YOUTH PITCHING KINEMATICS: ASSOCIATIONS WITH BODY OVERWEIGHT PARAMETERS

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ABSTRACT

Youth Pitching Kinematics: Associations with Body Overweight Parameters

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The objective of this study was to investigate associations between injury-related kinematic parameters and overweight measures for youth baseball pitchers. The injury-related kinematic parameters considered were measurements 1) at foot contact: stride length, front foot position, shoulder external rotation, shoulder abduction, and elbow flexion; 2) between FC and ball release: peak knee extension; and 3) at BR: shoulder abduction. Data from three separate collection sites examined pitching mechanics of 18 10- to 11-year-old pitchers, 11 14- to 16-year-old pitchers, and 104 16- to 18-year-old pitchers Linear regression analyses were performed to determine significant correlations between kinematic parameters and body mass index (BMI) for each of the three age groups (10- to 11-year-olds, 14- to 16-year-olds, 16- to 18-year-olds). The significant findings were 1) for 10- to 11-year-old pitchers, stride length was negatively correlated with BMI and front foot position was positively correlated with BMI and 2) for 16- to 18-year-old pitchers, shoulder external rotation was negatively correlated with BMI and elbow flexion was positively correlated with BMI. A key clinical implication of this study is that select kinematic parameters have been identified that could guide coaches and trainers when working with overweight pitchers. In addition, select kinematic parameters of concern have been identified for different age ranges.

Keywords: Baseball, Biomechanics, Motion Analysis, Body Mass Index

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Chapter 1

INTRODUCTION

Prevalence of youth baseball pitching injuries has not decreased despite adoption of safety guidelines, pitch count recommendations, and increased media coverage [1]. Among players, coaches, and parents, there is still a lack of awareness and knowledge surrounding safe throwing practices and compliance with safety recommendations [1]. Results from a study examining knowledge of injury prevention and prevalence of risk factors in youth baseball players indicated that 62 percent of baseball players between the ages of 4 and 18 disagreed with the statement "The more you throw, the more likely you are to get an injury" and 57 percent of youth baseball players indicated that they would not seek medical help if they experienced a tired or sore arm during the game[2]. For youth baseball players, especially those participating in multiple leagues and/or travel teams, pitching regulations are not strictly enforced. In addition, the schedules and season lengths of teams are of concern as youth pitchers are unable to get adequate rest between games [3] to avoid high and repetitive joint kinetics.

Strong evidence shows that high and repetitive joint kinetics (i.e., forces, torques) are a biomechanical mechanism for pitching injuries [4-5]. Further evidence suggests that flaws in pitching kinematics lead to an increase in joint kinetics and pitching injuries [6]. Studies aimed at correcting flaws in several kinematic parameters have been conducted for adults [6]. In one study [6], a pitcher was considered to have a flaw if their kinematic parameter fell outside of an established elite range (Appendix D). These normative ranges were created from a previous study with 100 elite pitchers [6]. To be considered elite, the participant had to be a professional player with no previous injuries in the last year. In addition, the participant's average fastball velocity had to be at least 88 mph during the analysis [6]. After first evaluation, amateur participants reviewed the detected flaws along with video, images, and other biomechanical data from the experiment with a biomechanics specialist. Pitchers then returned for a second evaluation 12 months later where 44% of flaws across all participants were corrected. However, similar studies do not exist for youth baseball pitchers.

Previous studies have demonstrated a need to evaluate certain injury-related kinematic parameters. In studies with adults, stride length was determined to be a signifier of overall exertion thus possibly influencing risk of arm injury [7]. Along those same lines, front foot position, or the direction of stride, was also found to influence shoulder force and torque [8-9]. Excessive shoulder rotation at foot contact was found to decrease ball velocity and performance [10], while deviations from the elite range in shoulder abduction put pitchers at risk for labral injury [5]. In addition, front knee extension from foot contact to ball release ties into the hip's forward motion which enables pelvis rotation and trunk forward flexion [11]. If the knee extension parameter deviates from the elite range, pitchers put themselves at risk for injury. These select injury-related kinematic parameters identified in adults are analyzed for youth pitchers in this study.

There is strong evidence to suggest that body overweight parameters, such as a higher body mass index (BMI), are related to an increase in injury rates across youth athletics [12]. Also, previous studies have shown that BMI has been linked to an increase in injury-related kinetic parameters [13]. However, there are no studies that have investigated relations between BMI and injury-related kinematic parameters. Being able to relate BMI to kinematic parameters is beneficial as BMI is simple to calculate given the participants body height and weight, making it an easily accessible measure for players, coaches, and parents alike, should significant correlations be found [13].

The goal of this study was to investigate associations between injury-related kinematic parameters and overweight measures for youth baseball pitchers. The hypothesis was that injury-related kinematic parameters would be associated with BMI. The injury-related kinematic parameters considered were measurements 1) at foot contact (FC): stride length (SL), front foot position (FFP), shoulder external rotation (SER), shoulder abduction (SAFC), and elbow flexion (EF); 2) between FC and ball release (BR): peak knee extension (KE); and 3) measurements at BR: shoulder abduction (SABR). All kinematic parameters listed above were chosen for analysis based on the previous study with adult pitchers [6].

Chapter 2
METHODS

2.1 Participant Recruitment

Motion analysis and anthropometric data were available from three studies: 1) a published study with 18 10- to 11-year-old male baseball players (body height 147.7 ± 7.4 cm, body weight 39.6 ± 7.3 kg, BMI 18.0 ± 2.2 kg/m^2) [14] and unpublished studies with 2) 11 14- to 16-year-old male baseball players (body height 180.3 ± 42.5 cm, body weight 79.8 ± 4.3 kg, BMI 27.9 ± 11.2 kg/m^2) [15], and 3) 104 16- to 18-year-old male baseball players (body height 188.7 ± 5.7 cm, body weight 90.5 ± 10.7 kg, BMI 25.4 ± 2.8 kg/m^2) [16]. All participants across the three studies had previous pitching experience and no history of pitching-related injury in the preceding year. In addition, since data for this analysis was taken from studies that did not investigate correlations with BMI, there was no attempt in any study to recruit pitchers of a specific BMI. Details are provided below for methods used in all three studies.

2.2 Informed Consent and Pre-Experiment Tests

For each study, informed assent and consent were obtained from each participant and for youth participants, their legal guardian as well. Participants completed standard pre-experiment tests to measure body height, body weight, and arm segment lengths using a standard scale and tape measure. Participant BMI was calculated as body mass divided by height squared (kg/m^2).

2.3 Experiments

In the 1st study [14], pitching kinematics data were captured using a motion analysis system. 12 motion analysis cameras (Motion Analysis, Santa Rosa, CA, USA) were used to track 38 retroreflective markers placed on anatomical landmarks based on the PitchTrak (Motion Analysis) software marker set (Appendix A). Participants pitched off a portable mound into a net 25 feet away with a scaled strike zone. Marker trajectories were recorded in Cortex analysis software (Version 7.4.6, Motion Analysis) at 200 Hz, interpolated (third-order spline), and filtered

(4^{th} order Butterworth filter, cutoff frequency 12 Hz) [17]. 10 pitches were recorded for each participant.

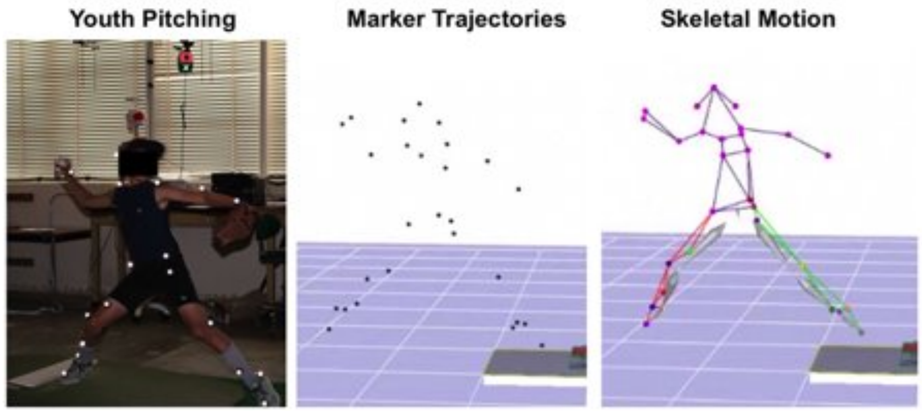

Figure 2.1: Left: Photo of youth participant pitching off portable mound during experiment. **Center:** Screenshot of marker position capture. **Right:** Screenshot of skeletal motion kinematics calculated by Cortex. [14]

In the 2nd study [15], pitching kinematics data were captured using a Real-Time Motion Capture System (Motion Analysis, Santa Rosa, CA, USA) consisting of eight visible-red cameras (Raptor-4S; Motion Analysis) at a sampling rate of 300 Hz [15]. 38 retroreflective markers were placed on anatomical landmarks (Appendix B) based on a model that combines the Helen Hayes lower body marker set [18] with an upper body maker set described by [19]. Participants pitched off a bullpen mound into a net 60 feet away with a strike zone. Marker trajectories were recorded in Cortex analysis software (Version 7.1, Motion Analysis) and filtered (4^{th} order zero-lag Butterworth filter, cutoff frequency 18 Hz) [15]. 15 pitches were recorded for each participant.

In the 3rd study [16], pitching kinematics data were captured using a Digital Real-Time motion analysis system (Motion Analysis Corporation, Santa Rosa, CA) at a sampling rate of 240 Hz. 38 retroreflective markers were placed on anatomical landmarks and used for analysis (Appendix C). Participants pitched from a mound into a net 60 feet from the pitching rubber with a strike zone. Marker trajectories were recorded in Cortex analysis and BioPitch software (Version 12.0, American Sports Medicine Institution) and filtered (4^{th} order Butterworth filter, cutoff frequency 13.4 Hz). Five full-effort fastballs were recorded for each participant [16].

2.4 Analysis

In the 1st study [14], kinematic parameters were obtained using PitchTrak (a subset of Cortex). The last three pitches with usable data were analyzed independently and averaged for each participant.

In the 2nd study [15], the fastest three pitches of the recorded 15 that hit the strike zone were analyzed independently for each participant using Cortex. However, only the fastest of the three pitches was used for this study [19]. Other research studies support the idea of analyzing one pitch as most pitchers have consistent mechanics pitch to pitch [20].

In the 3rd study [16], all five fastball pitches were analyzed independently and averaged for each participant. Kinematic parameters were obtained using BioPitch software [16].

2.4.1 Kinematic Parameters

This study considered seven kinematic parameters that were analyzed at different parts of the pitch cycle, which is defined from FC to BR. FC was determined by identifying the frame in which the front foot heel marker stops moving after contacting the ground (Figure 2.2). BR was determined based on how the wrist pronated during the pitch (Figure 2.3). A range of three to four frames during wrist pronation was selected as potential indicators of ball release. The middle frame of this range was chosen to be the frame at BR. The pitch cycle time was then normalized such that 0% and 100% represented times of FC and BR, respectively.

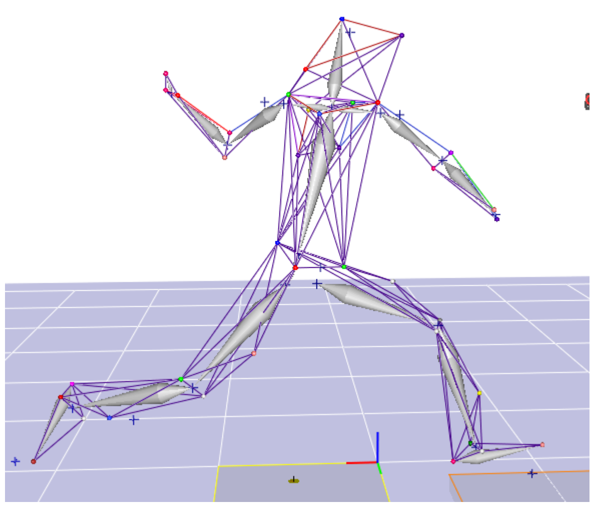

Figure 2.2: Foot contact when the heel initially strikes the ground.

