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Inverse dynamics analysis of youth pitching arm kinetics using body composition imaging

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ABSTRACT

This study's objectives were to: (1) assess whether dual energy X-ray absorptiometry (DXA)-mass inverse dynamics (ID) alters predictions of youth pitching arm kinetics and (2) investigate correlations between kinetics and body composition. Eighteen 10- to 11-year-olds pitched 10 fastballs. DXA scans were conducted to obtain participant-specific upper arm, forearm, and hand masses. Pitching arm segment masses and kinetics calculated with scaled and DXA masses were compared with paired t-tests and correlations were investigated with linear regression. Hand ($p < 0.001$) and upper arm ($p < 0.001$) DXA masses were greater, while forearm ($p < 0.001$) DXA masses were lesser, than their scaled masses. Shoulder compressive force ($p < 0.001$), internal rotation torque ($p < 0.001$), and horizontal adduction torque ($p = 0.002$) increased when using DXA masses. Shoulder compressive force correlated with body mass ($p < 0.001$) and body mass index (BMI; $p = 0.002$) and elbow varus torque correlated with body mass ($p < 0.05$). The main conclusions were that (1) using participant-specific mass ratios leads to different predictions of injury-related pitching arm kinetics and, thus, may improve our understanding of injury risk factors; and (2) pitching arm kinetics were correlated with body composition measures and a relatively high total body mass and/or BMI may increase shoulder and/or elbow injury risk.

KEYWORDS
Baseball; elbow; shoulder; throwing; inverse dynamics

Introduction

In recent years, injury prevention measures such as the Pitch Smart Programme (Pitch Smart, n.d.) have been developed and implemented to address concerns regarding increasing baseball pitching arm injury rates in young athletes (Fleisig & Andrews, 2012). One study reported an increase in ulnar collateral ligament (UCL) reconstructive (Tommy John) surgery rates in 15- to 19-year-olds by 9% per year from 2007 to 2011 (Erickson et al., 2015). In 2014, a study reported that 31% of 754 youth participants aged 9–18 years self-reported a pitching injury in the previous 12 months (Yang et al., 2014). Despite recent preventative efforts, shoulder and elbow injury rates among

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high school baseball players did not change from 2005–2015, with pitchers most likely to suffer shoulder (40%) and elbow (57%) injuries among those injured (Saper et al., 2017).

Pitching arm injuries are thought to be linked with high, repetitive shoulder and elbow torques (Anz et al., 2010; Sabick, Torry, Lawton, & Hawkins, 2004). Many of these overuse injuries may begin during youth baseball; therefore, improving the accuracy of pitching arm kinetic predictions may benefit the continued development of injury prevention strategies. Motion analysis studies of baseball pitchers, followed by inverse dynamic (ID) analyses using the equations of rigid body dynamics, are commonly used to predict pitching arm kinetics (e.g., joint forces and torques). The ID analysis input parameters consist of body segment (e.g., hand, forearm, upper arm) masses, estimated as described below, and measured body segment accelerations. For youth pitching analyses (Darke, Dandekar, Aguinaldo, Hazelwood, & Klisch, 2018; Garner, Macdonald, Wade, Johnson, & Ford, 2011), as with adult pitching analyses (Fleisig, Barrentine, Zheng, Escamilla, and Andrews 1999), scaled ID analyses typically use body segment masses scaled from total body mass using scaling parameters (i.e., mass ratios) based on adult cadaver studies (De Leva, 1996).

However, adult and youth scaled mass ratios have been shown to differ, especially for the upper arm segment (Jensen, 1986). Use of scaled adult pitching arm masses for children may affect ID predictions of pitching arm kinetics. For example, ID analyses have predicted different shoulder and elbow torques when varying the baseball mass by as little as 1 oz. (Fleisig et al., 2006), and that difference (~0.03 kg) is comparable to differences in hand masses that may be calculated for children using published values with adult and child scaled mass ratios.

Dual energy X-ray absorptiometry (DXA) has been used to measure participant-specific body segment masses for children; however, ID analyses of gait predicted similar ankle, knee, and hip joint torques when using participant-specific DXA vs. scaled mass ratios (Ganley & Powers, 2004). An explanation for that result is likely due to the observation that accelerations of the leg segments are relatively small during gait and, thus, differences in the assumed masses did not substantially change predicted joint torques. In contrast, during the pitching motion the arm segments experience much higher accelerations and, thus, body segment masses may have a greater effect on ID predictions of pitching arm kinetics.

According to Pitch Smart guidelines (‘Pitch Smart,’ n.d.), body composition measures (e.g., body weight, body mass index [BMI], and body fat percentage) have not been identified as risk factors for youth pitching injuries. However, previous epidemiological studies have concluded that body weight and height may be risk factors for youth pitching injuries (Lyman et al., 2001). Furthermore, biomechanical studies have concluded that youth pitching arm kinetics were correlated with body composition measures. In particular, shoulder and elbow torques were correlated with total body mass and total, fat and lean, arm masses for 12- to 16-year-old pitchers (Garner et al., 2011). Shoulder and elbow torques and forces were correlated with BMI in 9- to 10-year-old pitchers (Darke et al., 2018) and elbow valgus torque was correlated with total body weight for 12-year-old pitchers (Sabick et al., 2004). However, previous studies have neither used DXA-mass ID, where pitching arm segment masses are determined from

DXA scans, to determine baseball pitching arm kinetics nor have they investigated correlations between pitching arm kinetics and hand, forearm, and upper arm masses.

