Elimination Regressions
RQ3	Are whole-body composition measures associated with pitch velocity?	▪ BMI ▪ Whole BF% ▪ Body height ▪ Body mass	▪ Pitch velocity	▪ No Event	▪ Regression
RQ4	Do pitchers' upper arm, chest, waist, and hip girth correlate with trunk and throwing arm position at ball release of the pitch?	▪ Trunk flexion ▪ Trunk lateral flexion ▪ Trunk rotation ▪ Shoulder plane of elevation ▪ Shoulder elevation	▪ Upper arm girth ▪ Chest girth ▪ Waist girth ▪ Hip girth	▪ Ball release	▪ 4 Backwards Elimination Regressions
RQ5	Do peak angular velocity trunk rotation, shoulder flexion, elbow flexion, and wrist flexion correlate with pitch velocity, and do time series plots of segmental angular velocities differ between pitchers who have a high-fat% and a healthy-fat%?	▪ Pitcher groups: high-fat% vs. healthy-fat%	▪ Peak angular velocity of: Trunk rotation, shoulder flexion, elbow flexion, wrist flexion ▪ Pitch velocity	▪ Whole pitch: Events 1-5 ▪ 1000 ms prior to follow-through	▪ Correlation ▪ MANOVA ▪ 2 SPM(X2)

CHAPTER IV

RESULTS

The purpose of this project was to identify the influence of segmental and total body composition on softball pitchers' kinematics, kinetics, and pitch velocity. This chapter describes the results from each research question:

RQ1: Do pitchers with a high-fat% display a force-time curve during the propulsive phase different from pitchers who have a healthy-fat%?

RQ2: Is pitcher whole-body composition and throwing arm segmental composition correlated with peak throwing shoulder distraction force during the acceleration phase of the pitch?

RQ3: Are whole-body composition measures associated with pitch velocity?

RQ4: Do pitchers' upper arm, chest, waist, and hip girth correlate with trunk and throwing arm position at ball release of the pitch?

RQ5: Do peak angular velocity trunk rotation, shoulder flexion, elbow flexion, and wrist flexion correlate with pitch velocity, and do time series plots of segmental angular velocities differ between pitchers who have a high-fat% and a healthy-fat%?

RQ1: Comparison of High-fat Percentage and Healthy-fat Percentage Pitchers' Force-Time Curve during the Propulsive Phase

Thirty-four right-handed pitchers volunteered to participate (1.702 ± .060 m, 75.86 ± 17.19 kg, 15.2 ± 1.3 years, n = 34). Based on The American College of Sports Medicine criterion (Kaminsky, 2013), those pitchers with a total body fat percentage equal to or greater than 32% were grouped into the high-fat% category (1.713 ± .056 m, 84.59 ± 16.15 kg, 15.3 ± 1.6 years, n = 20), while those with a body fat percentage less than 32% were grouped into the healthy-fat% category (1.687 ± .066 m, 63.40 ± 9.19 kg, 15.1 ± 1.0 years, n = 14).

GRFxMax (anterior GRF), GRFyMax (vertical GRF), and GRFzMin (medial GRF) peak values of the push foot were found during the propulsion phase of the pitch: defined between the first event (Start) and the second event (Foot Off) (Please see Part A of Figure 4.1). All three variable peaks, GRFxMax, GRFyMax, and GRFzMin, were observed in the final portion of the propulsion phase, indicating these force contributions provided the last bit of push-off from the ground. GRFxMax, GRFyMax, and GRFzMin were each normalized to pitchers' body weight and were analyzed using SPSS software (SPSS Statistics 26 software, IBM Corp., Armonk, NY, USA). Variable means and standard deviations are presented in Table 4.1. All three variables were normally distributed, and there were no observed outliers based on visual analysis of boxplots. Linearity was assessed and confirmed with visual inspection of bivariate scatterplot matrices.

First, a multiple analysis of covariance (MANCOVA) was used to control for the effects of pitch velocity; however, not all assumptions for MANCOVA were met. Pitch velocity had a significant interaction with the factor (pitcher group); therefore, multiple analysis of variance

(MANOVA) was used to assess group differences. Homogeneity of variance-covariance matrices were evaluated using Box's M test of equality of covariance, which deemed data did not display equal variance. Therefore, Pillai's trace was reported to account for unequal variance. MANOVA showed pitchers' GRF differed significantly between those pitchers who had a healthy-fat% and those who had a high-fat% ($V^{(s)} = .279$, $F_{3,30} = 3.875$, $p = .019$, $\eta^2_p = .279$, with an observed power of .770). Univariate follow-up analyses revealed pitchers with a healthy-fat% had an increased weight-normalized medial GRF ($F_{1,32} = 7.264$, $p = .049$, $\eta^2_p = .192$, with an observed power of .763). There was no group difference in anterior GRF, ($F_{1,32} = 3.875$, $p = .058$, $\eta^2_p = .108$, with an observed power of .480), or vertical GRF ($F_{1,32} = .801$, $p = .378$, $\eta^2_p = .024$, with an observed power of .140).

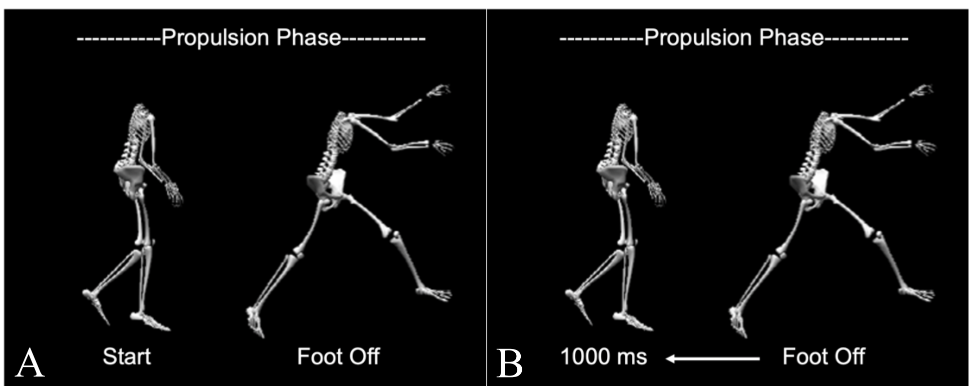

Figure 4.1. Propulsion phase of the pitch defined two ways: A) from "Start" to "Foot Off" of the pitch (101 samples included); and B) including 1000 ms prior to "Foot Off" (238 samples included).

Table 4.1. Means ± standard deviations of weight-normalized GRF peaks for RQ1.

	Category	N	Mean ± Standard Deviation
GRFxMax	Healthy-fat%	n = 14	19.85 ± 6.02 %
N (% BW)	High-fat%	n = 20	15.69 ± 6.10 %
GRFyMax	Healthy-fat%	n = 14	149.18 ± 10.27 %
N (% BW)	High-fat%	n = 20	144.83 ± 16.01 %
GRFzMin*	Healthy-fat%	n = 14	-20.48 ± 1.42 %
N (% BW)	High-fat%	n = 20	-16.43 ± 3.25 %

Notes: Ground reaction forces displayed as a percentage of body weight.
* denotes significance $p < .05$.

Statistical parametric mapping (SPM) was used to determine a more holistic view of the difference in GRF between heathy-fat% and high-fat% pitchers over the propulsion phase of the pitch. SPM was employed using MATLAB (MATLAB R2020a, MathWorks, Natick, MA, USA) to compare the combined GRF components between the high-fat% and healthy-fat% groups of pitchers. SPM is a statistical analysis technique that can forego the limitations that often accompany discretizing biomechanical signals and can account for the multiple observations over time (Pataky et al., 2013). Being that the GRF components were analyzed over the course of the propulsion phase, SPM was used as a means to analyze the large volume of data bounded by time.

Two separate 1-dimensional SPM(X2) (MANOVA) analyses were performed. The first SPM analysis was employed using 101 samples over the propulsion phase of the pitch defined between the first event (Start) and the second event (Foot Off). A second SPM(X2) analysis was employed using 238 samples over a 1000 ms period prior to the push foot leaving the force plate (Event Mark 2: Foot Off) (Figure 4.1). This second analysis was used to observe potential timing differences between groups as a previous report shows that softball pitch velocity was influenced by both the magnitude and timing of GRF (Nimphius et al., 2016).

Results revealed there were no statistically significant differences between the two groups of pitchers in weight-normalized GRF when data were normalized between the first two pitch events (Figure 4.2). Figure 4.2 shows that at 67% of the pitch, the two groups of pitchers differed the most, although this was not statistically significant ($SPM(X2)_{1,32} = 14.51$, $p > 0.05$). Means and standard deviations for each GRF component at this point in the pitch are displayed in Table 4.2.

Table 4.2. Means ± standard deviations of weight-normalized GRF at 67% of the propulsion phase (defined between two events).

	Category	N	Mean ± Standard Deviation
GRFxMax	Healthy-fat%	n = 14	.48 ± 1.67 %
N (% BW)	High-fat%	n = 20	-2.51 ± 4.23 %
GRFyMax	Healthy-fat%	n = 14	11.63 ± 26.72 %
N (% BW)	High-fat%	n = 20	19.62 ± 25.00 %
GRFzMin	Healthy-fat%	n = 14	-1.11 ± 4.20 %
N (% BW)	High-fat%	n = 20	-1.20 ± 3.21 %

Notes: Ground reaction forces displayed as a percentage of body weight.

Separate GRF component time series plots are displayed in Figure 4.3. The GRFx plot shows that prior to the push-off from the ground, the high-fat% group descriptively exhibits a slightly greater braking force while the push foot becomes loaded. The healthy-fat% pitchers do not present as great a braking force prior to propulsion. The GRFy plot also shows slight descriptive differences between pitcher groups. The high-fat% group has a slight increase in

GRF in the y-direction prior to the major peak that results during the predominant push-off from the ground. The GRFz plot also displays a slight difference. The healthy-fat% group shows descriptively increased medial ground reaction force during approximately the final 30% of the propulsive phase of the pitch (Figure 4.3).

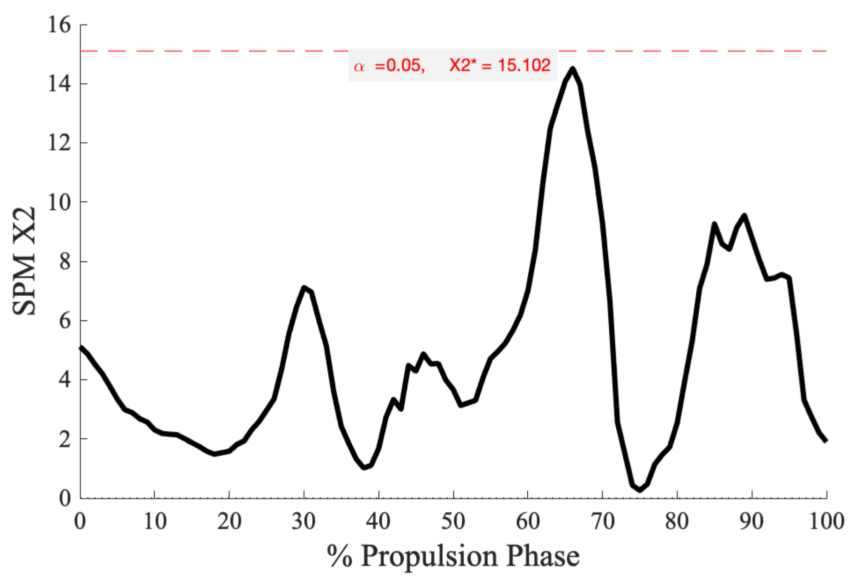

Figure 4.2. SPM(X2) of the combined multivariate dependent variable (GRFs) during the propulsion phase of the pitch defined between events 1 (Start) and 2 (Foot Off).

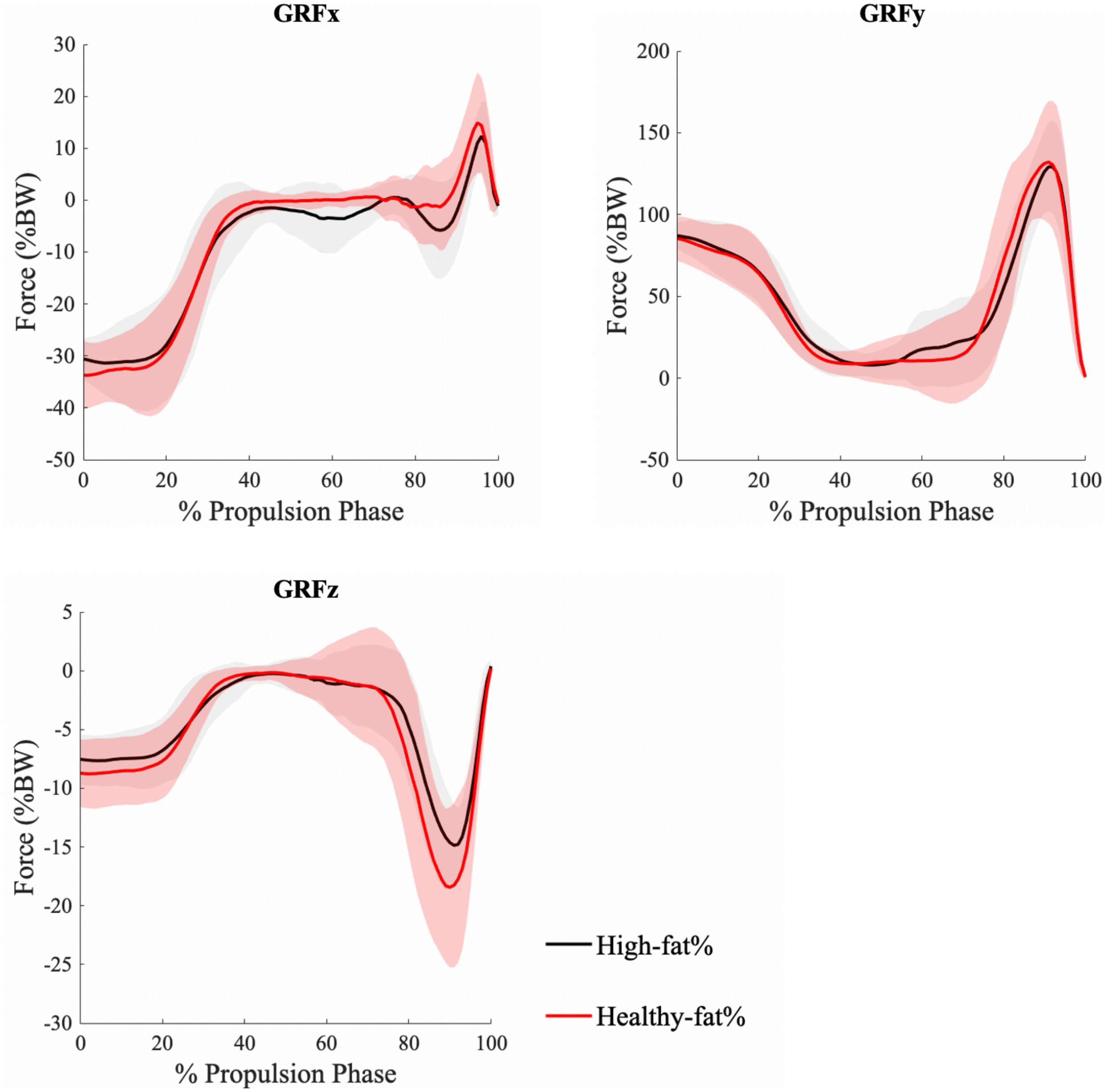

Figure 4.3. GRFx, GRFy, and GRFz (normalized to body weight) during the propulsion phase of the pitch. Lines represent group means and shaded areas represents 1 standard deviation from the group mean. Note: (+) GRFx = anterior GRF; (+) GRFy = vertical GRF; (-) GRFz = medial GRF.

Results revealed there were also no statistically significant differences between the two groups of pitchers in weight-normalized GRF when data were extracted over the last 1000 ms (238 samples) prior to foot off (Figure 4.4). Figure 4.4 shows that near sample number 189 is where the two groups of pitchers differed the most, although this was not statistically significant ($SPM(X2)_{1,32} = 11.47$, $p > 0.05$). Means and standard deviations for each GRF component at this point in the pitch are displayed in Table 4.3.

Table 4.3. Means ± standard deviations of weight-normalized GRF at sample number 189 of 238 during the propulsion phase (defined 1000 ms prior to foot off).

	Category	**N**	**Mean ± Standard Deviation**
GRFxMax	Healthy-fat%	n = 14	-.83 ± 18.14 %
N (% BW)	High-fat%	n = 20	-4.49 ± 8.87 %
GRFyMax	Healthy-fat%	n = 14	130.33 ± 15.37 %
N (% BW)	High-fat%	n = 20	122.98 ± 19.95 %
GRFzMin	Healthy-fat%	n = 14	-18.44 ± 4.81 %
N (% BW)	High-fat%	n = 20	-14.44 ± 3.07 %

Notes: Ground reaction forces displayed as a percentage of body weight.

Separate GRF component time series plots are displayed in Figure 4.5. Descriptively examining the GRFx plot, the healthy-fat% pitchers present a small propulsive/anterior GRF prior to the braking GRF. As well, the high-fat% pitchers still display a greater braking force upon front foot loading. Examining the GRFy plot, the high-fat% seem to keep more weight distributed on their push foot and begin to load the push foot earlier than the healthy-fat% pitchers, while also reaching a lower peak GRFy. The high-fat% group also shows an earlier medial GRF but again reaches a lower peak than the pitchers with a healthy-fat%.

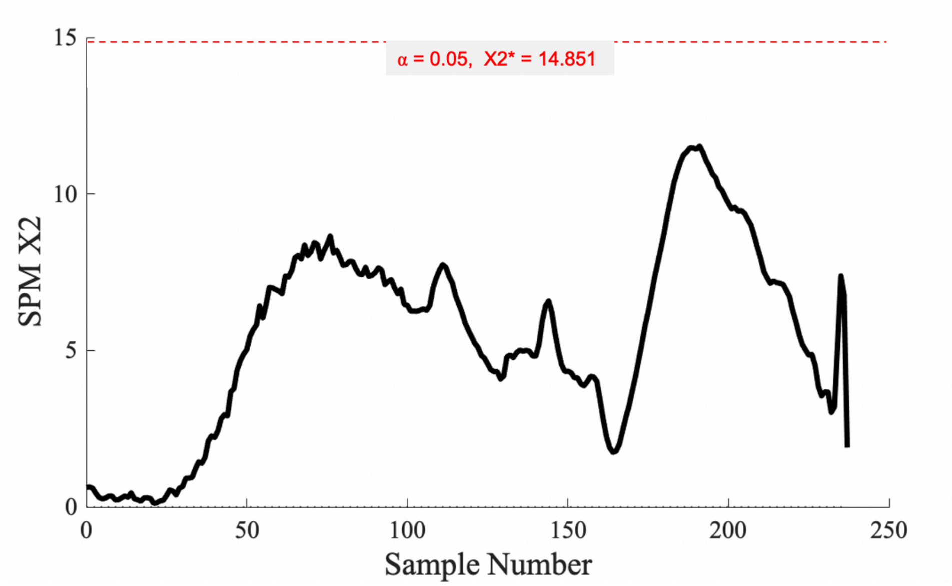

Figure 4.4. SPM(X2) of the combined multivariate dependent variable (GRFs) during the 1000 ms (238 frames) prior to foot off.

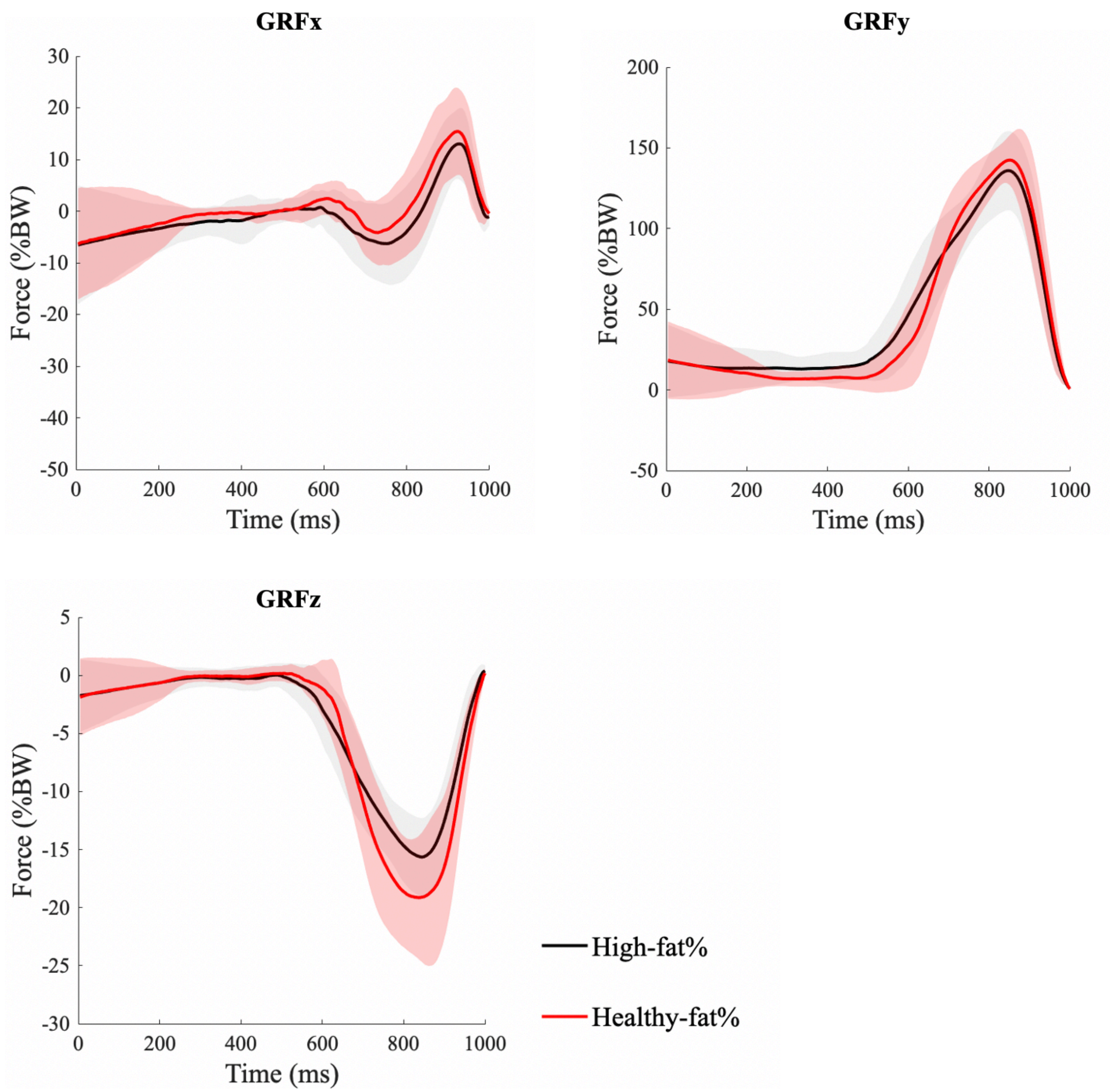

Figure 4.5. GRFx, GRFy, and GRFz (normalized to body weight) during 1000 ms (238 frames) prior to foot off. Lines represent group means and shaded areas represents 1 standard deviation from the group mean. Note: (+) GRFx = anterior GRF; GRFy = vertical GRF; (-) GRFz = medial GRF.

RQ2: Relationship of Pitcher Body Fat% and Absolute Throwing Arm Segmental Fat with Weight and Pitch Velocity Normalized Shoulder Distraction Forces

Forty-two pitchers volunteered to participate and were included in the analysis (1.706 ± .061 m, 74.98 ± 15.94 kg, 15.5 ± 1.7 years, n = 42) to assess the effects of body composition measures on peak throwing shoulder distraction force. The peak throwing shoulder distraction force over the acceleration phase of the pitch (defined between event 2 (Foot Off) and event 4 (Ball Release)) was used as the dependent variable.

Normality was assessed for each variable included in the analyses. Peak throwing shoulder distraction force was normally distributed. The independent variables whole-body (WB) lean mass, throwing arm (TA) lean mass, and TA length were normally distributed. The independent variables WB fat mass, and TA fat mass were non-normally distributed. Mahalanobis distance was used to verify there were no multivariate outliers. Homoscedasticity was concluded based on assessment of residual scatterplots of standardized residuals versus predicted values. Variable means and standard deviations are presented in Table 4.4.

Peak throwing shoulder distraction force was first correlated with pitch velocity and results revealed there was no significant association, $r = -.024$, $p = .880$. Therefore, pitch velocity was not included in the regression analyses. Next, two statistical backwards elimination regression analyses were completed. The first regression included WB measures, while the second regression included TA measures. During each backwards elimination regression equation, variables were excluded if there was greater than 10% probability of an association by chance alone ($p > .10$).

Each whole-body measurement (WB lean mass, WB fat mass) was entered into the backwards elimination regression equation. The final model retained both independent variables. The regression equation was statistically significant, $F(2,41) = 40.791$, $p < .001$, and explained approximately 66% of variance in peak throwing shoulder distraction force during the acceleration phase ($R^2 = .667$, Adj. $R^2 = .660$). A summary of the regression can be seen in Table 4.5. Figures 4.6 and 4.7 display the relationships between WB lean mass and WB fat mass with throwing shoulder distraction force, respectively.

The second backwards elimination regression equation was completed using segmental variables. The regression originally included TA lean mass, TA fat mass, and TA length. After removal of TA length, the regression equation was statistically significant. The final restricted model included TA lean mass and TA fat mass, $F(2,41) = 23.691$, $p < .001$, and explained approximately 53% of variance in peak throwing shoulder distraction force during the acceleration phase ($R^2 = .549$, Adj. $R^2 = .525$). A summary of the regression can be seen in Table 4.6. Figure 4.8 displays the relationships between TA lean mass and throwing shoulder distraction force. Table 4.7 shows the regression coefficients for both backwards elimination regressions.