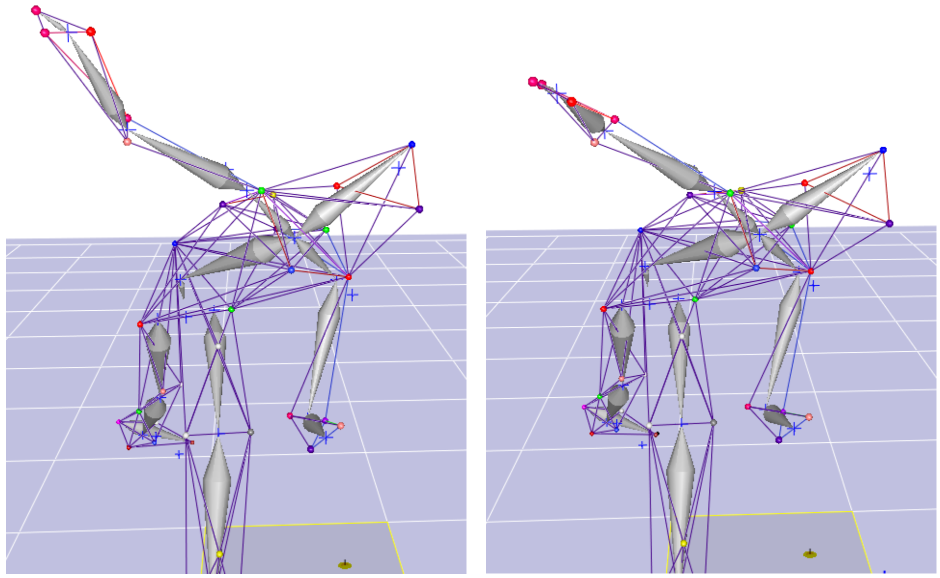

Figure 2.3: Left: Arm position a few frames before ball release. **Right:** Arm position at ball release with the wrist pronated.

SL was calculated by measuring the distance between left and right toe markers at front-FC in the direction of the axis parallel to the pitching mound to home plate vector (Figure 2.4), expressed as a percent of body height (BH). FFP was calculated by taking the distance, in the lateral direction (perpendicular to the pitching mound to home plate vector), between the front ankle's position at the instant of front FC (Figure 2.5, middle) and back ankle's position at maximum knee height (Figure 2.5, left) [6]. FFP was deemed positive when the front foot landed closed (i.e., towards the third base side for a right-handed pitcher) [6]. Both absolute and normalized (by BH) values were considered. SER (Figure 2.6, left) at FC, measured in degrees, was the external rotation angle of the throwing shoulder, SAFC (Figure 2.6, middle), also measured in degrees, was the abduction angle of the throwing shoulder at FC. EF (Figure 2.6, right) was the elbow flexion angle at FC measured in degrees. KE was calculated by taking knee flexion at FC minus knee flexion at BR (Figure 2.7) [6]. Finally, SABR was the shoulder abduction at BR and calculated the same way as at FC.

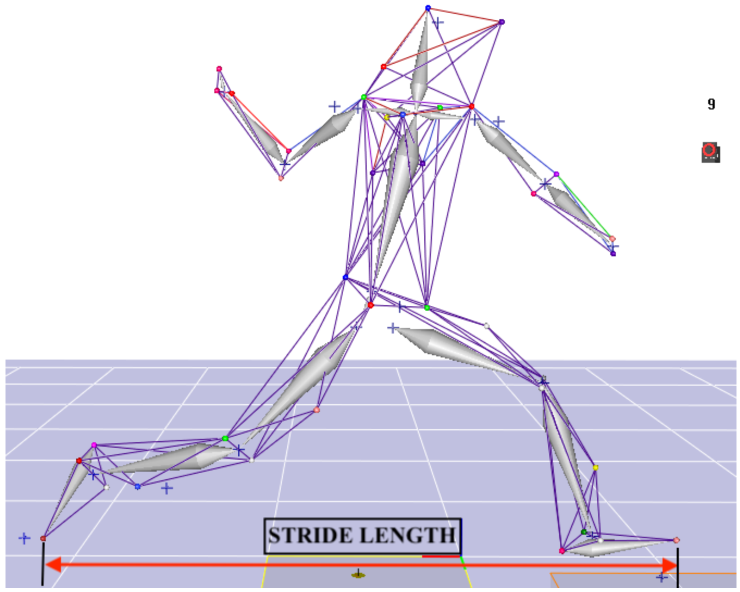

Figure 2.4: Stride length used in analysis.

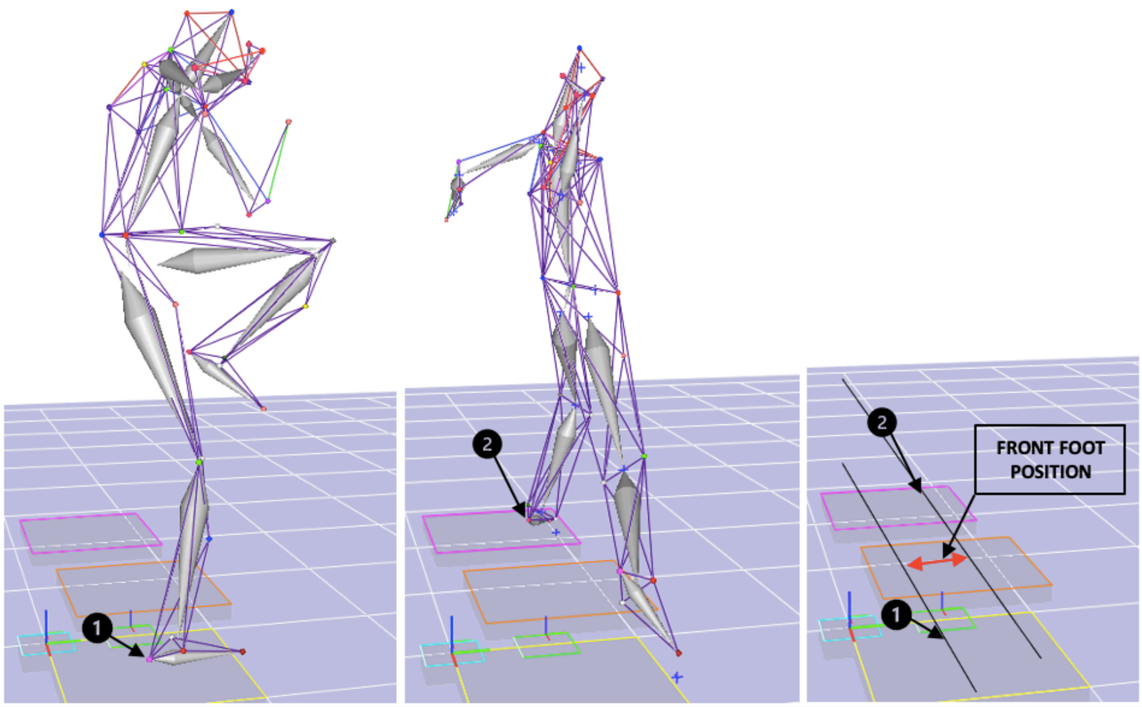

Figure 2.5: Front foot position used in analysis.

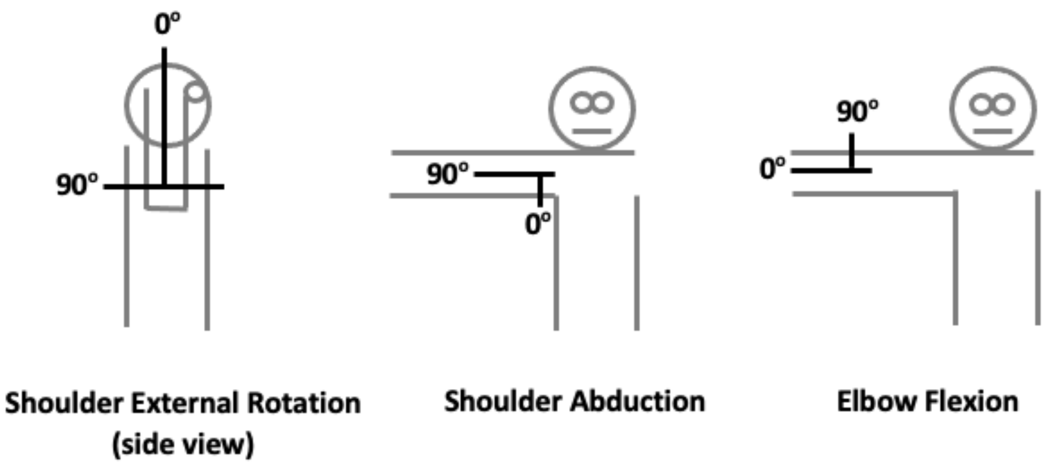

Figure 2.6: Anatomical shoulder and elbow angles used in analysis.

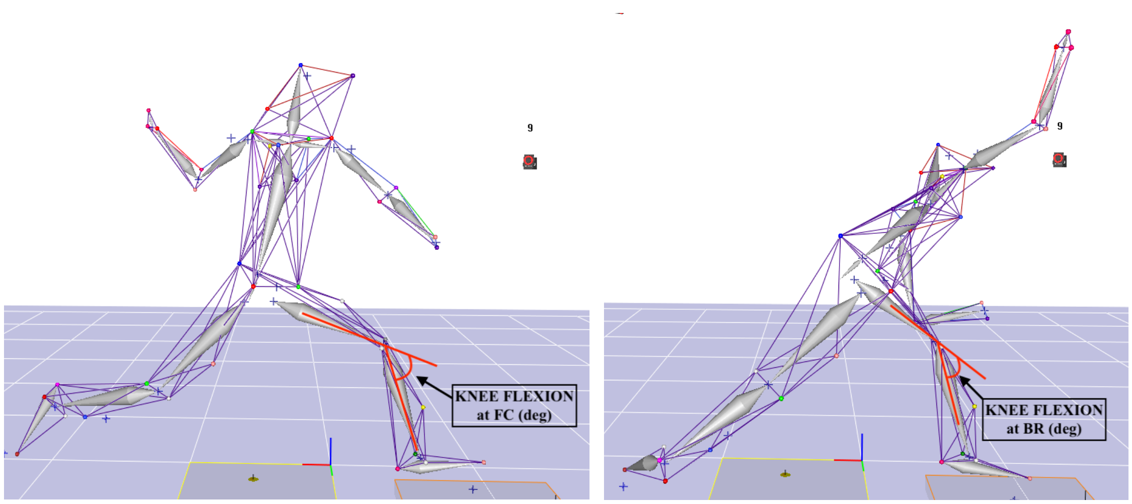

Figure 2.7: Knee flexion angles used to calculate knee extension from FC to BR in analysis.

2.4.2 Statistical Analysis

Data were separated into three groups based on data collection site to prevent possible analysis errors from different lab environments and procedures. Linear regression analyses were performed to determine significant correlations between kinematic parameters and BMI. Statistical significance was defined by $p<0.05$.

Chapter 3

RESULTS

A significant negative correlation was found between normalized SL and BMI for the pitchers in the 10- to 11-year-old age group (p=0.013). Pitchers in the 14- to 16- and 16– to 18-year-old studies had no significant correlation between SL and BMI (p=0.532 and p=0.437 respectively) (Table 3.1). A significant positive correlation was found between normalized FFP and BMI for the pitchers in the 10- to 11-year-old age group (p=0.009). Pitchers in the 14- to 16- and 16– to 18-year-old studies had no significant correlation between FFP and BMI (p=0.211 and p=0.421 respectively) (Table 3.1).

A significant negative correlation was found between SER and BMI for the pitchers in the 16- to 18-year-old age group (p=0.035). Pitchers in the 10- to 11- and 14- to 16-year-old studies had no significant correlation between SER and BMI (p=0.151 and p=0.327 respectively) (Table 3.1). A significant positive correlation was found between EF and BMI for the pitchers in the 16- to 18-year-old age group (p=0.042). Pitchers in the 10- to 11- and 14- to 16-year-old studies had no significant correlation between EF and BMI (p=0.092 and p=0.949 respectively) (Table 3.1). Significant correlations were not found for any of the other kinematic parameters.

