FINITE ELEMENT ANALYSIS OF THE ULNAR COLLATERAL LIGAMENT UNDER VARIOUS VALGUS LOADS

Ben Hansen, Motus Global, Rockville Centre, NY

OVERVIEW:

The goal of this project was to develop a more clear-cut relationship between elbow valgus torque and the stresses seen in the UCL. To develop this relationship, the UCL was investigated with a Finite Element Analysis (FEA) model. This model incorporates a variety of patient specific parameters, including UCL thickness gathered from ultrasound imaging, and magnetic resonance imaging from the involved elbow to determine the where in the UCL damage occurred, and where stresses should be mitigated.

This work lays the foundation for enhanced rehabilitation protocols using emerging workload measures from wearable sensors like the motusTHROW sleeve. Clinically, data from these three modalities (Ultrasound, MRI, Valgus Load from IMU) can help set patient specific effort limits at various periods throughout the rehabilitation process.

INTRODUCTION:

America's favorite pastime and is enjoyed annually by 28 million active participants on organized baseball teams.^[20] Most parents sign their children up at a young age, completely unaware of the injury risks their children's arm's will be subjected to. In fact, 58% of high school pitchers report throwing pain (a small price to pay for the chance to play the best sport in the world). ^[14]

However, arm injury in Major League Baseball (MLB) is a daunting epidemic. In 2003, 75 of 700 MLB pitchers (11%) have had Ulnar Collateral Ligament Reconstruction (commonly known as "Tommy John Surgery").^[13] In the past five years, MLB pitchers recovering from Tommy John Surgery have collectively spent 14,232 regular season days on the disabled list. During this time their teams have spent \$193,503,317 on those pitchers' salaries (all for the pitcher to sit on the bench and rehabilitate their arm). ^[3] If that isn't eye-opening enough, perhaps this comparison will put things in perspective: The National Diabetes Association reports that for the United States population over the age of twenty, 11.3% have diabetes. ^[5]

To date, numerous authors have investigated the kinetic and kinematic relationships of the upper extremity among baseball pitchers (Pappas 1985, Feltner and Dapena 1986, Werner 1993, 2002, Dillman 1993, Fleisig 1995, 1999, 2011, Hong 2001, Escamilla 2002, Sabick 2004, Chu 2009, Aguilando 2009). However, the degree to which these authors report their data is highly inconsistent. There appears to be no standard method of reporting biomechanical variables. What is more, these authors report kinetic values that are highly variable between studies. To this extent, it is very difficult for researchers to relate a risk of shoulder and elbow injury to the biomechanical values that are investigated. ^[1,4,8,10,11,12,13,14,15,16,18,19,24,25,28]

Regardless, it has been noted from these studies that internal rotational velocity of the shoulder ranges from 4927 – 7844 $^{\circ}$ /s, making baseball pitching one of the fastest recorded human motions. During the throwing motion, a high magnitude of valgus torque is induced in the throwing elbow. ^[1,4,8,10,11,12,13,14,15,16,18,19,24,25,28]

In the pitching biomechanics industry, the valgus torque is a highly relevant measure that is used to help predict injury in the throwing arm and during rehabilitation. The body compensates for the valgus torque by producing a varus torque within the internal musculature of the arm. This valgus motion is illustrated in Figure 1. Anatomically, the UCL may help resist a percentage of this illustrated valgus motion. It is extremely important to mitigate fatigue of the throwing arm to prevent overloading the stress in the ligament.



Figure 1 illustrates a valgus motion and its association with overhand baseball throwing. On the left, a valgus torque can be induced in the anatomical position by moving the hand away from the midline of the torso. On the Right, Aguidaldo et al illustrate this same type of valgus torque on the elbow. This instance illustrated is during maximal external rotation. This is approximately where the maximum elbow valgus torque occurs in the pitching motion.