Table 4.4. Means ± standard deviations for RQ2.

	Mean ± Standard Deviation
Shoulder Distraction Force (N)	622.75 ± 175.72
WB Lean Mass (kg)	45.99 ± 7.01
WB Fat Mass (kg)	25.71 ± 10.76
TA Lean Mass (kg)	1.24 ± 0.23
TA Fat Mass (kg)	0.66 ± 0.26
TA Length (m)	0.70 ± 0.03

Table 4.5. Summary table for the WB regression analysis.

	Full/Restricted Model
R Square	.667*
SE Estimate	102.5
	Beta
WB Lean Mass (kg)	.606*
WB Fat Mass (kg)	.316*

Notes: *denotes statistical significance $p < .05$.

Table 4.6. Summary table for the TA regression analysis.

	Full Model	*Restricted Model*
R Square	.549	.525*
SE Estimate	121.07	121.06
	Beta	***Beta***
TA Lean Mass (kg)	-.123	.577*
TA Fat Mass (kg)	.630	.248
TA Length (m)	.260	-

Notes: *denotes statistical significance $p < .05$.

Table 4.7. Regression coefficients for both regression equations in RQ2.

	B	*SE*	β	*t*	*p*
Whole-body Measures and Shoulder Distraction Force					
Intercept	-208.937	108.627	-	-1.923	0.062
Whole-body Lean Mass*	15.197	2.725	.606	5.576	<.001
Whole-body Fat Mass*	5.163	1.774	.316	2.910	0.006
Throwing Arm Measures and Shoulder Distraction Force					
Intercept	-24.747	102.390	-	-.242	.810
Throwing Arm Lean Mass*	434.648	96.184	.577	4.519	<.001
Throwing Arm Fat Mass	165.057	84.780	.248	1.947	.059

Notes: *Indicates a significant predictor of the dependent variable.

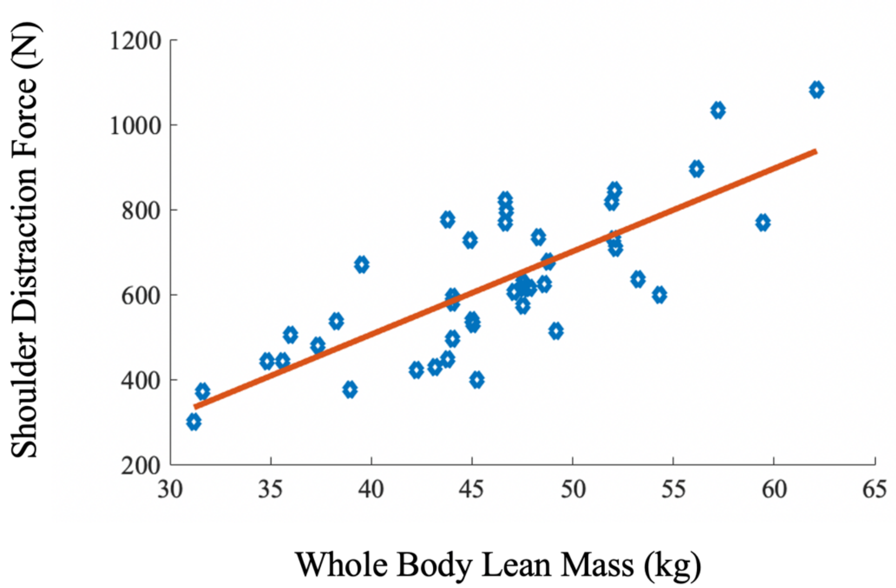

Figure 4.6. Scatterplot of peak throwing shoulder distraction force (N) and WB lean mass (kg). The orange line represents the regression line.

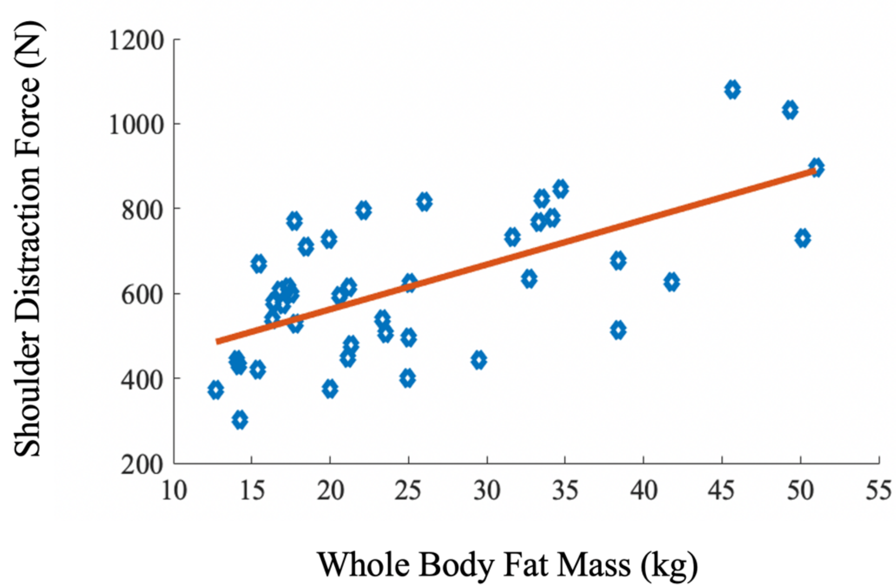

Figure 4.7. Scatterplot of peak throwing shoulder distraction force (N) and WB fat mass (kg). The orange line represents the regression line.

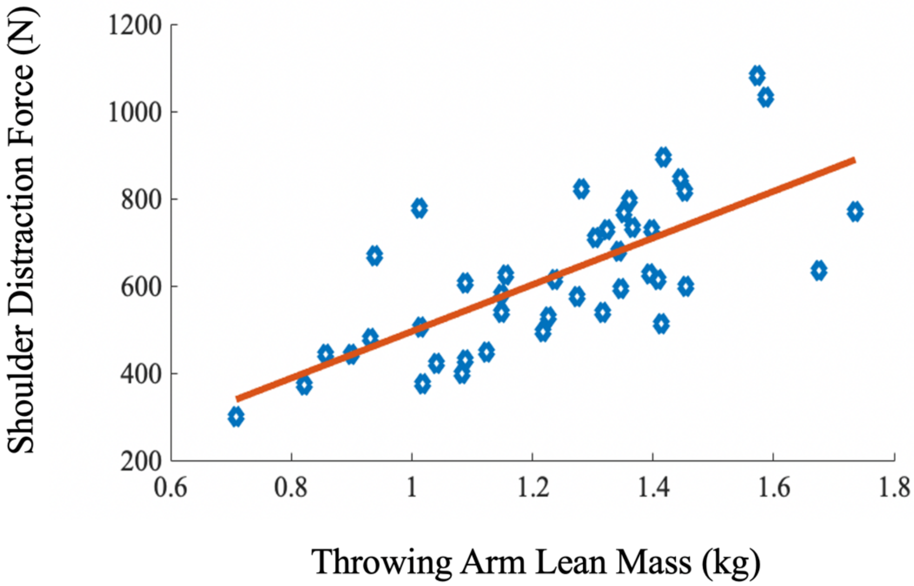

Figure 4.8. Scatterplot of peak throwing shoulder distraction force (N) and TA lean mass (kg). The orange line represents the regression line.

***RQ3*: Relationship of Body Mass Index and Body Fat Percentage with Pitch Velocity**

Forty-four pitchers volunteered to participate; however, one pitcher was removed from the analysis because their average pitch velocity was deemed an outlier according to visual assessment of a boxplot. Therefore, forty-three pitchers were included in the analysis (1.700 ± .070 m, 76.74 ±16.28 kg, 15.5 ±1.7 years, n = 43). Normality was assessed for each independent and dependent variable. The dependent variable, pitch velocity was normally distributed. The independent variable, body height, was also normally distributed. Body mass index (BMI), body fat percentage, and body mass were not normally distributed. The assumption of linearity was met based on visual analysis of bivariate scatterplot matrices. Homoscedasticity was assessed through a residual scatterplot and it was concluded that there was homogeneity of variance.

All four independent variables, along with the dependent variable, pitch velocity, were entered into a standard regression equation to determine the relationship between body size and composition measurements with pitch velocity. Descriptive statistics are represented in Table 4.8 and statistical results are displayed in Table 4.9. The regression model, $F(4,42) = 4.230$, $p = .006$, was statistically significant, and explained approximately 24% of variance in pitch velocity ($R^2 = .308$, Adj. $R^2 = .235$). Results revealed body fat percentage was the only significant predictor of pitch velocity (SE = .124, t = -3.379, $p = .002$) and had a negative relationship with pitch velocity (Figure 4.9).

Table 4.8. Means ± standard deviations for RQ3

	Mean ± Standard Deviation
Pitch velocity (mph)	55 ± 5
BMI[a] (m/kg^2)	26.66 ± 6.29
Body Fat (%)	35.22 ± 7.72
Body Height (m)	1.700 ± .070
Body Mass (kg)	76.14 ± 16.27

Notes: [a]BMI = Body Mass Index

Table 4.9. Regression coefficients for the regression equation in RQ3.

	B	***SE***	**b**	***t***	***P***
Intercept	41.756	69.583	-	.600	.552
BMI[a] (m/kg^2)	.002	1.130	.002	.001	.999
Body Fat (%)*	-.419	.124	-.722	-3.379	.002*
Body Height (m)	8.824	41.532	.138	.212	.833
Body Mass (kg)	.166	.428	.604	.389	.699

Notes: [a]BMI = Body Mass Index. * denotes significance at $p < .05$.

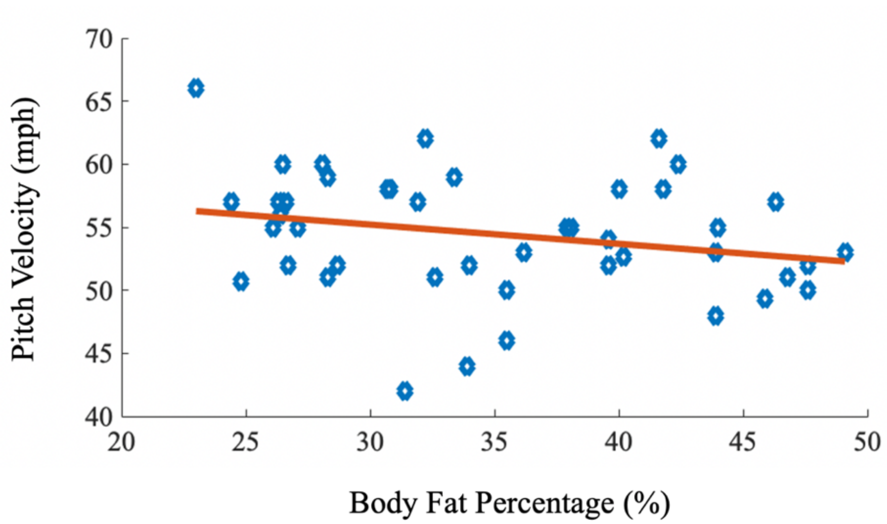

Figure 4.9. Scatterplot of pitch velocity (mph) and pitcher body fat percentage (%). The orange line represents the regression line.

***RQ4*: Relationship of Pitchers' Chest, Waist, Hip, and Upper Arm Girth Correlate with Trunk and Throwing Arm Position at Ball Release of the Pitch**

Forty-two pitchers volunteered to participate and were included in the analysis (1.706 ± .061 m, 74.98 ±15.94 kg, 15.5 ±1.7 years, n = 42). Normality was assessed for all variables. Waist and hip girth were both non-normally distributed. Initially a logarithmic transformation was used in attempt to normalize data, but the transformation was unsuccessful. As a result, an inverse transformation was used, as it has been suggested (Mertler & Reinhart, 2016) to successfully transform severely positively skewed data (Please see Appendix H for an explanation of the skewness and kurtosis before and after transformation, as well Figures H20 and H21 which represent histograms for the two transformed variables: waist and hip girth). Following inverse transformation of waist and hip girth, all measurements were normally distributed. The assumption of homoscedasticity was met via examination of residual scatterplots.

Four separate backwards elimination regression analyses were constructed, one for each dependent variable: upper arm circumference (UA_{circ}), chest circumference ($Chest_{circ}$), waist circumference ($Waist_{circ}$), and hip circumference (Hip_{circ}). Independent variables were measured at ball release (BR) and included trunk flexion, trunk lateral flexion, trunk rotation, throwing arm (TA) plane of elevation (POE) (also referred to as horizontal abduction), and throwing arm elevation (also referred to as abduction). Going forward, plane of elevation and elevation terminology will be used to be consistent with the International Society of Biomechanics Euler angle sequence rotation terminology (Wu et al., 2005). Each independent variable was entered into each backwards elimination regression equation, and variables were excluded if there was greater than a 10% probability of an association by chance alone ($p > .10$).

The backwards elimination regression equation predicting UA_{circ} was statistically significant, $F(2,41) = 3.886$, $p = .029$, and explained approximately 12% of variance in UA_{circ} ($R^2 = .166$, Adj. $R^2 = .123$). Although trunk rotation was included in the regression, it was not a significant predictor of UA_{circ} while TA POE was ($t = -2.462$, $p = .018$). The greater the pitchers' UA_{circ}, the less TA POE they experienced at BR. A summary of the regression analysis predicting UA_{circ} is shown in Table 4.10. The significant relationship between UA_{circ} and TA POE is shown in Figure 4.10.

The backwards elimination regression equation predicting $Chest_{circ}$ was statistically significant including trunk rotation and TA POE, $F(2,41) = 4.716$, $p = .015$. This equation explained approximately 15% of variance in $Chest_{circ}$ ($R^2 = .195$, Adj. $R^2 = .153$). Trunk rotation was not a significant predictor of UA_{circ} while TA POE was ($t = -2.897$, $p = .006$). The greater the pitchers' $Chest_{circ}$, the less TA POE they experienced at BR. A summary of the regression analysis predicting $Chest_{circ}$ is shown in Table 4.11. The significant relationship between $Chest_{circ}$ and TA POE is shown in Figure 4.11.

The backwards elimination regression equation predicting $Waist_{circ}$ was also statistically significant including only TA POE, $F(2,41) = 5.885$, $p = .020$. The equation explained approximately 11% of variance in $Waist_{circ}$ ($R^2 = .128$, Adj. $R^2 = .106$) with TA POE being the only significant predictor of $Waist_{circ}$ ($t = 2.426$, $p = .020$). The greater the pitchers' $Waist_{circ}$, the greater TA POE they experienced at ball release. The significant relationship between $Waist_{circ}$ and TA POE is shown in Figure 4.12. It is important to keep in mind that this equation was performed using inverse transformed data. Therefore, for consistency and ease of interpretation, the untransformed data have been presented in Figure 4.12 to demonstrate the consensus, increased girth measures were significantly associated with decreased TA POE at ball release. A summary of the regression analysis predicting $Waist_{circ}$ is shown in Table 4.12.

The backwards elimination regression equation predicting Hip_{circ} was not statistically significant. Regression coefficients for each regression can be seen in Table 4.13.

Table 4.10. Summary table for the regression analysis predicting upper arm circumference.

	Full Model	***Restricted Model***
R Square	.207	.166*
SE Estimate	3.991	3.932
	Beta	***Beta***
Trunk Flexion	.202	
Trunk Lateral Flexion	.087	
Trunk Rotation	-.238	-.301
TA POE	-.401	-.376*
TA Elevation	-.006	

Notes: *denotes statistical significance $p < .05$.

Table 4.11. Summary table for the regression analysis predicting chest circumference.

	Full Model	***Restricted Model***
R Square	.227	.195*
SE Estimate	10.253	10.051
	Beta	***Beta***
Trunk Flexion	.190	
Trunk Lateral Flexion	.025	
Trunk Rotation	-.217	-.273
TA POE	-.464	-.435*
TA Elevation	-.009	

Notes: *denotes statistical significance $p < .05$.

Table 4.12. Summary table for the regression analysis predicting waist circumference.

	Full Model	***Restricted Model***
R Square	.083	.106*
SE Estimate	.002	.002
	Beta	***Beta***
Trunk Flexion	-.141	
Trunk Lateral Flexion	-.024	
Trunk Rotation	.178	
TA POE	.463	.358*
TA Elevation	.056	

Notes: *denotes statistical significance $p < .05$.

Table 4.13. Regression coefficients for the segmental regression equations in RQ4.

	B	***SE***	**b**	***t***	***P***
		Upper Arm Circumference			
Intercept	34.631	2.941	-	11.776	<.001
Trunk Rotation	-0.114	0.058	-0.301	-1.968	0.056
TA POE*	-0.082	0.034	-0.376	-2.462	0.018*
		Chest Circumference			
Intercept	108.249	7.517	-	14.401	<.001
Trunk Rotation	-0.268	0.147	-0.273	-1.817	0.077
TA POE*	-0.248	0.086	-0.435	-2.897	0.006*
		Inverse Transformed Waist Circumference			
Intercept	0.010	0.001	-	8.547	<.001
TA POE*	3.267E-05	0.000	0.358	2.426	0.020*

Notes: *Indicates a significant predictor of the dependent variable. POE: plane of elevation; TA: throwing arm.

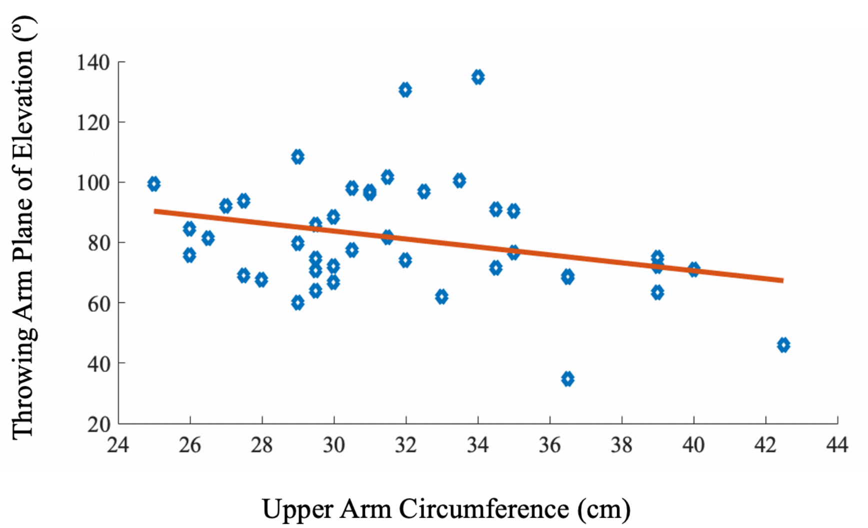

Figure 4.10. Scatterplot of upper arm circumference (cm) and throwing arm plane of elevation (°). The orange line represents the regression line.

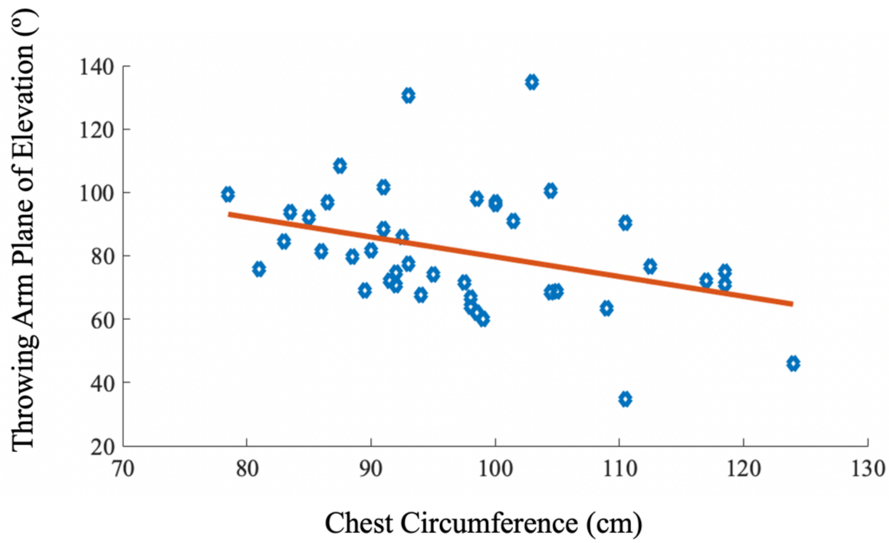

Figure 4.11. Scatterplot of chest circumference (cm) and throwing arm plane of elevation (°). The orange line represents the regression line.

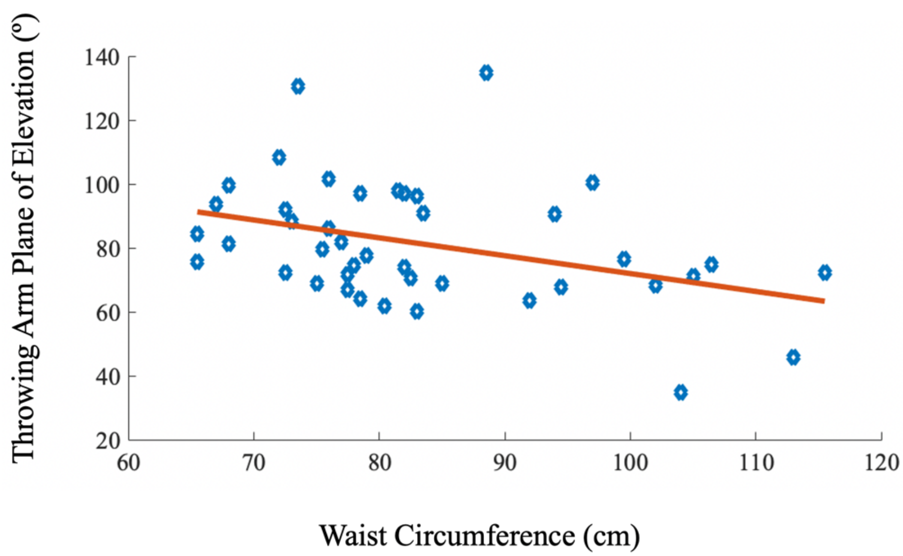

Figure 4.12. Scatterplot of waist circumference (cm) and throwing arm plane of elevation (°). The orange line represents the regression line.

RQ5: Relationship of Peak Magnitude Segmental Angular Velocities with Pitch Velocity and Comparison between High-Fat and Healthy-Fat Percentage Pitchers

Forty high school and college-aged pitchers were included in the analysis (1.706 ± .062 m, 75.53 ± 16.23 kg, 15.6 ± 1.8 years, n = 40). Peak segmental angular velocities were extracted between event 3 (Foot Contact) and event 5 (Follow-Through) to assess how segmental angular velocities influenced pitch velocity and potentially differed between body fat percentage groups. Normality was assessed for all variables using Shapiro-Wilks test of normality. Healthy-fat% peak trunk, shoulder, and elbow angular velocities were normally distributed. Both groups' peak wrist angular velocities and pitch velocities were also normally-distributed. High-fat% peak trunk, shoulder, and elbow angular velocities were non-normally distributed. Linearity was assessed through inspection of scatterplot matrices, and all bivariate relationships showed relatively elliptical patterns. Box's M test determined there was homogeneity of variance.

A correlation analysis was first used to identify if positive peak segment angular velocities were associated with pitch velocity. Peak angular velocities of the trunk (rotation towards the glove arm side), shoulder (flexion), elbow (flexion), and wrist (flexion) were also used as the dependent variables for the multivariate test.

The grouping variable for the MANOVA was based on body fat percentage. Those pitchers with a total body fat percentage equal to or greater than 32% were grouped into the high-fat% category (1.713 ± .059 m, 83.48 ± 15.55 kg, 15.5 ± 1.7 years, n = 23), while those with a body fat percentage less than 32% were grouped into the healthy-fat% category (1.698 ± .069 m, 64.78 ± 9.33 kg, 15.6 ± 1.9 years, n = 17).

Results showed pitch velocity was significantly correlated with peak elbow flexion angular velocity (r = .380, p =.016) and peak wrist flexion angular velocity (r = .621, $p < .001$). There were no other significant correlations ($p > .05$).

A MANCOVA was then used to examine the difference in peak angular velocity of the trunk (rotation towards the glove side), shoulder (flexion), elbow (flexion), and wrist (flexion), while controlling for pitch velocity. The MANCOVA did not meet all assumptions with pitch velocity as a covariate; therefore, the analysis proceeded as a MANOVA. The MANOVA was not statistically significant, F(1,38) = 1.502, p = .223, η^2_p =.147, with an observed power of .416.

To examine the time series of data over the course of the whole pitch, statistical parametric mapping was used. A SPM(X2) (MANOVA) analysis was used to compare the two groups of pitchers: healthy-fat% and high-fat%, in the combined dependent variable of segmental angular velocities of the trunk, shoulder, elbow and wrist. The SPM analysis was conducted twice. The first analysis was completed with data normalized to 101 data points between the first and last event. The second SPM analysis was completed by taking 238 samples (1000 ms) of data prior to follow-through. Angular velocity peaks were noted to be displayed near the acceleration phase of the pitch, therefore analyzing data from the latter portion of the pitch was done in attempt to look more closely at the higher angular velocities. As well, normalizing data to only one time point allowed for observations to be made regarding timing of segmental angular velocities.

The SPM analysis conducted with 101 samples over the whole pitch showed groups were significantly different at 99% of the pitch, just prior to the "Follow-Through" event ($SPM(X2)_{1,4}$ = 20.52, p = 0.0475) (See Figure 4.13). A plot representing mean ± standard deviation of the individual segment angular velocities between body fat percentage groups is presented in Figure 4.14.

