THE INFLUENCE OF AGE-RELATED FACTORS ON THE VARUS/VALGUS MOMENT CAPACITY OF THE ELBOW MUSCLES OF BASEBALL PITCHERS

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The purpose of this study was to investigate how age-related factors may influence the capacity of the muscles to protect the ulnar collateral ligament during baseball pitching. Three-dimensional marker position data from 30 pitchers (across three age groups) were incorporated into a musculoskeletal modeling framework, using OpenSim software. The effect of pitcher size, strength, and mechanics were represented by independent implementations of scaling factors, isometric muscle force values, and joint angles, resulting in 27 model combinations. For each combination, the maximum isometric varus/valgus moments that could be produced by all of the muscles were calculated and evaluated. While we found minimal age-related changes in joint angles, varus/valgus moments were highly sensitive to muscular strength and pitcher size.

KEYWORDS: musculoskeletal model, ulnar collateral ligament, varus torque, valgus stress

INTRODUCTION: Baseball pitching involves considerable loads in the throwing arm, such that even a single pitch can carry significant potential for injury (e.g., Fleisig et al., 2018b). The instant of maximum shoulder external rotation (MER) is a critical timepoint with high elbow valgus moments that are correlated to the occurrence of elbow injuries (Anz et al., 2010).

Three distinct components of the elbow can provide varus moment to directly counteract the dangerous valgus loads experienced near this critical timepoint: the bones (through joint reaction forces), the ulnar collateral ligament (UCL), and the muscles that cross the elbow (e.g., Buffi et al., 2014). When a substantial proportion of the varus moment comes from the osseous articulation, the bones can be damaged (e.g., Fleisig et al., 2018b). When an excessive proportion of the moment originates from the UCL, the ligament can tear (e.g., Fleisig et al., 2018b). Previous cadaver-based studies have been unable to investigate potential muscular contributions; however, musculoskeletal modeling techniques can provide a powerful framework for such an investigation (Buffi et al., 2014).

Elbow injuries are common in pitchers of all ages (e.g., Reiman et al., 2019), so any modeling framework must account for age-related differences (e.g., height, weight, skeletal proportions, muscular strength, and pitching mechanics). It is important to develop a set of model modifications corresponding to age-related factors and to also understand the sensitivity of the model to these factors.

The purposes of this study were to 1) develop a musculoskeletal model of the pitcher's elbow and 2) investigate how age-related factors such as size, strength, and mechanics may influence the capacity of the muscles to help protect the UCL during baseball pitching.

METHODS: Biomechanical data from 30 pitchers (10 each for three age groups) were analysed (Table 1). A set of 38 retroreflective markers was attached to each participant (Fleisig et al., 2017). After conducting their usual warmup routine, study participants threw a minimum of 3 fastballs at full effort off a mound towards a strike zone target located above home plate. Mound height, slope, and distance to home plate conformed to standard regulations for their competition level. Ball velocity for each pitch was recorded using a radar gun (Stalker Sports Radar, Plano, TX, USA), while three-dimensional marker position-time data were collected using an automated motion capture system sampling at 240 Hz (Motion Analysis Corporation, Santa Rosa, CA, USA). Three-dimensional marker position data were also collected for a static "T-pose" trial. Marker position data for left-handed pitchers were mirrored in order to emulate right-handed data. All pitchers did not have any injury that required them to miss playing time in the 12 months prior to testing. For each pitcher selected, data from the fastest recorded strike was chosen for further processing and analysis.

Table 1: Participant group demographics, means (standard deviations).

Group	Age, yrs	Height, m	Mass, kg	Fastball Velocity, m/s
Youth	12.8 (0.7)	1.57 (0.03)	45.1 (4.4)	25.7 (1.8)
High School	17.1 (0.5)	1.81 (0.07)	79.8 (9.7)	34.2 (1.1)
Adult	20.8 (2.4)	1.89 (0.07)	94.8 (7.1)	38.6 (0.8)