In further view of the elbow valgus torque, biomechanics research has found that when maximal valgus torque is applied (64 N-m), the elbow is flexed approximately 95 degrees.^[14] Following this notion, Dillman et al reported cadaveric limits of the UCL, where the UCL failed at 32.2 N-m of valgus torque.^[6] Morrey et al showed that when valgus loads are applied to the elbow at 90 degrees of flexion, the anterior band of the UCL generates 54% of the varus torque needed to resist valgus motion.^[21] The report of 64 N-m, or greater, of varus torque at the elbow can infer that the UCL is near its maximum capacity during a high intensity pitch.

Furthermore, in 2011, Hurd et al performed bilateral Magnetic Resonance Imaging on 23 high school pitchers. The results of his study showed that 15 of the 23 pitchers had a thickening of the anterior band of the UCL in their dominant arm. This may suggest adaptive remodeling of the UCL in the presence of increased stress over the lifetime of an active pitcher.^[17] Combining these findings from Morrey, Dillman, and Hurd, it seems impractical to say there is a clear cut relationship between the Elbow Valgus torque and the stresses seen in the UCL. Therefore, advanced methods that fuse a variety of patient specific and biomechanical data are needed in the rehabilitation of baseball pitchers.

MODEL DEVELOPMENT:

The UCL was modeled in Ansys 13.0 (Canonsburg, PA), using dimensions and mechanical properties gathered from relevant, peer-reviewed literature. The boundary conditions were modeled from kinetic data gathered from pitching motion analyses reported across the literature.^[1,2,4,7,8,9,10,11,12,13,14,15,16,18,19,22,,24,25,27,28,29]

In the first, there have been several authors that have investigated the anatomy of the anterior UCL (Nazarian 2003, Andrews 2007, 2012, Timmerman 1994, Hurd 2011). In 2003, Nazarian

performed ultrasound on 26 MLB pitchers. He reports the mean length of the anterior UCL from the end of the origin to the tip of the insertion as 19.6 \pm 2.4mm. He also reports that the thickness of the middle belly of the UCL ranged from 4.6–8.9 mm. This range of thickness is illustrated in Figure 2 above.^[22] In 2007, Dugas et al made measurements on 13 fresh-frozen cadaveric elbows. He reports the width of the anterior UCL



Figure 2 illustrates two ultrasonagraphs of the UCL in two MLB pitchers by Nazarian et al, in 2007. Note that the middle belly of the UCL has a varying thickness between both subjects. This phenomenon is exploited over the course of this project

at the proximal origin to be 6.8 ± 1.3 mm. He also reports the width of the anterior UCL at the distal insertion to be 9.2 ± 1.6 mm.^[7] In 1994, Timmerman made measurements on 10 fresh-frozen cadaveric elbows. She reports the thickness of the anterior UCL at the proximal origin to be approximately 2 mm. Also, she reports the thickness of the anterior UCL at the distal insertion to be approximately 4 mm.^[27] Based on these compiled dimensions of the anterior UCL anatomy, a model was generated in Solidworks 2016 (Waltham, MA). This model can be seen in Figure 3.



Figure 3 illustrates the 3D model generated in Solidworks. This is one of three models generated. Indicated, are the UCL's thicknesses at the proximal origin, middle belly, and distal insertion. These dimensions were compiled through three studies.^[7,22,27]

In the second, several authors have investigated the mechanical properties of the anterior UCL (Andrews 2011, Fang-Lin, 2007). In 2011, Andrews gathered five fresh-frozen cadaveric elbow specimens and loaded the UCL's to failure with a valgus torque. He measured the percent strain in each UCL, the tensile force applied, and the moment arm (from the center of the elbow joint to the UCL) of each subject. He reported the following results in Table 1.^[2]

	Strain (ΔL/L _o)	Force (N)	Moment Arm (m)	Proximal Thickness (m)	Proximal Width (m)	Cross Sectional Area (m²)
Mean	0.1196	347.7	0.038	0.0053	0.008	0.0000424
Stdev	.073	46.42	.003			

Table 1 – Stress and Strain relationships reported b	by Andrews et al, in 2011.
--	----------------------------

From this data I estimated Young's Modulus with the following equation:

$$E = \frac{Force*L_o}{Area*\Delta L} = 6.86E + 07 Pascals$$
(Equation 1.0)

The validity of this estimation is unknown, since no authors have reported discrete mechanical properties of the UCL. However, several authors have reported mechanical properties of other elbow and forearm ligaments. In 2011, Werner et al investigated the structural properties of 6 forearm ligaments and estimated Young's Modulus. A comparison of these values with the estimated UCL is shown in Figure 4.