The SPM analysis conducted with 238 samples over a 1000 ms time frame prior to follow-through was statistically significant at two points in the sample. SPM showed the two groups of pitchers differed at approximately 89% ($SPM(X2)_{1,4}$ = 18.067, p = .0497) and at 96-98% of this time frame ($SPM(X2)_{1,4}$ = 19.15-22.93, p = 0.0230) (See Figure 4.15). A plot representing mean ± standard deviation of the individual segment angular velocities between body fat percentage groups is presented in Figure 4.16.

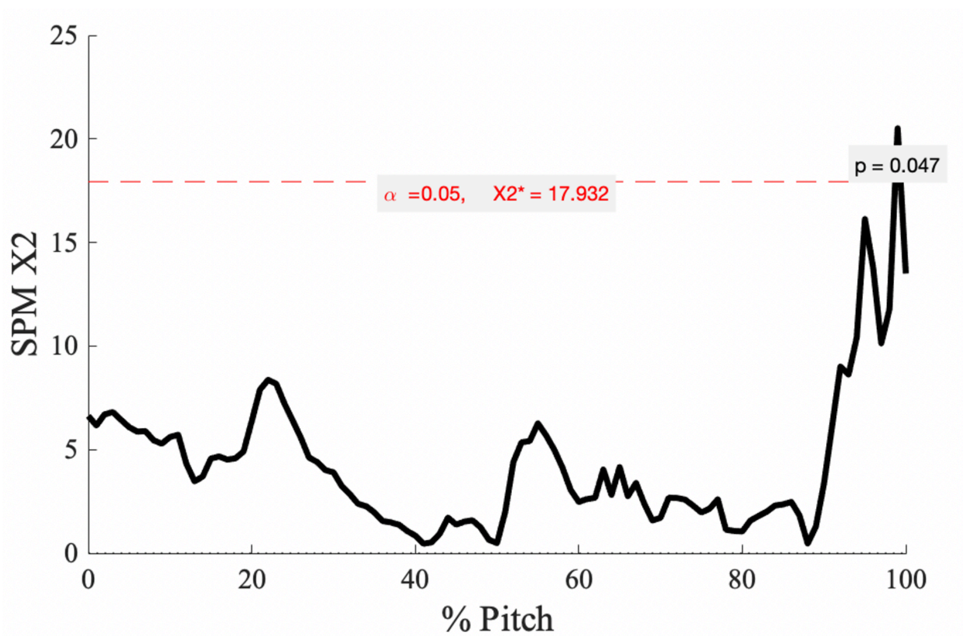

Figure 4.13. First SPM(X2) analysis of the combined multivariate dependent variable (segmental angular velocities) during the pitch. Data normalized to 101 samples between the first and last event of the pitch.

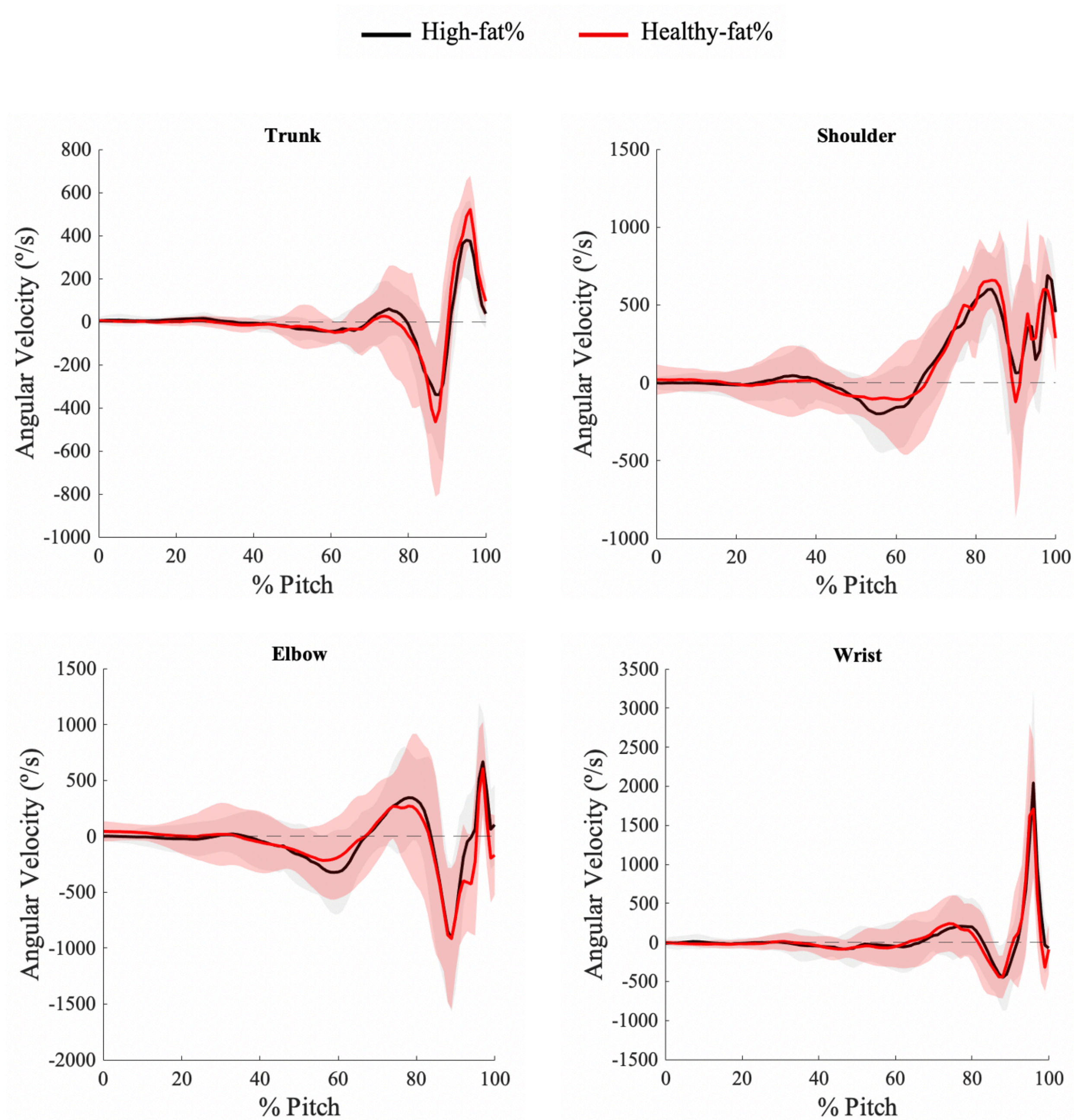

Figure 4.14. Distribution of mean ± 1 standard deviation of both groups of pitchers' trunk rotational velocity (top left), shoulder flexion velocity (top right), elbow flexion velocity (bottom left) and wrist flexion velocity (bottom right) during the pitch. Note: (+) Trunk Angular Velocity = rotation towards the glove arm side; (+) Shoulder/Elbow/Wrist Angular Velocity = flexion.

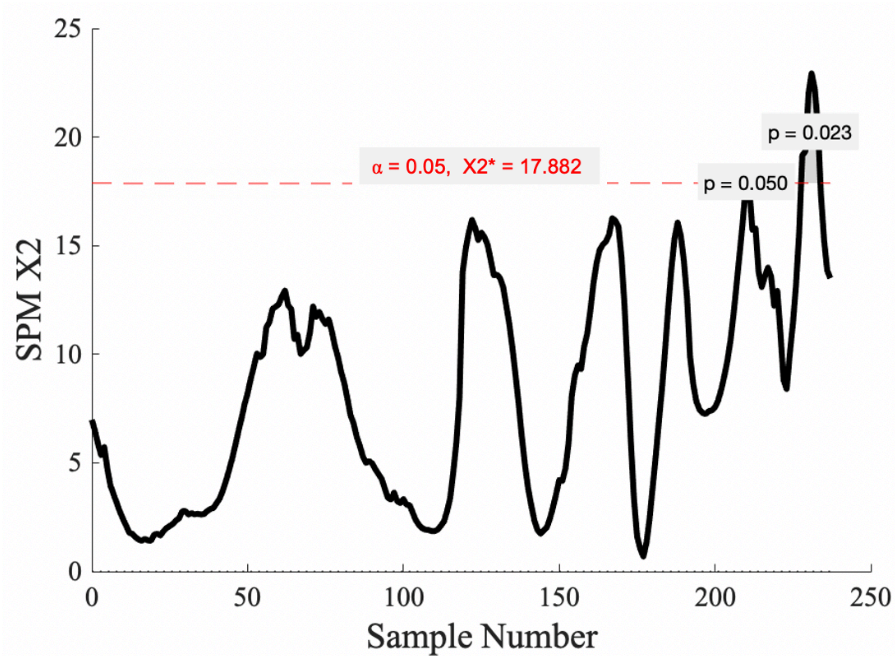

Figure 4.15. Second SPM(X2) analysis of the combined multivariate dependent variable (segmental angular velocities) during 1000 ms (238 samples) prior to follow-through.

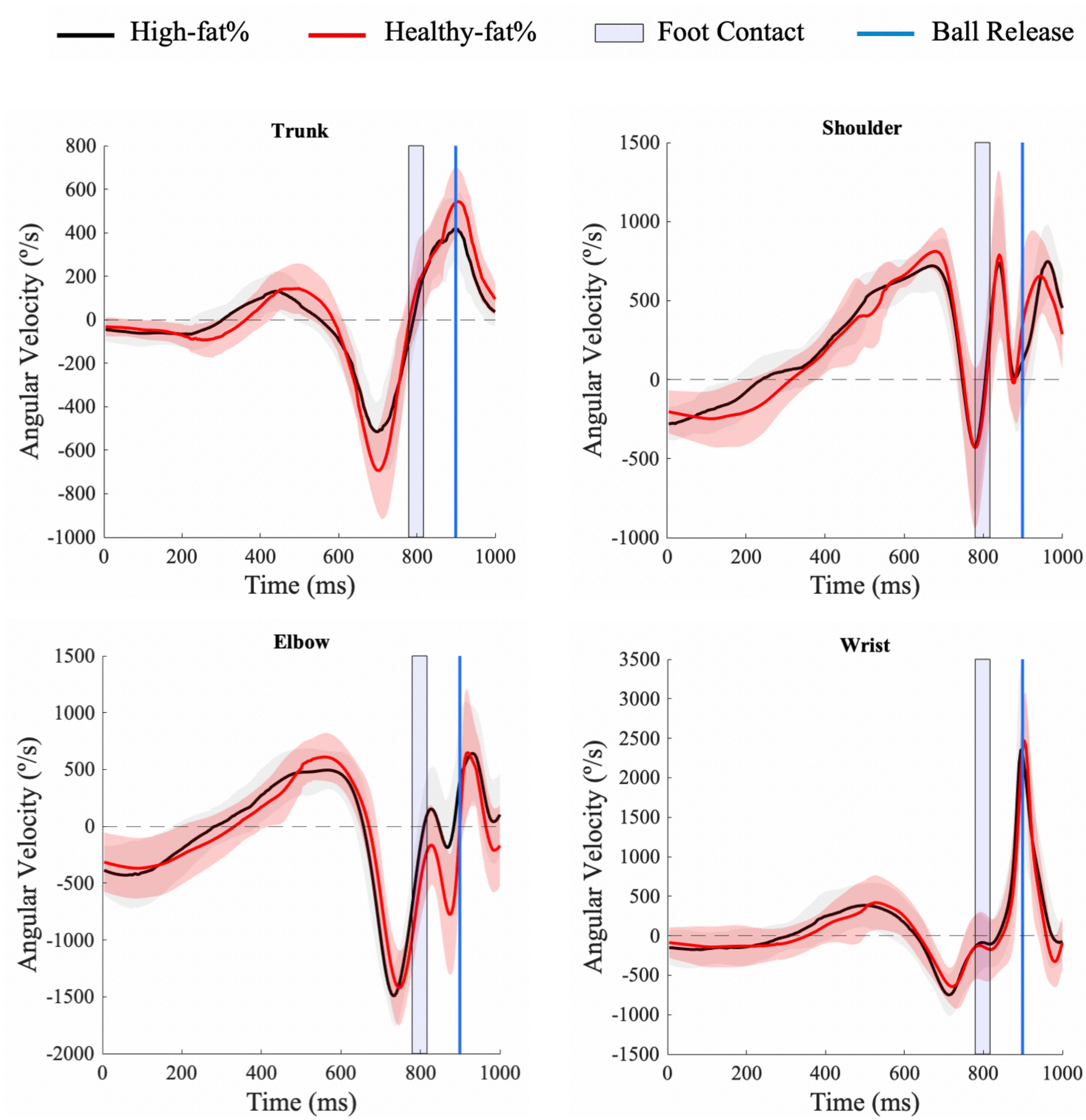

Figure 4.16. Distribution of mean ± 1 standard deviation of both groups of pitchers' trunk rotational velocity (top left), shoulder flexion velocity (top right), elbow flexion velocity (bottom left) and wrist flexion velocity (bottom right) during 1000 ms prior to follow-through. Note: (+) Trunk Angular Velocity = rotation towards the glove arm side; (+) Shoulder/Elbow/Wrist Angular Velocity = flexion. The blue shaded area of the plot represents the mean ± 1 standard deviation of the time frame at which foot contact occurred across participants. The solid blue line represents when ball release occurred.

The statistical approach and main findings for each research question are displayed in Table 4.14.

Table 4.14. Description of the main findings from each research question.

Research Question (RQ)		Pitch Event/Phase	Statistical Analysis	Main Findings
RQ1	Do pitchers with a high-fat% display a force-time curve during the propulsive phase different from pitchers who have a healthy-fat%?	▪ Propulsion Phase ▪ 1000 ms prior to foot off	▪ MANOVA ▪ 2 SPM(X2)	▪ Pitchers with a healthy fat percentage had an increased peak medial GRF. ▪ No significant differences were observed over the time series curve of pitch propulsion.
RQ2	Is pitcher whole-body composition and throwing arm segmental composition correlated with peak throwing shoulder distraction forces during the acceleration phase of the pitch?	▪ Accel-eration Phase	▪ 2 Backwards Elimination Regressions	▪ Whole-body (WB) backwards elimination regression final model included WB lean mass and WB fat mass. ▪ Throwing arm (TA) backwards elimination regression final model included TA lean mass.
RQ3	Are whole-body composition measures associated with pitch velocity?	▪ No Event	▪ Regression	▪ BF% was the only significant predictor of pitch velocity. ▪ Greater BF% is associated with decreased pitch velocity.
RQ4	Do pitchers' upper arm, chest, waist, and hip girth correlate with trunk and throwing arm position at ball release of the pitch?	▪ Ball Release	▪ 4 Backwards Elimination Regressions	▪ The elimination regression final model for UA_{circ}, $Chest_{circ}$, and $Waist_{circ}$ included only TA POE. ▪ Increased UA_{circ}, $Chest_{circ}$, and $Waist_{circ}$ girth was significantly associated with decreased TA POE at ball release.
RQ5	Do peak angular velocity trunk rotation, shoulder flexion, elbow flexion, and wrist flexion correlate with pitch velocity, and do time series plots of segmental angular velocities differ between pitchers who have a high-fat% and a healthy-fat%?	▪ EM 3-5 ▪ Whole Pitch: Events 1-5 ▪ 1000 ms prior to follow-through	▪ Correlation ▪ MANOVA ▪ SPM(X2)	▪ Elbow flexion velocity and wrist flexion velocity both correlated with pitch velocity. ▪ According to the time series of data, segmental angular velocities differed slightly during the final portions of the pitch.

CHAPTER V

DISCUSSION

The purpose of this project was to identify the influence of segmental and total body composition on softball pitchers' kinematics, kinetics, and pitch velocity. Results described in the previous section are now discussed in detail below. The main results revealed pitchers with a healthy-fat% displayed increased peak medial GRF during the propulsion of the pitch. Secondly, body fat percentage was positively related to peak throwing shoulder distraction force during the acceleration phase of the pitch, as well as decreased pitch velocity. Increased circumference of the upper arm, chest, and waist segments were related to altered throwing arm kinematics at ball release. Finally, elbow and wrist flexion angular velocity were positively related to pitch velocity, and differences existed during the final portion of the pitch between the healthy-fat% and high-fat% pitcher groups' segmental angular velocities.

RQ1: Comparison of High-fat and Healthy-fat Percentage Pitchers' Force-Time Curve during the Propulsive Phase

This research question sought to examine differences in ground reaction force (GRF) development during the propulsive phase of the pitch between those pitchers who displayed a high body fat percentage (high-fat%) and those who had a healthy body fat percentage (healthy-fat%). It was hypothesized that those pitchers with a high-fat% would have a greater weight-normalized peak vertical GRF and would need a longer period of force development. Results revealed that the healthy-fat% group of pitchers displayed a higher weight-normalized peak medial GRF than the high-fat% group of pitchers (mean difference = 4.05% BW).

Prior to analysis, it was hypothesized that pitchers with a higher body-fat percentage would generate additional force to help push them off the ground and towards home plate. This initial projection was made in lieu of a large number of pitcher athletes who portray additional mass, specifically fat mass, and are successful at high levels of the game. Despite larger pitchers needing additional force to create similar accelerations as those with decreased mass, large pitchers often reach high pitch velocities. Research has noted a strong relationship between pitch velocity and vertical GRF (MacWilliams et al., 1998; Nimphius et al., 2016); therefore, it was hypothesized that the pitchers with a high-fat% would display greater GRF and higher pitch velocities.

Previous reports have suggested that heavier adults portray increased lower-extremity muscle mass, which was expected to benefit the larger athletes (Lafortuna et al., 2005; Rolland et al., 2004). Descriptive data for pitcher groups' whole-body and lower extremity composition (Table 5.1) reveals the high-fat% pitchers did have increased absolute lower extremity muscle mass; however, high-fat% pitchers also had decreased weight-normalized lower extremity muscle mass. High-fat% pitchers exhibiting decreased weight-normalized lower extremity muscle mass could explain the lower weight-normalized peak medial GRF observed during the propulsion phase of the pitch. While increased mass may initially have been considered advantageous in force generation, the study population involving predominantly high school athletes suggests that there may be altered weight-normalized GRFs according to body-fat percentage.

Study results revealed that medial GRF was the only GRF component to significantly differ between pitcher groups. It was observed that the healthy-fat% group of pitchers generated a greater lateral push as opposed to the high-fat% group of pitchers. However, it is important to keep in mind that the 'medially' directed GRF does not explicitly mean that the pitchers were directing force laterally off of their push foot into the ground. Pitchers regularly perform some degree of external rotation of the push foot while it becomes loaded following the initial backwards weight shift. Greater external rotation of the push leg before push-off may increase medially directed GRF during the propulsion of the pitch. Perhaps the group of healthy-fat% pitchers experienced greater external rotation of the push foot or push hip before leaving the force plate, which might explain why healthy-fat% pitchers display a higher mean peak medial GRF during propulsion. While healthy-fat% pitchers exhibit less body mass on average, they would likely also have less weight on their push foot while shifting weight from the stride leg in preparation for the push off of the ground. The time series plot of GRFy (Figure 4.3) shows the high-fat% pitchers maintain more weight on their push foot while weight is mainly shifted onto the stride leg. As a result, larger pitchers might have a more challenging time rotating the push foot because of the additional weight and friction between the push foot and the ground.

Although early push foot rotation is not considered advantageous for the pitcher (Fry et al., 2019), there may have been an increased degree of early push foot rotation due to an absence of a pitcher's mound, which can offer resistance. The lack of a pitching rubber is a limitation and difference between prior studies and the current work, possibly influencing pitchers to adopt a different strategy. Further research is needed to examine the position of push foot contact and the development of GRF during the propulsion phase.

The overall time series curve of GRF was not significantly different throughout the propulsion phase of the pitch, either when data were normalized between the first two pitch events, or when data represented 1000 ms prior to foot off. Although there were no significant differences, attention should be drawn near the 65-70% portion of the propulsion phase of the SPM(X2) analysis (Figure 4.2). While the analysis lacked statistical significance, the author believes that there is a notable performance difference. By examining the three individual GRF component plots (Figure 4.3 and Figure 4.5), it should be noted that the vertical GRF time series curve shows the high-fat% group of pitchers began their push-off from the force plate slightly earlier than the healthy-fat% group. Although these results were not significant, the difference is noticeable and worth discussing. Additional time of force development may be necessary to account for the increased mass exhibited in those pitchers who carry excess body fat. Although these findings are not yet associated with performance or injury, it is important to note that differences exist in the propulsion of the pitch between healthy-fat% and high-fat% pitchers.

Another interesting observation is within the GRFx plot representing 1000 ms before foot off (Figure 4.5). This plot shows that the pitchers with a healthy-fat% have a slight propulsion force prior to the more noticeable braking force. The braking force represents the pitcher's body weight becoming loaded onto the push foot after being predominantly on the stride foot (which is positioned behind the pitcher's mound during early propulsion). The small propulsive force occurring slightly earlier and observed only in the healthy-fat% pitchers is likely due to a small backwards slide of the push foot over the force plate. Pitchers sometimes adopt this slight backwards slide of the push foot to serve as a counter-movement before push-off. Interestingly, the pitchers with a high-fat% do not present this same minuscule anterior GRF prior to the larger posterior force, which is observed within both groups of pitchers. While high-fat% pitchers do not create this early propulsive force, it may again highlight the additional weight placed on the push foot and the greater friction possibly limiting early foot movement.

In conclusion, the presence of increased body fat percentage may have an effect on GRF development during the propulsion of the pitch. The development of force during this phase has been related to pitch velocity, and as such, is a crucial factor in softball pitching. Although only medial GRF was statistically significantly different between pitcher groups, the healthy-fat% pitchers displaying increased peak medial GRF can offer insight to how body composition may alter pitch biomechanics and force generation. Future work should include a pitching rubber to allow for game-like strategies to be observed in the lab, as well as to control for the suspected altered approach adopted by pitchers in the absence of a pitching rubber. Future research is also needed to understand the implications of the observed GRF differences. Understanding how body mass and body fat influence force development and softball pitch biomechanics from the ground up is essential to safe pitcher development.

Table 5.1. Means ± standard deviations for both pitching groups' lower extremity composition.

	Healthy-fat%	**High-fat%**
Total: Weight (lbs)	138.10 ± 20.07	184.65 ± 35.60
Legs: Lean Tissue (lbs)	31.79 ± 7.57	37.69 ± 7.13
Legs: Lean Tissue (% BW)	23.32 ± 3.54	20.68 ± 1.68
Legs: Fat Tissue (lbs)	14.95 ± 2.35	26.02 ± 7.63

RQ2: Relationship of Pitcher Whole-Body and Segmental Fat Percentage with Body Weight Normalized Shoulder Distraction Forces

The purpose of this research question was to examine the relationship between body composition and peak throwing shoulder distraction force during the acceleration phase of the softball pitch. It was hypothesized that whole-body and throwing arm composition measures would correlate with throwing shoulder distraction force. Results revealed significant associations between peak throwing shoulder distraction force, and whole-body lean mass, whole-body fat mass, and throwing arm lean mass.

Currently in the literature, three phenomena are becoming more understood: 1) softball pitchers' upper extremities are injured most often possibly due to the high stress at the shoulder joint (Oliver et al., 2018; Oliver et al., 2019), 2) larger pitchers are injured most often (Greenberg et al., 2017; Hill et al., 2004), and 3) according to this research study, larger athletes accrue more stress at the shoulder joint. While increased adipose tissue and obesity are widely accepted as deleterious for overall health (Bollinger, 2017), this study's findings reveal increased whole-body and segmental composition may also negatively impact softball pitch biomechanics previously associated with pain (Oliver et al., 2018).

A study by Oliver et al. (2018) noted that those pitchers who are currently experiencing upper extremity pain accrue higher throwing shoulder distraction force during the softball pitch (Oliver et al., 2018). Therefore, although throwing shoulder distraction force has not yet been related to injury, it is a suspected culprit of throwing arm pain and a potential factor leading to upper extremity injury (Oliver et al., 2019; Oliver et al., 2018). While the current study reveals body composition is related to peak throwing shoulder distraction force, it is suggested that those athletes with an increased body fat percentage may be more susceptible to injury due to the increased stress observed at the throwing shoulder.

The acceleration phase of the pitch is of particular interest as it is during this phase that the throwing arm biceps brachii is shown to be especially active (Rojas et al., 2009). Furthermore, the acceleration phase is also the portion of the pitch where peak upper extremity forces and moments are experienced (Alexander & Haddow, 1982; Barrentine et al., 1998; Werner et al., 2006). The biceps brachii works to resist both throwing shoulder distraction force and produce an elbow flexion torque throughout this part of the throwing motion. The large role of the biceps tendon and the stress that ensues on the anterior portion of the shoulder is speculated to contribute to the high upper extremity injury rates present among softball pitchers (Barrentine et al., 1998).

Baseball and softball research have also noted injury rate is increased among those pitchers who are taller, heavier, and have a higher body mass index (Chalmers et al., 2015; Greenberg et al., 2017; Hill et al., 2004). A report of youth and high school baseball pitchers shows that throwing arm shoulder and elbow moments are significantly associated with body mass and total body fat (Garner et al., 2011). Further, when the regression model was restricted to include only throwing arm composition measures, the amount of variance explained was unchanged, which suggests throwing arm composition affects throwing arm kinetics, perhaps more than whole-body composition.