The percentage of participants in the elite range was highest for the 16- to 18-year-old age group for each kinematic parameter except for SL (10- to 11-year-old age group had the highest) and SABR (same percentage as 10- to 11-year-old age group) (Table 3.2).

The trendline for SL and BMI (Figure 3.3, left) shows that at a higher BMI, pitchers in the 10- to 11-year-old age group are predicted to have too short of a SL while those with a lower BMI are predicted to have too long of a SL, both considered flaws. Similarly, the trendline for normalized FFP and BMI (Figure 3.3, right) shows that at a higher BMI, pitchers in the 10- to 11-year-old age group are predicted to land their front foot too far towards the third base side while those with a lower BMI are predicted to land their front foot not far enough towards the third base side upon foot contact.

The trendline for SER and BMI (Figure 3.4, left) shows that at a higher BMI, pitchers in the 16- to 18-year-old age group are predicted to have too little SER while those with a lower BMI are predicted to have too much SER, both considered flaws. Similarly, the trendline for EF position and BMI (Figure 3.4, right) shows that at a higher BMI, pitchers in the 16- to 18-year-old age group are predicted to have too little EF while those with a lower BMI are predicted to have too much EF, both considered flaws.

Table 3.1. Single linear regression results of select kinematic parameters vs BMI. * = significant correlation with BMI; $p < 0.050$.

Kinematic Parameter	10- to 11-year-olds (n = 18)	14- to 16-year-olds (n = 11)	16- to 18-year-olds (n = 104)
	R^2 (p)	R^2 (p)	R^2 (p)
Stride Length	0.3261 (0.013*)	0.0946 (0.358)	0.0059 (0.437)
Normalized Front Foot Position	0.3574 (0.009*)	0.1474 (0.244)	0.0064 (0.421)
Shoulder External Rotation	0.1244 (0.151)	0.1067 (0.327)	0.0427 (0.035*)
Shoulder Abduction at Foot Contact	0.0497 (0.374)	0.2753 (0.098)	0.0003 (0.856)
Elbow Flexion	0.1668 (0.092)	0.0005 (0.949)	0.0400 (0.042*)
Knee Extension	0.0002 (0.955)	0.1727 (0.204)	0.0042 (0.511)
Shoulder Abduction at Ball Release	0.0497 (0.374)	0.1708 (0.206)	0.0042 (0.514)

Table 3.2. Percentage of participants in elite range for select kinematic parameters.

Kinematic Parameter	10- to 11-year-olds (n = 18)	14- to 16-year-olds (n = 11)	16- to 18-year-olds (n = 104)
	% in elite range	% in elite range	% in elite range
Stride Length	77.78	0.00	62.5
Normalized Front Foot Position	22.22	9.09	66.35
Shoulder External Rotation	33.33	54.55	57.69
Shoulder Abduction at Foot Contact	44.44	9.09	62.50
Elbow Flexion	61.11	36.36	61.54
Knee Extension	16.67	9.09	26.92
Shoulder Abduction at Ball Release	50.00	9.09	50.00

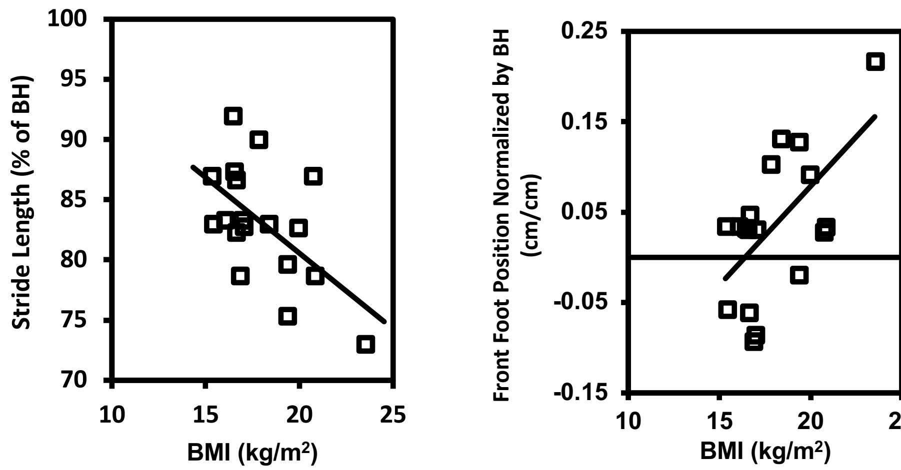

Figure 3.1: Correlations between stride length (SL) and front foot position (FFP) normalized by body height (BH) and BMI for 10- to 11-year-old participants.

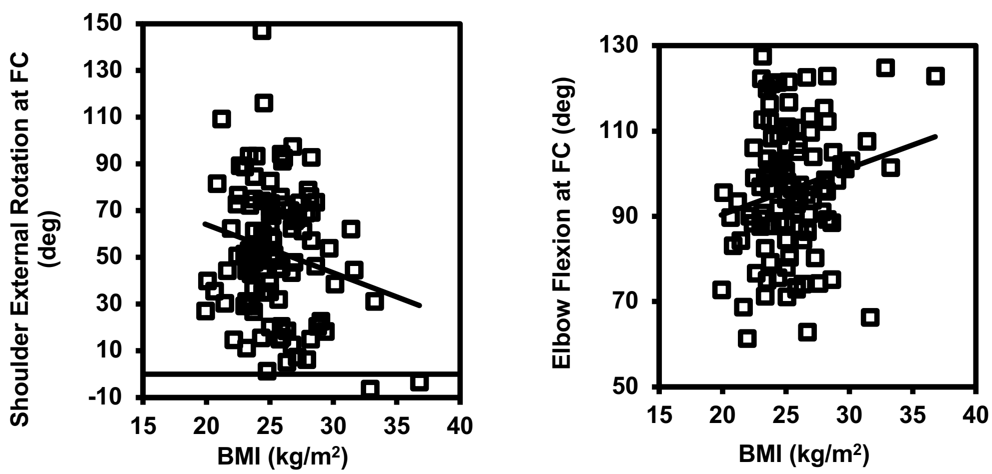

Figure 3.2: Correlations between shoulder external rotation (SER) and elbow flexion (EF) and BMI for 16- to 18-year-old participants.

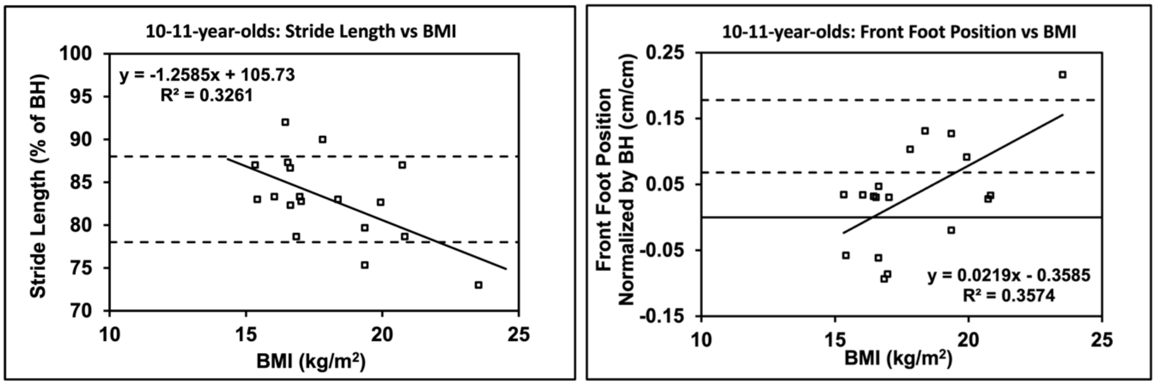

Figure 3.3: Comparison to elite ranges for significant kinematic parameter correlations in the 10- to 11-year-old age range.

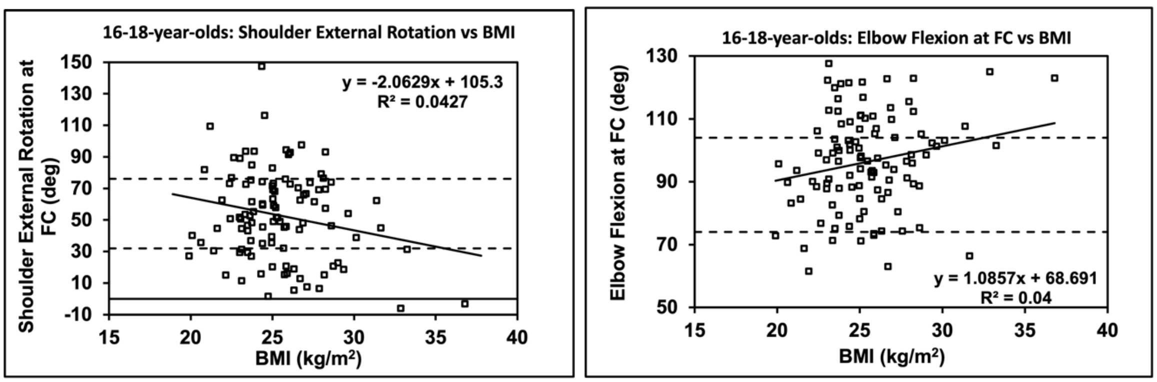

Figure 3.4: Comparison to elite ranges for significant kinematic parameter correlations in the 16- to 18-year-old age range.

Chapter 4

DISCUSSION

There were several evaluations made from this study. First, this study calculated and evaluated select injury-related kinematic parameters for youth pitchers. Second, the results were used to analyze associations between these injury-related kinematic parameters and BMI. Third, the associations were used to analyze injury-related kinematic parameters across three different age groups and compare them to established elite ranges.

The correlations between four of the seven kinematics parameters (SL, FFP, SER, EF) and BMI support the hypothesis that injury-related kinematics parameters are associated with overweight measures. The associations between SL and FFP were significant for only the youngest age group. The difference in SL and FFP trends between the age groups suggest that pitchers in the 10- to 11-year-old range with a higher BMI have more difficulty stabilizing their body during the pitching motion. Thus, these pitchers are unable to use their lower body efficiently when striding with their front foot, resulting in a loss of power or overcompensation in another pitching parameter. Previous studies have aimed to evaluate and understand the flow of energy through the kinetic chain across body segments during a pitch cycle [21]. From one study, energy generated by net torques in the trunk were found to significantly contribute to elbow valgus torque [15]. A lack of lower-extremity strength, signified by the inefficient use of the lower-body during the pitch cycle (e.g., too little stride length), leads to improper transfer of energy from the trunk to the arms. Thus, youth pitchers with a higher BMI and a predicted too little stride length are more susceptible to injury. In addition, trunk rotation timing was found to significantly contribute to elbow valgus torque [15]. For youth pitchers with a higher BMI and a higher front foot position value, the onset of peak rotation could be delayed. This change in trunk movement during the pitch cycle could result in a loss of energy transfer through the kinetic chain from the lower body to the upper extremities, ultimately affecting throwing arm kinetics and pitching performance [22]. With age and improved technique, these difficulties may be resolved as prior studies have shown that pitching kinematics improve rapidly from 9-12 years [23]. Another possible explanation is that 10- to 11-year-old pitchers with flawed pitching kinematics are no longer pitching at the 14+ age range. While it is difficult to make a definitive conclusion, both arguments are in favor of placing emphasis on proper pitching kinematics at a younger age when pitching injuries begin to develop [24].