Figure 4 illustrates the comparison of the modulus of elasticity among various forearm ligaments with respect to the estimated modulus of elasticity of the UCL.

From Figure 4, it can be seen that the estimation of the UCL's modulus of elasticity is higher than the modulus of elasticity found in other forearm and elbow ligaments; however, the goal of this study is not to validate the mechanical properties of the UCL.

In the third, an experimental procedure was designed to investigate the relationship of different loading conditions and UCL thicknesses with the stresses seen in the UCL. Table 2 below summarizes the model parameters chosen.

Model Parameter	Value
Young's Modulus (Pa)	6.86 E 07
Poisson's ratio	0.3
Element Type	20 node Brick
# of Dimensions	3
Mesh Coarseness	Fine (1)
# of Nodes (6mm)	1724
# of Elements (6mm)	967
Assumptions:	Linear
	Isotropic
	Elastic
	Solid Model
	196
Run Time (s)	6.86
Max Bandwidth (at	251362
Element 805)	

Table 2 – Model Parameters

The stress in the UCL was computed for three different valgus loading conditions based on common values found in literature (Table 1).



Figure 5 illustrates the type of loading the UCL undergoes. Note that this load is always reported as a Valgus Torque. In order to partition a Tensile force to the UCL, the moment arm must be known. Using a measured moment arm, a tensile force can be calculated from any given valgus moment. [17]

 $^{[1,4,8,10,11,12,13,14,15,16,18,19,24,25,28]}$ These valgus loads were converted to tensile loads based on a mean moment arm measurement.^{[2].} This method of conversion is seen in Figure 5. A tensile load was then converted to a distributed pressure based on the computed cross sectional area of the proximal attachment and was applied as such. The distal insertion was held fixed with a displacement of zero in the x, y, and z directions.

Parameter	MCW Database (2011)	Aguilando (2009)	Chu (2009)+	Sabick (2004)*	Escamilla (2002)	Fleisig (1999) ^	Fleisig (1995)	Werner (1993)	Feltner (1986)
Sample Size	302	69	11	14	11	115	26	7	8
Pitch Speed (mph)	85±5	75.8 ± 9.2	60	48.7	85	78.8	85.6 ± 1.6	81.4	74.9
Varus Torque (N-m)	54.8	50 ± 29	46 ± 9	18	61 ± 10	55 ± 12	64 ± 12	120	100 ± 20

Table 3 – Compiled Elbow Valgus Torques in Relevant Literature

* Indicates a youth population.

+ indicates a female population

^ indicates a Collegiate population

Additionally, the stress in the UCL was computed for three different thickness values of the middle belly of the UCL. These thicknesses were chosen from the literature referenced above ^[22]. The structural model was changed for each thickness value and was loaded into Ansys as such.

Two additional computations were done to justify the use of the chosen model parameters. One of the additional computations was modified with a more coarse mesh (6). The second additional computation was modified with the use of 10-node tetrahedron elements in lieu of 20-node brick elements. Therefore, a total of eleven different computations were made in Ansys 13.0 (Canonsburg, PA).

Seen in the right, the UCL model was discretized using a fine mesh. The loading conditions (an applied pressure) is labeled as a red arrows on the proximal end of the UCL. The distal insertion was fixed. The reaction forces were computed in ANSYS and are shown as purple arrows.



Figure 6 illustrates the loading conditions of the UCL Model in Ansys 13.