The current study found whole-body measures, lean mass and fat mass, to be associated with absolute throwing shoulder peak distraction force. Additionally, throwing arm lean mass was also shown to significantly associate with throwing shoulder distraction force. While throwing arm fat mass was included in the segmental regression equation’s final model, it was not found to be a significant predictor of throwing shoulder distraction force. Throwing arm lean mass was more strongly correlated with throwing shoulder distraction force than throwing arm fat mass upon initial correlation analyses. This was an unexpected finding, as it was hypothesized that specifically fat mass would mainly contribute to increased throwing shoulder distraction force. Perhaps the presence and ability of additional throwing arm lean mass changes pitch biomechanics in a way that leads to altered kinetics at the throwing shoulder.

The association between throwing shoulder distraction force and body composition has also been reported among baseball pitchers. Baseball reports show that throwing arm forces and torques are regularly related to pitch velocity and pitcher age (Aguinaldo & Chambers, 2009; Slowik et al., 2019), noting size of player is largely the reason for increased kinetics. However, there have also been reports which suggest the relationship between body size and kinetics does not always exist (Luera et al., 2018). A previous baseball report shows that professional pitchers demonstrate altered biomechanics compared to their younger counterparts, which minimize the weight-normalized forces generally associated with injury during baseball pitching (Luera et al., 2018). The ability of some professional pitchers to decrease conceivably harmful pitch kinetics via altered kinematics, is important as pitchers inevitably develop into larger and heavier athletes with age. Therefore, while body composition may affect throwing shoulder force, there is a possibility of minimizing such kinetics in lieu of improved or altered kinematics. Perhaps older and larger athletes who are successful at high levels of the game have adapted mechanics to lessen the effect of their body size on throwing shoulder kinetics. More research is needed to examine these hypotheses.

While distraction force is becoming more regularly associated with injury, one may theorize that increased whole-body lean and fat tissue, as well as increased segmental lean tissue, may increase pitchers' risk of throwing arm injury. Softball pitchers regularly display the greatest whole-body mass on collegiate softball teams (Czeck et al., 2019). Further, research has shown an increase in pitcher's body mass is related to increased pitch velocity (Werner et al., 2008). Therefore, while literature has suggested increased mass is beneficial for pitching, it is also important to acknowledge too much of a good thing may be detrimental. Additional mass may increase injury susceptibility of softball pitchers' throwing arms. The relationship between body composition and specific injury mechanisms needs to be further studied to make causal claims and better understand why larger athletes are more commonly injured.

Future analyses should work to understand how increased throwing shoulder distraction force affects softball pitchers. Previous research shows that baseball pitchers' ulnar collateral ligament (UCL) size is positively correlated with pitch velocity, and increases during in-season play (Chalmers et al., 2020). The UCL's adaptative response to stress may be considered beneficial for the throwing athlete, highlighting the need to further examine both the advantages and disadvantages of throwing athletes sustaining greater stress to their throwing shoulder. Similarly, research is needed to understand how distraction force influences anatomical structures, humeral head positioning, and mechanics.

While softball pitching is a complex sporting task, there are likely many other variables related to pitcher athlete development which may have ramifications related to throwing shoulder distraction force. Additional research is needed to continue identifying pain predictors for softball pitchers in effort to decrease the vast upper extremity injury rates observed at most levels of the sport. Finally, additional research is needed to examine how body composition measures may affect these potential injury risk factors.

Limitations of the current study exist and should be acknowledged. Pain and injury were not measured as part of the current study, so while previous research suggests potential links between shoulder distraction force and injury, these conclusions are not within the scope of this study. Secondly, while most athletes who volunteered to participate demonstrated a high level of skill given their age, it is necessary to understand that as athletes age and their skill level increases, there are fewer performance differences separating those at the highest level of the game. Within an even more homogenous group of talent and an older cohort, we might find that body composition has an altered effect on throwing shoulder distraction force and other potential injury risk parameters.

RQ3: Relationship of Body Size and Composition with Pitch Velocity

The purpose of this research question was to examine the influence of body size and composition on pitch velocity. While it is commonly inferred that the fastest throwing baseball and softball pitchers are the larger athletes, the study findings showed body fat percentage was negatively associated with pitch velocity, while BMI, body height, and body mass showed no significant relationship with pitch velocity.

Pitch velocity is a highly sought-after trait regularly used as an indicator for pitch performance. The ability to throw a softball with increased pitch velocity allows pitchers an advantage over the batters they face. A faster-moving softball decreases the amount of time a batter has to adjust to the incoming pitch. Although softball pitchers report the highest body fat percentage on collegiate softball teams (Czeck et al., 2019), this study shows that a lower body fat percentage is more advantageous in performance. Specifically, those pitchers with a decreased body fat percentage exhibited higher average pitch velocities. Therefore, although a pitcher can be successful and carry an increased amount of body fat, these study findings highlight the potential negative effects of increased body fat on performance. While some pitchers may train to add weight to increase pitch velocity, increasing specifically body fat mass may have disadvantages. Likely it is the presence of particularly lean body mass that will benefit a pitcher; therefore, it is important to differentiate between how total body mass, lean mass, and fat mass all affect pitching biomechanics.

Baseball pitch studies have shown that body weight is a significant predictor of pitch velocity, noting larger athletes are expected to achieve greater forces and torques that contribute to an increased pitch velocity (Werner et al., 2008). The relationship between body mass and pitch velocity is theorized due to additional muscle mass and subsequent strength present among those who are heavier (Werner et al., 2008). Additional research is needed to examine the influence of specifically muscle mass on pitch velocity, as well as other variables related to pitch velocity, such as ground reaction force. Additionally, muscle contributions and muscle activity analyses are needed to understand how activation of particular muscle groups may affect pitch performance. Many factors contribute to a pitcher's success, and the high variability in mechanics may limit the direct effects of a pitchers' body size and composition on pitch velocity. Therefore, further research is needed to control the other biomechanical factors associated with pitch velocity and the drastic differences in pitching styles (especially within the preparatory motion) while examining the effects of body composition.

Results show an increased body fat percentage may inhibit pitch velocity; therefore, perhaps athletes, coaches, and clinicians should prioritize fitness conditioning alongside strength training among high school level athletes as a means to improve body composition. Developing pitch velocity is an important factor related to pitch performance; therefore, offering athletes information regarding the association of body composition and performance needs to be handled with sensitivity. Altering body composition in a healthy way takes time and should be conducted safely and with the assistance of trained professionals.

While working to improve performance, a focus needs to be placed on injury prevention efforts as well. Performance and injury regularly go together, as athletes tend to perform their best while pain- and injury-free. As a result, any attempt to improve performance needs to be implemented with injury prevention efforts in mind. Not only does a healthier body composition possibly impact pitch velocity, but data presented in research question two also suggests higher body fat percentage may negatively associate with potential pain-predictors.

Research highlights the high rates of musculoskeletal injury and the burden sports-related injuries can have, especially among young athletes (Conn et al., 2003). Although sport is encouraged to improve athlete health and well-being, there is additional risk placed on those who participate in sports (Emery & Pasanen, 2019). Specifically, those who specialize in one sport at the exclusion of others are at an increased risk of sustaining an injury (Bell et al., 2018), primarily due to the athletes experiencing overuse. Interestingly, 26 of the 43 athletes examined in this research question did not play another sport, showing the high rate of specialization already occurring in early high school-aged athletes.

Exclusion of other sports can increase injury risk and lead to the cessation of activity once injured (Bell et al., 2018). Young athletes who choose to sport specialize also risk under-developing multidimensional and diverse athletic skills (Myer et al., 2015). As a result, pitchers who specialize early and whose aerobic capacity is rarely emphasized within their specialized sport and position, may not prioritize body composition and fitness to the degree that other positions and sports might. This could explain why over half of the participants included in this study were placed in the high-fat% category. Despite the current norms suggesting that most high school pitchers have an unhealthy amount of excess adipose tissue, this study shows that decreased body fat percentage is related to increased pitch velocity. As a result, greater aerobic training and conditioning should be emphasized among young athletes, specifically softball pitchers.

It is important to keep in mind that the population studied was predominantly high school athletes (93% of participants). It is hypothesized that the younger age range of the current study athletes may affect the study results. In research question one, it was assumed that the larger pitchers would generate greater weight-normalized GRF during the propulsion phase of the pitch, which was not found to be true. As a result, it is no surprise that the players with a higher body fat percentage also do not throw with an increased pitch velocity. While most study participants appeared skilled given their age group, at higher levels of the game, there is very little that separates the top pitchers. In lower levels of the game, there can often be a wider gap in experience, expertise and skill. It is possible that older and more elite pitchers may present altered effects of body composition on pitch velocity.

RQ4: Relationship of Pitchers' Chest, Waist, Hip, and Upper Arm Girth Correlate with Trunk and Throwing Arm Position at Ball Release of the Pitch

The purpose of this research question was to examine the influence of additional adipose tissue and therefore increased segmental girth on pitch kinematics at ball release. All pitch events are completed with the end goal of placing the body in an ideal position to release the ball in the right location, with the right spin, and at a high velocity. Therefore, the event of ball release is of particular interest. Similarly, previous studies have shown that kinematics and kinetics at ball release can be associated with presence of upper extremity pain (Oliver et al., 2019; Oliver et al., 2018). Likewise, the event of ball release is also of interest, while the throwing arm passes the plane of the body. It is theorized that at this position of the pitch, biomechanics may be most susceptible to alterations given the close proximity of segments and the potential impingement issues that additional mass and girth may cause.

The current study found that girth measurements were most associated with throwing arm plane of elevation, commonly referred to as horizontal abduction (Please refer to Figure 5.1 for a descriptive illustration). While girth measurements were all strongly correlated with one another, only specific girth measurements were associated with throwing arm plane of elevation. Those pitchers with increased upper arm, chest, and waist girth displayed less throwing arm plane of elevation at ball release, meaning their throwing arm had less horizontal abduction. This was not expected as it was originally hypothesized that the larger athletes would have greater plane of elevation relative to the trunk. This was initially hypothesized due to the expectation that larger athletes would not complete as much trunk rotation as the smaller athletes, due to the above-average inertia of the trunk and the added difficulty in rotating heavier segments. With decreased trunk rotation originally expected among those with increased mass, it was then hypothesized that those pitchers would need additional plane of elevation to keep the position of their throwing arm in line with home plate. Trunk rotation was part of the upper arm and chest restricted regression equations; however, post-hoc analyses showed trunk rotation was not a significant predictor of any girth measurement. Therefore, trunk rotation was not shown to significantly vary according to pitcher size, only shoulder plane of elevation. While there were no significant associations between trunk rotation and girth measures, there was also no positive relationship between increased throwing arm plane of elevation and increased girth measures, as originally hypothesized.

It was anticipated that the larger athletes would display increased throwing arm plane of elevation because research has acknowledged larger pitchers are injured more often (Hill et al., 2004), as well as that those pitchers who are currently experiencing upper extremity pain exhibit increased throwing arm plane of elevation at foot contact of the pitch (Oliver et al., 2018). As a result, the larger athletes who are more prone to injury (those athletes with increased girth measures) were expected to exhibit increased throwing shoulder plane of elevation. While those athletes with increased girth displayed decreased throwing arm plane of elevation, the discrepancy may be in lieu of the varied pitch events at which these measures were associated. The previous study which associated pain with an increased plane of elevation noted this relationship occurred at foot contact, while the current study reveals the opposite relationship at ball release.

The relationship observed between decreased throwing arm plane of elevation and increased girth measures may result from larger pitchers needing to throw ‘around’ the additional tissue present at both the throwing arm and trunk. While ball trajectory is extremely important in being able to throw strikes consistently, it is reasonable to predict that the larger pitchers would need to release the ball slightly closer to the plate and in front of their body to avoid the enlarged trunk girth (chest, waist). Although findings were not as expected, results revealing that girth measures were significantly associated with throwing arm plane of elevation suggests that those pitchers who carry increased adipose tissue present altered throwing arm kinematics. Further research is needed to understand how throwing arm positioning may impact pitchers' risk of injury and pain prevalence.

Previous reports show that those pitchers who are heavier have higher pain prevalence (Oliver et al., 2019), acknowledging the risk of increased weight on pain and potentially injury susceptibility. Furthermore, research has shown that pitcher body mass index is related to increased trunk flexion at ball release, suggesting that pitchers needed to create space for their throwing arm to pass via increased trunk flexion (Friesen et al., 2020). Although no trunk kinematics were associated with girth measures, the decreased throwing shoulder plane of elevation may have been a similar attempt to create space necessary for the throwing arm to release the ball at the intended target successfully. To avoid the additional girth, less throwing arm plane of elevation may be a compensation technique to get 'out and around' the increased girth and still release the ball with proper timing for strike trajectory.

Although the current study findings were not consistent with previous reports, alterations in movement according to the size of pitcher should be of interest to athletes, coaches, and clinicians. While particular body composition is rarely emphasized in softball, varied kinematics resulting from additional girth and adipose tissue suggests larger athletes may need to compensate or modify movement to account for the extra load. Previously in research question three, increased body fat percentage was negatively associated with pitch velocity. This might suggest that the altered kinematics observed at ball release in the current research question, may contribute to decreased pitch velocity and poorer pitch performance; however, additional research is needed to examine these hypotheses further. It could also be that increased girth alters kinematics in such a way that is beneficial for performance, but more research is needed to explore these relationships. Future work should look to examine how plane of elevation at ball release might influence a pitcher's health and performance.

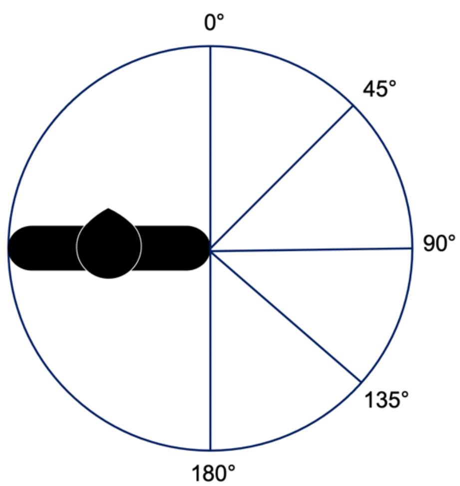

Figure 5.1. Top down view of a straight-forward facing, right-handed pitcher with throwing shoulder plane of elevation represented relative to trunk position. First represented by Doorenbosch et al. (Doorenbosch et al., 2003).

RQ5: Relationship of Peak Segmental Angular Velocities with Pitch Velocity and Comparison between High-Fat and Healthy-Fat Percentage Pitchers

The purpose of research question five was two-fold: 1) to assess if peak segmental angular velocities were related to pitch velocity and, 2) to assess if segmental angular velocities differed between pitcher groups based on body fat percentage. Pitch velocity is a prominent indicator of pitching performance and is therefore highly emphasized during training and competition. Understanding how body composition might influence segmental velocity and pitch velocity may provide insight into the physical development of softball pitchers.

Peak angular velocities including trunk rotation (towards the glove arm side), shoulder flexion, elbow flexion and wrist flexion were all noted in the latter portion of the pitch. The current study found that peak elbow and wrist flexion angular velocity were positively related to pitch velocity, while trunk rotation and shoulder flexion velocity were not. Throughout the acceleration phase of the pitch, as the throwing arm approaches ball release, there is a prominent elbow flexor moment (Barrentine et al., 1998) during which the biceps brachii produces an eccentric muscle action to resist external elbow extension torque (Rojas et al., 2009). The elbow then flexes as the throwing arm undergoes ball release and follow-though. Perhaps the additional 'whipping' action of elbow flexion occurring near ball release aids in the added pitch velocity. Research has shown that more skilled pitchers displayed a better proximal to distal sequencing of segments (Oliver et al., 2010); thus, the increased elbow flexion velocity exhibited in those who throw the ball with a higher velocity may be an example of this.

Because the biceps brachii is a primary muscle producing throwing arm elbow flexion, it might also be suggested that those athletes who are better able to create this torque may be at an advantage during softball pitching. Although peak segmental velocities did not significantly differ between pitcher body-fat% groups, it is important to remember that research question three showed that pitch velocity was negatively related to increased body fat percentage. Therefore, although the current research question did not identify differences in peak segmental angular velocities between pitcher groups, there is still reason to believe that body fat percentage influences pitch velocity via different factors. The study finding which notes elbow flexion velocity was related to pitch velocity, might suggest that those pitchers with greater dynamic elbow flexion strength may create higher-velocity elbow flexion, leading to increased pitch velocity. Future research is needed to examine the potential relationships between lean mass, strength, and muscle activation with pitch velocity.

Wrist flexion was also correlated with pitch velocity. This same relationship has been displayed in baseball literature (Elliott et al., 1988; MacWilliams et al., 1998); therefore, it is not surprising that this relationship also exists within softball pitching. Research question three presented that the group of pitchers with a healthy-fat% threw with an increased pitch velocity. It could then be hypothesized that the pitchers with a healthy-fat% were able to accrue a higher peak elbow and wrist angular flexion velocity; however, that is not supported in this research question. The MANOVA examining angular velocities between pitcher groups revealed no statistically significant differences in peak segmental angular velocities.

Since the pitchers within the high-fat% group are typically larger, they will have an increased segmental mass moment of inertia. Therefore, if both groups of pitchers applied the same torque to rotate segments, pitchers with heavier segments would achieve lower angular accelerations. As a result, it was hypothesized that high-fat% pitchers would have altered timing of segmental sequencing. Specifically, it was believed the larger pitchers would require more force to accelerate segments due to the greater inertia (resistance to change motion). Simultaneously, it was hypothesized these pitchers would require more time following ball release to slow these segments.

Time series analyses revealed slight differences between pitcher groups' segmental angular velocities near the final portions of the pitch. Shortly after ball release is when peak elbow flexion velocity was noted. According to the time series plot (Figure 4.16), the pitchers with a healthy-fat% reached greater elbow extension velocity between foot contact and ball release. Shortly after ball release, the healthy-fat% pitchers reached a slightly greater elbow flexion velocity over a shorter period. The greater ability of those pitchers with a healthy-fat% to change elbow flexion angle may be a result of the decreased segmental inertia common among those with less body-fat. Similarly, Figure 4.16 shows that from approximately 600 – 800 ms, the high-fat% pitchers seem to be subtly lagging behind the healthy-fat% pitchers in terms of the progression of elbow angular velocity, again alluding to the potential timing differences that exist between high-fat% and healthy-fat% pitchers.

A plot of elbow flexion angle shows healthy-fat% pitchers have greater elbow flexion through the majority of the pitch but then display less elbow flexion near follow-through than the high-fat% group (Figure 5.2). Perhaps the high-fat% pitchers needed greater elbow flexion near follow-through to shorten the throwing arm and decrease the torque placed on the shoulder joint. Decreasing arm length (lever arm) via increased elbow flexion can lessen the amount of force needed to slow the segment. With the high-fat% pitchers exhibiting greater segmental mass on average, it seems reasonable that additional elbow flexion during pitch follow-through would be a common adaptation to help slow the forward motion of the throwing arm.

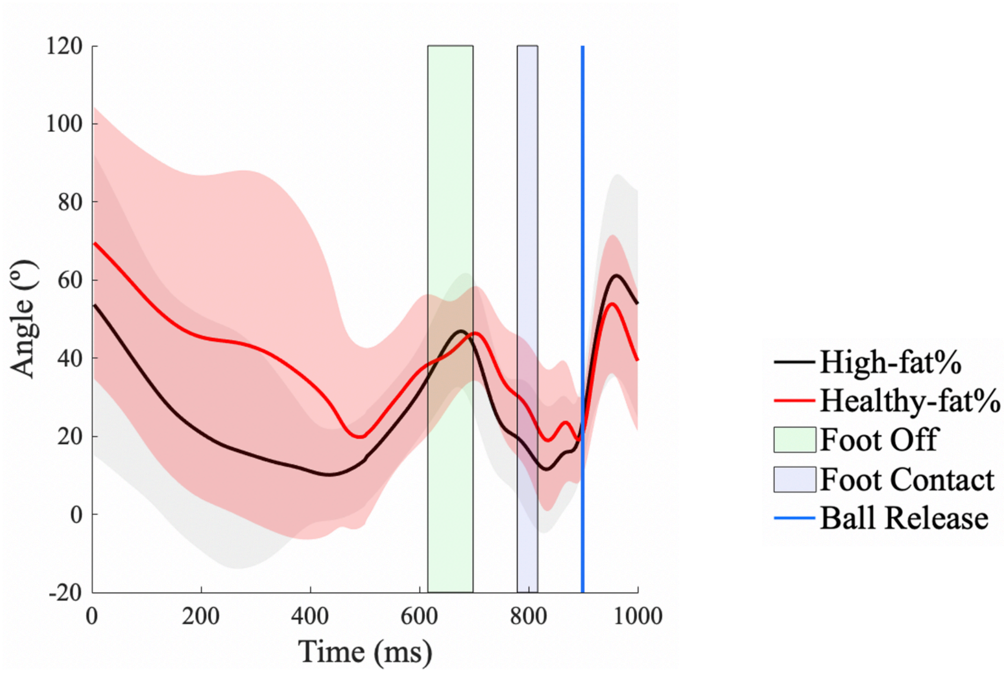

Figure 5.2. Elbow flexion (+)/extension (-) angle during 1000 ms prior to follow-through.

The shoulder angular velocity plot also shows the high-fat% pitchers do not slow after ball release as quickly as the healthy-fat% group, again pointing to the increased inertia and increased difficulty in slowing heavier segments (Figure 4.16). Likewise, the trunk rotational velocity plot shows the healthy-fat% pitchers attain higher angular velocities both in rotation towards the throwing arm and in the rotation back towards the catcher (Figure 4.16). Lastly, the wrist flexion plot (Figure 4.16) reveals pitchers with a healthy-fat% achieved a greater peak wrist flexion velocity near ball release and did so in a shorter time frame than the high-fat% pitchers. Perhaps this is another example of the healthy-fat% pitchers displaying less rotational inertia and greater ease in performing rotational movements.

Additional research is needed to continue identifying the advantages and disadvantages associated with varied body composition. Initial findings suggest there are some differences present between pitcher groups in segmental sequencing. While results highlight the relationship between peak segmental angular velocities and pitch velocity, understanding how segmental composition might influence segmental sequencing is imperative for pitcher development.

Conclusions

Study findings suggest that excess body fat alters softball pitch biomechanics and influences both measures of performance and projected injury risk factors. High-fat% pitchers displayed decreased peak medial GRF and body fat percentage was negatively associated with pitch velocity. While GRF and pitch velocity are related, results suggest that the high-fat% pitchers may have increased difficulty providing adequate force to push-off of the ground, which may subsequently lead to a decreased pitch velocity. Additionally, whole-body lean mass, fat mass, and throwing arm lean mass were associated with increased peak throwing shoulder distraction force, commonly associated with upper extremity injury. Similarly, kinematics, including shoulder plane of elevation were also affected by increased girth measurements, suggesting increased adipose tissue influences body positioning throughout the pitch. Lastly, slight alterations in segmental sequencing were observed between groups and hypothesized to result from the increased inertia among those with heavier body segments. These results suggest that although pitchers with a high-fat% can successfully perform softball pitching, increased adipose tissue may alter pitch performance while influencing biomechanical measures previously associated with pain and injury. Besides the well-known health concerns associated with obesity, softball pitchers, trainers, and coaches should understand the influence excess fat can have on pitch biomechanics and work to emphasize a healthy body composition among softball pitchers. While more research is needed to further develop these initial findings and hypotheses, study findings highlight the potential adverse effects of increased body fat percentage, especially among high school-aged softball pitchers. The growing health concerns for obese individuals and the high injury rates among softball pitchers (especially those of larger stature) suggest that softball pitchers should prioritize fitness conditioning for general and sport-specific health concerns.

Extra efforts are needed to incorporate aerobic, cardiorespiratory fitness training during practice sessions to safely emphasize a healthy body composition among young softball pitchers. Similarly, practice plans should involve various stations to keep all athletes physically active and moving for a majority of the practice time. Outside of practice, athletes should be encouraged to participate in sport sampling, increasing the amount of time spent being active throughout the week and simultaneously decreasing sedentary behavior.

Extra attention should also be warranted regarding diet and tournament snacks. A healthy snack break can help improve athletes' energy levels; meanwhile, poor snack choices can decrease energy availability and potentially lead to unhealthy eating habits. While these recommendations involve effort on behalf of the parents and coaches, these steps can encourage young athletes to adopt a healthier lifestyle, which may also lead to better athletic function. The overarching goal is to optimize softball pitchers' general and athletic health, as well as improve pitch performance, so young athletes can continue to participate and successfully compete in activities they enjoy.

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Appendix A

Participant Recruitment Email Script

The Auburn University Institutional Review Board has approved the use of this document from June 4, 2020 to January 9, 2021. Protocol #19-540 EP 2001

Hello,
The Sports Medicine & Movement Lab is currently conducting a research study to examine the influence of body composition on softball pitching biomechanics. We will measure body composition, pitching mechanics, muscle activation, and hip and shoulder range of motion.

You must be a softball pitcher athlete between the ages of 14 – 23 and you must be injury, and surgery free for the last 6 months. Softball pitchers need to have pitched in a game within the last year. You must also not have an allergy to adhesive tape. Those that meet study criteria and choose to participate will receive a total body iDXA scan in order to measure body mass, as well as a one-time monetary gift of $20.

Following the consenting process, you will be asked to complete a health history questionnaire. Next, you will complete an iDXA total body composition scan. The scan is an x- ray that measures the amount of muscle and fat in your body. The radiation you are exposed to during this scan is less than walking outside on a sunny day for 10 minutes.

Next, range of motion and strength of the shoulder and hip will be measured and recorded. Eight EMG sensors will be placed on the following muscles: throwing arm serratus anterior (under arm pit), pectoralis major (lateral chest), biceps brachii (upper arm), deltoid (shoulder), and bilateral gluteus medius (hip), and gluteus maximus. Then, 14 sensors will be affixed to the skin using non-adhesive tape. You will be allotted an unlimited time to warm-up after all sensors are affixed. You will perform a single leg squat on each leg, and then pitch a total of 30 maximal effort fastball pitches at 43 feet.