The associations between SER and EF were significant for only the oldest age group. The difference in SER and EF trends between the age groups suggests that BMI may more significantly affect flexibility during the pitching motion for the 16- to 18-year-old participants as opposed to the 10- to 11- and 14- to 16-year-old participants. Those with a higher BMI in this age range may have a more significant flexibility loss as clear correlations between decreased range of motion and increased BMI in youth have been demonstrated [25]. In turn, this can result in less SER. This loss of SER is of concern as studies have shown that pitchers exhibiting decreased SER at foot contact are subject to an increase in magnitude of shoulder distraction force [26]. This increase in shoulder distraction force has been associated with tensile failure of the rotator cuff and other injuries in baseball pitchers [26]. In addition, higher SER has been linked to higher pitch velocity [27] implying that pitchers in the 16- to 18-year-old range with a higher BMI are losing pitch velocity due to inflexibility in their shoulder. Furthermore, larger amounts of elbow flexion have also been linked to an increase in pitch velocity [28]. Thus, this is a possible explanation as to why there is a negative correlation for shoulder external rotation versus BMI and a positive correlation for elbow flexion versus BMI. As pitchers lose pitch velocity due to limited shoulder flexibility, they are trying to overcompensate by increasing their elbow flexion. This would lead to a higher risk of injury in the elbow as they try to maintain a high pitch velocity. Another possible explanation is that the 3rd study with the 16- to 18-year-olds analyzed significantly more participants (104 participants) than the other two studies for the 10- to 11-year-olds and 14- to 16-year-olds (18 and 11 participants respectively). This could have amplified the results, thus more clearly showing a correlation for this age group alone. Based on these findings, it is important to continue monitoring and placing emphasis on proper pitching kinematics as pitchers get older to reduce injury risk. While most pitching injuries develop at a younger age [24], continued flaws in kinematics may lead to significant injury.

Looking across the different age groups and their kinematic parameters, the oldest age group (16- to 18-year-olds) had the highest percentage of pitchers fall in the elite range (Appendix G). This agrees with the previously stated explanations that pitching kinematics improve rapidly from 9- to 12-years-old [29], and that pitchers with flawed pitching kinematics at a younger age are no longer pitching at the 14+ age range. Pitchers in the 16- to 18-year-old range have pitching mechanics falling within the elite range, making them less susceptible to future injury should they respect pitch count recommendation and follow proper safety protocol.

There were several limitations in the 1st study for the 10- to 11-year-olds. First, the pitching distance was limited to 25 feet due to lab size constraints. This could have inadvertently altered pitches among participants who are used to pitching further distances during games and practice. In addition, it makes it difficult to determine if the pitchers are throwing strikes during the experiment, a key indication to if participants are emulating game-like throwing form. Second, the number of overweight and obese participants was limited as participants were selected at random with no regard to their body type. The total numbers of overweight and obese participants (16.6% and 5.5%) in this study were comparable to the percentage of overweight but not obese youth baseball pitchers currently playing [30]. Third, there is an error of approximately 3% that may occur from visually selecting frames associated with FC and wrist pronation, which signified BR during post-processing. Fourth, with the use of skin-based markers there is potential for marker placement error. Marker placement error has been identified to be the largest source of kinematic variability, and studies have been conducted to remove these errors known as “crosstalk” in gait and cycling [31]. In a previous study, principal component analysis, or PCA, was found to minimize correlations between flexion-extension, abduction-adduction, and internal-external rotation angles thus reducing the crosstalk errors in gait and cycling [31]. In the future, it would be beneficial to use the error reduction methods currently used in gait and cycling for pitching to ensure accurate location of markers and thus accurate kinematic parameter data for analysis.

In addition to the study specific limitations, there were also several overall limitations. The first limitation is that the data came from three different experimental sites with different experimental methods. This introduced variability in the marker sets and placement, pitching distances, and post-processing methods. Thus, a future recommendation would be to perform all experiments for the different age groups in one lab with the same methods.

Second, for all three studies, participants were not in a game-like environment. This could present another limitation as it is hard to replicate the mental and physical experience of pitching in a game while participants are pitching in the lab space. Differences between pitching off AstroTurf instead of dirt, being barefoot or wearing tennis shoes instead of cleats, having the markers placed on the body, or silence instead of cheering may all alter the participant's pitching mechanics and thus their kinematic parameters during the experiment [16].

Third, there was a large difference in the number of participants used in each of the three studies. The 1st study consisted of 18 participants, the 2nd study consisted of 11 participants, and the 3rd study consisted of 104 participants. Thus, when looking at kinematic parameters and their associations with BMI, it is hard to ensure statistical significance with the low number of observations for the younger two age groups. Future analysis should consider a larger sample of participants for the 10- to 11-year-olds and the 14- to 16-year-olds. Furthermore, due to the nature of data collection for this study, there is a gap in the ages analyzed and their respective kinematic parameters from 11- to 14-years-old. It would be beneficial to include this age gap for future work as previous studies have suggested that pitching mechanics and kinematics do improve rapidly from 9- to 12-years-old as youth pitchers start developing and focusing on proper pitching technique [23].

Fourth, participant selection and recruitment for each of the studies was solely dependent on familiarity or experience with pitching and no recent history of injury. Thus, there is a wide range of outside factors including if a participant plays on a club team, takes private pitching lessons, or how long a participant has been pitching that could change their pitching mechanics and thus their kinematic parameters.

A key clinical implication of this study is that select kinematic parameters have been identified that could guide coaches and trainers when working with overweight pitchers. In addition, select kinematic parameters of concern have been identified for different age ranges. For the youngest age group (10- to 11-year-olds), these include lower-body parameters focused on body control and balance seen by correlations for SL and FFP with BMI. For the oldest age group in this study (16- to 18-year-olds), upper-body parameters, SER and EF, are of more concern.

The results suggest that future work should investigate if a coaching intervention for overweight youth pitchers can correct flaws in injury-related pitching kinematics, similar to the study completed for adults [6]. Noting the fourth overall limitation above, it would be important to note the pitching history of each participant prior to conducting this intervention to establish a baseline for analysis.

BMI has been found to lead to an increase in injury occurrences across youth athletics [12], and to an increase in select joint torques and forces [32]. However, there has also been research to suggest that shoulder kinetics are more strongly correlated with arm segment mass (SMI) than to overall body weight represented by BMI [33]. Thus, future work should also investigate correlations between SMI and the select injury-related kinematic parameters.

Seven regressions, one for each of the select kinematic parameters, were performed for this study. Thus, a Bonferroni correction should be performed to account for these simultaneous statistical tests. While this study was an exploratory analysis and thus there was no need to perform this correction, future work should reconsider the significant correlations with the correction in mind.

In summary, the objective of the current study was to investigate youth pitching injury-related kinematic parameters with BMI. Novel results for 10- to 11-year-old pitchers were as follows: stride length was negatively correlated with BMI and front foot position was positively correlated with BMI. In addition, novel results for 16- to 18-year-old pitchers were as follows: shoulder external rotation was negatively correlated with BMI and elbow flexion was positively correlated with BMI. No significant findings were found for any of the other kinematic parameters in any of the three age groups.

Players, parents, and coaches should begin and continue to focus on the development of proper pitching mechanics from a young age in hopes of decreasing future pitching arm injuries. In addition, due to high and repetitive joint kinetics that come from baseball pitching, awareness and knowledge of pitch count recommendations and compliance of safety procedures should continue to be at the forefront of injury prevention for youth players.

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APPENDICES

APPENDIX A: PitchTrak Marker Set – 1st Study

The complete PitchTrak marker set (Figure A.1) was used for participants in the 1st study. A total of 38 markers were placed on anatomical landmarks for both right- and left-handed pitchers. The sole difference between the right- and left-handed marker set is the placement of the hand marker on the dominant or throwing arm.

A **right-handed pitcher** would have the following marker set: right acromion, right clavicle, left acromion, back head, top head, front head, left radial wrist, left ulnar wrist, left lateral epicondyle, left medial epicondyle, **right hand,** left inferior scapula, left medial scapula, right medial scapula, right inferior scapula, right lateral epicondyle, right medial epicondyle, right radial wrist, right ulnar wrist, right ASIS, sacral, left ASIS, right thigh, right medial knee, right knee, right shank, right ankle, right medial ankle, right heel, right toe, left thigh, left medial knee, left knee, left shank, left ankle, left medial ankle, left heel, and left toe.

A **left-handed pitcher** would have the following marker set: right acromion, right clavicle, left acromion, back head, top head, front head, left radial wrist, left ulnar wrist, left lateral epicondyle, left medial epicondyle, **left hand,** left inferior scapula, left medial scapula, right medial scapula, right inferior scapula, right lateral epicondyle, right medial epicondyle, right radial wrist, right ulnar wrist, right anterior superior iliac spine (ASIS), sacral, left ASIS, right thigh, right medial knee, right knee, right shank, right ankle, right medial ankle, right heel, right toe, left thigh, left medial knee, left knee, left shank, left ankle, left medial ankle, left heel, and left toe.

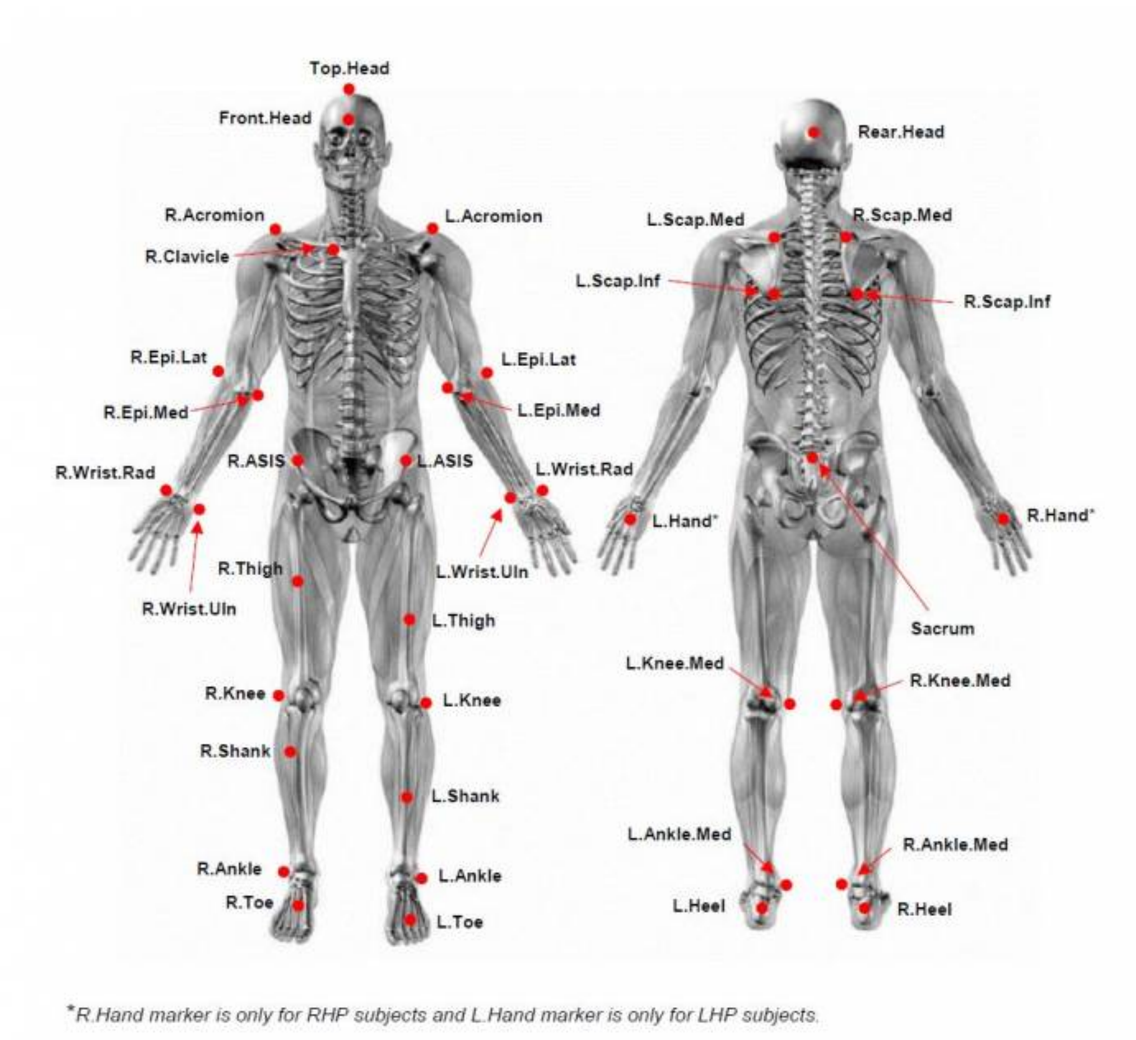

Figure A.1 – PitchTrak marker set for a right- or left-handed pitcher.