RESULTS:



Figure 7 represents how stress in the x-direction was gathered. A path was defined in the center of the structure (center of the x-axis) along the y-axis (Thick Red Arrow). The stress in the x-direction was then output to a text file. The stress in the x direction nearest to 4mm (approximately one half of the width in the center of the model) on the y-axis was tabulated. This stress was gathered along the centerline on the Anterior, Center, and Posterior faces of the UCL. These 3 faces are indicated on the right of the figure above. The center surface of the UCL was chosen as the focus area due to a discussion with an orthopedic surgeon who is familiar with UCL tears. The center surface of the UCL is the common site for partial thickness tears.^[31]

				Stres	s in x-direction	n (pa)
Thickness(m)	Valgus Torque(Nm)	Tensile Force (N)	Pressure (pa)	Center of Ligament	Anterior of Midline	Posterior of Midline
0.004	40	5.68E+02	3.09E+07	9.42E+06	-6.53E+06	1.61E+07
0.004	60	8.53E+02	4.63E+07	1.81E+07	-9.29E+06	4.91E+07
0.004	80	1.14E+03	6.18E+07	3.09E+07	-1.27E+07	6.61E+07
0.006	40	5.68E+02	3.09E+07	1.42E+07	-7.63E+06	2.62E+07
0.006	60	8.53E+02	4.63E+07	1.64E+07	-1.13E+07	3.94E+07
0.006	80	1.14E+03	6.18E+07	2.80E+07	-1.53E+07	5.26E+07
0.008	40	5.68E+02	3.09E+07	4.44E+06	-6.04E+06	2.24E+07
0.008	60	8.53E+02	4.63E+07	6.65E+06	-8.91E+06	3.35E+07
0.008	80	1.14E+03	6.18E+07	8.88E+06	-1.21E+07	4.47E+07

<u>Table 4 – Summarized Stress table for nine different loading and thickness conditions.</u>

Table 5 –	Summarized	Stress table	for varied	model	narameters
Table J	Juillinalizeu	Juess table	IOI vancu	model	parameters

					Stress in x-direction (pa)			
Model	Thickness	Valgus	Tensile	Pressure	Center of	Anterior	Posterior	
Variation	(m)	Torque(Nm)	Force (N)	(pa)	Ligament	of Midline	of Midline	
Normal	0.006	60	8.53E+02	4.63E+07	1.64E+07	-1.13E+07	3.94E+07	
Coarse	0.006	60	8.53E+02	4.63E+07	1.29E+07	-1.16E+07	4.24E+07	
Tetrahedron	0.006	60	8.53E+02	4.63E+07	2.28E+07	-1.13E+07	3.94E+07	

<u>Table 6 – Multivariate Analysis of Variance Statistics generated in Minitab 16 for Anterior</u> Segment of Ligament x-directional stresses

Stress _x (Pa) = -791606 - 11633.6 * Tensile Force (N) + 1.23e+08 * Thickness(m)
Coefficients
Term Coef SE Coef T P
Constant -791606 2285729 -0.34633 0.741
Tensile Force (N) -11634 1861 -6.24977 0.001
This $max(m) = 122050222 - 264521772 - 0.46402 - 0.650$
Trickness(m) 122958555 204521772 0.40485 0.058
Summary of Model
S = 1295887 R-Sq = 86.75% R-Sq(adj) = 82.33%

<u>Table 7 – Multivariate Analysis of Variance Statistics generated in Minitab 16 for Center of</u> <u>Ligament x-directional stresses</u>

Stress _x (Pa) = 1.45e+07 + 23278.2 * Tensile Force (N) - 3.20e+09 * Thickness(m)
Coefficients
Term Coef SE Coef T P
Constant 14571817 9472312 1.53836 0.175
Tensile Force (N) 23278 7714 3.01764 0.023
Thickness(m) -3201516667 1096207142 -2.92054 0.027
Summary of Model
S = 5370296 R-Sq = 74.61% R-Sq(adj) = 66.15%
Analysis of Variance
Source DF Seq SS Adj SS Adj MS F
Regression 2 6.59565E+13 6.59565E+13 3.29783E+13 19.6378
Tensile Force (N) 1 6.55937E+13 6.55937E+13 6.55937E+13 39.0596
Thickness(m) 1 3.62850E+11 3.62850E+11 3.62850E+11 0.2161
Error 6 1.00759E+13 1.00759E+13 1.67932E+12
Total 8 7.60325E+13

Table 8 – Multivariate Analysis of Variance Statistics generated in Minitab 16 for Posterior Section of Ligament x-directional stresses

Stress _x (Pa) = 4.85e+06 + 57912.5 * Tensile Force (N) - 2.55e+09 * Thickness(m)
Coefficients
Term Coef SE Coef T P
Constant 4854278 11726495 0.41396 0.693
Tensile Force (N) 57912 9550 6.06425 0.001
Thickness(m) -2554750000 1357078115 -1.88254 0.109
Summary of ModelS = 6648298 R-Sq = 87.05% R-Sq(adj) = 82.73%
*Tables 6-8 were computed in Minitab 16 under the general linear model.



(b) 4mm - 60 Nm

(c) 4mm - 80 Nm





(g) 8mm - 40 Nm

(h) 8mm - 60 Nm

(i) 8mm - 80 Nm

Figure 8 is a graphical compilation of x-direction stress distributions in 9 separately loaded UCL Models. (a) - (c) depict the stress distributions for a 4mm thick UCL. (d) – (f) depict the stress distributions for a 6mm thick UCL. (g) – (i) depict the stress distributions for a 8mm thick UCL.



(a) 4mm - 40 Nm



(c) 4mm - 80 Nm





Figure 9 is a graphical compilation of strain in 9 separately loaded UCL Models. (a) - (c) depict the strains for a 4mm thick UCL. (d) – (f) depict the strains for a 6mm thick UCL. (g) – (i) depict the strains for a 8mm thick UCL.



Figure 10 is a graphical compilation of x-direction stress distributions on the posterior side of the UCL in 9 separately loaded UCL Models. (a) - (c) depict the stress distributions for a 4mm thick UCL. (d) – (f) depict the stress distributions for a 6mm thick UCL. (g) – (i) depict the stress distributions for a 8mm thick UCL.



Figure 11 is a graphical compilation of x-direction stress distributions on the anterior side of the UCL in 9 separately loaded UCL Models. (a) - (c) depict the stress distributions for a 4mm thick UCL. (d) – (f) depict the stress distributions for a 6mm thick UCL. (g) – (i) depict the stress distributions for a 8mm thick UCL.



Figure 12 depicts the comparison of the normal, tetrahedron meshed, and coarsely meshed strain and stress distributions. Visually, there are minimal differences between the normal (20 – node Brick mesh), and the 10-node tetrahedron meshed results. These differences are quantified in Figure 13



(d)

Figure 13 graphically represents the results in Table 4 (a)-(c). (d) represents a comparison of the two modifications made versus the 20-node brick model used throughout the experiment. In (b), it is clear that as the thickness of the UCL increases, and as the Valgus torque decreases, so do the stresses in the UCL. In (d), for the center of the ligament, there are large differences between the use of a 10-node tetrahedron, coarse, and 20-node brick mesh.

DISCUSSION:

The UCL is one of the most relevant anatomical structures of the pitching elbow in regards to pitching injuries. In a world where motion analysis and wearable technology is beginning to impact a plethora of MLB teams, there are growing needs to more accurately monitor the true stresses that occur within the pitching arm. From compiling nine separate cases of FEA models of the UCL, three regression equations were found that relate two patient specific measurements of UCL maximal thickness and elbow tensile force to longitudinal tensile stress in the UCL.

 $\sigma_x = -7.92 * 10^5 - 1.16 * 10^4 * force_{tensile}(N) + 1.23 * 10^8 * thickness_{UCL}(m)$ (1)

$$\sigma_x = 1.45 * 10^7 - 2.33 * 10^4 * force_{tensile}(N) - 3.20 * 10^9 * thickness_{UCL}(m)$$
(2)

$$\sigma_x = 4.85 * 10^6 + 5.79 * 10^4 * force_{tensile}(N) - 2.55 * 10^9 * thickness_{UCL}(m)$$
(3)

Where (1) refers to the longitudinal stress, in Pascals, of the anterior side of the UCL, (2) the longitudinal stress, in Pascals, of the middle of the UCL, and (3), the longitudinal stress, in Pascals, of the posterior side of the UCL. Of these three, Equation (2) resulted in the only statistically significant relationship between tensile force, UCL thickness, and longitudinal direction stress. Therefore, the final and valid regression equation is as follows:

$$\sigma_x = 1.45 * 10^7 - 2.33 * 10^4 * force_{tensile}(N) - 3.20 * 10^9 * thickness_{UCL}(m)$$
(4)

In regards to this equation, the R² was 74.61%. Of this percentage of explained variability, 86.27% of the sum of the squared error was due to the Tensile Force applied and less than 1% of the sum of the squared error was due to the UCL thickness. The remaining 13% of variability can be attributed to error in the model. Statistically speaking, the thickness of the UCL plays a significant role; however, this role is not as large as originally thought. Other parameters such as cross sectional area of the UCL in its midband region may be a better measure. More likely, the limitations of this study are what caused the measure of UCL thickness to play a smaller role than though. These limitations will be outlined in subsequent sections.

Graphically, the role of both the varus torque and the UCL thickness are present in Figure 13(b). For comparison in this graph, the longitudinal stress of the middle belly of the UCL under 60 Nm of valgus torque for a 4mm thick UCL is 4.65 times larger in magnitude than an 8mm thick UCL under the same loading condition. This is astounding! Consider the following case: Pitcher A and Pitcher B both underwent motion analysis and both were recorded to have 60 Nm of Valgus Torque at their elbow. Their UCL thicknesses were then measured. Pitcher A's UCL thickness was 4 mm thicker than Pitcher B. The actual stress at the UCL would be 4.65x greater in Pitcher B than in Pitcher A! There's absolutely no way that elbow valgus torque alone could statistically predict a UCL rupture if there is this much variance in what is actually occurring inside the UCL.

In addition to the center belly stresses, the stresses on the anterior and posterior surfaces were tabulated and graphically compared in Table 4 and Figure's 10 and 11. It should be noted that there was no statistical significance in the longitudinal stresses for these surface cases. Figure 13 (a),(c) show that there is a small tendency for longitudinal stress to decrease in thicker UCL's,

albeit very small and inconsistent. An interesting note is that the anterior side of the UCL underwent compression in all cases. This would not occur in a UCL and is likely to bring skepticism on the validity of these results. Again, this is most likely due to limitations of the study that will be outlined in a subsequent section of this report.

The strain of each loaded UCL was not tabulated. Only graphical comparisons are to be made from Figure 9, in which the strain appeared to be similar in each case. However, the strain that would be seen would be small and cannot be visualized. This parameter should have been tracked for validation of this model. Again, the limitations of this model that will be explained in subsequent sections will suggest that this model is not an entirely valid method of measuring longitudinal stress in the UCL.

The validation of this model in Ansys 13 was only comparable to changing two model parameters. The nine simulations were done under a fine (1) mesh with 20-node brick elements. The first model parameter that was changed was the element type. Under a loading condition of 60 Nm of Valgus torque with a 6mm thick UCL, a 10 node tetrahedron was replaced in the fine(1) mesh. Seen in Figure 13(d), this model estimated similar stresses in the anterior and posterior stress instances; however, for the center of the UCL, the tetrahedron model overestimated the longitudinal stress by 38.7%. This is not desirable and can perhaps be attributed to the tetrahedron element having fewer nodes to compute a path of stress. For the second modification, the meshing was reduced to a coarse(6) mesh. Visually, in Figure 12, the coarse mesh resulted in a very staggered solution. This introduces a large amount of error in Ansys' ability to compute stress distributions in the location consistent to the finely meshed model. Quantitatively, the coarsely meshed model yielded a 21.48% lower longitudinal stress than the finely meshed model.

The current model has many limitations. To begin with, the material properties assigned to this model are not ideal. In the first, the UCL has extremely non linear properties. In the second, the UCL is anisotripic due to the orientation of the ligament fibers. This was not accounted for in the model at hand; however, only longitudinal direction stresses were analyzed. Also, Young's Modulus was only estimated. No measure of Young's Modulus for the UCL was found in the literature. In the third, the type of loading of the UCL is during a dynamic action. While I have access to these dynamic loading conditions, a static model was computed for simplicity. In the fourth, the dimensions of the model are elementary at best. While the UCL has an anatomical size and shape of the model used, the true contours of the UCL were not accurately modeled. If I were to redo this exact experiment with the same limitations, I would have made both the anterior and posterior sides curved to eliminate the skewed results that occurred due to asymmetry in the current UCL model. For instance, since one end was straight, the curved edge underwent compression. This would not occur in a UCL and invalidates the measurements made on the anterior side of the UCL.

In the future, these four limitations need to be addressed.

On the note of future work and addressing said limitations, there is a strong need to investigate the material properties of UCL's from a pitcher's arm. While UCL's have been tested under

various loading conditions, authors have used elderly ligaments which can be shown to be far less strong than ligaments from young adults. As well, no author reported any modulus of elasticity or other non-linear parameter useful for mechanical modeling of the UCL.

Additionally, for a more accurate relationship to be developed and reported, the UCL dimensions need to be gathered from an MRI. The thickness could then be modified such that the orientation and characteristics of the UCL do not deviate from the true shape. With both accurate material properties and an accurately shaped model, perhaps more variability could then be explained by the regression equations.

REFERENCES:

- [1] Aguinaldo, A; Chambers, H "Correlation of Throwing Mechanics with Elbow Valgus Load in Adult Baseball Pitchers" – The American Journal of Sports Medicine 2009 (37) 2043-2048.
- [2] Andrews, JR; Erik, J; Heggland, H; Fleisig, GS; Zheng, N "Relationship of Ulnar Collateral Ligament Strain to Amount of Medial Olecranon Osteotomy" – The American Journal of Sports Medicine (2001) – Vol.29 No.6 – (716-721)
- [3] Berra, Lindsay "Force of Habit" ESPN The Magazine http://espn.go.com/mlb/story/_/id/7712916/tommy-john-surgery-keeps-pitchersgame-address-underlying-biomechanical-flaw-espn-magazine, Published 3/23/2012, Accessed 4/21/2012.
- [4] Chu, Yungchien; Fleisig, G; Simpson, K; Andrews, J "Biomechanical comparison between elite female and male baseball pitchers" – Journal of Applied Biomechanics – 2009 (25) 22-31.
- [5] Center for Diabetes "Fast Facts on Global Diabetes" http://diabetes.niddk.nih.gov/dm/pubs/statistics/#fast – Accessed 4/21/2012.
- [6] Dillman, C; Fleisig, G; Andrews, J "Biomechanics of Pitching with Emphasis upon Shoulder Kinetics" – Journal of Orthopedics and Sports Physical Therapy 1993 (18) 402-408.
- [7] Dugas, JR; Ostrander, RV; Cain,L; Kingsley, D; Andrews, JR "Anatomy of the anterior bundle of the ulnar collateral ligament" – Journal of Shoulder and Elbow Surgery (2007) – Vol.16 No.5 (657-660).
- [8] Escamilla, R; Fleisig, G; Barrentine, S; Andrews, J; Moorman, C "Kinematic and Kinetic Comparisons between American and Korean Professional Baseball Pitchers" – Journal of Sports Biomechanics – 2002 (1) 213-228.
- [9] Fang-Lin, DS; Navojat, K; Perlmutter, S; Lim, D; Nuber, G; Makhsaus, M "Muscle contribution to elbow joint valgus stability" – Journal of Shoulder and Elbow Surgery (2007) – Vo.16 No.6 (795-802)
- [10] Feltner, Michael; Dapena, Jesus "Dynamics of the Shoulder and Elbow Joints of the Throwing Arm During a Baseball Pitch" – International Journal of Sport Biomechanics – 1986 (2) 235-259.

- [11] Feltner, Michael; Dapena, Jesus "Three-Dimensional Interactions in a two-segment kinetic chain. Part 1: General Model" – International Journal of Sport Biomechanics – 1989 (5) 403-419.
- [12] Feltner, Michael "Three-Dimensional Interactions in a Two-Segment Kinetic Chain. Part II: Application to the throwing arm in baseball pitching" – International Journal of Sport Biomechanics – 1989 (5) 420-450.
- [13] Fleisig, G; Andrews, J; Dillman, C; Escamilla, R "Kinetics of Baseball Pitching with Implications About Injury Mechanisms" – American Journal of Sports Medicine 1995 (23.2).
- [14] Fleisig, G; Barrentine, S; Zheng, Nigel; Escamilla, R; Andrews, J "Kinematic and kinetic comparison of baseball pitching among various levels of development" – Journal of Biomechanics - 1999 (32) 1371-1375.
- [15] Garner, J "Kinematic and kinetic comparison of overhand and underhand pitching: implications to proximal-to-distal sequencing" – Unpublished dissertation – Auburn University, 2007.
- [16] Hong, D; Cheung, Tak; Roberts, E "A three-dimensional, six-segment chain analysis of forceful overarm throwing" – Journal of Electromyography and Kinesiology – 2001 (11) 95-112.
- [17] Hurd, W; Eby, S; Kaufman, K; Murthy, N "Magnetic Resonance Imaging of the Throwing Elbow in the Uninjured, High School-Aged Baseball Pitcher" – The American Journal of Sports medicine – 2011 (39.4) 722-728
- [18] Long, J; Hansen, B Medical College of Wisconsin Sports Medicine Laboratory Database (2005-2011).
- [19] Long J; Hansen, B; Raasch, W "The Influence of Pitch Velocity on Upper Extremity Biomechanics" Pending Publication (2010-2011).
- [20] Mirowitz, SA; London, SL "Ulnar Collateral Ligament Injury in Baseball Pitchers: MR Imaging Evaluation" - Journal of Radiology 1992 – Vo. 185, N. 2 (573-576)
- [21] Morrey, B; An, K "Articular and Ligamentous contributions to the stability of the elbow joint" The American Orthopedic Society for Sports Medicine 1983 (11) 315-319.
- [22] Nazarian, L; McShane, JM, Ciccotti, MG; O'Kane, PL; Harwood, Marc "Dynamic US of the Anterior Band of the Ulnar Collateral Ligament of the Elbow in Assymptomatic Major League Baseball Pitchers" – Journal of Radiology (2003) – Vol. 227 No.1 (149-154).
- [23] Neumann, Donald; "Kinesiology of the Musculoskeletal System" Section 1: The Upper Extremity, Chapters 2-8.
- [24] Pappas, A; Zawacki, R; Sullivan, T "Biomechanics of baseball pitching. A preliminary report" American Journal of Sports Medicine 1985 (4) 216-222
- [25] Sabick, M; Torry, M; Lawton, R "Valgus torque in youth baseball pitchers: A biomechanical study" Journal of Shoulder and Elbow Surgery 2004 (13) 349-355
- [26] Synder, S; Karzel, R; Pizzo, D "SLAP lesions of the Shoulder" Journal of Arthroscopy 1990 (6) 275-279
- [27] Timmerman, LA; Andrews, JR "Histology and Arthroscopic Anatomy of the Ulnar Collateral Ligament of the Elbow" – The American Journal of Sports Medicine (1994) – Vo.22 No.5 (667-673)

- [28] Werner, S; Flesig, G; Dillman, C; Andrews, J "Biomechanics of the Elbow during Baseball Pitching" - Journal of Orthopedics and Sports Physical Therapy 1993 (17) 274-278
- [29] Werner, FW; Toarmina, JL; Sutton, LG; Harley, BJ "Structural Properties of 6 Forearm Ligaments" Journal of Hand Surgery (2011) Vol.36A (1981-1987)
- [30] Werner, S; Murray, T; Hawkins, R; Gill, T "Relationship between throwing mechanics and Elbow Valgus in professional baseball pitchers" 2002 (11) 151-155
- [31] Raasch, WG Personal Discussion of UCL Tears in Baseball Pitchers, 4/15/2012.