Testing should take approximately 1 hour and 30 minutes to complete. Please wear loose fitting athletic attire including shorts, t-shirt, and shoes you will be able to pitch with on a hard platform. If you, or anyone you know, are interested in participating in this study please let me know. The trials are non-invasive and possible risks and discomforts associated with this study are no greater than those involved in competitive pitching. Included are muscle strain, muscle soreness, and ligament and tendon damage.

Due to COVID-19, we will have strict measures in place for any investigator who needs to come less than 6 feet in contact with the participant. The investigator(s) will wear the appropriate personal protective equipment and 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.

If you have any questions about the study, don't hesitate to contact me or Dr. Gretchen Oliver (goliver@auburn.edu).

Thanks,

Kenzie Friesen (kfriesen@auburn.edu)

The Auburn University Institutional Review Board has approved this Document for use from 06/04/2020 to 01/09/2021
Protocol # 19-540 EP 2001

Recruitment Tweet/Instagram Post

"If you are a high school or college pitcher interested in participating in a pitching analysis study, please email me, Kenzie Friesen, for more information! [kfriesen@auburn.edu]

Looking for participants for a softball pitching study!

This project will examine body composition, biomechanics, performance and injury prevalence of softball pitchers.

AUBURN UNIVERSITY
SCHOOL OF KINESIOLOGY
MOVEMENT. HEALTH. PERFORMANCE.

Who?
- Softball pitchers aged 14-23 years old
- Without surgery or injury in the past 6 months
- Need to have pitched in a game within the past year

***Failure to meet the above participant inclusion criteria will result in exclusion from participation**

Where?
- Sports Medicine and Movement Laboratory, Auburn University
  - 301 Wire Rd, Auburn AL, 36849
- Free parking

Why Should I Participate?
- Participants will receive
  - a full body composition iDXA output
  - $20 cash

What?
- Participation includes a one-time testing session lasting ~1.5 hours
- Data Collected:
  - one full body iDXA scan (this will measure full body composition)
    - Exposures btw 3-6 micro-Seiverts radiation (less than a dental x-ray)
  - shoulder and hip strength and range of motion
  - single leg squat performance
  - up to 30 fastballs recorded at game-like intensity

How?
- For more information, please contact either:
  - Kenzie Friesen (kfriesen@auburn.edu) or
  - Dr. Gretchen Oliver (goliver@auburn.edu)

Notice: Additional precautions in line with Auburn University's Human Research Protection Program will be followed due to the situation involving COVID-19.

The Auburn University Institutional Review Board has approved this Document for use from 06/04/2020 to 01/09/2021
Protocol # 19-540 EP 2001

Appendix B

The Auburn University Institutional Review Board has approved this Document for use from 06/04/2020 to 01/09/2021 Protocol # 19-540 EP 2001

SCHOOL OF KINES IOLOGY
301 Wi re 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
INFORMED CONSENT TO PARTICIPATE IN RESEARCH

Influence of Body Composition on Softball Pitching Biomechanics

Explanation and Purpose of the Research

You are being asked to take part in a research study for the Sports Medicine and Movement Laboratory. This research study is voluntary, meaning you do not have to take part in it. 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, precautions, and alternatives of this research. This statement describes your right to confidentiality 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 influence of body composition on softball pitching biomechanics in softball players. To investigate this, participants will be scanned using iDXA technology, have strength and range of motion measured, perform 2 single leg squats, and then perform 30 pitch trials using motion capture.

Research Procedures

To be considered for this study, you must be a softball pitcher between the ages of 14-23 years old. You must have pitched in a game within the past year and have no injuries or have undergone surgery within the past six months.

Testing for this research will require you to be dressed in athletic clothes including shorts, t-shirt, and shoes that you can pitch in. Testing in this research will require the evaluation of body composition which will be obtained through the use of Dual X-ray Absorptiometry (iDXA) that establishes fat mass, lean mass and visceral fat.

Once all preliminary paperwork has been completed including a brief health history questionnaire, you will partake in an iDXA scan. Standard Operating Procedures (SOP) for the iDXA will be followed. You will lie still on your back while the scan occurs. Auburn University's Radiation Safety Committee has approved the use of the iDXA. Exposure to between 3 - 6 mirco-Seiverts radiation from the iDXA scan occurs; however, this is less than a dental X-ray and equivalent to approximately 10 minutes in the sun.

Participant's Initials _________ 1 of 4

Following the iDXA, range of motion of the shoulders and hips will be measured and recorded. To measure shoulder range of motion, you will lay supine on the table with your arm abducted out to the side at the shoulder.

An investigator will hold your forearm perpendicular to the ground with your elbow bent to ninety degrees. The investigator will then passively rotate your arm until maximal internal rotation is reached. This will then be repeated for maximal external rotation. For hip range of motion, you will sit on a table with your lower leg hanging off the side. An investigator will passively rotate your lower leg until maximal internal rotation is reached. This will then be repeated for maximal external rotation.

Similar procedures will be performed to measure isometric strength. To measure shoulder strength, you will be positioned lying on a table with your upper arm parallel to the floor and elbow bent. You will then externally/internally rotate against the investigator for 3 seconds. The investigator will hold a handheld dynamometer against your forearm to record the force. In order to reduce the effects of fatigue, a rest period of 20-30 seconds will be allotted between trials.

Following these measures, you will be given up to 10 minutes of time to complete a dynamic warm up of your choice.

Next, eight surface electrodes will be placed on the following muscles: throwing arm serratus anterior (under arm pit), pectoralis major (lateral chest), biceps brachii (upper arm), deltoid (shoulder), and bilateral gluteus medius (hip), and gluteus maximus. Following sensor placement, manual muscle testing will be performed to establish baseline muscle activity in which all data will be compared.

Next, fourteen electromagnetic sensors will be placed on your legs, arms, torso, and neck. Placement of the markers at these locations will allow the movement of the joint centers to be properly monitored during testing.

At this point, we will take approximately 5 minutes to digitize your body segment endpoints and joint centers in order to create a digital skeleton. You will then be given an unlimited amount of time to complete a pitching warm up. During this time, we ask that you complete your warmup with the intention of being prepared to throw a game at maximal effort.

After completing the warm-up, a total of 30 maximal effort pitches will be recorded. We ask that you pitch at max effort aiming for the strike zone. A 20 second rest period will be allotted between each pitch to mitigate potential effects of fatigue.

Potential Risk

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 pitching and may include muscle strain, muscle soreness, ligament and tendon damage, and general overuse injury to the pitching athlete. There is also a risk of slight radiation exposure from the iDXA scan. Every effort will be made to minimize these risks and discomforts. 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.

Participant's Initials _________

Due to COVID-19 we will have strict measures in place for any investigator who needs to come less than 6 feet in contact with the participant. The investigator(s) will wear the appropriate personal protective equipment (PPE) of a N-95 respirator, 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. During the pitching protocol, one board certified exercise physiologist will be present to monitor you as you pitch. Ample warm-up and cool-down periods will be required of you, water will be provided to you as needed, and ice will be available upon conclusion of the study.

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 she will help you. Should an emergency arise, we will call 911 and follow our Emergency Action Plan. 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.

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.

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 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. Participants will receive a one-time monetary gift of $20 cash. There are no other direct benefits to you for participating in this study.

Alternatives
The alternative is to not participate in this study.

Questions Regarding the Study

If you have questions about this study, please ask them now. If you have questions later you may contact Dr. Gretchen Oliver, 844-1497 or goliver@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, Kenzie Friesen Date

Appendix C

SCHOOL OF KINES IOLOGY
301 Wi re Road
Auburn, AL
36849
(334) 884-4483

AUBURN UNIVERSITY
COLLEGE OF EDUCATION

The Auburn University Institutional Review Board has approved this Document for use from 06/04/2020 to 01/09/2021
Protocol # 19-540 EP 2001

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

Auburn University

Parental Permission/Minor Assent

INFORMED CONSENT TO PARTICIPATE IN RESEARCH

Influence of Body Composition on Softball Pitching Biomechanics

Explanation and Purpose of the Research

Because your child is less than 18 years old, we must have your permission for them to participate in a research study for the Sports Medicine & Movement Laboratory in the Department of Kinesiology. Before agreeing to allow your child 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 confidentiality and their right to discontinue 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 influence of body composition on softball pitching biomechanics in softball players. To investigate this, your child will be scanned using iDXA technology, have strength and range of motion measured, perform 2 single leg squats, and then perform 30 fastball pitch trials using motion capture.

Research Procedures

To be considered for this study, your child must be a softball pitcher between the ages of 14-23 years old. They must have pitched in a game within the past year and have no injuries or have undergone surgery within the past six months.

Testing for this research will require your child to be dressed in athletic clothes including shorts, t-shirt, and shoes. Testing in this research will require the evaluation of body composition which will be obtained through the use of Dual X-ray Absorptiometry (iDXA) that establishes fat mass, lean mass and visceral fat.

Once all preliminary paperwork has been completed including a brief health history questionnaire, your child will partake in an iDXA scan. Standard Operating Procedures (SOP) for the iDXA will be followed. They will lie still on their back while the scan occurs. Auburn University's Radiation Safety Committee has approved the use of the iDXA. Exposure to between 3 - 6 mirco-Seiverts radiation from the iDXA scan occurs; however, this is less than a dental X-ray and equivalent to approximately 10 minutes in the sun.

Participant's Initials _________
Parent's Initials __________

Following the iDXA, range of motion of the shoulders and hips will be measured and recorded. To measure shoulder range of motion, your child will lay supine on the table with their arm abducted out to the side at the shoulder. An investigator will hold their forearm perpendicular to the ground with their elbow bent to ninety degrees. The investigator will then passively rotate their arm until maximal internal rotation is reached. This will then be repeated for maximal external rotation. For hip range of motion, your child will sit on a table with their lower leg hanging off the side. An investigator will passively rotate their lower leg until maximal internal rotation is reached. This will then be repeated for maximal external rotation.

Similar procedures will be performed to measure isometric strength. To measure shoulder strength your child will be positioned lying on a table with their upper arm parallel to the floor and elbow bent. Your child will then externally/internally rotate against the investigator for 3 seconds. The investigator will hold a handheld dynamometer against their forearm to record the force. In order to reduce the effects of fatigue, a rest period of 20-30 seconds will be allotted between trials.

Following these measures, your child will be given up to 10 minutes of time to complete a dynamic warm up of your choice.

Next, eight surface electrodes will be placed on the following muscles: throwing arm serratus anterior (under arm pit), pectoralis major (lateral chest), biceps brachii (upper arm), deltoid (shoulder), and bilateral gluteus medius (hip), and gluteus maximus. Following sensor placement, manual muscle testing will be performed to establish baseline muscle activity in which all data will be compared.

Next, fourteen electromagnetic sensors will be placed on your child's legs, arms, torso, and neck. Placement of the markers at these locations will allow the movement of the joint centers to be properly monitored during testing.

At this point, we will take approximately 5 minutes to digitize your child's body segment endpoints and joint centers in order to create a digital skeleton. Your child will then be given up to 15 minutes of time to complete a pitching warm up. During this time, we ask that your child complete their warmup with the intention of throwing a game at maximal effort.

After completing the warmup, a total of 30 maximal effort pitches will be recorded. We ask that your child pitch at max effort aiming for the strike zone. A 20 second rest period will be allotted between each pitch to mitigate potential effects of fatigue.

Potential Risk

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 pitching and may include muscle strain, muscle soreness, ligament and tendon damage, and general overuse injury to the pitching athlete. There is also a risk of slight radiation exposure from the iDXA scan. Every effort will be made to minimize these risks and discomforts and ice will be made available. It is your responsibility, as a parent of the participant, to inform the investigators if you notice any indications of injury or fatigue or notice symptoms of any other possible complications that might occur during testing.

Participant's Initials _________

Parent's Initials __________

Due to COVID-19 we will have strict measures in place for any investigator who needs to come less than 6 feet in contact with the participant. The investigator(s) will wear the appropriate personal protective equipment (PPE) of a N-95 respirator, 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. During the pitching protocol, one board certified exercise physiologist will be present to monitor your child as they pitch. Ample warm-up and cool-down periods will be required of them, water will be provided to your child as needed, and ice will be available upon conclusion of the study.

The researcher will try to prevent any problem that could happen because of this research. If at any time there is a problem, you or your child should let the researcher know and she will help you. Should an emergency arise, we will call 911 and follow our Emergency Action Plan. In the unlikely event that your child sustains 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.

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.

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 your child participating, you can withdraw at any time during the study. Your child's 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 yours or your child's future relations with Auburn University or the School of Kinesiology. Your child will receive a one-time monetary gift of $20 cash. There are no other direct benefits to you or your child for participating in this study.

Alternatives
The alternative is to not participate in this study.

Participant's Initials _________
Parent's Initials __________

Questions Regarding the Study

If you have questions about this study, please ask them now. If you have questions later you may contact Dr. Gretchen Oliver, 844-1497 or goliver@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 Parent Date of Birth of Participant

________________________________ ________________

Signature of Parent Date

____

Printed Name of Participant

________________________________ ________________

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, Kenzie Friesen Date

Appendix D

College of Education
School of Kinesiology
Standard Operating Procedure: Dual Energy X-Ray Absorptiometry (DXA)

Intent of Service:
Research conducted by the School of Kinesiology occasionally requires that bone density and/or body composition be obtained in human participants via a DXA scan. This scan is conducted in the School of Kinesiology DXA Laboratory which contains a GE Healthcare iDXA scanner that is capable of measuring site specific or whole-body bone density, vertebral fracture risk and body composition. The DXA Lab contains the iDXA scanner and a computer station for operation of the equipment.

Participants:
All research conducted in the School of Kinesiology, including those studies requiring a DXA scan, must be approved by Auburn University's Institutional Review Board for the Protection of Human Subjects in Research (IRB). All participants are required to sign a consent form that has been approved by the IRB before having this test in the School of Kinesiology. All female participants need to affirm that they are not pregnant, nor have they been attempting to become pregnant in the eight weeks prior to the DXA scan.

Licensing:
The DXA facility has been certified by the State of Alabama and has a permit for its operation. Auburn University's Office of Risk Management and Safety (RMS) oversee this facility and provides the required permit and training related to radiation exposure associated with the use of this equipment. All DXA tests are performed by trained DXA personnel from the School of Kinesiology (operator). The operators will be a faculty member or a designated graduate student who have received both initial and semi-annual refresher training prior to conducting research with the iDXA machine.

Procedures:
1. In advance of the iDXA scan the Principal Investigator (PI) will provide participants with the attached iDXA Information Sheet, and an IRB approved Health Questionnaire, and Informed Consent.
2. The PI or his or her designee will review these documents with the human participant, ask the human participant if they have any questions, and obtain written consent.
3. On the day of the iDXA scan the PI or his or her operator will confirm the identity of the human participant, obtain their height and weight and record this information on their questionnaire.
4. The operator will confirm with all female participants that they are not pregnant, nor have they been attempting to become pregnant in the eight weeks preceding the scan date.
5. The operator will review and update the quality compliance log documenting operation stability of iDXA based on the daily/weekly iDXA phantom scans.
6. The operator will ask the subject to remove jewelry, body piercings, clothing with zippers or metal buttons, etc. and to put on a gown or other unrestrictive clothing for the scan.
7. Operator will position the patient on the iDXA table and explain the procedure requesting that the patient remain still during the entire scan.

Equipment and Supplies:

Computer, printer, iDXA, all positioning aids needed for site specific DXA scans.

Potential Risks:

There are minimal risks associated with the amount of radiation provided by the iDXA scan.

Preventive Measures:

1. All iDXA tests are performed by a trained investigator or graduate student who has accomplished either initial or refresher training in the semester that the research is being conducted.
2. All human participants will be provided with an Information Sheet on iDXA and be asked to complete a Participant Questionnaire.
3. All female human participants will be queried about their status concerning pregnancy and no pregnant female will be scanned.
4. All precautions necessary will be taken when positioning subjects on the iDXA table.
5. Any Auburn University faculty/staff/students involved with human participants research will have completed human subjects training.
6. The iDXA facility has been certified by the State of Alabama and has a permit for its operation.
7. Auburn University's Risk Management and Safety oversee the iDXA Laboratory, provides the required permit and training related to radiation exposure associated with the use of the DXA. RMS ensures the operator's station is outside the 2-meter distance required to avoid emitted radiation from the iDXA.

College of Education

School of Kinesiology

Information Sheet: Dual Energy X-Ray Absorptiometry (DXA)

Research conducted in the School of Kinesiology occasionally requires that bone density and/or body composition be obtained in human participants via DXA. This DXA scan is conducted in the DXA Lab which contains a GE Healthcare iDXA scanner that is capable of measuring site specific or whole-body bone density, vertebral fracture risk and body composition. This unit also has the capacity to scan neonates for bone density and body composition.

DXA is a method used to measure body composition. This procedure uses x-rays that yield precise, high quality images of your body compartments (e.g., fat and muscle tissues) that involves exposure to very low amounts of x-ray radiation. For all radiation sources, the standard measure of radiation dose to our bodies is called the Sievert (Sv) or millisievert (mSv) where 1 Sv is equal to 1000 mSv. Every person is exposed daily to natural background radiation from sources like soil, rocks, radon, and natural radiation in our bodies, the sun, and outer space. On average, a person in the United States receives about 3 mSv per year from natural background radiation, or about .01 mSv per day. When a person receives radiation as part of a research study at Auburn, their extra radiation dose is limited by Auburn to 1 mSv, which is the annual regulatory limit for the general public. Children under the age of 18 are limited to 0.1 mSv per year.

Example of Radiation Dosages:

Annual Background Radiation	0.01 mSv	Mammogram	0.400 mSv
Dental X-ray	0.01 mSv	iDXA AP spine scan	0.146 mSv
Chest X-ray	0.08 mSv	iDXA Whole Body scan	0.003 mSv
Roundtrip Transatlantic Flight	0.08 mSv		

Risks of Research Radiation: The amount of radiation exposure received in this study is below the levels that are thought to result in a significant risk of harmful effects. One possible indirect effect is an increase in the risk of cancer. The potential increase in the risk of cancer or potential increased risk of other adverse health consequences, from the low level of radiation used in this study is too small to be estimated accurately. If you have additional questions, please contact the research staff.

What will be Expected of You: You must be able to lie still on a padded table and breathe normally for the duration of the scan which is approximately 10 minutes. The table will move horizontally and vertically during the scan. You will be asked to remove jewelry, body piercings, clothing with zippers or metal buttons, etc. and to put on a gown or other unrestrictive clothing for the scan. You may bring your own unrestrictive clothing with you.

Before you arrive for your scan at the School of Kinesiology it's important that you read this document and the attached questionnaire and consent form. The questionnaire and consent form should be completed immediately before your scan. The Consent Form must be signed in the presence of the Principal Investigator.

Results of DXA Scan: The DXA machine will automatically generate a report of body composition for each scan. The analysis is based on a standard operating procedure for body composition analysis designed by the manufacturer of the DXA scanner. Research scans are not read by a radiologist. You may request a copy of this report from the Principal Investigator.

Pregnancy: If you are a female of childbearing age, you will be asked to affirm that you are not currently pregnant and have not been attempting to become pregnant in the eight
(8) weeks preceding the scan.

Recent Previous Procedures: DXA should not be performed on participants who have had any procedure that included Iodine, Barium or Nuclear Medicine Isotopes within the last 7 days. Please inform us if this is the case.

Previous Surgery, Prosthetic Devices and Foreign Bodies: Since the body composition assessment involves a scan of the whole-body, it is important to disclose any surgeries you may have had since they might impact the results of the DXA scan. For example, it is important to know if you have a prosthetic device, pacemaker leads, radioactive seeds, metal implants, or surgical staples. The same caution is also given to foreign bodies such as shrapnel and radio-opaque catheters or tubes.

General Requirements for DXA scans: Physical and hydration factors may affect the results of the scan and therefore, we ask that you ensure that you:

- are able to lie still on a padded table and breathe normally for approximately 7 - 13 minutes;
- weigh less than 450 pounds (204 kg);
- wear clothing with no metal and remove all jewelry prior to the procedure;
- refrain from heavy exercise 12 hours prior to study;
- consume no alcohol, nicotine, or caffeinated beverages 12 hours prior to study;
- fast for at least 2 hours prior to study with only light meals in the 10 hours prior to fasting.

Please make every effort to meet these criteria since they are important for the accuracy of the scan.

Thank you

Appendix E

Health History Form

Researcher use only

Participant Code: ______________________________

Date: ____________________________________

For participant

Part 1. General Information
(fill in your responses)

Age:______________Home State: ____________________

Height:____________ft_____in Weight:_________lbs

Are you pregnant? YES NO

Part 2. Athletic Participation
(Circle or fill in your responses)

1. Are you currently cleared to participate in pitching activities? YES NO
2. Have you had an injury or surgery within the past 6 months? YES NO
3. Which is your pitching arm? RIGHT LEFT
4. What is your primary position in softball? ________________
5. Approximately, how many pitches do you complete in practice?_______In a game? ________
6. How many practices do you have per week in season? ____________
7. How many games do you have per week in season? _____________
8. How many practices do you have per week out of season? ____________
9. How many games do you have per week out of season? _____________
10. What is your "go to"/favorite pitch to throw?________________(drop, rise, etc.)

Page 1 of 4

11. At what competition level are you currently playing? [Please circle]

NCAA Div. I NCAA Div. II NCAA Div. III Junior College
High School Junior High Youth League Other __________

12. For how many years have you been a pitcher? ___________

13. Do you pitch in every game? YES NO

14. Is softball your primary sport? YES NO

15. Do you currently play other sports besides softball? YES NO
If yes, list all sports you play competitively:

____

____

If no, did you ever play another sport besides softball? YES NO

If yes, at what age did you quit playing other sports? _____________

16. At what age did you begin to play competitive softball? _____________

17. At what age did you begin pitching? ____________________________

Part 3. Medical History
(Circle or fill in your responses)

18. Are you allergic to adhesive tape or other adhesive products? YES NO
If YES, explain:

____

19. Have you ever had surgery before? YES NO
If YES, explain:

____

____

If YES, how long ago?____________Years

20. Have you ever had a softball-related injury that has caused you to miss a practice or game?
 YES NO

If YES, explain:

____
____
____
____
____

If YES, on what body part(s)? Check all that apply

_____ SHOULDER
_____ ELBOW
_____WRIST
_____HAND/FINGER
_____BACK
_____THIGH
_____LOWER LEG
_____FOOT

21. Do you currently experience pain/stiffness before, during or after pitching? YES NO
If YES, please explain and continue onto question 22:

____

>>If NO, please skip to question 31.

>>IF you answered YES to question 21:

22. For how long have you been experiencing pain? (Indicate a number next to 1 category)
_____________Years_____Months_____Days

23. When you do experience pain, how would you describe the onset of pain? (Circle one)
 SUDDEN GRADUAL

24. When you do experience pain, how is it related to activity? (Circle one)
ASSOCIATED WITH USE INTERMITTENT ALL THE TIME

25. Have you changed your training/competition habits because of pain? YES NO
If YES, explain:

____
____

26. Have your activities of daily living been affected by your pain? YES NO

If YES, explain:

____

____

27. Has your pain disrupted your sleep? YES NO

If YES, explain:

____

____

28. Have you sought medical consultation because of your pain? YES NO

If YES, explain:

____

____

29. Have you been given treatment for your pain? YES NO

If YES, explain:

____

____

30. When you do experience pain, what is the intensity of the pain (1= NO pain; 10= unbearable pain)?

NO PAIN 1 2 3 4 5 6 7 8 9 10 UNBEARABLE PAIN

31. Have you had a growth spurt in height within the last 6 months? YES NO

32. Have you had a growth spurt in weight within the last 6 months? YES NO

I hereby state, to the best of my knowledge, my answers to the above questions are complete and correct.
Signature of Participant (or parent/guardian):

____ Date: ___________________________

Appendix F

Table F1. Description of sample size for each research question. Total n = 44 pitchers.

Research Question (RQ)		Original Sample Size	Sample Size After Data Screening	Reasoning
RQ1	Do pitchers with a high-fat% display a force-time curve during the propulsive phase different from pitchers who have a healthy-fat%?	44	34	▪ No outliers ▪ Only right-handed pitchers were included (n = 36) ▪ Two pitchers excluded due to incorrect hardware settings
RQ2	Is pitcher whole-body composition and throwing arm segmental composition correlated with peak shoulder distraction forces during the acceleration phase of the pitch?	44	42	▪ No outliers ▪ Two pitchers excluded due to incorrect hardware settings
RQ3	Are whole-body composition measures associated with pitch velocity?	44	43	▪ One pitcher deemed an outlier based on their pitch velocity being outside the boxplot
RQ4	Do pitchers' upper arm, chest, waist, and hip girth correlate with trunk and throwing arm position at ball release of the pitch?	44	42	▪ No outliers ▪ Two pitchers excluded due to incorrect hardware settings
RQ5	Do peak angular velocity trunk rotation, shoulder flexion, elbow flexion, and wrist flexion correlate with pitch velocity, and do time series plots of segmental angular velocities differ between pitchers who have a high-fat% and a healthy-fat%?	44	40	▪ No outliers ▪ Two pitchers excluded due to incorrect hardware settings ▪ Two pitchers' angular velocity data could not be displayed

Appendix G

Data Collection Sheet

Participant Code: ________________________MM Height: __________MM Weight: __________

R or L U. Arm Circumference:________Chest C.:_________Waist C.:_________Hip C.:__________

	IR ROM (º)	ER ROM (º)	IR ISO (kgf)	ER ISO (kgf)
Push Hip	1)	1)	1)	1)
	2)	2)	2)	2)
Average:				
Stance Hip	1)	1)	1)	1)
	2)	2)	2)	2)
Average:				
Dominant Shoulder	1)	1)	1)	1)
	2)	2)	2)	2)
Average:				
Non-Dominant Shoulder	1)	1)	1)	1)
	2)	2)	2)	2)
Average:				

EMG Sensors Placement Order:

1. Biceps Brachii
2. Deltoid
3. Serratus anterior
4. Pectoralis major
5. Stride gluteus medius
6. Stride gluteus maximus
7. Push gluteus medius
8. Push gluteus maximus

Participant Code: ____________________________

Total Time of Warm-up(mins): ___________________

Total # of Throw/Pitches prior to warm-up (overhand and underhand): ____________

RMS error	#1	#2	#3	#4
Left Shoulder				
Right Shoulder				

SLS Left:______________ SLS Right: ________

Pitch #	Pitch Type	Velocity (radar gun - mph)	Yak #	On FP properly? (Y/N)	Code

Appendix H

RQ1 Normality

Normality was assessed through use of the Shapiro-Wilks test of normality. GRFxMax for the healthy-fat% group of pitchers (19.85 ± 6.02% BW, n = 14) was normally distributed with a skewness of $\alpha_3 = 1.029$, (SEM_{skew} = .597) and a kurtosis of $\alpha_4 = 1.400$, (SEM_{kurt} = 1.154) (Figure H1, Table H1).