APPENDIX B: Aguinaldo/Chambers Marker Set

A combination of an upper body marker set described by Aguinaldo and Chambers [19] and the lower body Helen Hayes marker set [18] described by Kadaba was used for the 2nd study with a total of 38 markers. The difference between marker sets for right- and left-handed pitchers is the hand marker on the dominant or throwing arm.

The upper body set (Figure B.1) for a **right-handed pitcher** contains the following makers: right acromion, left acromion, right spine of the scapula, left spine of the scapula, right inferior angle, left inferior angle, right lateral epicondyle, left lateral epicondyle, right ulnar styloid, left ulnar styloid, right radial styloid, left styloid, and **right hand** [19].

The upper body set (Figure B.1) for a **left-handed pitcher** contains the following makers: right acromion, left acromion, right spine of the scapula, left spine of the scapula, right inferior angle, left inferior angle, right lateral epicondyle, left lateral epicondyle, right ulnar styloid, left ulnar styloid, right radial styloid, left styloid, and **left hand** [19].

The lower body set was the same for right- and left-handed pitchers containing the following markers: right ASIS, left ASIS, right greater trochanter, left greater trochanter, right posterior superior iliac spine (PSIS), left PSIS, sacrum, right knee, left knee, right medial knee, left medial knee, right fibula, left fibula, right thigh, left thigh, right shank, left shank, right ankle, left ankle, right medial ankle, left medial ankle, right toe, left toe, right heel, left heel.

APPENDIX C: Escamilla Marker Set – 3rd Study

For the 3rd study, a total of 38 retroreflective markers were used during motion capture. Similar marker sets were used for right- and left-handed pitchers with differences seen in the last five markers listed.

The marker set for a **right-handed pitcher** is as follows: top head, front head, right side head, left side head, C7 spinous process, left acromion, right acromion, left sterno-clavicular joint, right sterno-clavicular joint, right lateral elbow epicondyle, right medial elbow epicondyle, left lateral elbow epicondyle, left medial elbow epicondyle, right ulnar styloid, right radial styloid, left ulnar styloid, left radial styloid, right greater trochanter, left greater trochanter, right ASIS, left ASIS, right lateral femoral epicondyle, right medial femoral epicondyle, left lateral femoral epicondyle, left medial femoral epicondyle, right lateral malleoli, right medial malleoli, left lateral malleoli, left medial malleoli, right toe, left toe, **right hand, right proximal third of the ulna, right inferior scapula, left distal third of the ulna, left heel** [16].

The marker set for a **left-handed pitcher** is as follows: top head, front head, right side head, left side head, C7 spinous process, left acromion, right acromion, left sternoclavicular joint, right sternoclavicular joint, right lateral elbow epicondyle, right medial elbow epicondyle, left lateral elbow epicondyle, left medial elbow epicondyle, right ulnar styloid, right radial styloid, left ulnar styloid, left radial styloid, right greater trochanter, left greater trochanter, right ASIS, left ASIS, right lateral femoral epicondyle, right medial femoral epicondyle, left lateral femoral epicondyle, left medial femoral epicondyle, right lateral malleoli, right medial malleoli, left lateral malleoli, left medial malleoli, right toe, left toe, **left hand, left proximal third of the ulna, left inferior scapula, right distal third of the ulna, right heel** [16].

APPENDIX D: Elite Range for Identifying Flaws in Pitching Kinematics

An elite range for each biomechanical parameter analyzed in this study was established previously. The normative range was created by the mean value of the kinematic parameter plus or minus one standard deviation [6] from 100 elite pitchers. Pitchers were classified as elite if they had an average fastball velocity of 88 mph, were a professional player, and had been healthy for at least one year prior to the analysis. The following elite ranges are shown below (Table D.1). Pitchers were determined to have a flaw if their kinematic parameter fell out of the established normative range [6].

Table D.1. Elite ranges for select kinematic parameters.

Parameter	Elite Range
Stride Length (% of BH)	78 – 88
Front Foot Position Normalized by BH (cm/cm)	0.068 – 0.178
Shoulder External Rotation at FC (deg)	32 - 76
Shoulder Abduction at FC (deg)	81 - 103
Elbow Flexion at FC (deg)	74 - 104
Knee Extension from FC to BR (deg)	7 - 14
Shoulder Abduction at BR (deg)	84 - 101

APPENDIX E: Kinematic Predictions vs Body Mass Index – Regression Results 10-11-year-olds

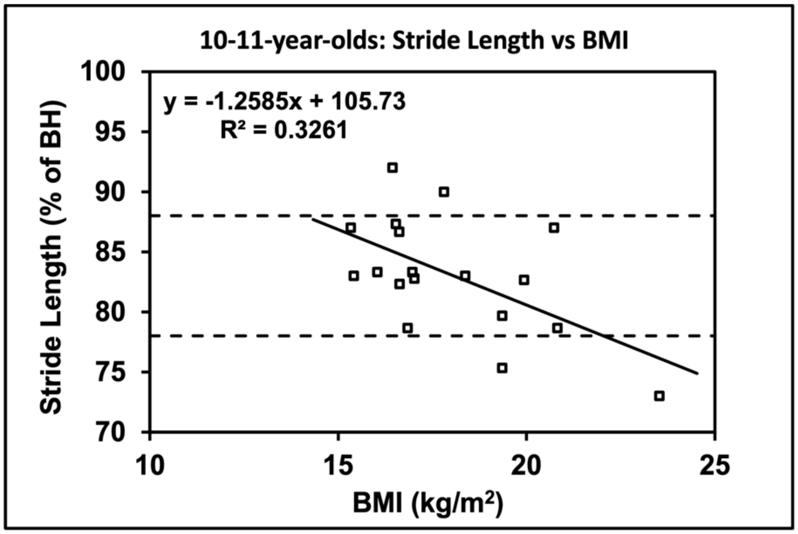

Figure E.1: Regression plots for 10- to 11-year-olds stride length (as a percentage of body height) against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and stride length as the dependent variable.

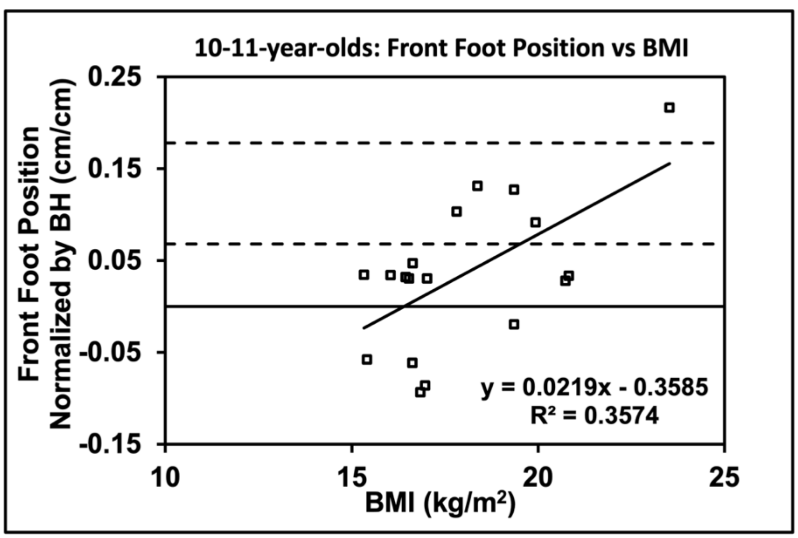

Figure E.2: Regression plots for 10- to 11-year-olds front foot position (normalized by body height) against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and front foot position as the dependent variable.

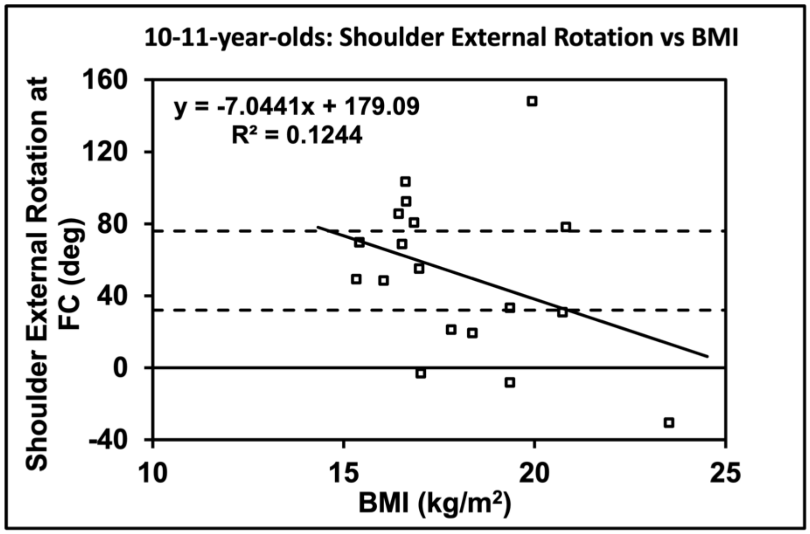

Figure E.3: Regression plots for 10- to 11-year-olds shoulder external rotation at foot contact against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and shoulder external rotation as the dependent variable.

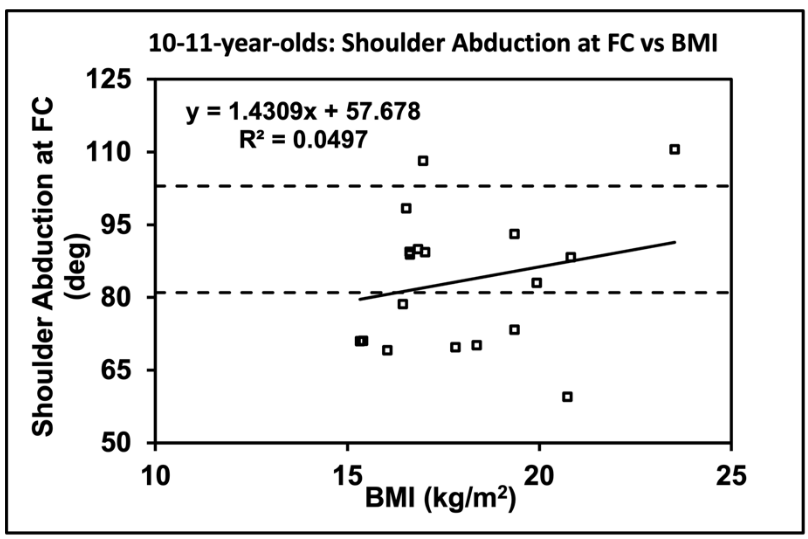

Figure E.4: Regression plots for 10- to 11-year-olds shoulder abduction at foot contact against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and shoulder abduction as the dependent variable.

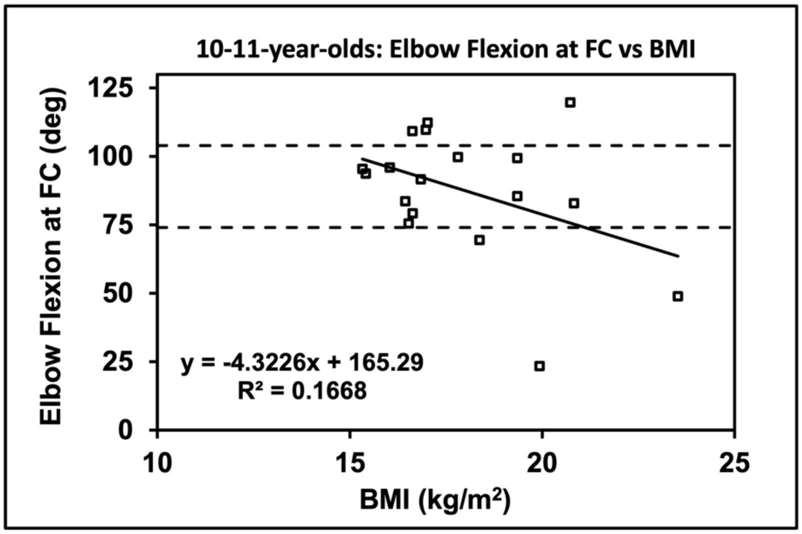

Figure E.5: Regression plots for 10- to 11-year-olds elbow flexion at foot contact against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and elbow flexion as the dependent variable.