A generic musculoskeletal model of the upper limb of a 50th percentile young-adult male (Saul et al., 2015) was modified in the OpenSim 3.3 modeling environment (Delp et al., 2007; Seth et al., 2018). We added an elbow varus-valgus degree-of-freedom (DOF) according to a previously-described axis for elbow valgus deviation (Buchanan et al., 1998). We also added six DOFs to the model to define the position and orientation of the trunk relative to the ground. Overall, the updated model included 14 DOFs: six for the trunk, three in the shoulder (elevation, elevation plane, external rotation), two in the elbow (flexion and varus), one in the forearm (pronation), and two in the wrist (flexion and radial deviation). The model excluded all muscles that could not produce a moment about the varus-valgus axis (i.e., they did not span the elbow), leaving the updated model with 21 muscles. Eleven markers were incorporated into the model, representing the locations of 11 of the 38 previously-mentioned retroreflective markers. On the throwing arm side, these were located on the dorsal surface of the hand between the 2nd and 3rd distal metacarpals, styloid processes (ulnar and radial), proximal third of the ulna, elbow epicondyles (lateral and medial), lateral superior tip of the acromion, inferior angle of the scapula, and sternal end of the clavicle. The final two markers were located on the C7 vertebra and sternal end of the contralateral clavicle.

A subject-specific model for each of the 30 pitchers was created by scaling the generic model using his marker position data from the static trial. Each segment had a scaling factor for each of three orthogonal axes, accounting for subject-specific anthropometric proportions. Using the subject-specific model, the OpenSim Inverse Kinematics function, and the dynamic trial data, we computed the joint angles that allowed the model to best reproduce the recorded motion. As there is very little laxity about the elbow varus-valgus axis, we set the varus-valgus joint angle as zero throughout the motion (Buffi et al., 2014).

We took the subject-specific scaling factors and calculated the average (arithmetic mean) within each group, creating group-specific sets of scaling factors, which were then used to create group-specific models. Similarly, we created group-specific sets of joint angles by taking the subject-specific joint angle values at MER and calculating the average values within each group. Finally, three different sets of muscle strength values (i.e., maximum isometric muscle forces) were implemented. We first created a set representing an adult pitcher as previously described by Buffi et al. (2014). We then created sets representing a high school (HS) pitcher and a youth pitcher by scaling the adult pitcher values using the quotients of the group-averaged masses and heights (Correa and Pandy, 2011).

These methods allowed us to simulate three age-related factors: scaling accounted for growth in size, the joint angle sets accounted for differences in pitching mechanics, and the maximum isometric muscle force values accounted for differences in muscular strength. We created simulations from all of the possible combinations of the three factors, resulting in 27 simulations. For each combination, we used the model to calculate both the maximum isometric varus and valgus moments that could be produced by each of the individual muscles at MER. We then summed the values across all muscles to determine the maximum isometric varus and valgus moments that could be produced by the elbow muscles (i.e., their varus and valgus capacities). These results could then be compared across simulations, using standard mathematical comparison techniques such as percent difference calculations.

RESULTS: The group averages of the subject-specific joint angles at the instant of MER are provided in Table 2. All values were similar across age groups, with no discernible trends.

Table 2: Group averages (SD) of the subject-specific joint angles at MER. Values in degrees.

Group	Shoulder Elevation	Elevation Plane	External Rotation	Elbow Flexion	Forearm Supination	Radial Deviation	Wrist Extension
Youth	87.4 (7.4)	0.1 (5.1)	145.9 (12.3)	74.5 (9.7)	3.5 (9.9)	3.7 (10.3)	49.0 (9.3)
HS	88.2 (5.0)	0.4 (3.7)	146.1 (12.3)	78.5 (11.8)	8.7 (7.1)	-0.2 (9.0)	56.4 (5.8)
Adult	87.9 (4.7)	3.2 (3.6)	146.6 (8.3)	78.1 (10.2)	14.8 (9.5)	3.5 (12.4)	48.9 (11.5)

The maximum isometric varus and valgus moments that could be produced by the elbow muscles are provided in Tables 3-5. When examining both scaling and strengths, the maximum isometric varus and valgus moments increased with advanced age (i.e., from youth to high school to adult). Minimal changes occurred due to the different sets of joint angles.

Table 3: Maximum isometric varus (valgus) moments, at youth school joint angles, in Nm.

	Youth Scaling	HS Scaling	Adult Scaling
Youth Strength	46.1 (-12.7)	51.0 (-14.8)	54.6 (-16.4)
HS Strength	71.1 (-19.6)	78.6 (-22.9)	84.2 (-25.3)
Adult Strength	80.6 (-22.2)	89.0 (-25.9)	95.4 (-28.7)

Table 4: Maximum isometric varus (valgus) moments, at HS school joint angles, in Nm.