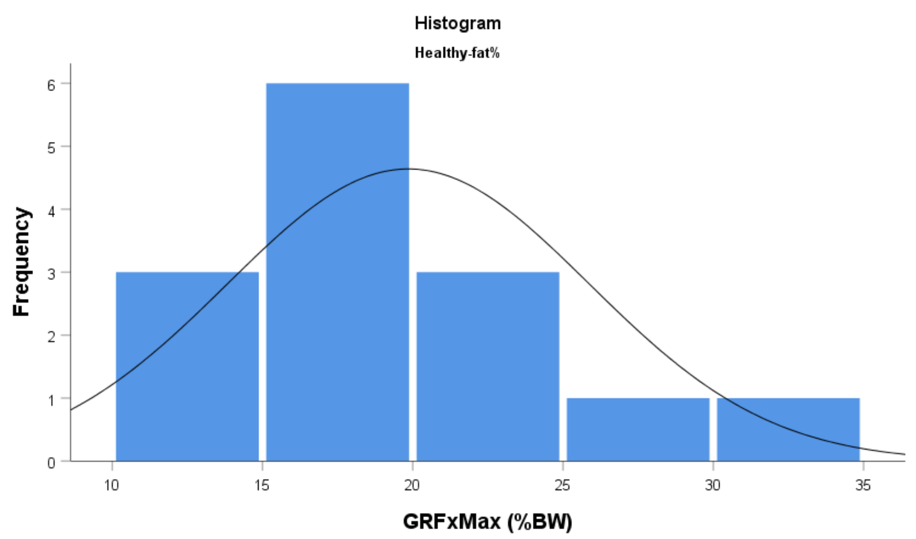

Figure H1. Histogram of healthy-fat% pitchers' GRFxMax (% BW).

GRFxMax for the high-fat% pitchers (15.69 ± 6.10% BW, n = 20) was normally distributed with a skewness of $\alpha_3 = -.185$, ($SEM_{skew} = .512$) and a kurtosis of $\alpha_4 = -.430$, ($SEM_{kurt} = .992$) (Figure H2, Table H1).

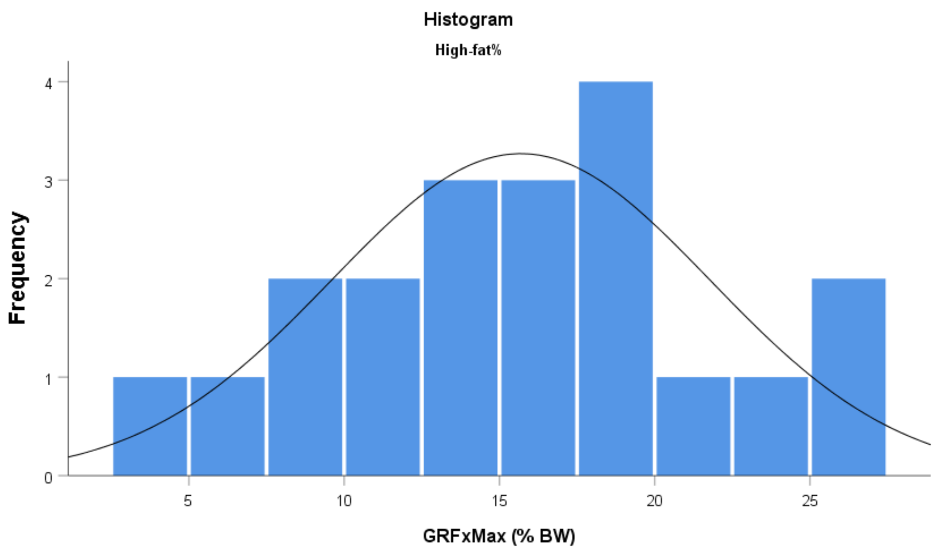

Figure H2. Histogram of high-fat% pitchers' GRFxMax (% BW).

GRFyMax for the healthy-fat% group of pitchers (149.18 ± 10.27% BW, n = 14) was normally distributed with a skewness of $\alpha_3 = .285$, ($SEM_{skew} = .597$) and a kurtosis of $\alpha_4 = -1.391$, ($SEM_{kurt} = 1.154$) (Figure H3, Table H1).

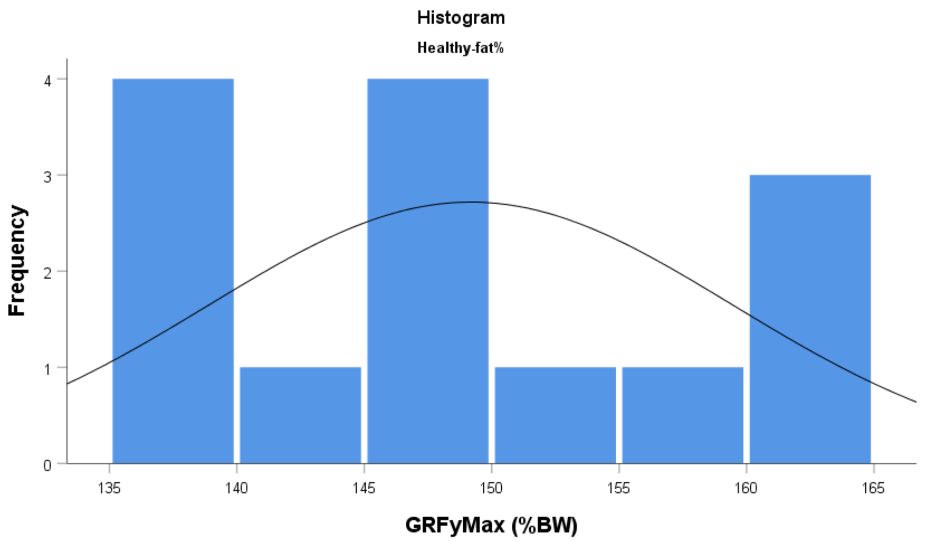

Figure H3. Histogram of healthy-fat% pitchers' GRFyMax (% BW).

GRFyMax for the high-fat% pitchers (144.83 ± 16.01% BW, n = 20) was normally distributed with a skewness of $\alpha_3 = .324$, ($SEM_{skew} = .512$) and a kurtosis of $\alpha_4 = -.709$, ($SEM_{kurt} = .992$) (Figure H4, Table H1).

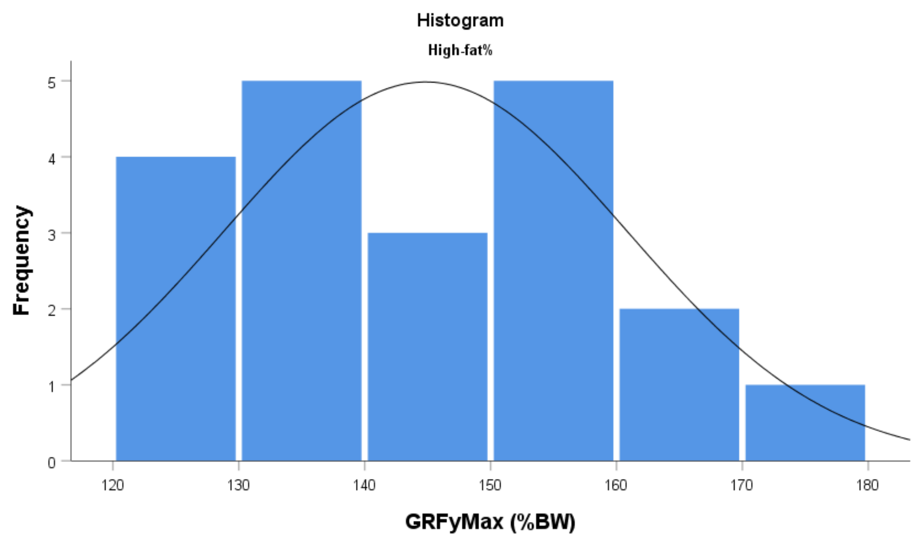

Figure H4. Histogram of high-fat% pitchers' GRFyMax (% BW).

GRFzMin for the healthy-fat% group of pitchers (-20.48 ± 5.31% BW, n = 14) was normally distributed with a skewness of α_3 = -.955, (SEM_{skew} = .597) and a kurtosis of α_4 = -.990, (SEM_{kurt} = -.124) (Figure H5, Table H1).

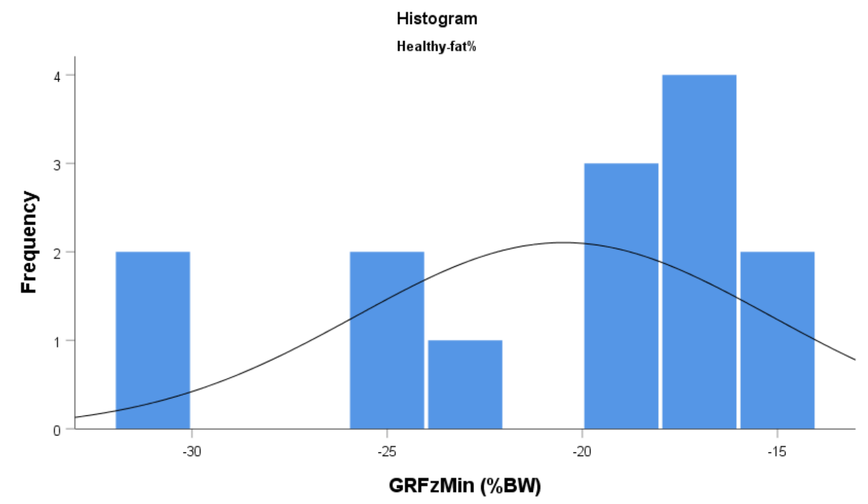

Figure H5. Histogram of healthy-fat% pitchers' GRFzMin (% BW).

GRFzMin for the high-fat% pitchers (-16.43 ± .727% BW, n = 20) was normally distributed with a skewness of α_3 = -.002, (SEM_{skew} = .512) and a kurtosis of α_4 = -.665, (SEM_{kurt} = .992) (Figure H6, Table H1).

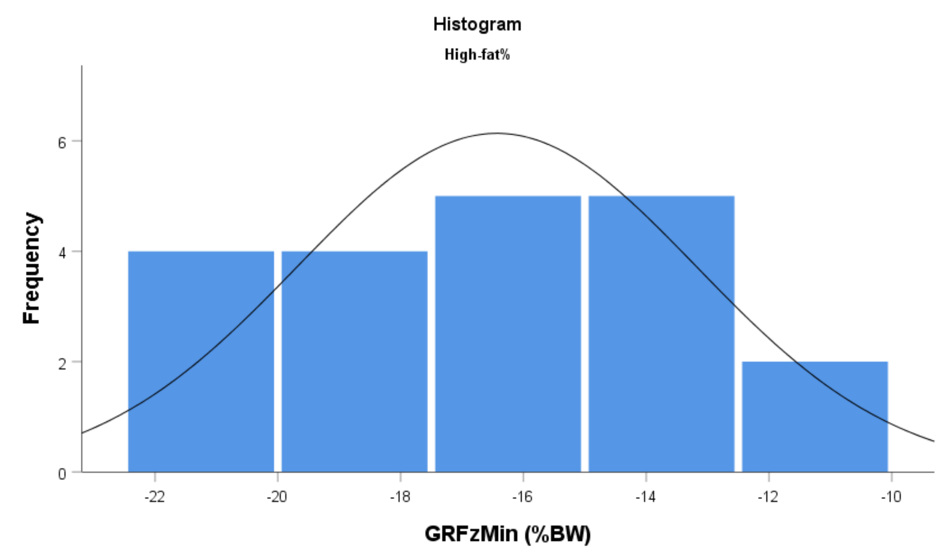

Figure H6. Histogram of high-fat% pitchers' GRFzMin (% BW).

Table H1. Normality table for RQ1.

	Group	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
GRFxMax (% BW)	Healthy-fat%	.135	14	.200*	.941	14	.428
	High-fat%	.083	20	.200*	.972	20	.794
GRFyMax (% BW)	Healthy-fat%	.143	14	.200*	.898	14	.107
	High-fat%	.118	20	.200*	.966	20	.676
GRFzMin (% BW)	Healthy-fat%	.183	14	.200*	.875	14	.050
	High-fat%	.101	20	.200*	.979	20	.926

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

RQ2 Normality

Normality was assessed through use of the Shapiro-Wilks test of normality. Peak throwing shoulder distraction force (622.75 ± 175.72 N, n = 42) was non-normally distributed with a skewness of $\alpha_3 = .539$, ($SEM_{skew} = .365$) and a kurtosis of $\alpha_4 = .162$, ($SEM_{kurt} = .717$) (Figure H7, Table H2).

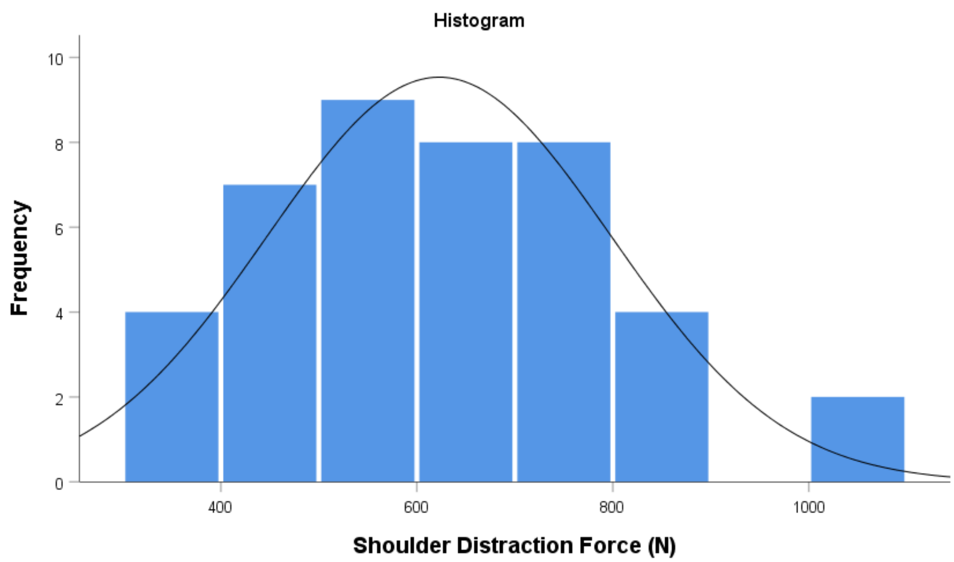

Figure H7. Histogram of pitchers' peak throwing shoulder distraction force (N).

Whole-body lean mass (45.99 ± 7.01 kg, n = 42) was non-normally distributed with a skewness of $\alpha_3 = -.039$, ($SEM_{skew} = .365$) and a kurtosis of $\alpha_4 = .064$, ($SEM_{kurt} = .717$) (Figure H8, Table H2).

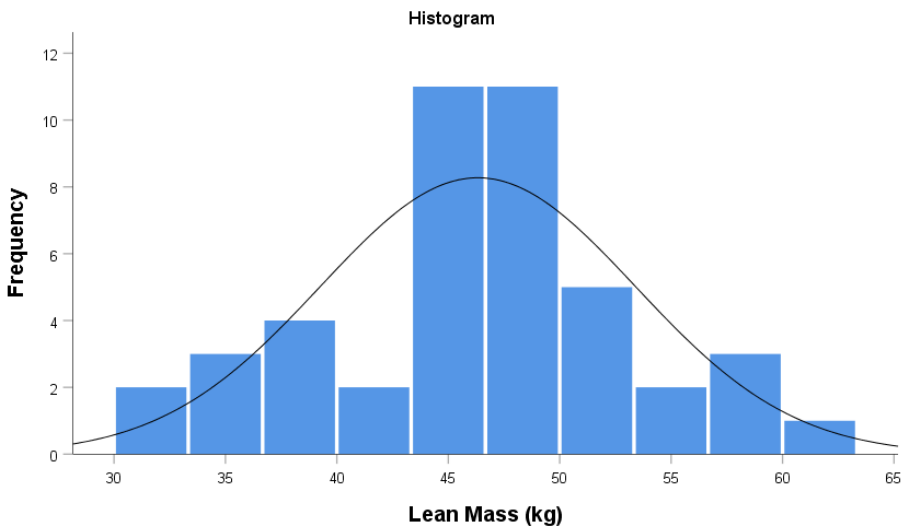

Figure H8. Histogram of pitchers' whole-body lean mass (kg).

Whole-body fat mass (25.71 ± 10.76 kg, n = 42) was non-normally distributed with a skewness of $\alpha_3 = .978$, ($SEM_{skew} = .365$) and a kurtosis of $\alpha_4 = -.005$, ($SEM_{kurt} = .717$) (Figure H9, Table H2).

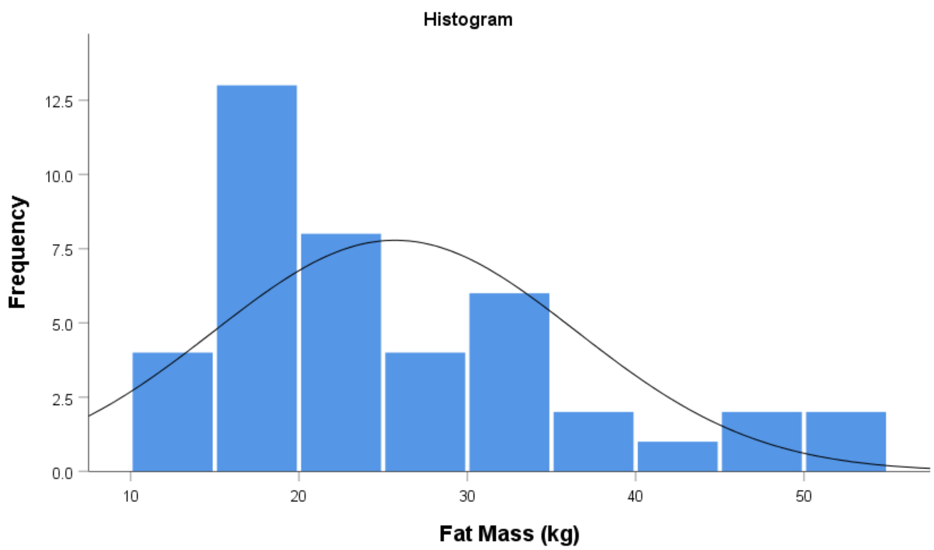

Figure H9. Histogram of pitchers' whole-body fat mass (kg).

Throwing arm fat mass (.66 ± .26 kg, n = 42) was non-normally distributed with a skewness of $\alpha_3 = .739$, ($SEM_{skew} = .365$) and a kurtosis of $\alpha_4 = -.662$, ($SEM_{kurt} = .717$) (Figure H10, Table H2).

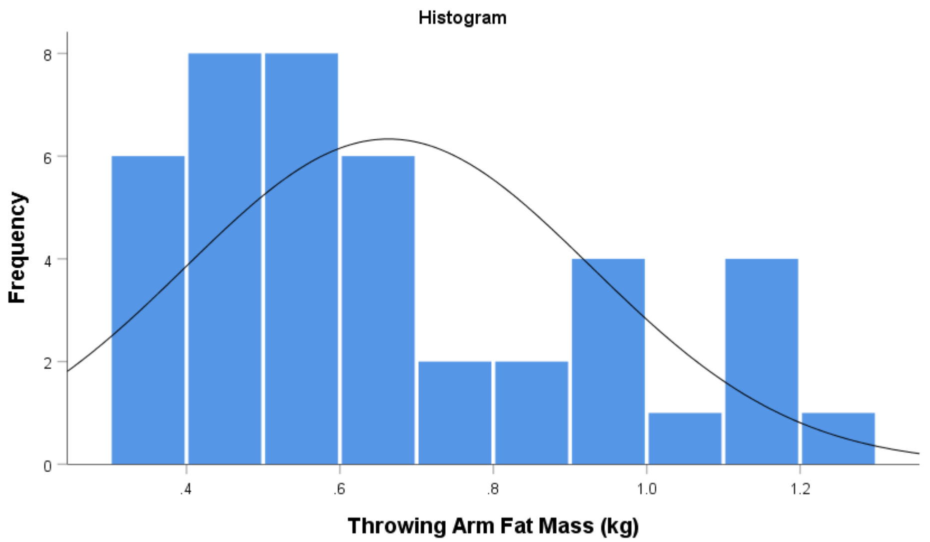

Figure H10. Histogram of pitchers' throwing arm fat mass (kg).

Throwing arm lean mass (1.24 ± .23 kg, n = 42) was non-normally distributed with a skewness of α_3 = -.149, (SEM_{skew} = .365) and a kurtosis of α_4 = -.302, (SEM_{kurt} = .717) (Figure H11, Table H2).

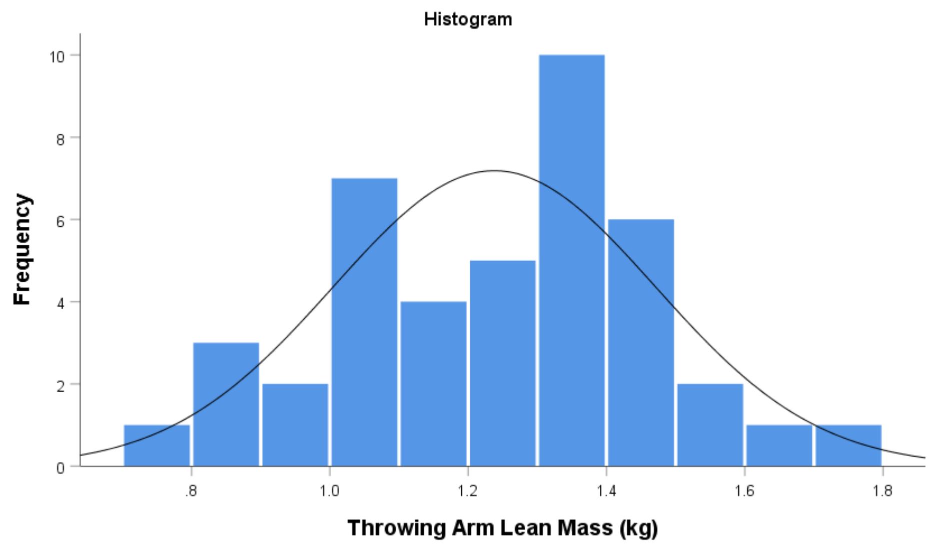

Figure H11. Histogram of pitchers' throwing arm lean mass (kg).

Throwing arm length (.70 ± .03 m, n = 42) was non-normally distributed with a skewness of $\alpha_3 = .355$, ($SEM_{skew} = .365$) and a kurtosis of $\alpha_4 = -.110$, ($SEM_{kurt} = .717$) (Figure H12, Table H2).

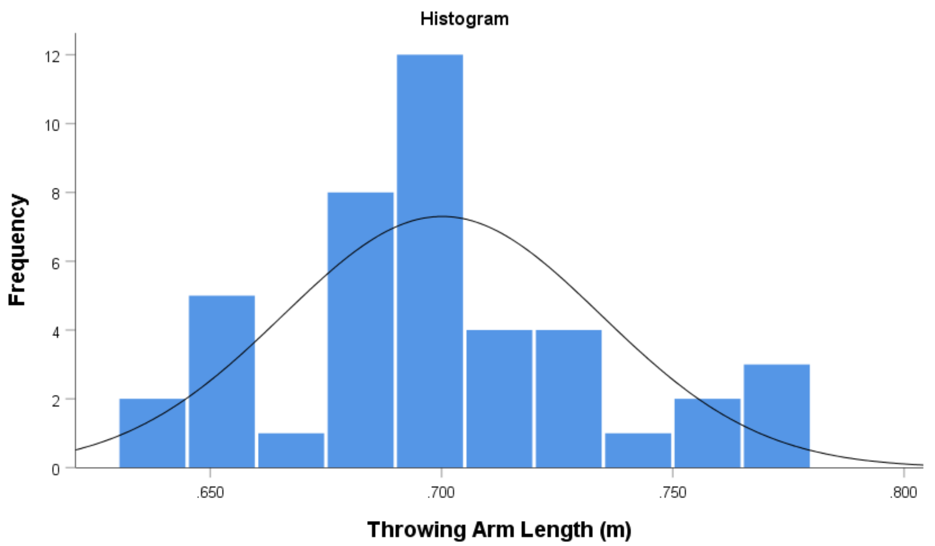

Figure H12. Histogram of pitchers' throwing arm length (m).

Table H2. Normality table for RQ2.