Thus, the goals of this study were to assess whether DXA-mass ID alters predictions of youth pitching arm kinetics and, further, to investigate correlations between kinetics and body composition. The hypotheses were that for 10- to 11-year-old baseball pitchers (1) participant specific DXA hand, forearm, and upper arm masses would differ from their respective scaled masses, (2) scaled and DXA-mass ID would predict different injury-related shoulder and elbow joint kinetics (shoulder compressive force, internal rotation torque, horizontal adduction torque; elbow varus torque), and (3) shoulder and elbow joint kinetics would correlate with DXA body composition measures (hand, forearm and upper arm masses; total body mass; total body fat percentage; and BMI)

Methods

Protocols were approved by the California Polytechnic State University (San Luis Obispo, CA, USA) Institutional Review Board and were designed to minimise risks.

Recruitment

To be eligible, a participant must have qualified as a 10-year-old and had pitching experience during the preceding little league season, and had no recent history of pitching related injuries. The relatively narrow age range was chosen because youth pitching biomechanics vary substantially with age (Fleisig et al., 2018). Eighteen male participants (age 10.6 ± 0.5 years, height 147.8 ± 7.4 cm, body mass 39.6 ± 7.3 kg, BMI 18.0 ± 2.2 kg/m^2) volunteered and their data were used. Twelve were normal weight, five were overweight, and one was obese as defined per recommended guidelines (5th percentile to 85th percentile is normal weight, 85th to 95th percentile is overweight, and above 95th percentile is obese) with an age-specific BMI growth chart for boys (About Children & Teen BMI,’ 2015). No effort was made to recruit pitchers of any specific body type, because the investigation of significant correlations of kinetics with body composition measures requires such measures to be random and, thus, representative of the target population (i.e., 10- to 11-year-old youths with pitching experience in the preceding season).

Consent and DXA scans

Youth participants and a parent came to the lab where informed consent and participant assent was obtained. It was confirmed that the participants had not pitched in the previous 4 days. Participants completed pre-game tests to measure body weight, height, and arm segment lengths. Then, participants underwent a DXA scan using a Lunar iDXA scanner (GE Healthcare, Madison, WI, USA). Participants were asked to fast, or eat as little as possible, before getting scanned to allow for accurate data collection. Some DXA scans may have produced slightly skewed values for mass ratios if the participant did not fast before the scan, but this was allowed to minimise risk and would primarily affect the torso segment and, thus, only the investigated correlations with total body mass and BMI. During the scan, the participant laid in a supine position with a strap placed around their toes for comfort. A licenced technician conducted the scan while the participant laid still for approximately 5 minutes. After the scan was completed, participants were given healthy snacks to ensure they were adequately nourished for the following pitching experiment.

Pitching experiment

Participants completed warm-up exercises (stretching, jogging, and 20–25 non-pitching throws). Participants changed into compression clothing and 38 retroreflective markers (19 or 12.7 mm diameters) were placed on the participant based on the PitchTrak software (Motion Analysis, Santa Rosa, CA, USA) marker set. The markers were separated into two groups: anatomical markers that were placed on specific landmarks and tracking markers that were arbitrarily placed on a segment. For a right handed pitcher the marker set consisted of the following anatomical markers: left acromium, right acromium, right medial scapula, right inferior scapula, left medial scapula, left inferior scapula, left lateral humeral epicondyle, left medial humeral epicondyle, left radial styloid process, left ulnar styloid process, right lateral humeral epicondyle, right medial humeral epicondyle, right radial styloid process, right ulnar styloid process, right asis, sacral, left asis, right lateral femoral epicondyle, right lateral malleolus, right calcaneus, left lateral femoral epicondyle, left lateral malleolus, left calcaneus, right medial femoral epicondyle, right medial malleolus, left medial femoral epicondyle, and left medial malleolus. The tracking markers were the top head, front head, back head, right clavicle, right hand, right thigh, right shank, right toe, left thigh, left shank, and left toe.

Participants pitched off a portable mound (height = 6 in) (Figure 1) in the room's centre and into a net 23 feet away with a scaled strike zone. The pitching protocol included 10 warm up pitches followed by 10 fastball pitches at maximum effort that were recorded for analysis. Markers fell off the participant during ~20% of the pitches; those pitches were repeated and not counted in the required 10 pitches.

A motion analysis system with six Owl, three Osprey, two Eagle, and one Kestrel digital cameras (Motion Analysis) was used to track markers. Marker trajectory was recorded in Cortex analysis software (Version 7.0, Motion Analysis) at 200 Hz, interpolated (third-order spline), and filtered (4th order Butterworth filter, cut-off frequency 12 Hz) (Matsuo, Matsumoto, Takada, & Mochizuki, 1999). Cortex was used to record pitch speed, which was not disclosed to participants. The last 3 pitches with usable data for each participant were analysed independently to obtain averaged kinetic values.

Analysis—DXA and scaled masses

The DXA software (GE Healthcare) reported total body fat percentage as well as the tissue mass and bone mineral content, which make up the total mass, for each default region (e.g., total pitching arm). The scan was then manually segmented into custom regions of interest, isolating the pitching upper arm, forearm, and hand (Figure 2). The upper arm segment was defined from the humeral head with its surrounding tissue to the humeral epicondyle which agrees with a previous study that reported youth anthropometric data (Jensen, 1986). The forearm segment was defined from the humeral epicondyle to the styloid process and the hand segment was defined from the styloid process to

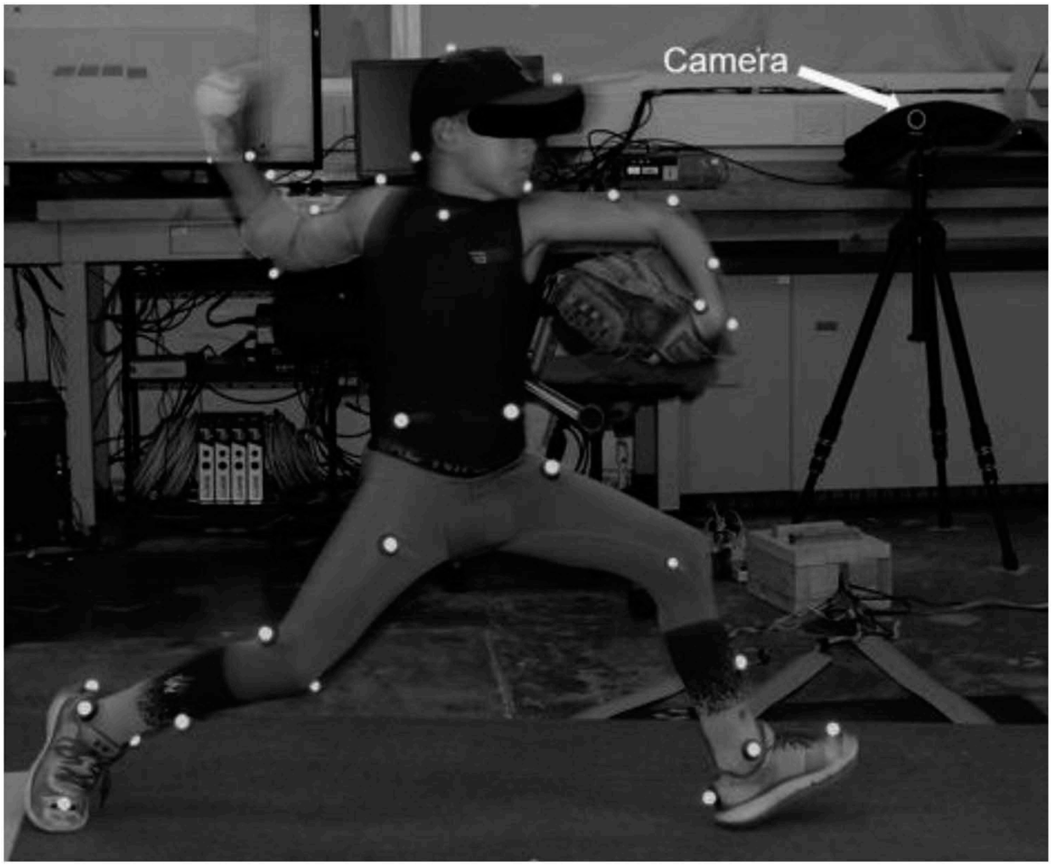

Figure 1. Participant pitching off portable pitching mound with retroreflective markers to capture kinematic data with one of 10 motion analysis cameras shown.

the phalanges. The software reported the tissue mass and bone mineral content of those custom segments which were added up and compared to the DXA reported total mass of the arm; if needed, segmentation boundaries were revised in an iterative manner until the sum of the custom segment masses was within ±1% of the DXA total mass value.

The DXA pitching arm, forearm, and upper arm masses were converted to mass ratios (by dividing by total body mass) for use in PitchTrak; the mass of the ball (147 grams) was accounted for in the hand mass ratio as required by PitchTrak. Finally, scaled mass ratios were based on values found in cadaver studies (De Leva, 1996) as in previous pitching studies. The centres of mass and radii of gyration were kept constant between scaled and DXA mass segments.

Analysis—kinetics

All kinetic parameters were calculated in PitchTrak using both scaled and DXA pitching arm segment masses for each participant. Analysed kinetic parameters included maximum shoulder compressive force, shoulder internal rotation torque, shoulder horizontal adduction torque, and elbow varus torque (Figure 3). These parameters were extracted at the maximum value within the pitching cycle defined from foot contact to ball release. Kinetic parameters were expressed as internal joint loads (e.g., an external elbow valgus

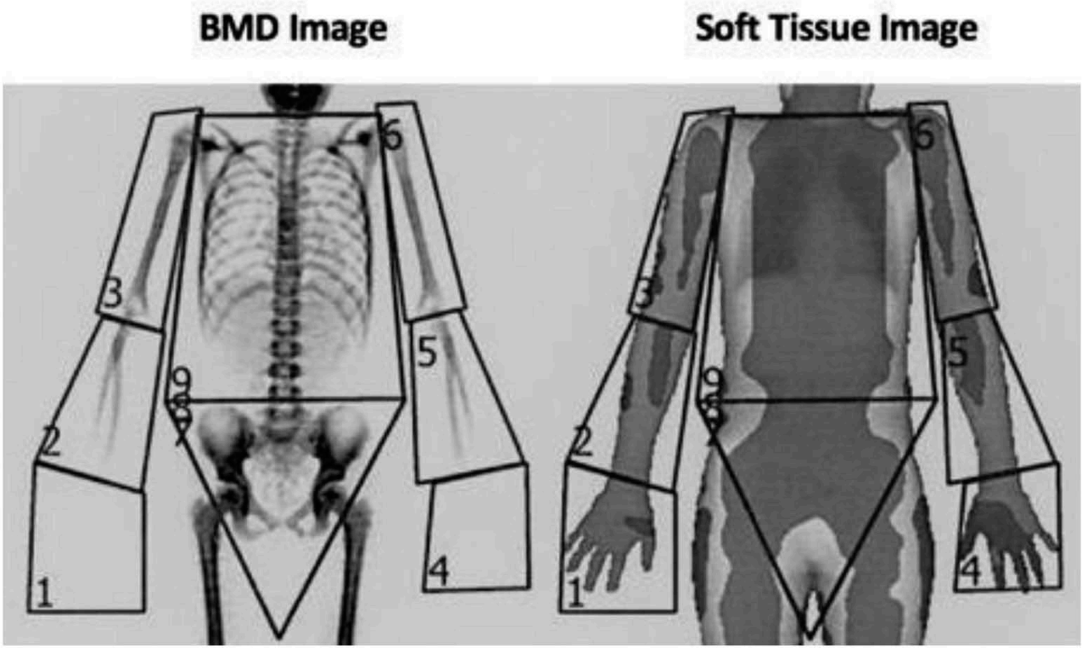

Figure 2. (Left) bone mineral density (BMD) and (right) soft tissue image of a youth participant. BMD scan: higher greyscale intensity indicates higher bone density. Soft tissue scan: higher greyscale intensity indicated lower body fat percentage. Regions 1 and 4 represent hands, regions 2 and 5 represent forearms, and regions 3 and 6 represent upper arms.

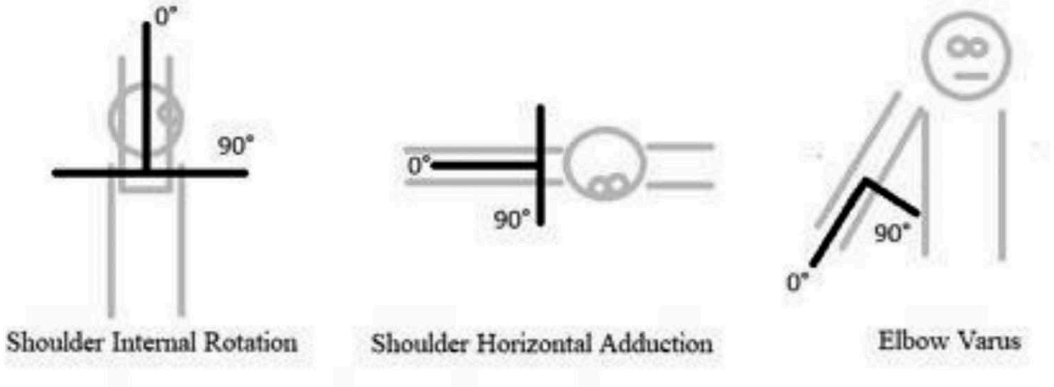

Figure 3. Schematic of PitchTrak angle definitions used for torque directions for a right-handed pitcher.

torque produces an internal varus torque generated by tissues including the UCL (Buffi, Werner, Kepple, & Murray, 2015)).

Statistics

When applicable, results are reported as mean ± 1 standard deviation. Paired t-tests were performed to determine significant differences between scaled and DXA masses, as well as the differences between kinetic parameters calculated using scaled and DXA-mass ID at a significance level of 0.05. Simple linear regression analyses were performed to determine the relationships between joint kinetics (dependent variables) and upper arm mass, forearm mass, hand mass, body mass, BMI, or body fat percentage (independent variables). Since there were 3 shoulder measurements (compressive force, internal rotation torque, horizontal adduction torque) a Bonferroni correction of 3 was applied when analysing these parameters ($p < 0.0167$), while there was only one dependent elbow variable (i.e., varus torque), so significance for the elbow measurement was defined as $p < 0.05$.

Multiple regression analyses were run with hand, forearm, and upper arm masses as independent variables and strong multicollinearity existed. This is because hand, forearm, and upper arm mass are not truly independent because they all are strongly correlated with total body mass. Thus, results were not reported.

Results

Pitch speeds averaged 25.5 ± 1.9 m/s (57.0 ± 4.3 miles per hour). All segment masses showed significant differences between scaled and DXA values (Table 1). Hand ($p < 0.001$) and upper arm ($p < 0.001$) DXA masses were greater, while forearm ($p < 0.0001$) DXA masses were lesser, than their respective scaled masses. The mean DXA mass ratios and masses differed most for the upper arm segment with mass ratios 23% higher and masses 24% higher on average than scaled values.

Shoulder kinetic parameters (Table 2) were all larger when using DXA-mass ID compared to the corresponding values using scaled ID for compressive force ($p < 0.001$), internal rotation torque ($p < 0.001$), and horizontal adduction torque ($p = 0.002$). Elbow varus torque ($p = 0.280$) (Table 2) did not differ when using DXA-mass vs. scaled ID.

In general, nearly all shoulder and elbow kinetic parameters were correlated to hand, forearm, and/or upper arm masses (Table 3). Shoulder compressive force ($p < 0.001$),

Table 1. Scaled and DXA upper arm, forearm, and hand mass ratios and masses used for inverse dynamic calculations.

	Scaled Mass Ratio (%)	DXA Mass Ratio (%)	Scaled Mass (kg)	DXA Mass (kg)
Hand	0.60[a]	0.66 ± 0.05	0.24 ± 0.04	0.26 ± 0.04*
Forearm	1.62[a]	1.51 ± 0.11	0.64 ± 0.12	0.60 ± 0.11*
Upper Arm	2.71[a]	3.34 ± 0.26	1.08 ± 0.20	1.34 ± 0.33*

* = significant difference between scaled and DXA masses; $p < 0.050$. [a]From published results with adult cadavers (De Leva, 1996).

Table 2. Shoulder and elbow kinetics calculated using scaled and DXA-mass ID.

	Scaled ID	DXA Mass ID
Shoulder		
Compressive Force (N)	245 ± 56	258 ± 63 *
Internal Rotation Torque (Nm)	14.4 ± 4.1	15.2 ± 4.6 *
Horizontal Adduction Torque (Nm)	27.8 ± 11.2	29.1 ± 12.0 *
Elbow		
Varus Torque (Nm)	11.6 ± 2.4	11.8 ± 2.5

* = significant difference between shoulder kinetic parameters, $p < 0.050$.

Table 3. Single linear regression results of forces and torques using DXA-mass ID vs. DXA segment masses.

	Hand mass R^2 (p)	Forearm mass R^2 (p)	Upper arm mass R^2 (p)
Shoulder			
Compressive Force (N)	0.60(<0.001*)	0.66(<0.001*)	0.55(<0.001*)
Internal Rotation Torque (Nm)	0.40(0.006*)	0.30(0.019)	0.38(0.007*)
Horizontal Adduction Torque (Nm)	0.31(0.016*)	0.17(0.091)	0.21(0.055)
Elbow			
Varus Torque (Nm)	0.33(0.012*)	0.46(0.002*)	-

* = significant correlation; $p < 0.0167$ for shoulder measurements and $p < 0.050$ for elbow measurements.

shoulder internal rotation torque ($p = 0.006$), shoulder horizontal adduction torque ($p < 0.016$), and elbow varus torque ($p = 0.012$) were positively correlated with hand mass. Shoulder compressive force ($p < 0.001$) and elbow varus torque ($p = 0.002$) were positively correlated with forearm mass. Shoulder compressive force ($p < 0.001$) and shoulder internal rotation torque ($p = 0.007$) were positively correlated with upper arm mass.

Also, several shoulder and elbow kinetic parameters were correlated to body mass and/or BMI (Table 4). Shoulder compressive force ($p < 0.001$) and elbow varus torque ($p = 0.026$) were positively correlated with body mass (Figure 4). Shoulder compressive force ($p = 0.002$) was positively correlated with BMI (Figure 4). None of the measured kinetics were correlated with body fat percentage.

Discussion and implications

The current study was novel for three reasons. First, it found that participant specific DXA hand, forearm, and upper arm masses significantly differed from their corresponding scaled masses. Second, it used participant-specific hand, forearm, and upper arm masses to compare scaled and DXA-mass ID predictions of pitching arm kinetics. Third, it investigated correlations between shoulder and elbow kinetics with DXA hand, forearm, and upper arm masses.

The results supported the first hypothesis as participant-specific DXA hand, forearm, and upper arm mass ratios were 10% higher, 7.2% lower, and 23% higher than their respective scaled masses. One explanation for the observed differences between all scaled and DXA arm segment masses are that the scaled masses corresponded to adult bodies (De Leva, 1996). It has been shown that the distribution of body mass differs

Table 4. Single linear regression results of forces and torques using DXA-mass ID vs. body mass, body mass index (BMI), and body fat percentage.

	Body mass R^2 (p)	BMI R^2 (p)	Body Fat Percentage R^2 (p)
Shoulder			
Compressive Force (N)	0.58(<0.001*)	0.46(0.002*)	0.14(0.129)
Internal Rotation Torque (Nm)	0.20(0.060)	0.16(0.100)	0.07(0.302)
Horizontal Adduction Torque (Nm)	0.23(0.031)	0.06(0.309)	0.03(0.513)
Elbow			
Varus Torque (Nm)	0.27(0.026*)	0.13(0.137)	0.02(0.574)

* = significant correlation; $p < 0.0167$ for shoulder measurements and $p < 0.050$ for elbow measurements.

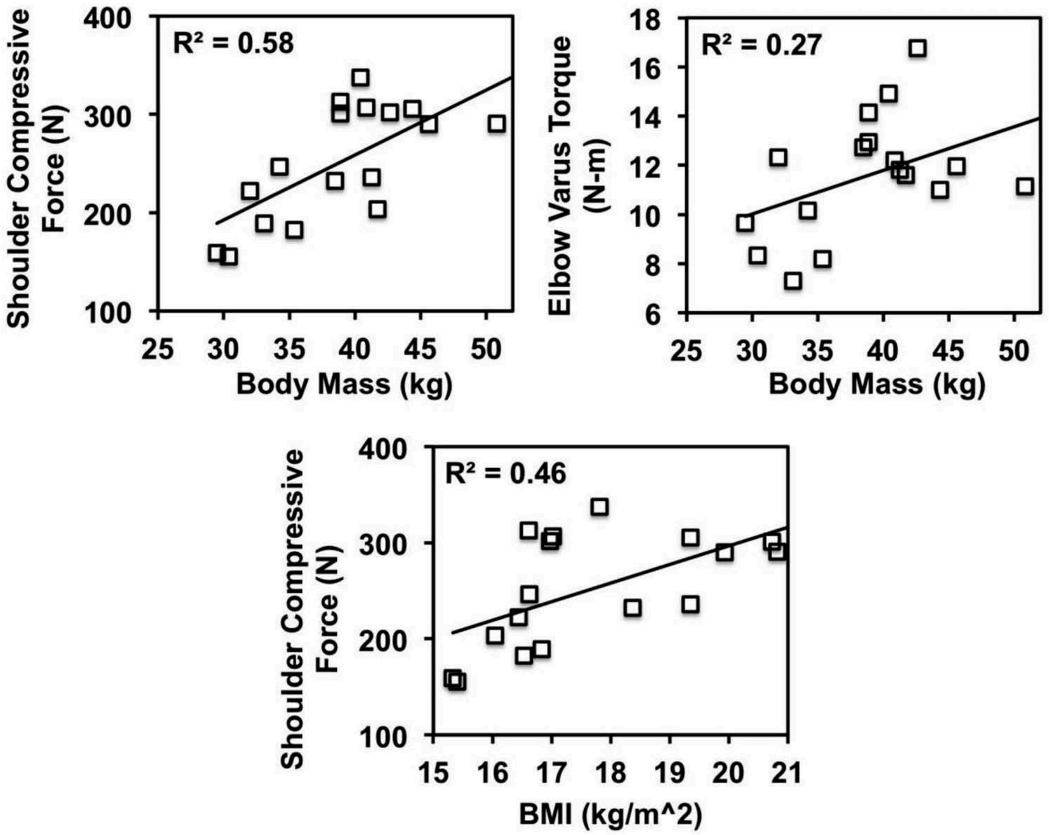

Figure 4. Linear regression plots of kinetic parameters that were significantly correlated with total body composition measures. Top: shoulder compression force ($p < 0.001$) and elbow varus toque ($p = 0.026$) vs. body mass. Bottom: shoulder compressive force ($p = 0.002$) vs. body mass index (BMI; kg/m^2).

between a fully mature adult and a child (Jensen, 1986), likely contributing to the observed differences between scaled and DXA masses obtained in this study. Also, the relatively large difference observed between scaled and DXA upper arm masses may be explained by how the upper arm mass ratios were calculated in this study compared to a previous study (De Leva, 1996). In the previous study (De Leva, 1996), an upper arm mass ratio of 2.7%, which is similar to values reported in (Clauser, McConville, & Young, 1969; Dempster, 1955), was obtained without considering some of the tissue superior and inferior to a transverse plane through the shoulder joint centre. This study, and apparently previous studies (Fleisig, Andrews, Dillman, & Escamilla, 1995), used such upper arm mass ratios for scaled ID analyses. For the DXA-mass ID in this study, those soft tissues surrounding the shoulder joint have been included in the mass of the upper arm, a definition that agrees with the DXA software definition of the upper arm (see regions 3 and 6 of Figure 2) and a prior anthropometric study with children (Jensen, 1986). During the pitching motion those tissues surrounding the shoulder appear to rotate about the shoulder joint centre with the arm motion and likely contribute to shoulder kinetic values, and therefore should be included in the upper arm segment mass for more realistic predictions. It is important to note that values for upper arm mass ratios for 12-year-olds have been reported as 3.2% (Jensen, 1986) where the upper arm segment was defined to include the mass surrounding the head of the humerus and the acromion, which agrees with values found for the upper arm here. The participant specific forearm mass ratios were likely lower than the scaled forearm mass ratios because the scaled mass ratios were based on adults, and it has been shown that forearm mass accounts for a lesser percentage of overall body mass in children than in fully developed adults (Jensen, 1986).

The results supported the second hypothesis as scaled and DXA-mass ID predicted different shoulder, but not elbow, kinetics; the mean shoulder kinetic parameters (compressive force, internal rotation torque, and horizontal adduction torque) were higher when using DXA-mass ID. Those results can be explained by the observation that Pitchtrak uses a 'top-down' ID method that proceeds in a distal to proximal direction in the pitching arm. Specifically, the ID analysis proceeded in the following steps: (1) calculated wrist (i.e., most distal) joint loads, which depend on ball and hand masses; (2) calculated elbow joint loads, which depend on wrist loads and ball, hand, and forearm masses; and (3) calculated shoulder (i.e., most proximal) joint loads, which depend on wrist and elbow loads and ball, hand, forearm, and upper arm masses. Thus, shoulder, but not elbow, kinetic parameters depended on the upper arm mass, which was the arm segment mass that differed the most between scaled and DXA-mass ID methods.

The results supported the third hypothesis as shoulder and elbow kinetics were correlated to DXA body composition measures (hand, forearm and upper arm masses, total body mass, and BMI). While shoulder and elbow kinetics were generally correlated with one or more pitching arm segment masses, correlations with hand segment masses occurred most often. That finding likely resulted from the observation that the hand segment on average had higher accelerations and moment arms than other arm segments (data not shown). Regardless, the results showed that each of the 4 injury-related pitching arm kinetics were correlated with at least one arm segment mass. The positive correlations between shoulder compressive force and elbow varus toque with total body mass and/or BMI appears to be reasonable, because independent analyses revealed that pitching arm segment masses (hand, forearm, and upper arm masses) were positively correlated with those body composition measures. There were no correlations with body fat percentage, likely because ID analysis depends on the total masses of the segments and thus correlations would be expected to be weaker with bone, lean, and fat masses.

These results may have several implications for baseball players. One relevant result is that, for 10- to 11-year old pitchers, using participant-specific mass ratios leads to different predictions of injury-related pitching arm kinetics and, thus, may improve our understanding of injury risk factors. High joint torques are likely related to overuse injuries at the shoulder and elbow (Fleisig et al., 1995). An increasingly common injury for youth ptichers is UCL sprain which has been linked to high elbow varus torques (Andrews, Heggland, Fleisig, & Zheng, 2001). Other common injuries are labrum and rotator cuff sprains and tears which have been linked to high shoulder internal rotation torques, horizontal abduction torques, compression forces, and internal rotation veclocity (Fleisig, Barrentine, Escamilla, & Andrews, 1996). Although the current study reported slight (but significant) increases in predictions of joint kinetics with DXA-mass ID, those differences may be even higher in older youth and adult pitchers due to their higher body masses. Thus, future studies should aim to look at the effects of using DXA-mass ID with older youth and adult pitchers.

A limitation is that while the kinetic differences between the scaled and DXA-mass ID results were significantly different, it is unknown whether the differences are clinically significant. When analysing results for a group of participants, the results may not be clinically significant as DXA mass ID predicted shoulder kinetic values were 5-6% higher, on average, than scaled ID (Table 2). However, if the focus of a pitching biomechanics study is participant-specific, the results could be clinically significant as differences between scaled and DXA-mass ID were as high as 15% for some participants. Also, it is possible that differences may be clinically significant for older and/or overweight pitchers due to higher kinetic values that increase with increasing pitch speed and arm mass. Finally, for investigating associations with possible injury risk factors or overweight measures such as BMI, use of DXA-mass ID should produce more accurate regressions due to use of more accurate body segment masses in the ID equations.

Thus, another clincially relevant result was that, for 10- to 11-year-old pitchers (representing a relatively narrow age range and thus body masses), pitching arm kinetics were correlated with body composition measures and a relatively high total body mass and/or BMI may increase shoulder and/or elbow injury risk. As mentioned earlier, such overweight measures have not been formally identified as risk factors for youth pitching injuries, and the results suggest a need for a better understanding of the relationship between body composition and pitching injuries, which is critical in light of the increasing and high prevalence of overweight and obesity in children (Kumar & Kelly, 2017) and professional baseball pitchers (Conroy, Wolin, & Carnethon, 2016). In the United States one-third of children and adolescents are classified as overweight or obese (Kumar & Kelly, 2017). BMI has been shown to be a good predictor of excess body fat mass in children with a relatively high BMI (Freedman & Sherry, 2009). A high BMI can result from either a large fat mass or a large lean mass, the later not being a health risk. However, BMI does appear to be a reliable predictor of injury risk to pitchers because it is the total mass of the arm, and not the individual fat and lean masses, that appear to affect kinetics. This is explained through the correlations found between most pitching arm kinetics and segment masses, while there was no correlation between pitching arm kinetics and body fat percentage.

While significant correlations were found between pitching arm kinetics and arm segment masses, the corresponding R^2 values were relatively low (Table 3). This was also the case when looking at correlations between pitching arm kinetics and body mass and BMI (Table 4). Although these results suggest that body segment masses are associated with pitching kinetics, there is substantial variability in other parameters that affect pitching kinetics, such as pitching mechanics, pitch speed, and other inertial parameters. Regarding the influence of other inertial parameters, this study only adjusted arm segment masses using DXA data. Thus, the other inertial parameters (centre of mass, radii of gyration) that influence pitching kinetics were based on scaled values and may have introduced considerable errors. Thus, future studies should calculate all pitching arm inertial parameters directly from DXA data and investigate if their use significantly changes the regression results.

Our kinetics results agreed with previous studies; in particular, shoulder and elbow joint kinetics for the 10- to 11-year-olds fell between values reported for younger and older pitchers (Table 5). The corresponding values from this study were all larger than values reported in a previous study with 9- to 10-year-old (Darke et al., 2018), most likely

Table 5. Shoulder and elbow kinetics found in this study compared to other studies involving children.

	9- to 10-year-old[a]	10- to 11-year-old[b]	13- to 18-year-old[c]
Shoulder			
Compression Force (N)	183 ± 70	258 ± 63	750 ± 140
Internal Rotation Torque (N-m)	8 ± 3	15.2 ± 4.6	51 ± 13
Horizontal Adduction Torque (N-m)	4 ± 3	29.1 ± 12	69 ± 25
Elbow			
Varus Torque (N-m)	9 ± 4	11.8 ± 2.5	48 ± 13

[a] = (Darke et al., 2018) [b] = Current study [c] = (Fleisig et al., 1999).

due to the participant's ages also being greater. Another study reported elbow varus torques in 12 year old pitchers of 18 ± 4 N-m further validating the values found in this study (Sabick et al., 2004). Also, the results agreed with a previous study with youth pitchers that reported correlations between shoulder and elbow kinetics with DXA body composition measures (Garner et al., 2011). However, the time in the pitch cycle where the maximum forces and torques occurred were not consistent between participants and did not agree with other studies (Fleisig et al., 1996). A preliminary analysis of those results showed that although some pitchers exhibited timing of maximum kinetics that agreed with published results, most did not (Figure 5). This inconsistency is likely due to the large variability in pitching mechanics in the studied age group when compared to the mechanics and consistency of older pitchers, making it difficult to interpret the results (Fleisig et al., 1999). Thus, analysing the temporal changes of youth pitching kinetics for this age group would be a significant project and should be considered for a future study.

There are limitations in the current study. First, the size of the lab limited the pitching distance to approximately 25 feet instead of the regulation distance for youth

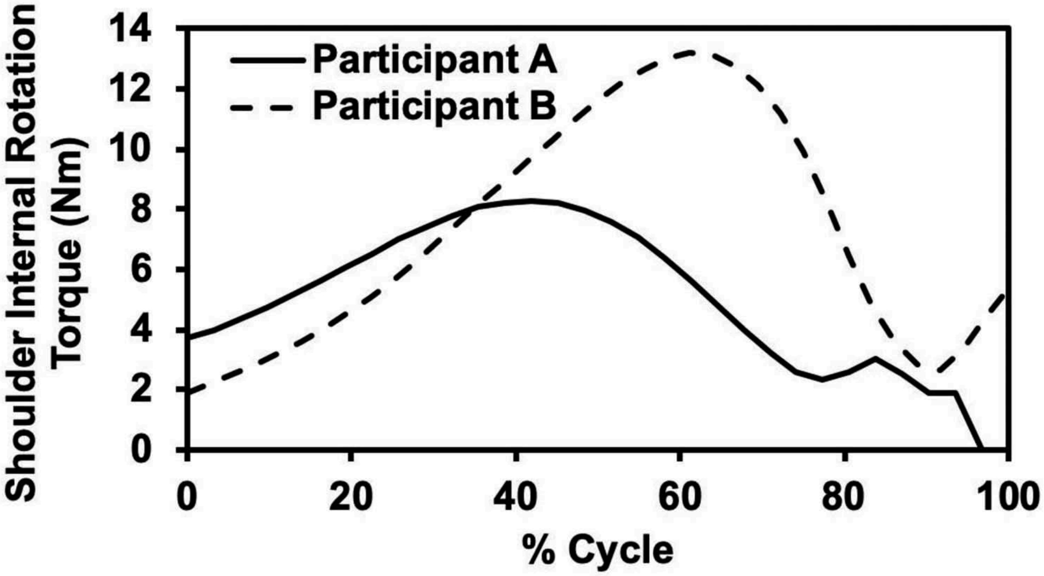

Figure 5. Shoulder internal rotation torque vs. pitch cycle (0% = foot contact to 100% = ball release) for two participants. The timing of maximum shoulder internal rotation torque for participant B (~62%), but not participant A (~42%), was similar to the timing (~64%) reported for adult pitchers in (Fleisig et al., 1995).

pitchers, so the strike zone was scaled accordingly. Second, the use of ground force plates and optimisation of whole-body kinetics could improve the accuracy of the results (Buffi et al., 2015). Third, some DXA scans may have produced slightly skewed values for mass ratios if the participant did not fast before the scan, but this would primarily affect the torso segment, which was not used in this study. Fourth, participant-specific mass ratios could also differ by 1% based on how the regions of interest were manually created. For example, the mass of the upper arm, forearm, and hand segment were added up and compared to the mass of the total arm reported by the software. The regions would be redefined until the sum of masses and the total mass was within 1% so that no extra mass from the torso was accidentally being included in the arm. Fifth, this study only reported joint forces and torques that are not direct indicators of overuse injuries due to soft tissue and bone stresses. Future studies should continue to advance models that calculate muscle forces and joint contact loads through advance inverse dynamic analyses (Buffi et al., 2015). Finally, this study did not account for the effects of participant-specific centres of mass and moments of inertia of pitching arm segments. Our ongoing work involves developing custom computer algorithms to calculate such inertial properties from DXA data, which is a challenging endeavour, and those results will be reported in a follow-up study.

Although use of participant-specific, DXA-driven ID may be undesirable for some applications due to the challenges of conducting and analysing DXA scans, studies with youth pitchers may consider using the new mass ratios found in this study or those reported elsewhere (Jensen, 1986). Since use of age-specific inertial property scaling ratios may lead to more accurate models of pitching arm kinetics, future studies should investigate the accuracy of scaling ratios for all age groups and, furthermore, seek to develop less expensive and less invasive imaging techniques to determine participant-specific inertial properties.

Conclusion

In summary, the current study was the first to investigate youth pitching arm kinetics calculated with participant-specific DXA hand, forearm, and upper arm masses. Three novel results for 10–11year old pitchers were: (1) DXA upper arm, forearm, and hand masses were different than their respective scaled masses; (2) DXA-mass ID predicted higher shoulder kinetic parameters than scaled ID; and (3) there existed correlations between shoulder and elbow kinetic parameters and some body composition measures, including BMI.

These novel results suggest that DXA-mass ID may provide more accurate models for predicting shoulder forces and torques than scaled ID for youth baseball pitchers. The large differences in upper arm scaled mass ratios reported here vs. other studies should be considered when doing ID calculations, if participant-specific DXA mass ratios cannot be calculated. Our findings also reinforce the suggestion by previous studies that injury-correlated torques and forces are correlated with body composition measures for baseball pitchers. However, it was also found that pitching arm kinetics were independent of body fat percentage and, thus, are most related to the masses of the pitching arm segments. Future studies may consider the use of full DXA ID with age-related pitching arm segment inertial properties to improve the accuracy of shoulder and elbow kinetic predictions and, ultimately, to enhance injury prevention methods.

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