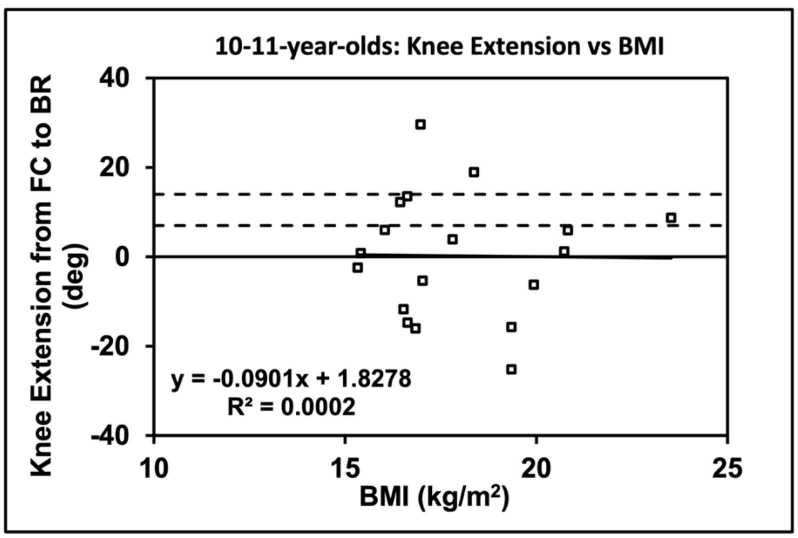

Figure E.6: Regression plots for 10- to 11-year-olds knee extension (from foot contact to ball release) against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and knee extension as the dependent variable.

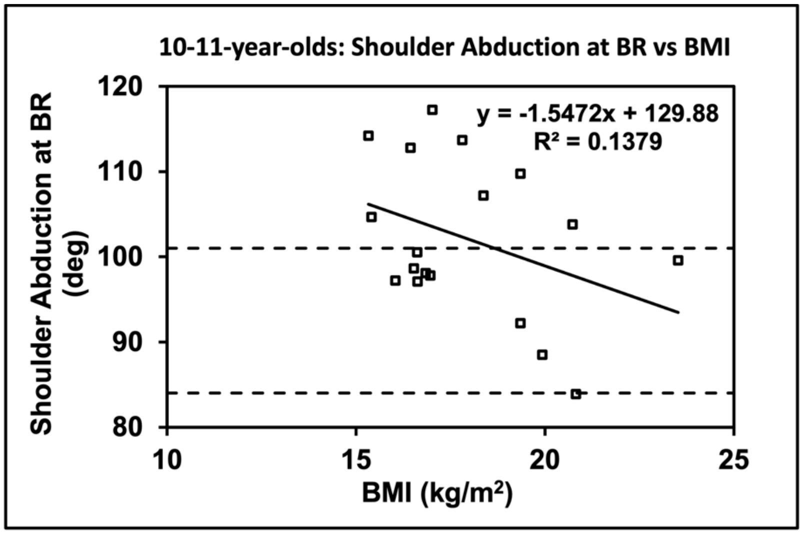

Figure E.7: Regression plots for 10- to 11-year-olds shoulder abduction at ball release against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and shoulder abduction as the dependent variable.

APPENDIX F: Body Mass Index vs Kinematic Predictions – Regression Results 14-16-year-olds

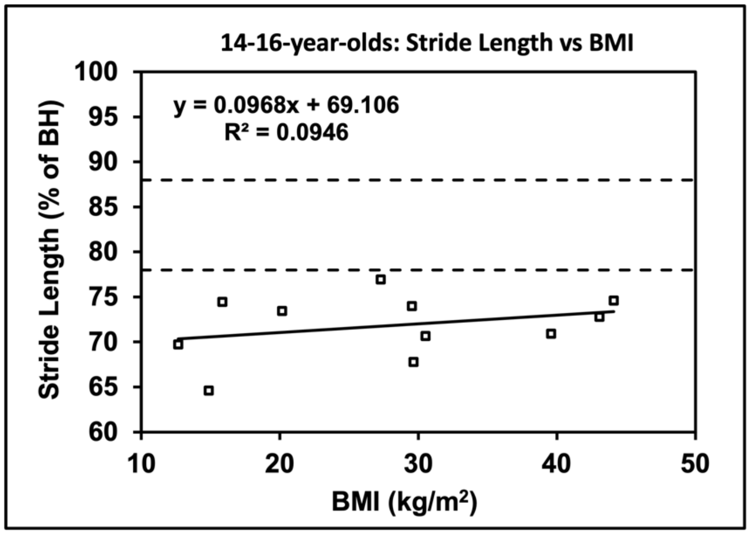

Figure F.1: Regression plots for 14- to 16-year-olds stride length (as a percentage of body height) against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and stride length as the dependent variable.

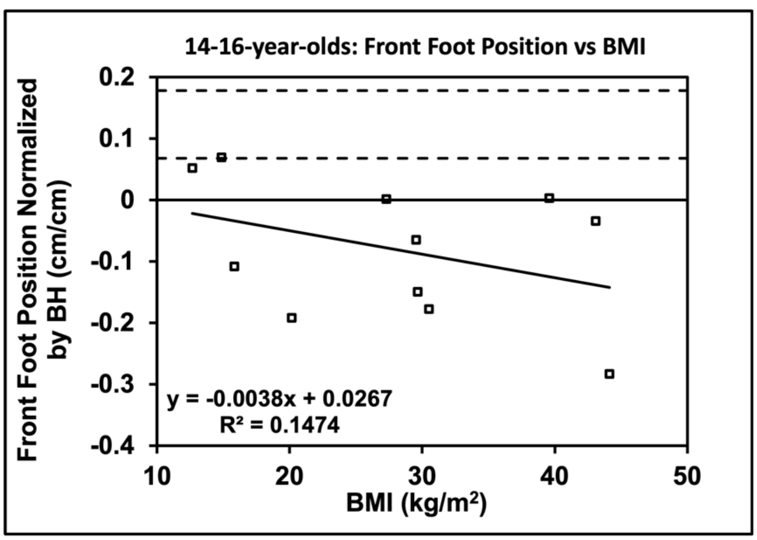

Figure F.2: Regression plots for 14- to 16-year-olds front foot position (normalized by body height) against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and front foot position as the dependent variable.

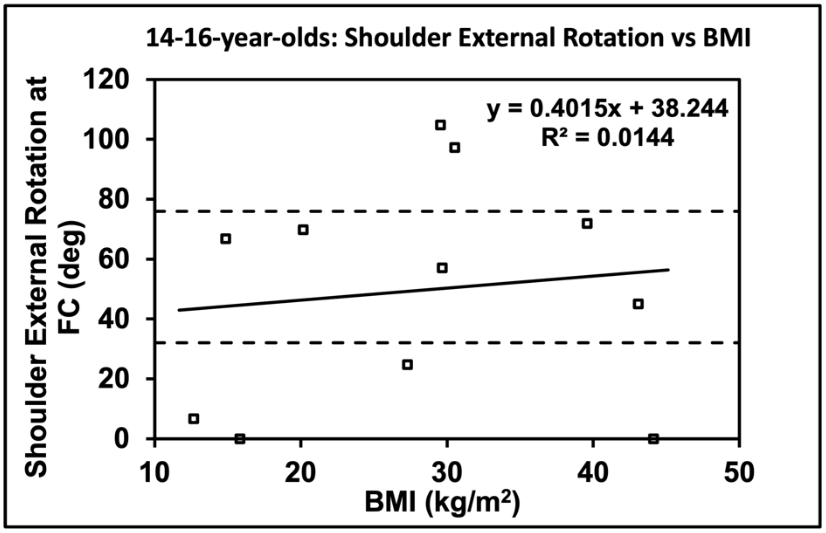

Figure F.3: Regression plots for 14- to 16-year-olds shoulder external rotation at foot contact against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and shoulder external rotation as the dependent variable.

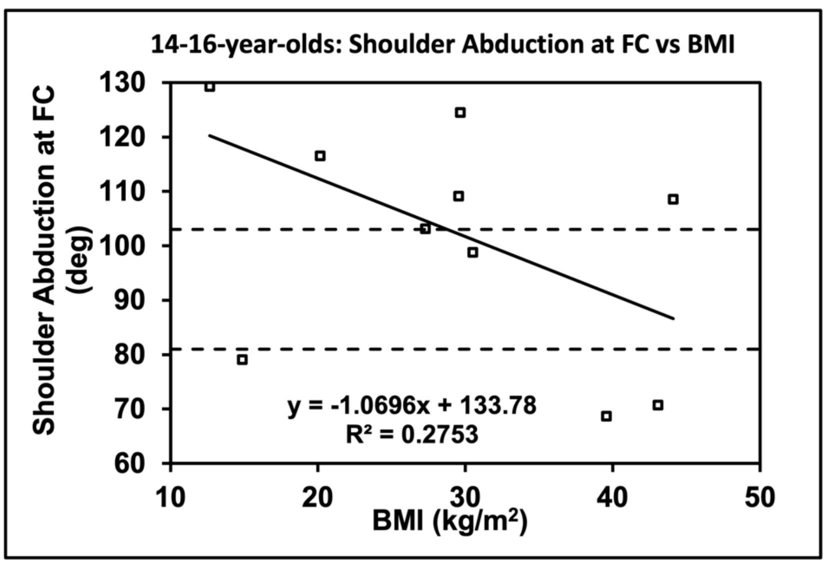

Figure F.4: Regression plots for 14- to 16-year-olds shoulder abduction at foot contact against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and shoulder abduction as the dependent variable.

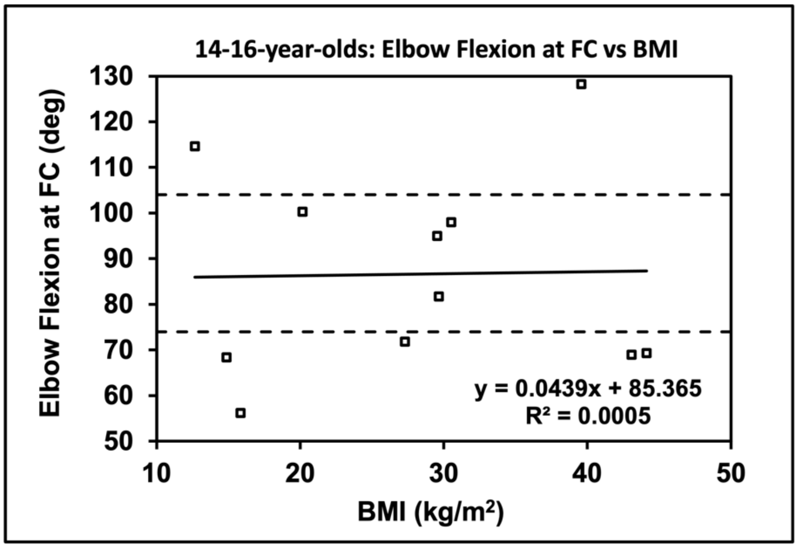

Figure F.5: Regression plots for 14- to 16-year-olds elbow flexion at foot contact against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and elbow flexion as the dependent variable.

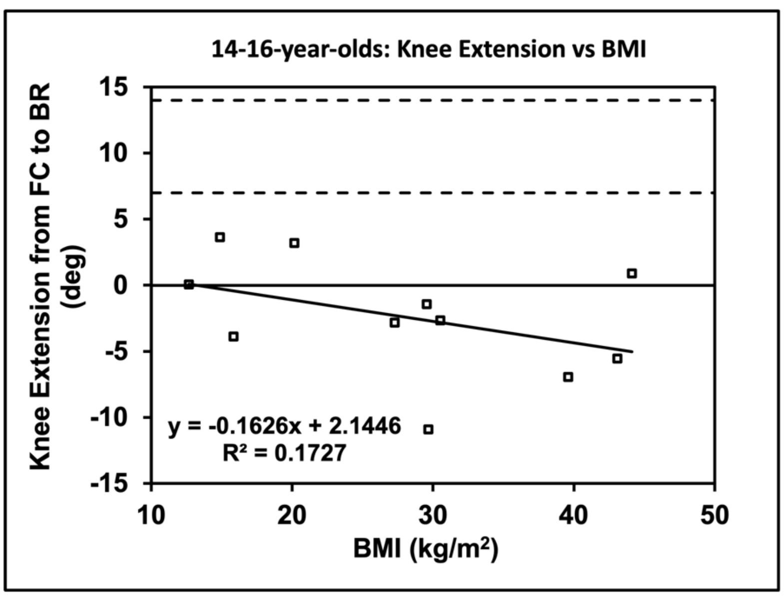

Figure F.6: Regression plots for 14- to 16-year-olds knee extension (from foot contact to ball release) against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and knee extension as the dependent variable.

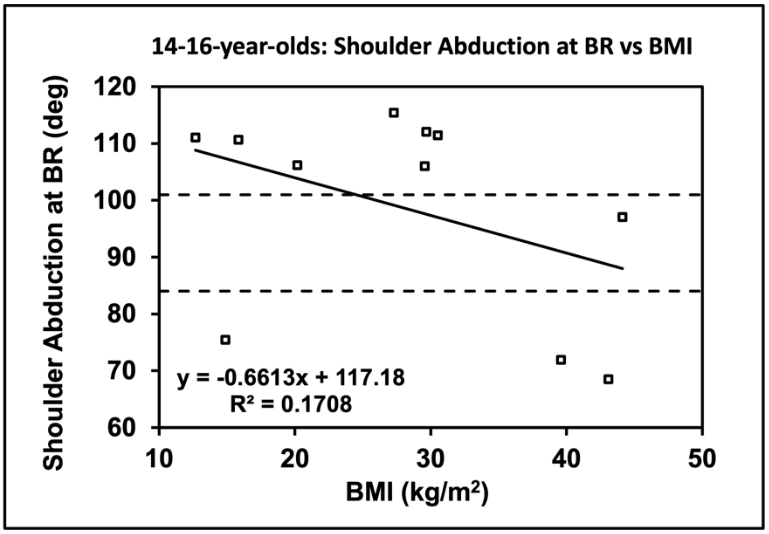

Figure F.7: Regression plots for 14- to 16-year-olds shoulder abduction at ball release against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and shoulder abduction as the dependent variable.

APPENDIX G: Body Mass Index vs Kinematic Predictions – Regression Results 16-18-year-olds

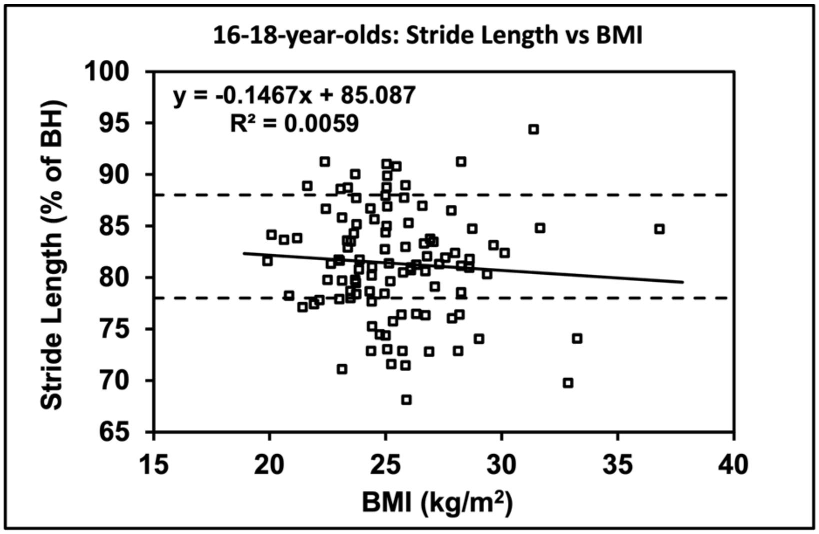

Figure G.1: Regression plots for 16- to 18-year-olds stride length (as a percentage of body height) against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and stride length as the dependent variable.

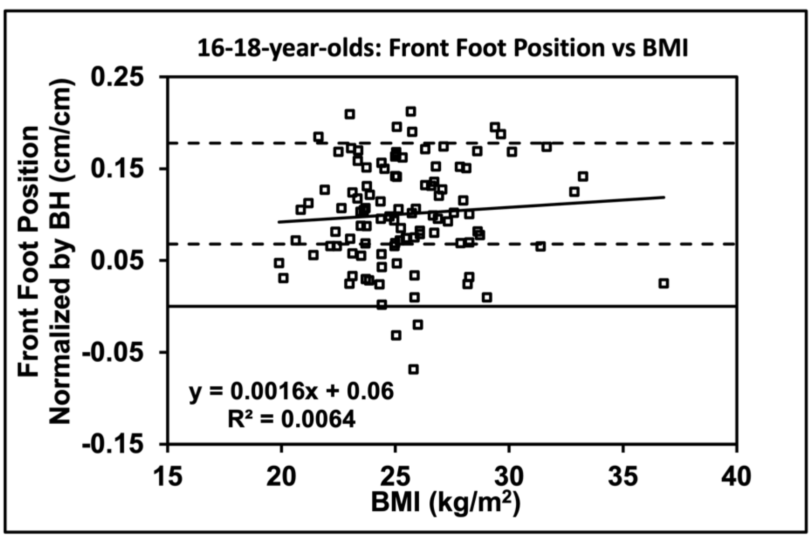

Figure G.2: Regression plots for 16- to 18-year-olds front foot position (normalized by body height) against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and front foot position as the dependent variable.

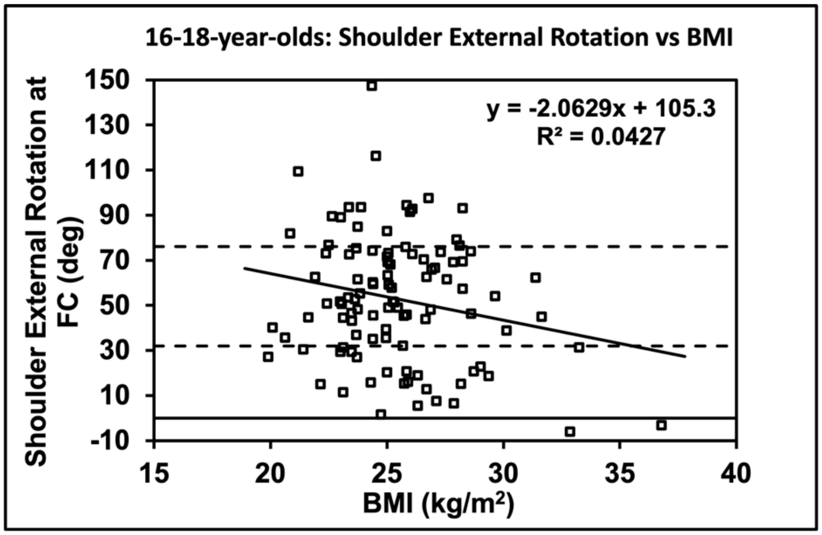

Figure G.3: Regression plots for 16- to 18-year-olds shoulder external rotation at foot contact against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and shoulder external rotation as the dependent variable.

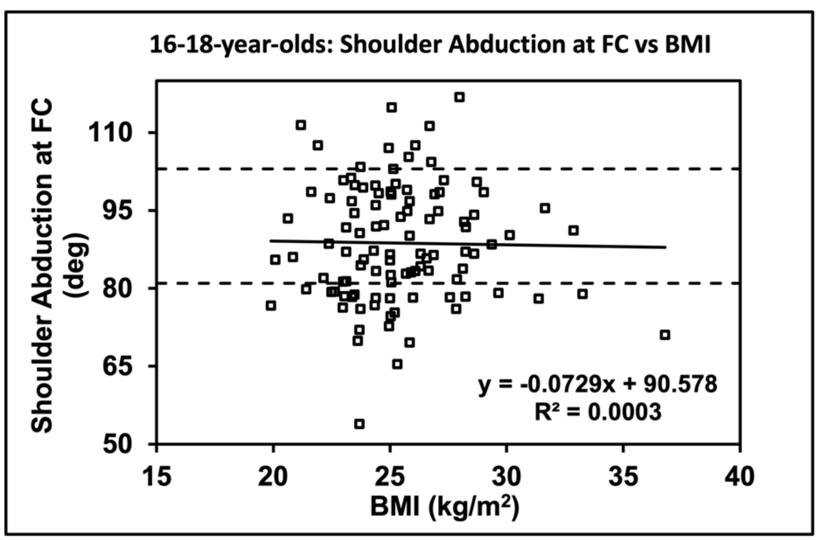

Figure G.4: Regression plots for 16- to 18-year-olds shoulder abduction at foot contact against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and shoulder abduction as the dependent variable.

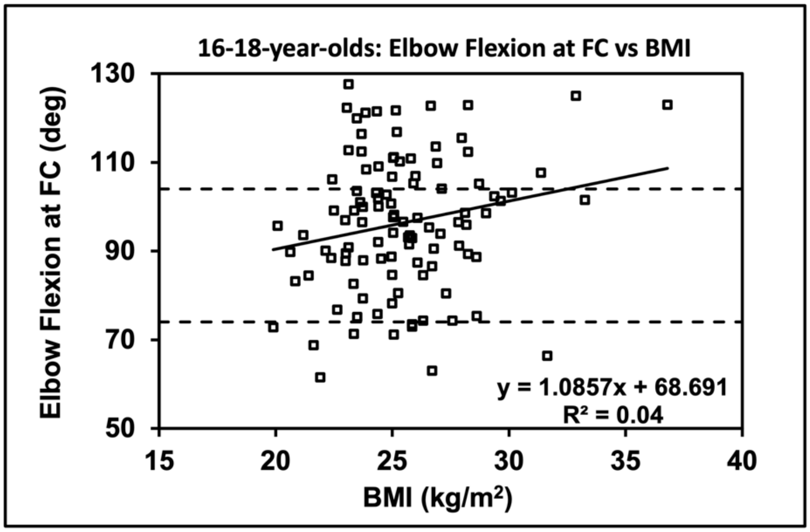

Figure G.5: Regression plots for 16- to 18-year-olds elbow flexion at foot contact against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and elbow flexion as the dependent variable.

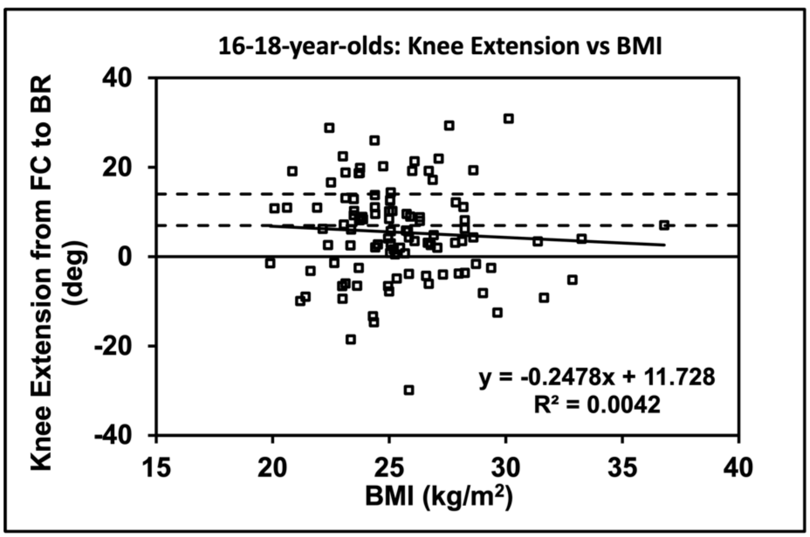

Figure G.6: Regression plots for 16- to 18-year-olds knee extension (from foot contact to ball release) against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and knee extension as the dependent variable.

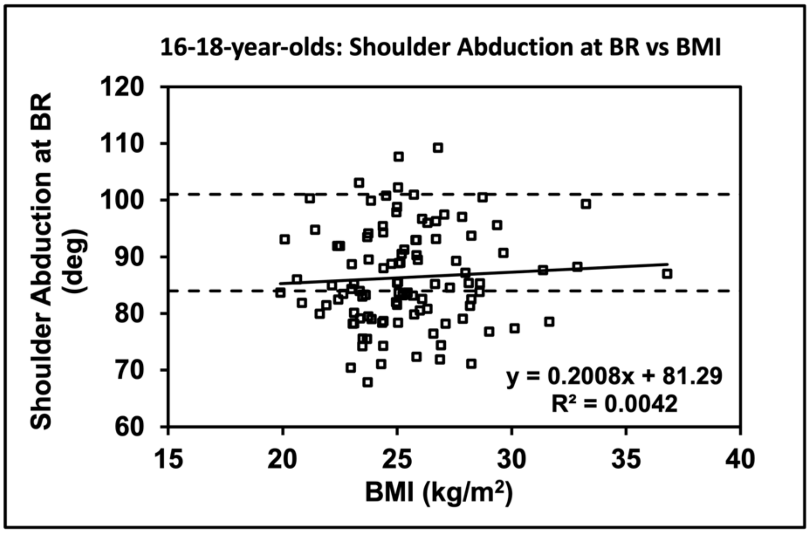

Figure G.7: Regression plots for 16- to 18-year-olds shoulder abduction at ball release against body mass index with elite ranges [6] denoted by the dashed lines. *Note:* Trendline and R^2 displayed on plot with body mass index as the independent variable and shoulder abduction as the dependent variable.

APPENDIX H: Full Kinematic Parameter Statistical Results – 10- to 11-year-olds

Regression Analysis: Stride Length (% of BH) versus BMI (kg/m2)

Regression Equation

Stride Length (% of BH) = 105.7 - 1.259 BMI (kg/m2)

Model Summary

S	R-sq	R-sq(adj)
4.11619	32.61%	28.40%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	131.199	131.199	7.74	0.013
Error	16	271.089	16.943		
Total	17	402.288			

Figure H.1: Linear regression statistics for SL versus BMI 10- to 11-year-olds.

Regression Analysis: Normalized Front Foot Position (cm/cm) versus BMI (kg/m2)

Regression Equation

Normalized Front Foot Position (cm/cm) = - 0.3585 + 0.02186 BMI (kg/m2)

Model Summary

S	R-sq	R-sq(adj)
0.0666934	35.74%	31.72%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.039580	0.0395795	8.90	0.009
Error	16	0.071168	0.0044480		
Total	17	0.110748			

Figure H.2: Linear regression statistics for normalized FFP versus BMI 10- to 11-year-olds.

Regression Analysis: Shoulder External Rotation (deg) @ FC versus BMI (kg/m2)

Regression Equation

Shoulder External Rotation @ FC (deg) = 179.1 - 7.044 BMI (kg/m2)

Model Summary

S	R-sq	R-sq(adj)
42.5278	12.44%	6.96%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	4110.3	4110.27	2.27	0.151
Error	16	28937.8	1808.61		
Total	17	33048.1			

Figure H.3: Linear regression statistics for SER at FC versus BMI 10- to 11-year-olds.

Regression Analysis: Shoulder Abduction (deg) @ FC versus BMI (kg/m2)

Regression Equation

Shoulder Abduction @ FC (deg) = 57.68 + 1.431 BMI (kg/m2)

Model Summary

S	R-sq	R-sq(adj)
14.2325	4.97%	0.00%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	169.61	169.607	0.84	0.374
Error	16	3241.02	202.563		
Total	17	3410.62			

Figure H.4: Linear regression statistics for SAFC versus BMI 10- to 11-year-olds.

Regression Analysis: Elbow Flexion (deg) @ FC versus BMI (kg/m2)

Regression Equation

Elbow Flexion @ FC (deg) = 165.3 - 4.323 BMI (kg/m2)

Model Summary

S	R-sq	R-sq(adj)
21.9819	16.68%	11.47%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	1547.80	1547.80	3.20	0.092
Error	16	7731.27	483.20		
Total	17	9279.06			

Figure H.5: Linear regression statistics for EF at FC versus BMI 10- to 11-year-olds.

Regression Analysis: Knee Extension from FC to BR (deg) versus BMI (kg/m2)

Regression Equation

Knee Extension from FC to BR (deg) = 1.83 - 0.090 BMI (kg/m2)

Model Summary

S	R-sq	R-sq(adj)
14.3514	0.02%	0.00%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.67	0.673	0.00	0.955
Error	16	3295.39	205.962		
Total	17	3296.07			

Figure H.6: Linear regression statistics for KE from FC to BR versus BMI 10- to 11-year-olds.

Regression Analysis: Shoulder Abduction at BR (deg) versus BMI (kg/m2)

Regression Equation

Shoulder Abduction @ BR (deg) = 129.9 - 1.547 BMI (kg/m2)

Model Summary

S	R-sq	R-sq(adj)
8.80380	13.79%	8.40%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	198.28	198.284	2.56	0.129
Error	16	1240.11	77.507		
Total	17	1438.39			

Figure H.7: Linear regression statistics for SABR versus BMI 10- to 11-year-olds.

APPENDIX I: Full Kinematic Parameter Statistical Results – 14- to 16-year-olds

Regression Analysis: Stride Length (% of BH) versus BMI (kg/m2)

Regression Equation

Stride Length (% of BH) = 69.11 + 0.09684 BMI (kg/m^2)

Model Summary

S	R-sq	R-sq(adj)
3.52998	9.46%	0.00%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	11.716	11.7157	0.94	0.358
Error	9	112.147	12.4607		
Total	10	123.862			

Figure I.1: Linear regression statistics for SL versus BMI 14- to 16-year-olds

Regression Analysis: Normalized Front Foot Position (cm/cm) versus BMI (kg/m2)

Regression Equation

FFP normalized by BH (cm/cm) = 0.02671 - 0.003832 BMI (kg/m^2)

Model Summary

S	R-sq	R-sq(adj)
0.108591	14.74%	5.26%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.018341	0.0183414	1.56	0.244
Error	9	0.106129	0.0117921		
Total	10	0.124470			

Figure I.2: Linear regression statistics for normalized FFP versus BMI 14- to 16-year-olds.

Regression Analysis: Shoulder External Rotation (deg) @ FC versus BMI (kg/m2)

Regression Equation

Shoulder External Rotation @ FC = 33.29 + 0.8679 BMI (kg/m^2)

Model Summary

S	R-sq	R-sq(adj)
29.5839	10.67%	0.75%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	940.93	940.927	1.08	0.327
Error	9	7876.88	875.209		
Total	10	8817.80			

Figure I.3: Linear regression statistics for SER at FC versus BMI 14- to 16-year-olds.

Regression Analysis: Shoulder Abduction (deg) @ FC versus BMI (kg/m2)

Regression Equation

Shoulder Abduction @ FC = 133.8 - 1.070 BMI (kg/m^2)

Model Summary

S	R-sq	R-sq(adj)
20.4472	27.53%	19.48%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	1429.26	1429.26	3.42	0.098
Error	9	3762.80	418.09		
Total	10	5192.07			

Figure I.4: Linear regression statistics for SAFC versus BMI 14- to 16-year-olds.

Regression Analysis: Elbow Flexion (deg) @ FC versus BMI (kg/m2)

Regression Equation

Elbow Flexion @ FC (deg) = 85.36 + 0.0439 BMI (kg/m^2)

Model Summary

S	R-sq	R-sq(adj)
23.5925	0.05%	0.00%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	2.41	2.407	0.00	0.949
Error	9	5009.46	556.606		
Total	10	5011.86			

Figure I.5: Linear regression statistics for EF at FC versus BMI 14- to 16-year-olds.

Regression Analysis: Knee Extension from FC to BR (deg) versus BMI (kg/m2)

Regression Equation

Knee Ext FC - BR (deg) = 2.145 - 0.1626 BMI (kg/m^2)

Model Summary

S	R-sq	R-sq(adj)
4.19233	17.27%	8.08%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	33.031	33.0314	1.88	0.204
Error	9	158.180	17.5756		
Total	10	191.212			

Figure I.6: Linear regression statistics for KE from FC to BR versus BMI 14- to 16-year-olds.

Regression Analysis: Shoulder Abduction at BR (deg) versus BMI (kg/m2)

Regression Equation

Shoulder Abduction @ BR = 117.2 - 0.6613 BMI (kg/m^2)

Model Summary

S	R-sq	R-sq(adj)
17.1681	17.08%	7.87%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	546.40	546.397	1.85	0.206
Error	9	2652.69	294.743		
Total	10	3199.09			

Figure I.7: Linear regression statistics for SABR versus BMI 14- to 16-year-olds.

APPENDIX J: Full Kinematic Parameter Statistical Results – 16- to 18-year-olds

Regression Analysis: Stride Length (% of BH) versus BMI (kg/m2)

Regression Equation

Stride Length (% of BH) = 85.09 - 0.1467 BMI (kg/m^2)

Model Summary

S	R-sq	R-sq(adj)
5.36636	0.59%	0.00%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	17.56	17.5611	0.61	0.437
Error	102	2937.38	28.7979		
Total	103	2954.94			

Figure J.1: Linear regression statistics for SL versus BMI 16- to 18-year-olds

Regression Analysis: Normalized Front Foot Position (cm/cm) versus BMI (kg/m2)

Regression Equation

FFP Normalized by BH (cm/cm) = 0.06002 + 0.001593 BMI (kg/m^2)

Model Summary

S	R-sq	R-sq(adj)
0.0563043	0.64%	0.00%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.002070	0.0020701	0.65	0.421
Error	102	0.323358	0.0031702		
Total	103	0.325428			

Figure J.2: Linear regression statistics for normalized FFP versus BMI 16- to 18-year-olds.

Regression Analysis: Shoulder External Rotation (deg) @ FC versus BMI (kg/m2)

Regression Equation

Shoulder External Rotation @ FC (deg) = 105.3 - 2.063 BMI (kg/m^2)

Model Summary

S	R-sq	R-sq(adj)
27.6149	4.27%	3.33%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	3471.3	3471.28	4.55	0.035
Error	102	77783.7	762.59		
Total	103	81255.0			

Figure J.3: Linear regression statistics for SER at FC versus BMI 16- to 18-year-olds.

Regression Analysis: Shoulder Abduction (deg) @ FC versus BMI (kg/m2)

Regression Equation

Shoulder Abduction @ FC = 90.58 - 0.0729 BMI (kg/m^2)

Model Summary

S	R-sq	R-sq(adj)
11.4544	0.03%	0.00%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	4.3	4.341	0.03	0.856
Error	102	13382.7	131.203		
Total	103	13387.0			

Figure J.4: Linear regression statistics for SAFC versus BMI 16- to 18-year-olds.

Regression Analysis: Elbow Flexion (deg) @ FC versus BMI (kg/m2)

Regression Equation

Elbow Flexion @ FC (deg) = 68.69 + 1.086 BMI (kg/m^2)

Model Summary

S	R-sq	R-sq(adj)
15.0456	4.00%	3.06%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	961.7	961.723	4.25	0.042
Error	102	23089.7	226.370		
Total	103	24051.5			

Figure J.5: Linear regression statistics for EF at FC versus BMI 16- to 18-year-olds.

Regression Analysis: Knee Extension from FC to BR (deg) versus BMI (kg/m2)

Regression Equation

Knee Ext FC - BR (deg) = 11.73 - 0.2478 BMI (kg/m^2)

Model Summary

S	R-sq	R-sq(adj)
10.7291	0.42%	0.00%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	50.1	50.112	0.44	0.511
Error	102	11741.6	115.114		
Total	103	11791.7			

Figure J.6: Linear regression statistics for KE from FC to BR versus BMI 16- to 18-year-olds.

Regression Analysis: Shoulder Abduction at BR (deg) versus BMI (kg/m2)

Regression Equation

Shoulder Abduction @ BR = 81.29 + 0.2008 BMI (kg/m^2)

Model Summary

S	R-sq	R-sq(adj)
8.75069	0.42%	0.00%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	32.90	32.8987	0.43	0.514
Error	102	7810.61	76.5747		
Total	103	7843.51			

Figure J.7: Linear regression statistics for SABR versus BMI 16- to 18-year-olds.