	Kolmogorov-Smirnov[a]			**Shapiro-Wilk**		
	Statistic	df	Sig.	Statistic	df	Sig.
Shoulder Distraction Force (N)	.074	42	.200*	.988	42	.940
WB Lean Mass (kg)	.114	42	.193	.981	42	.687
WB Fat Mass (kg)	.166	42	.005	.883	42	.000
TA Lean Mass (kg)	.087	42	.200*	.985	42	.839
TA Fat Mass (kg)	.168	42	.004	.899	42	.001
TA Length (m)	.122	42	.123	.965	42	.226

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

RQ3 Normality

Normality was assessed through use of the Shapiro-Wilks test of normality. Pitch velocity (55 ± 5 mph, n = 43) was the dependent variable and was normally distributed with a skewness of $\alpha_3 = .032$, ($SEM_{skew} = .361$) and a kurtosis of $\alpha_4 = .146$, ($SEM_{kurt} = .709$) (Figure H13, Table H3).

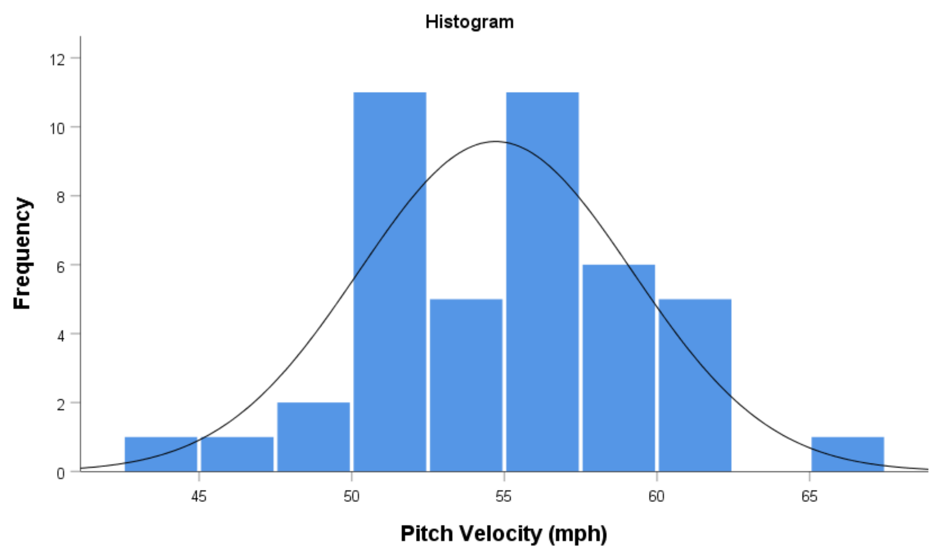

Figure H13. Histogram of pitch velocity (mph).

BMI (26.66 ± 6.29 m/kg^2, n = 43) was non-normally distributed with a skewness of $\alpha_3 = 1.475$, (SEM_{skew} = .361) and a kurtosis of $\alpha_4 = 1.810$, (SEM_{kurt} = .709) (Figure H14, Table H3).

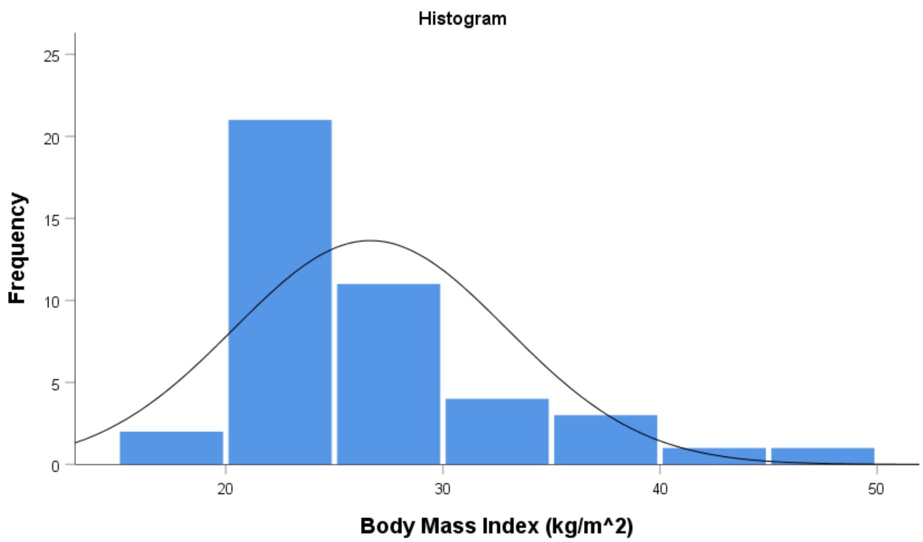

Figure H14. Histogram of body mass index (m/kg^2).

Body fat percent (35.22 ± 7.72 %, n = 43) was non-normally distributed with a skewness of α_3 = .194, (SEM_{skew} = .361) and a kurtosis of α_4 = .-1.264, (SEM_{kurt} = .709) (Figure H15, Table H3).

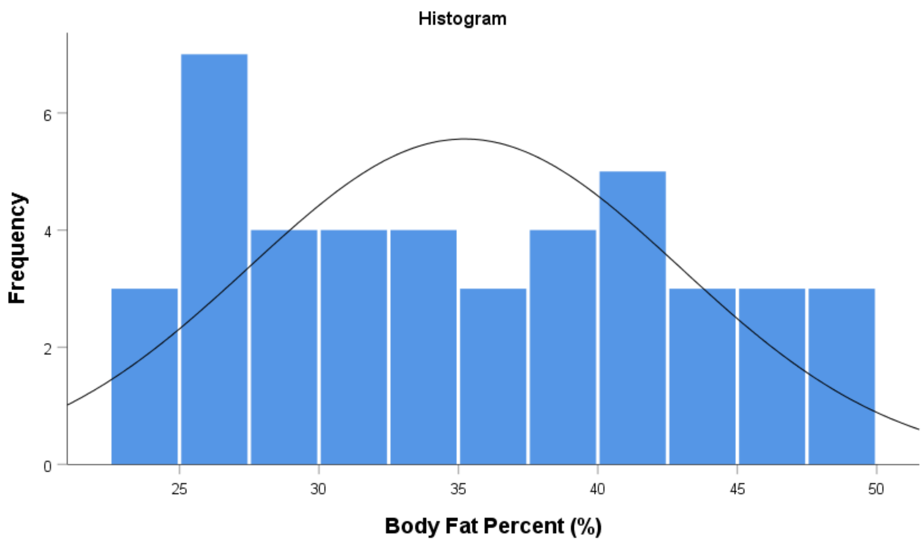

Figure H15. Histogram of body fat percent (%).

Body height (1.700 ± .070 m, n = 43) was normally distributed with a skewness of $\alpha_3 = -.660$, (SEM_{skew} = .361) and a kurtosis of $\alpha_4 = .982$, (SEM_{kurt} = .709) (Figure H16, Table H3).

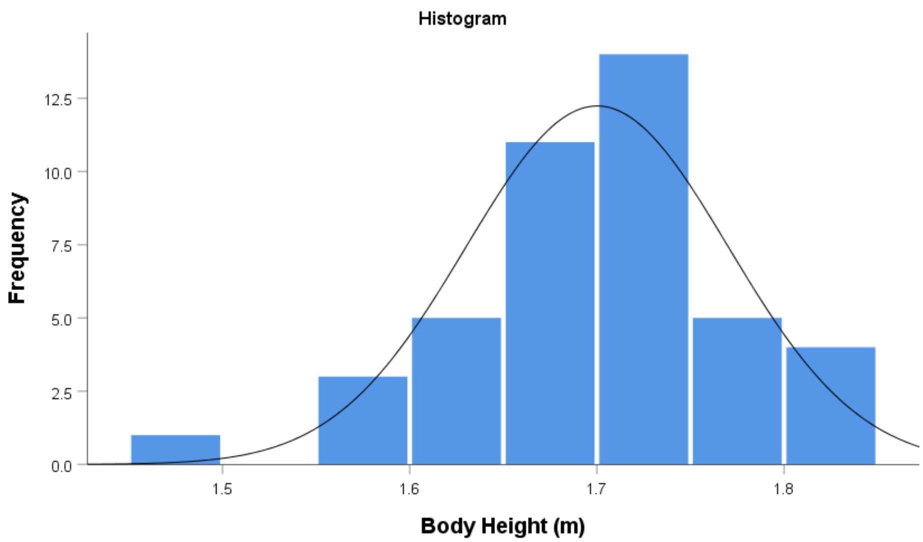

Figure H16. Histogram of body height (m).

Body mass (76.14 ± 16.27 kg, n = 43) was non-normally distributed with a skewness of $\alpha_3 = .745$, (SEM_{skew} = .361) and a kurtosis of $\alpha_4 = .045$, (SEM_{kurt} = .709) (Figure H17, Table H3).

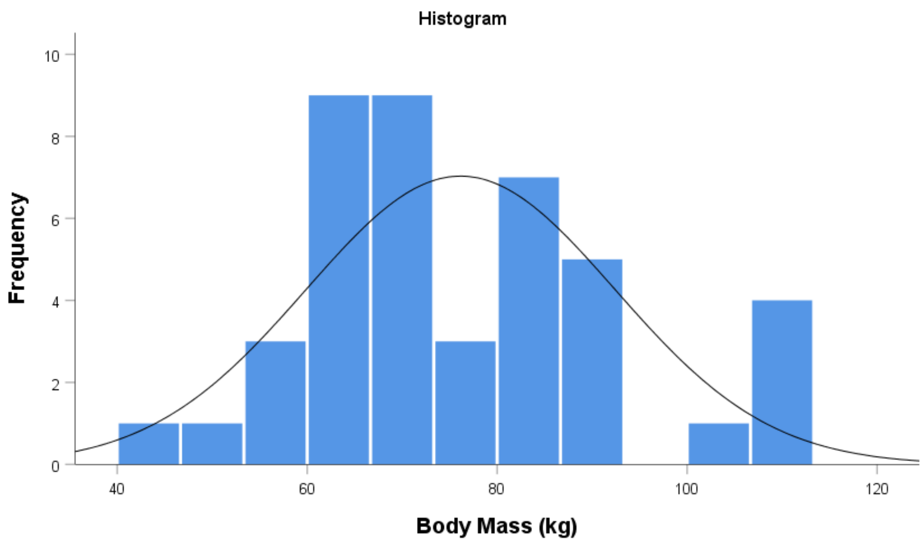

Figure H17. Histogram of body mass (kg).

Table H3. Normality table for RQ3.

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Pitch velocity (mph)	.091	43	.200*	.988	43	.921
BMI (m/kg^2)	.195	43	.000	.848	43	< .001
Body Fat (%)	.126	43	.083	.940	43	.025
Body Height (m)	.087	43	.200*	.971	43	.355
Body Mass (kg)	.137	43	.040	.932	43	.014

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

RQ4 Normality

Normality was assessed through use of the Shapiro-Wilks test of normality. Upper arm circumference (32.0 ± 4.0 cm, n = 42) was normally distributed with a skewness of $\alpha_3 = .627$, ($SEM_{skew} = .365$) and a kurtosis of $\alpha_4 = -.171$, ($SEM_{kurt} = .717$) (Figure H18, Table H4).

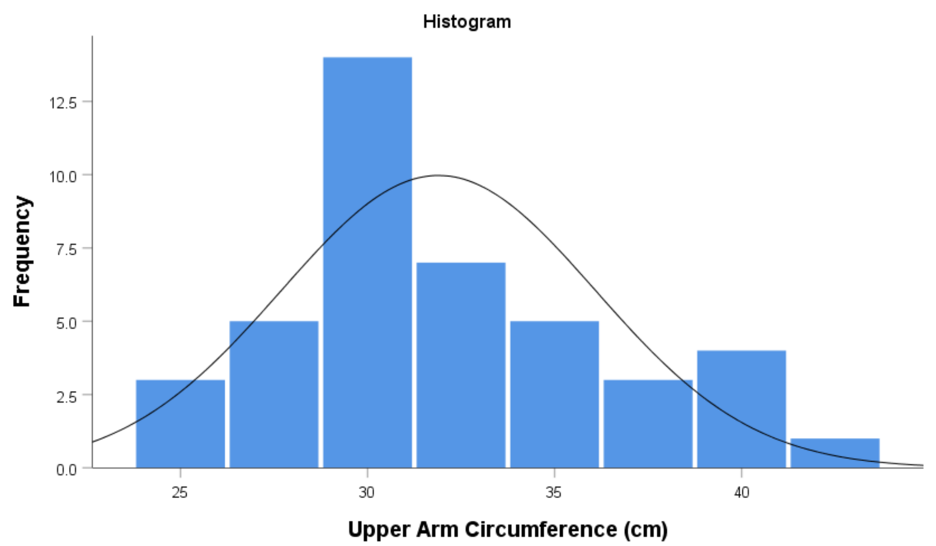

Figure H18. Histogram of upper arm circumference (cm).

Chest circumference (97.5 ± 11.0 cm, n = 42) was normally distributed with a skewness of α_3 = .590, (SEM_{skew} = .365) and a kurtosis of α_4 = -.171, (SEM_{kurt} = .717) (Figure H19, Table H4).

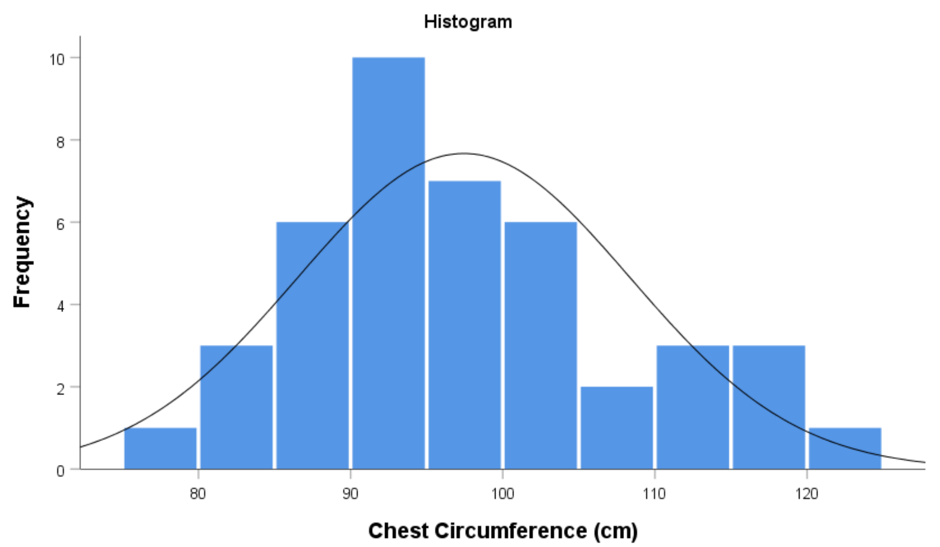

Figure H19. Histogram of chest circumference (cm).

Waist circumference (83.5 ± 13 cm, n = 42) was non-normally distributed with a skewness of $\alpha_3 = .887$, ($SEM_{skew} = .365$) and a kurtosis of $\alpha_4 = .034$, ($SEM_{kurt} = .717$). Therefore, an inverse transformation was used to compute a new waist circumference variable. The transformed waist circumference was normally distributed with a skewness of $\alpha_3 = -.338$, ($SEM_{skew} = .365$) and a kurtosis of $\alpha_4 = -.550$, ($SEM_{kurt} = .717$) (Figure H20, Table H4).

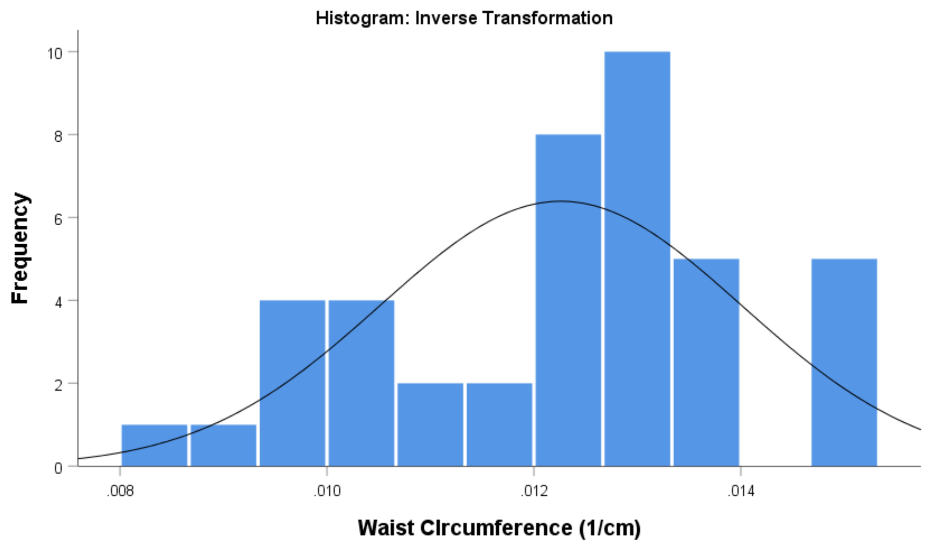

Figure H20. Histogram of transformed waist circumference (1/cm).

Hip circumference (104.5 ± 10.5 cm, n = 42) was non-normally distributed with a skewness of α_3 = 1.044, (SEM_{skew} = .365) and a kurtosis of α_4 = 1.167, (SEM_{kurt} = .717). Therefore, an inverse transformation was used to compute a new waist circumference variable. The transformed hip circumference was normally distributed with a skewness of α_3 = -.479, (SEM_{skew} = .365) and a kurtosis of α_4 = .434, (SEM_{kurt} = .717) (Figure H21, Table H4).

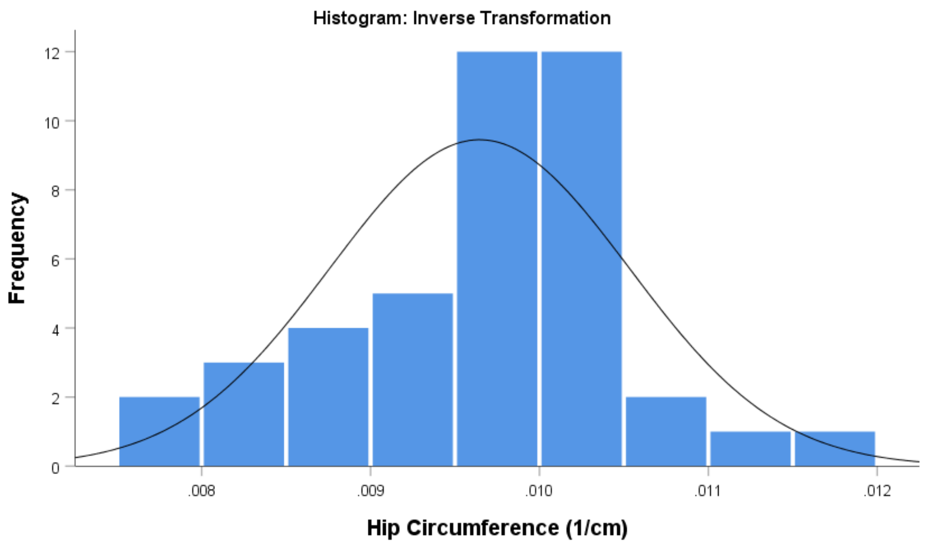

Figure H21. Histogram of transformed hip circumference (1/cm).

Trunk flexion at ball release (BR) (6.49 ± 9.08º, n = 42) was normally distributed with a skewness of $\alpha_3 = -.588$, ($SEM_{skew} = .365$) and a kurtosis of $\alpha_4 = .750$, ($SEM_{kurt} = .717$) (Figure H22, Table H4).

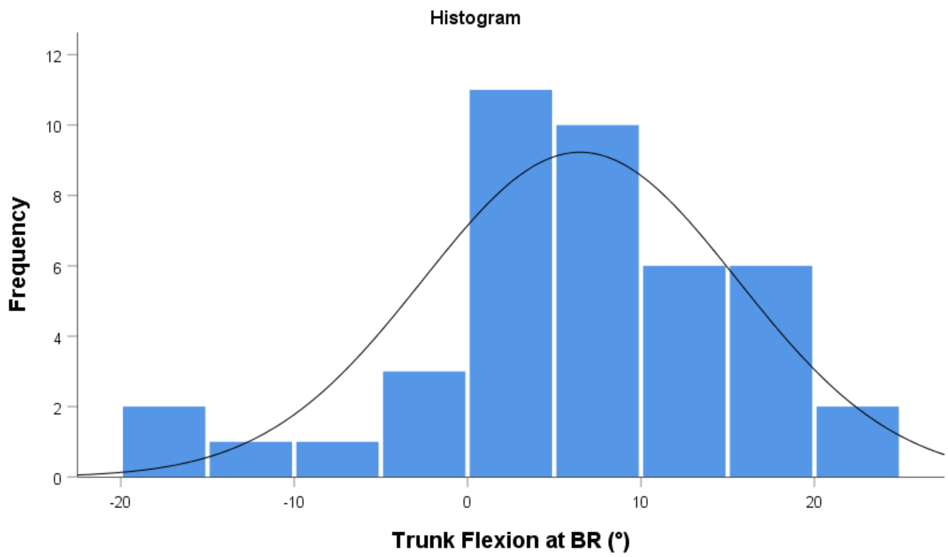

Figure H22. Histogram of trunk flexion at BR (º).

Trunk lateral flexion at BR (15.79 ± 10.19º, n = 42) was normally distributed with a skewness of $\alpha_3 = -.618$, ($SEM_{skew} = .365$) and a kurtosis of $\alpha_4 = -.387$, ($SEM_{kurt} = .717$) (Figure H23, Table H4).

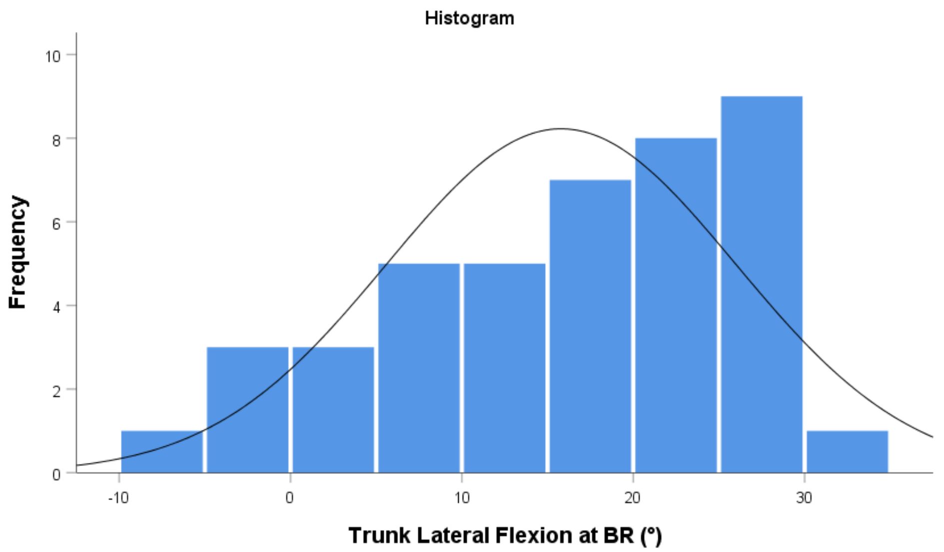

Figure H23. Histogram of trunk lateral flexion at BR (º).

Trunk rotation at BR (-34.93 ± 11.13º, n = 42) was normally distributed with a skewness of α_3 = -.314, (SEM_{skew} = .365) and a kurtosis of α_4 = -.470, (SEM_{kurt} = .717) (Figure H24, Table H4).

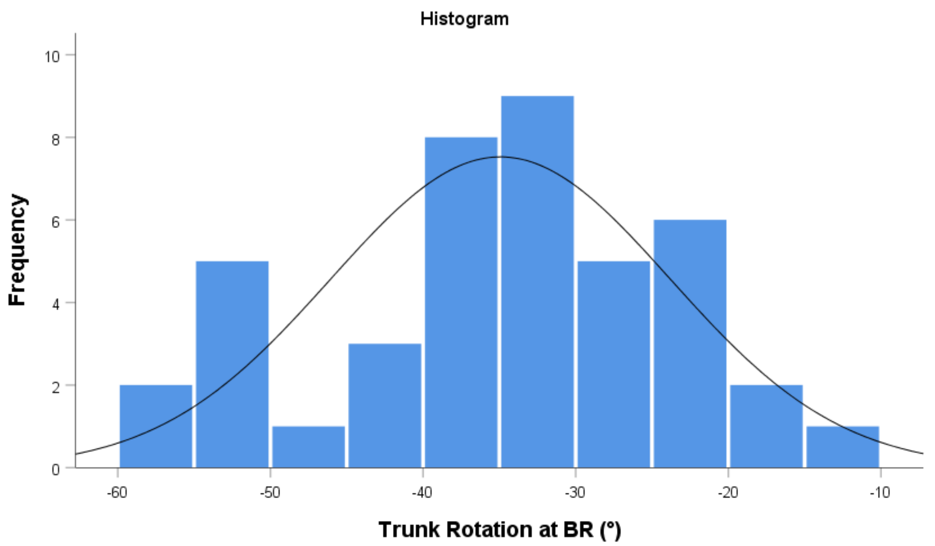

Figure H24. Histogram of trunk rotation at BR (º).

Throwing arm plane of elevation (81.28 ± 19.16º, n = 42) was normally distributed with a skewness of $\alpha_3 = .526$, ($SEM_{skew} = .365$) and a kurtosis of $\alpha_4 = 1.434$, ($SEM_{kurt} = .717$) (Figure H25, Table H4).