	Youth Scaling	HS Scaling	Adult Scaling
Youth Strength	45.0 (-12.3)	49.8 (-14.5)	53.5 (-16.0)
HS Strength	69.4 (-19.0)	76.7 (-22.3)	82.4 (-24.7)
Adult Strength	78.6 (-21.6)	86.9 (-25.3)	93.4 (-28.0)

Table 5: Maximum isometric varus (valgus) moments, at adult school joint angles, in Nm.

	Youth Scaling	HS Scaling	Adult Scaling
Youth Strength	44.9 (-12.9)	49.7 (-15.1)	53.3 (-16.7)
HS Strength	69.3 (-19.9)	76.6 (-23.3)	82.2 (-25.7)
Adult Strength	78.5 (-22.6)	86.7 (-26.4)	93.1 (-29.2)

DISCUSSION: We developed a musculoskeletal model of the baseball pitcher's elbow that can be applied to a variety of research questions. In addition, through the analysis of pitchers across three different age groups, we have learned about the sensitivity of the model to three possible techniques for modeling subject-subject characteristics (e.g., age-related factors).

The varus moment capacities found in this study when all three model modifications were implemented (youth: 46.1 Nm; HS: 76.7 Nm; adult: 93.1 Nm) were slightly higher than the values of net elbow varus moment reported in the literature (e.g., youth: 37.0 Nm; HS: 62.6 Nm; minor league: 83.1 Nm) (Fleisig et al., 2016). This suggests that under absolutely ideal conditions, the elbow muscles may be able to carry most/all of the valgus load, greatly reducing the load on the UCL.

Individually, the different implementations of age-related factors had varying degrees of effect on varus moment capacities. Modifications to muscle strengths had a large effect, with percent differences of approximately 54% between the youth and adult values (e.g., 46.1 Nm vs. 80.6 Nm in Table 3). Many musculoskeletal modeling studies do not modify these values from those of their generic model (e.g., Hicks et al., 2015), instead allowing capacity-related errors to be compensated for in the magnitudes of activation patterns. However, for studies investigating muscle capacities, the activation levels are often set at 100%, making muscle strength estimate accuracy critical. Scaling also had a large effect on the resulting moment capacity values (~17% differences, e.g., 46.1 Nm vs. 54.6 Nm in Table 3). Much of this difference can be explained by an increase in the moment arms; however, there may be other unexpected factors involved. Future work will analyze the origins of these differences. Of the three model modifications, the one representing pitching mechanics had the smallest effect (<5% differences, e.g., 46.1 Nm in Table 3 vs. 44.9 Nm in Table 5). This is likely because the MER joint angles were similar across all age groups (Table 2). Considering that the kinematics of youth pitchers change most dramatically prior to age 13 (Fleisig et al., 2018a) and the average age of our youth group was 12.8 yrs, many of our participants may have already undergone these changes. While the largest differences between youth and elite adult pitching kinematics is in their velocities (e.g., Fleisig et al., 2018b), our study was unable to examine the effect of velocity differences due to its quasi-static nature.

The lack of velocity-related effects is a key limitation of the current study; however, the large differences observed with the scaling and strength modifications suggest that the overall trends across age groups (i.e., capacities increasing with age) would have been unaffected by their inclusion. Still, future work will incorporate the model into a dynamic simulation framework in order to account for these effects. Another limitation is that the muscles may be unable to reach full activation prior to the instant of MER. Thus, the maximum moments in our results are likely an optimistic ceiling that is unlikely to be reached during pitching. Despite the acknowledged limitations, the results of this study are an important addition to the literature. Previous studies applying advanced musculoskeletal modeling to pitching analyzed only one subject (e.g., Buffi et al., 2014). As a result, they were unable to examine model sensitivities to potential implementations of subject-specific differences.

CONCLUSION: The results of this study highlight the influence of age-related factors on the varus/valgus moment-generating capacity of the elbow muscles in baseball pitchers, as well as the sensitivity of potential implementations in a musculoskeletal model. While we found minimal age-related changes in joint angles, age-related changes in muscular strength and pitcher size had large effects on elbow moment.

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