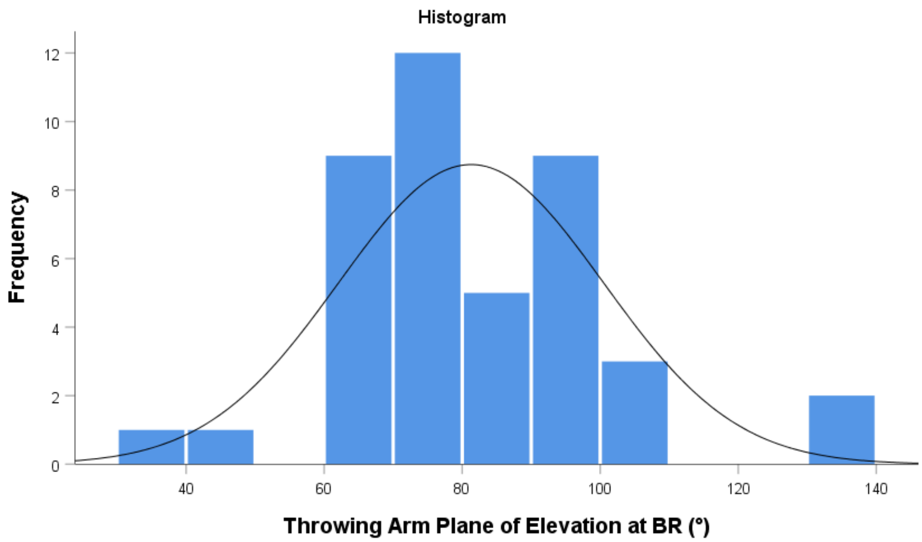

Figure H25. Histogram of throwing arm plane of elevation at BR (º).

Throwing arm elevation (18.45 ± 7.55º, n = 42) was normally distributed with a skewness of α_3 = .239, (SEM_{skew} = .365) and a kurtosis of α_4 = -.034, (SEM_{kurt} = .717) (Figure H26, Table H4).

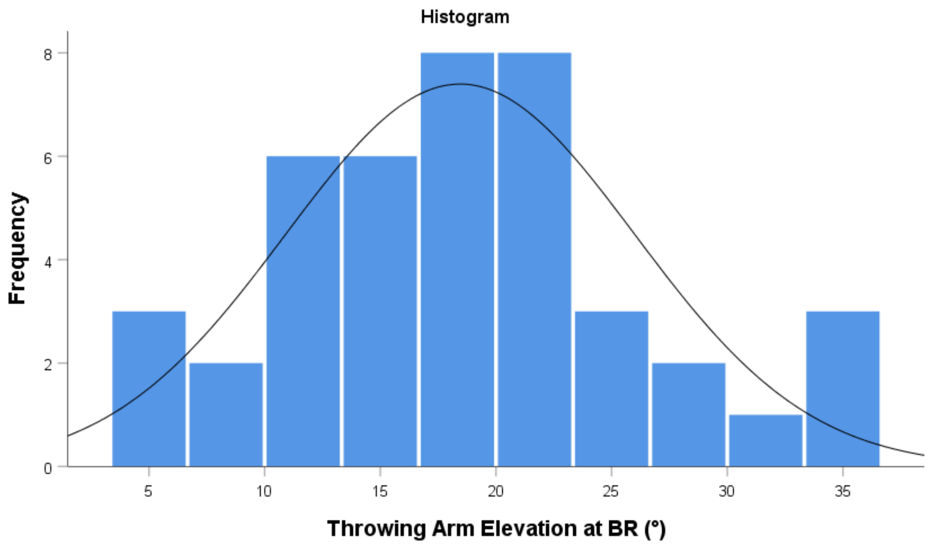

Figure H26. Histogram of throwing arm elevation at BR (º).

Table H4. Normality table for RQ4.

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Upper Arm Circumference	.109	42	.200*	.957	42	.115
Chest Circumference	.110	42	.200*	.963	42	.192
Waist Circumference (Inverse transformation)	.126	42	.092	.962	42	.178
Hip Circumference (Inverse transformation)	.148	42	.022	.963	42	.195
Trunk Flexion at BR	.104	42	.200*	.966	42	.248
Trunk Lateral Flexion at BR	.110	42	.200*	.950	42	.064
Trunk Rotation at BR	.086	42	.200*	.973	42	.416
Throwing Arm Plane of Elevation at BR	.102	42	.200*	.954	42	.092
Throwing Arm Elevation at BR	.085	42	.200*	.975	42	.474

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

RQ 5 Normality

Normality was assessed through use of the Shapiro-Wilks test of normality. Trunk angular velocity for the healthy-fat% group of pitchers (624.88 ± 142.83 °/s, n = 17) was normally distributed with a skewness of $\alpha_3 = -.179$, ($SEM_{skew} = .550$) and a kurtosis of $\alpha_4 = -.387$, ($SEM_{kurt} = 1.063$) (Figure H27, Table H5).

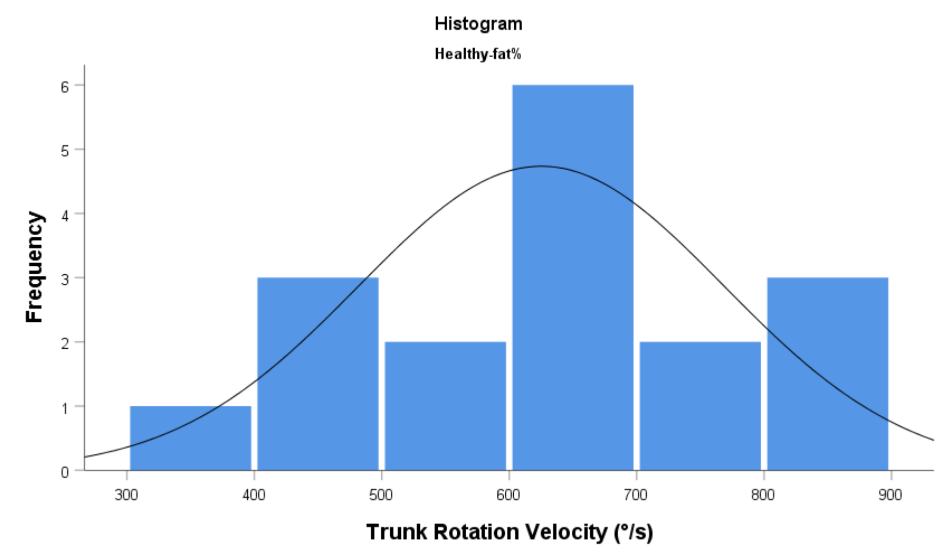

Figure H27. Histogram of trunk rotation velocity of the healthy-fat% group of pitchers (º/s).

Trunk angular velocity for the high-fat% group of pitchers (517.57 ± 132.39 °/s, n = 23) was non-normally distributed with a skewness of $\alpha_3 = 1.105$, (SEM_{skew} = .481) and a kurtosis of $\alpha_4 =$ .803, (SEM_{kurt} = .935) (Figure H28, Table H5).

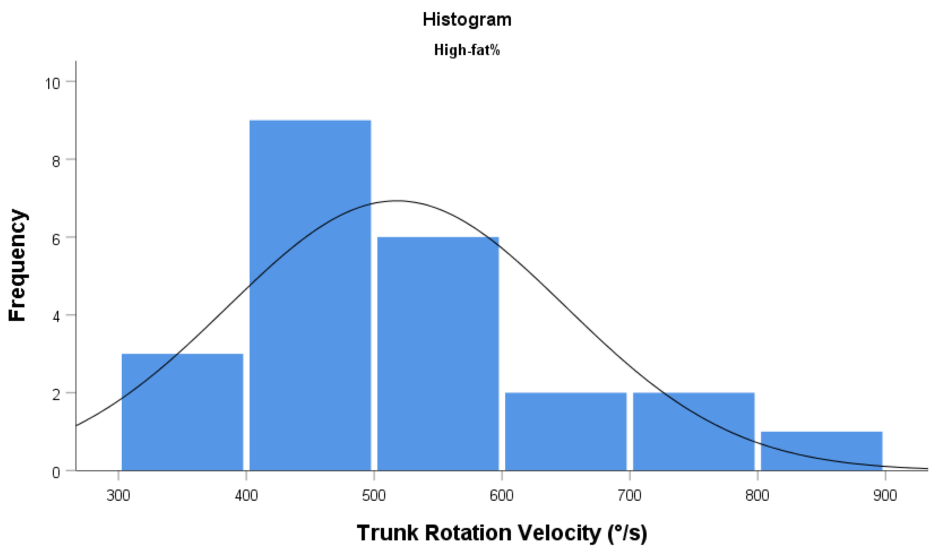

Figure H28. Histogram of trunk rotation velocity of the high-fat% group of pitchers (°/s).

Shoulder flexion angular velocity for the healthy-fat% group of pitchers (1120.72 ± 332.34 °/s, n = 17) was normally distributed with a skewness of $\alpha_3 = .714$, ($SEM_{skew} = .550$) and a kurtosis of $\alpha_4 = -.248$, ($SEM_{kurt} = 1.063$) (Figure H29, Table H5).

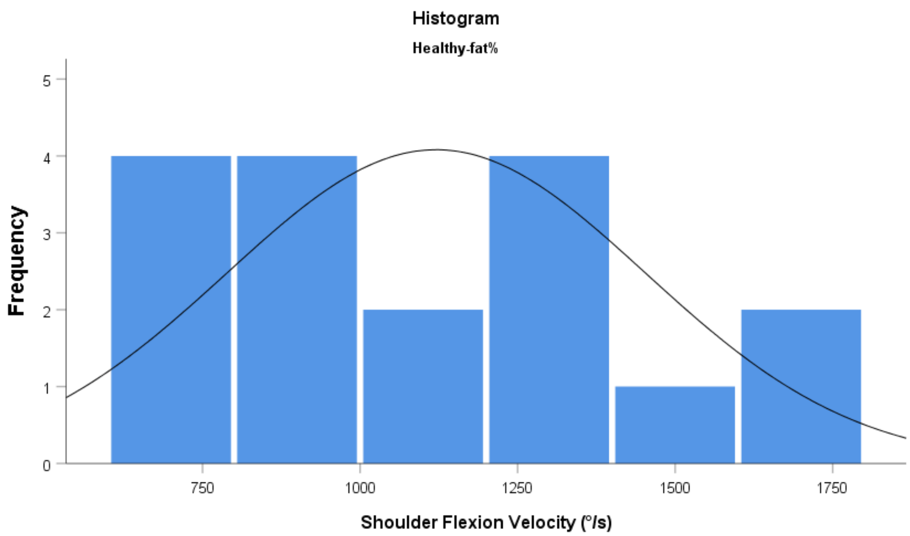

Figure H29. Histogram of shoulder flexion velocity of the healthy-fat% group of pitchers (º/s).

Shoulder flexion angular velocity for the high-fat% group of pitchers (973.31 ± 286.46 °/s, n = 23) was non-normally distributed with a skewness of $\alpha_3 = 1.223$, (SEM_{skew} = .481) and a kurtosis of $\alpha_4 = 2.089$, (SEM_{kurt} = 0.935) (Figure H30, Table H5).

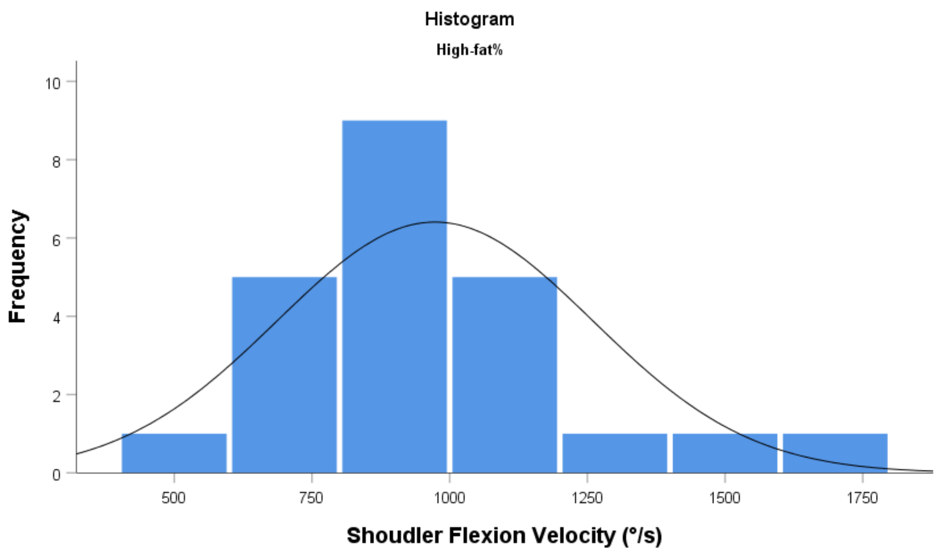

Figure H30. Histogram of shoulder flexion velocity of the high-fat% group of pitchers (º/s).

Elbow flexion angular velocity for the healthy-fat% group of pitchers (874.28 ± 104.41 °/s, n = 17) was normally distributed with a skewness of $\alpha_3 = .735$, ($SEM_{skew} = .550$) and a kurtosis of $\alpha_4 = -.040$, ($SEM_{kurt} = 1.063$) (Figure H31, Table H5).

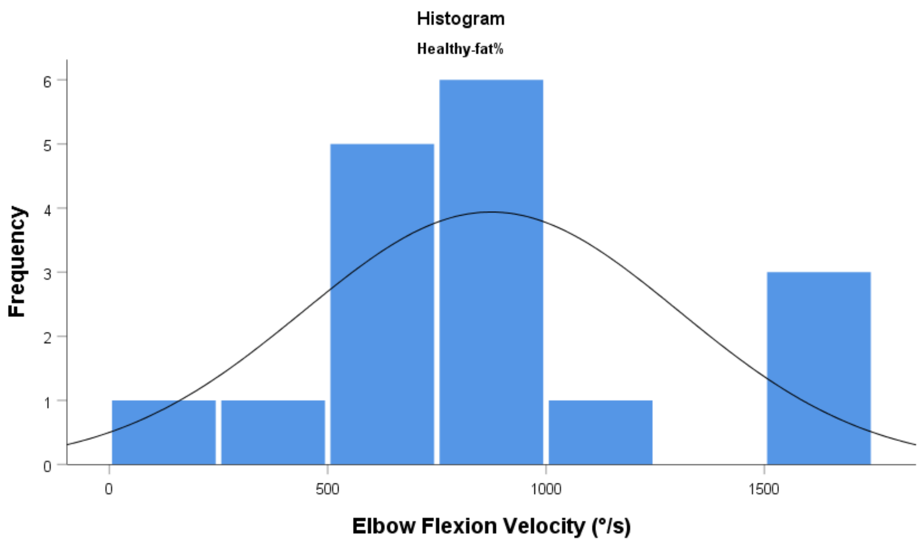

Figure H31. Histogram of elbow flexion velocity of the healthy-fat% group of pitchers (°/s).

Elbow flexion angular velocity for the high-fat% group of pitchers (949.16 ± 480.51 °/s, n = 23) was non-normally distributed with a skewness of $\alpha_3 = 1.811$, (SEM_{skew} = .481) and a kurtosis of $\alpha_4 = 5.125$, (SEM_{kurt} = .935) (Figure H32, Table H5).

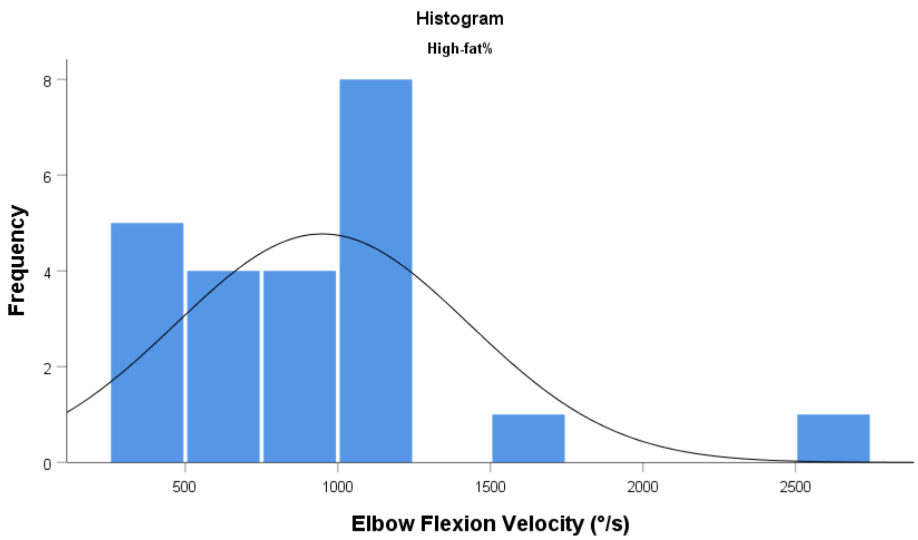

Figure H32. Histogram of elbow flexion velocity of the high-fat% group of pitchers (°/s).

Wrist flexion angular velocity for the healthy-fat% group of pitchers (2859.84 ± 475.35 °/s, n = 17) was normally distributed with a skewness of α_3 = -.040, (SEM_{skew} = .550) and a kurtosis of α_4 = -1.149, (SEM_{kurt} = 1.063) (Figure H33, Table H5).

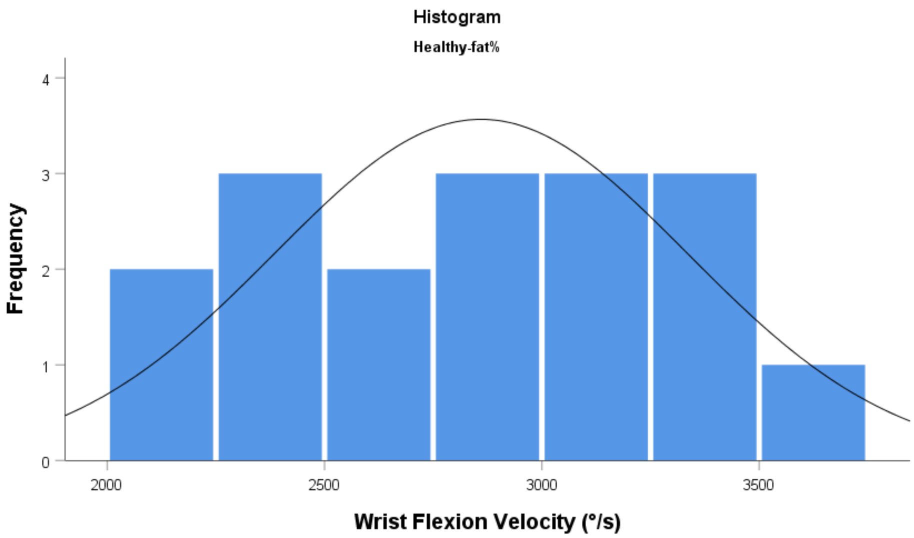

Figure H33. Histogram of wrist flexion velocity of the healthy-fat% group of pitchers (°/s).

Wrist flexion angular velocity for the high-fat% group of pitchers (3002.17 ± 922.63 °/s, n = 23) was non-normally distributed with a skewness of $\alpha_3 = 1.259$, (SEM_{skew} = .481) and a kurtosis of $\alpha_4 = 2.738$, (SEM_{kurt} = .935) (Figure H34, Table H5).

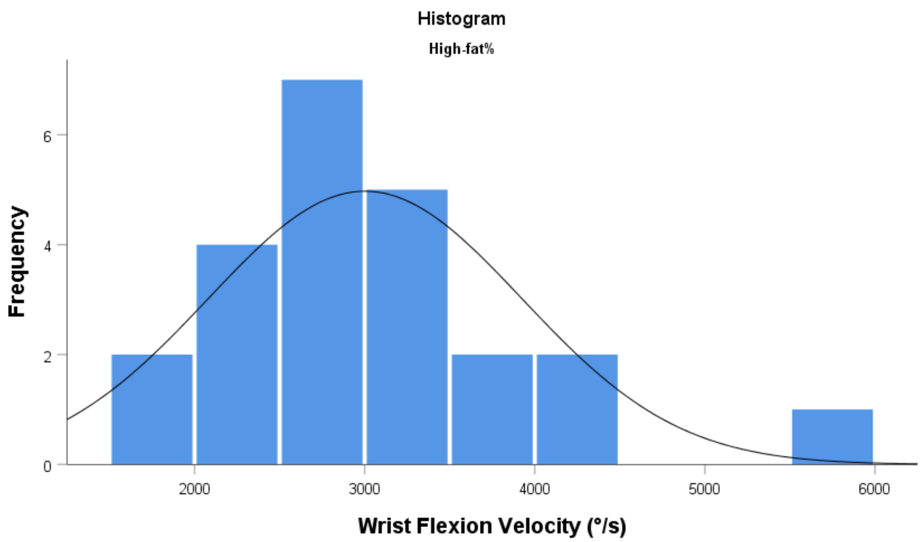

Figure H34. Histogram of wrist flexion velocity of the high-fat% group of pitchers (°/s).

Pitch velocity for the healthy-fat% group of pitchers (56 ± 5 mph, n = 17) was normally distributed with a skewness of $\alpha_3 = -.954$, ($SEM_{skew} = .550$) and a kurtosis of $\alpha_4 = 2.961$, ($SEM_{kurt} = 1.063$). (Figure H35, Table H5).

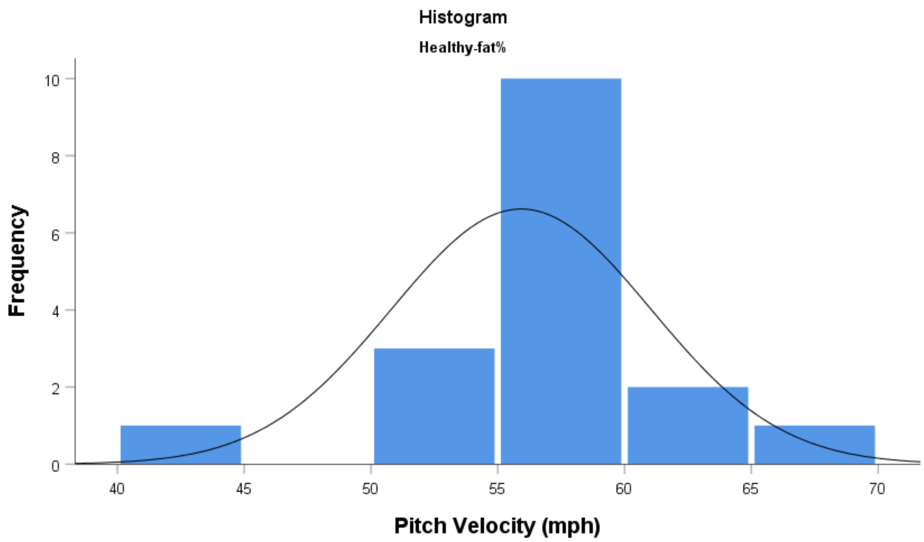

Figure H35. Histogram of pitch velocity of the healthy-fat% group of pitchers (mph), n = 17.

Pitch velocity for the high-fat% group of pitchers (54 ± 5 mph, n = 23) was normally distributed with a skewness of $\alpha_3 = -.109$, ($SEM_{skew} = .481$) and a kurtosis of $\alpha_4 = -.160$, ($SEM_{kurt} = .935$). (Figure H36, Table H5).

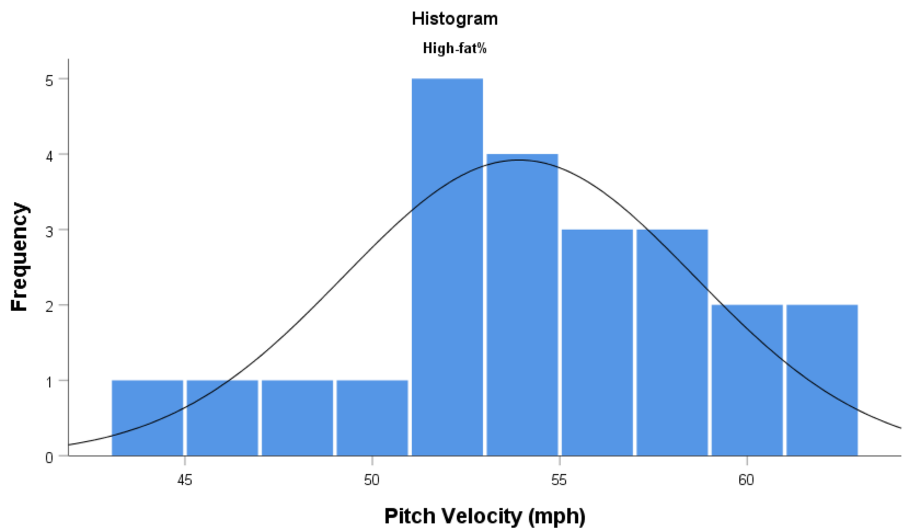

Figure H36. Histogram of pitch velocity of the high-fat% group of pitchers (mph), n = 23.

Table H5. Normality table for RQ5.

	Group	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Trunk Rotation Angular Velocity	Healthy-fat%	.122	17	.200*	.970	17	.811
	High-fat%	.155	23	.157	.907	23	.035
Shoulder Flexion Angular Velocity	Healthy-fat%	.135	17	.200*	.908	17	.092
	High-fat%	.147	23	.200*	.910	23	.042
Elbow Flexion Angular Velocity	Healthy-fat%	.209	17	.047	.915	17	.120
	High-fat%	.187	23	.036	.834	23	.001
Wrist Flexion Angular Velocity	Healthy-fat%	.138	17	.200*	.946	17	.402
	High-fat%	.146	23	.200*	.914	23	.051
Pitch Velocity	Healthy-fat%	.193	17	.091	.906	17	.086
	High-fat%	.104	23	.200*	.975	23	.811

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction