Spring 5-5-2015

Comparison of Neutral versus Extended Wrist Pushup for Patients with Wrist Injury

Emily Tucci
Syracuse University

Abstract

Introduction: The scapholunate interosseous ligament (SLIL) is a crucial stabilizing structure of the wrist. Damage to this ligament often results from falling upon an outstretched hand, leading to carpal instability.[1,2,3] Tears to the SLIL create a gap in the scapholunate joint and allow the scaphoid to flex and the lunate to extend, rather than moving with one another as they do in healthy physiologic motion.[4,5] The SLIL is normally repaired following injury in order to decrease the risk of arthritis and pain.[1,2,5,6,7] Patients will often begin rehabilitation exercises after SLIL repair in order to reduce recovery time.[8,9] In high activity patients, such as athletes, a pushup regimen of gradually increasing difficulty is often implemented to strengthen the upper body for rehabilitation.[9] We hypothesize that normal military style pushups, with the wrist in extension, produce greater loads on the scaphoid and lunate than pushups performed with the wrist in neutral.

Methods: Four fresh cadaver arms with Geissler Classification of III or IV were selected for testing.[10] Each specimen was sinusoidally loaded in axial compression using a MTS Bionix 858 to 50% body weight with the wrist first in neutral and then in extension. The radius and ulna of each specimen were cut 6" proximally of the radialulnarcarpal joint (RUCJ) and were potted in a metal alloy. Molds of the hand curled into a fist were made in order to stably fix the hand during testing with the wrist in neutral. Pressure sensors were inserted through the dorsal side of the hand into the RUCJ and anchored to screw eyes in the radius and ulna with sutures. Optical sensors were rigidly fixed to the lunate, scaphoid, and radius in order to track relative motion during testing.

Results: The peak pressures in the ulnar carpal, radiolunate, and radioscaphoid fossas increased from the neutral to extended wrist position by 243%, 145%, and 183%, respectively. Two-sided paired t-tests showed a significant difference in peak pressure for all three fossa ($p < 0.05$). The centroid of the pressure also moved more dorsally in extension than neutral. The dorsal change in the centroid was: 5.3 mm for the ulnar carpal fossa ($p < 0.05$); 6.2 mm for the radiolunate fossa ($p < 0.05$); and 5.3 mm for the radioscaphoid fossa ($p < 0.001$). There was no significant difference in the area of pressure or change in centroid location in the radial/ulnar direction for each fossa for the two wrist positions.

Discussion: Increases in pressure inside a joint is associated with an increase in pain for the patient. Therefore, the significant increase in peak pressure during military pushups suggests that neutral pushups will result in less pain in the wrist. Specifically, the high pressures on the dorsal rim of the RUCJ during the extended wrist pushups could lead to degradation of the joint within that area. The lower peak pressures experienced in the RUCJ indicate that patients with a damaged or weakened SLIL should employ neutral rather than military style pushups in order to minimize recovery time and pain.

Executive Summary

Prevalence of wrist injuries is on the rise and is a large orthopedic issue today.[11] Many of these injuries are caused by falls, where the person reaches out palm first to the ground to catch him or herself.[1,2,3] This commonly results in a tear to the SLIL; the ligament connecting the scaphoid and lunate (Figure 1). If this ligament is not surgically repaired, the capitate can drop between the scaphoid and lunate, creating a gap and causing pain and increased potential for development of arthritis (Figure 2). [1,2,5,6] A spectrum of surgical repair options exist, each of which require a long rehabilitation time.

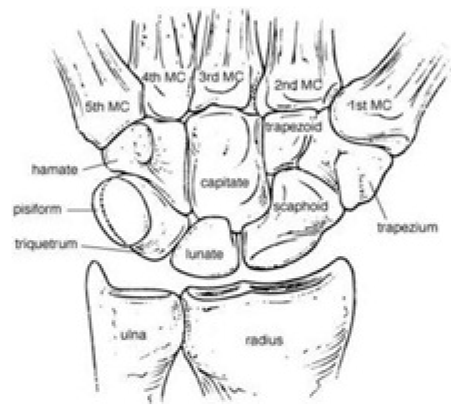

Figure 1. Bones of the Wrist
http://classconnection.s3.amazonaws.com

This type of wrist injury is prevalent among athletes. [2,3,5,9] Their rehabilitation normally includes exercises to return them to their activity level before injury.[8,9] A common rehabilitation practice for strengthening the upper body includes a pushup regimen.[9] Normally, pushups are performed in military style with the wrist extended (Figure 3), which will often cause wrist pain in people even without prior damage to the wrist.[12] Another style of pushup is where the person makes a fist and does the pushup with the wrist in the

Figure 2. Wrist with gap between scaphoid and lunate
http://www.learningradiology.com/

neutral position (Figure 3). Rehabilitation specialists try to minimize the recovery time and therefore would want to use the pushup style that has the lowest potential to damage the surgical repair. These two pushup styles can be compared by looking at the contact pressures in the RUCJ and the positional change of the scaphoid and lunate. We hypothesize that pushups done with the wrist extended cause higher peak RUCJ pressures than those done in the neutral position, which may lead to arthritis. In addition, we believe that pushups performed in the extended position with the presence of a weak SLIL repair or torn SLIL will cause abnormal positions of the scaphoid and lunate, leading to more pain and extending rehabilitation time. A cadaver study was used in order to test this hypothesis.

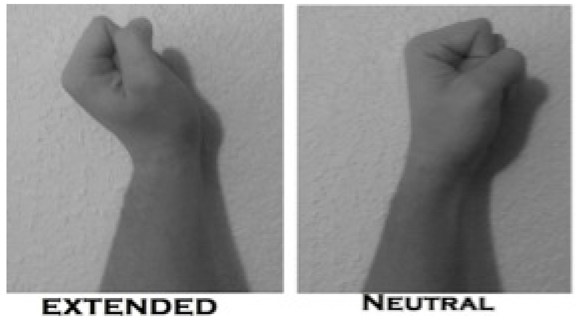

Figure 3. Wrist Position
http://1.bp.blogspot.com/

Each “pushup” was simulated by applying a sinusoidal force equal to half the donor’s body weight. The forearm was fixed to one side of the testing device using a metal pot (Appendix C Figure 7), and the hand was held in place on the opposite side through use of one of two fixtures. For tests with the wrist in extension, a board with dowels inserted between the fingers is used to prevent the hand from sliding (Appendix C Figure 6a). In neutral wrist position, a low melting point metal alloy was used to make a mold of the fist (Appendix C Figure 6b-c) that the hand could be placed in before testing. Pressure sensors were inserted into the RUCJ through the dorsal side of the wrist (Figure 4). The sensors were held securely to screw eyes in the radius and ulna by sutures. The resultant contact pressure map between the proximal carpal bones and the radius was used to determine the change in the peak pressure and its location in the joint. Optical motion sensors were attached to the scaphoid, lunate, and radius to collect positional data during testing. This data was then used in order to create three-dimensional models of the bones in order to analyze their movement during testing.

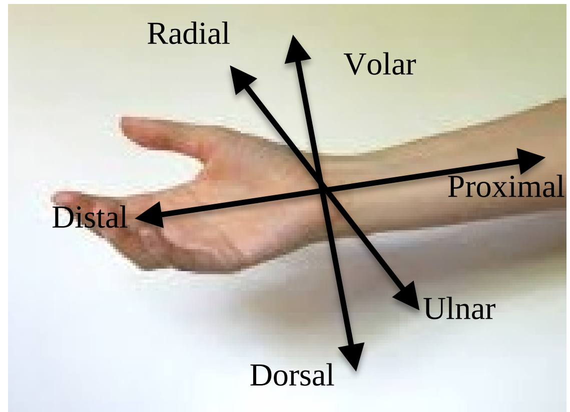

Figure 4. Definition of Axes Directions
isostock.deviantart.com

The results from this study can be used to improve the quality of life of people suffering from SLIL injury. Hand and wrist injuries account for 5 – 9% of all sports injuries.[2,5] At the high school level, fractures of the hand were the most common, at 40%.[2] Of these the scaphoid has the highest rate of fracture, 60 – 90% of all carpal fractures.[9] Guidelines for rehabilitation following SLIL injury not only apply to athletes, but to all patients who wish to return to a high level of activity after recovery. Epidemiological data reported an incidence of wrist trauma to be at 69 out of 10,000 inhabitants a year.[13] Approximately 20-30% of patients who injure their wrists have carpal instability; of which 75% were due to ligament disruption.[11] Applying this to the current population of the United States, the total number of ligamentous wrist injuries in the US would be about half a million people per year.

Table of Contents

Acknowledgements

I would like to thank Professor Frederick Werner for his guidance and assistance throughout the completion of my capstone. Additionally, I would like to thank Brett Daly for performing the Geissler classifications necessary for specimen selection, as well as Mark Miller for helping to make the optical sensors. Thanks to Dr. Julie Hasenwinkel for reviewing the written portion of my capstone. This project would not have been possible without the support of Upstate Medical University and the Renee Crown University Honors Program Crown Award.

Introduction

In normal physiologic motion, the SLIL connects the scaphoid and lunate causing them to move in unison with each other.[3,4] Dissociation of the scaphoid and lunate is the most common cause of carpal instability.[1,2,6,7] This dissociation is typically caused by damage to the SLIL, often resulting from a fall upon an outstretched palm.[1,2,3] Degree of tearing in the SLIL is defined by the four Geissler classes.[10] Complete tears fall under Geissler class III and IV, where the radiocarpal joint displays incongruence and a probe or 2.7 mm arthroscope can be passed between the scaphoid and lunate.[10] Such injury will cause rotatory subluxation of the scaphoid, as well as abnormal loading patterns and kinematics within the wrist.[1,7] Previous studies have found that severe damage to the SLIL allows the scaphoid to flex and the lunate to extend.[4,5] If left untreated, these alterations typically lead to pain and development of scapholunate advanced collapse arthritis.[1,2,5,6]

Acute repair of the SLIL provides the greatest chance for long-term recovery.[1] There is currently a large range of repairs including capsulodesis, ligament reconstruction or replacement, Kirschner wire fixation, and intercarpal fusion.[1,6,7] Although each of these modes of repair differ from each other, all are followed by a long rehabilitation period, during which the patient has reduced strength and range of motion.[4,5] Depending upon the level and type of activity to which the patient plans on returning, the estimated time for full recovery can range from several months to over 6 months.[5] Injury to the wrist is very common among the athletic population, with damage to the scaphoid being the greatest occurrence within this subset of injuries.[2,3,5,9]

In order to return to the high performance level demanded of athletes, rehabilitation normally includes pushups of gradually increasing difficulty.[9] Different variations of a pushup, such as wall, modified, or full body weight pushups, can be used to change the degree of difficulty.[9] The commonly accepted form used for full body weight pushups is military style, with the wrist in extension. However, knuckle pushups, where the wrist is in neutral, also utilize the person's full body weight. Pressures within the RUCJ, as well as motion of the scaphoid and lunate, have yet to be compared between these two pushups styles in the presence of a damaged SLIL.

We hypothesize that military style pushups cause higher peak RUCJ pressures than knuckle pushups, which could lead to arthritis. In addition, we believe that pushups performed with the wrist in extension that have a weakened or torn SLIL will result in atypical motions of the scaphoid and lunate, increasing the magnitude of pain and duration of rehabilitation.

Methods

Four fresh cadaver forearms were tested using a MTS Bionix 858 Testing System. In order to select specimens with SLIL injury, the arms were first examined arthroscopically to determine Geissler Classification.[10] Only specimens of class III and IV were selected for use, while class I and II were excluded from the study. The specimens collected were numbered 9858, 9794, 9865, and 9968. Based off of prior studies analyzing forearm rotation during a pushup, the forearms were fixed at 65^{o} of pronation by inserting a screw through the radius and ulna.[14] If 65^{o} could not be achieved, then maximum pronation was used. The radius and ulna of each forearm was then cut 6 inches proximally of the RUCJ and all soft tissue down to the interosseous membrane was dissected away from the 4 most proximal inches. The proximal 2 inches of the radius and ulna were potted in a low melting point metal alloy such that the radius was vertical (Appendix C Figure 7). Utilizing an alignment device, a mold was taken of the hand curled into a fist for stable fixation in neutral flexion/extension with the 2^{nd} metacarpal vertical to produce slight ulnar deviation (Appendix B Figures 6b-c). The skin was removed from the dorsal side of the hand and fingers in order to reduce compliance that could lead to sliding of the hand within the mold. The metal alloy was built up higher on the dorsal side of the hand to prevent buckling of the wrist that could occur in specimens with carpal instability.

Composite posts were then inserted into the scaphoid and lunate in order to achieve rigid fixation of optical sensors to track motion during testing.

Kirschner wires were first drilled into the desired locations and fluoroscopic images were taken to check for proper positioning (Appendix A Figure 6a-b). A 3.2 mm cannulated drill was then aligned over the Kirschner wires and used to create the holes for the composite posts. Two posts were inserted into the radial side of the scaphoid, such that neither impinged on the radial styloid during testing (Appendix A Figure 6a). Originally, one post was secured into the dorsal side of the lunate so that it was ulnarly deviated (Appendix A Figure 6a-b). A second volar post was then added into the lunate to more rigidly hold the lunate optical sensor. Epoxy was used to set the posts into the bones and allowed to fully harden before testing. Two metal posts were also drilled into the radius at the proximal end of the exposed bone for attachment of the radial sensor. Optical sensors implementing passive markers were used with a NDI Polaris Spectra system for this study (Appendix C Figure 7).

Tekscan 10,000 psi pressure sensors were used to collect pressure data in the RUCJ. The quad fingers of each sensor were calibrated before testing. Either two or three quad fingers were aligned next to each other in a pressure packet so that they would be able to cover the area from the radial styloid to just past the radiolunate fossa (Appendix C Figure 8). The specimens were cut along the dorsal side of the hand to gain access to the RUCJ. The incision was just long enough to insert the pressure packet while maintaining as much of the supporting dorsal ligaments as possible. Screw eyes were drilled into the dorsal and volar side of both the radius and ulna. Three sutures tied around the volar edge of the pressure packet (radial, neutral, and ulnar side) were then anchored to the volar screw eyes to hold the sensors in place. Two sutures on the dorsal side (radial and ulnar) were tied to the dorsal screw eyes.

During testing in the MTS the radial pot was bolted to one platen and the fixture for the hand was secured on the opposite platen. For neutral testing this fixture was the metal alloy mold described previously and was also bolted into place. For extension, a polymer board was clamped to the opposite platen. Dowels could be placed between the fingers of the hand and into the board at multiple locations allowing for adjustability for different hand sizes (Appendix B Figure 6a). Simulation of a pushup was achieved by sinusoidally applying a compressive axial force to the specimens under load control to a peak of 50% donor's body weight. Each trial was run for 10 cycles, at 5 seconds per cycle, to allow for relaxation of the tissue. Force data from the MTS, pressure data from the Tekscan sensor, and optical data from the NDI Polaris were collected at 102 Hz, 60 Hz, and 30 Hz, respectively. The optical data often required multiple trials in order to get the optical sensor positioning and camera placement correct such that all the sensors could be seen for the duration of the trial. To prevent degradation of the pressure sensor, which could occur over the course of multiple trials, the specimens were first tested collecting only pressure and force data. Neutral wrist position was tested first, followed by extended. Optical data was then collected for both neutral and extension.

Following testing, the borders of the radioscaphoid, radiolunate, and ulnar carpal fossas were drawn on the pressure packet (Appendix C Figure 8). Using these borders the corresponding rows and columns of each quad finger was determined for each fossa. Peak pressure, centroid location, and area of pressure were determined for all three fossas. The origin of the x and y coordinates of the centroid was the most ulnar and volar corner of the pressure packet. The pressure data from the Tekscan sensors was synchronized with the axial loading using a cross correlation (Appendix E Figures 10a-b). Using this, data from the 9^{th} cycle of both the neutral and extension tests could be extracted and compared using two-sided paired t-tests. The percent change in max pressure from neutral to extension was calculated for each fossa with the exception of fossa that experienced no pressure above the threshold of the sensor.

Three-dimensional models were created for each specimen. All soft tissue was removed from the scaphoid, lunate, and radius after testing. Points describing the surface of the bone were collected at 20 Hz using a stylus. This cloud of points was then imported into Geomagic Studio in order to create a surface wrap of the bones. These models were then imported into 3D Studio Max. The optical data collected during testing was transformed from Quaternions to Euler Angles and used to drive the motion of the models. The radial sensor was used as the global reference during testing, so the scaphoid and lunate move relative to the radius in the models. Motion was observed qualitatively for the lunate and scaphoid.

Results

The peak pressure in the RUCJ was greater in extension than in neutral for all three fossas (Table 1). There was no pressure detected in the ulnar carpal fossa of specimen 9794 or the radiolunate fossa of specimens 9794 or 9858 when in the neutral wrist position. Percent change in peak pressure was not calculated for these fossas. The average increase in peak pressure for the radioscaphoid, radiolunate, and ulnar carpal fossas were 183%, 145%, and 243%, respectively. The pressures in the two wrist positions were statistically different (Table 3).

Location of the centroid was more dorsal in extension than in neutral (Tables 2a-b). On average the centroid moved dorsally in extension by 5.3 mm for the radioscaphoid fossa, 6.2 mm for the radiolunate fossa, and 5.3 mm for the ulnar carpal fossa. The difference in location of the centroids in the dorsal/volar direction was statistically significant for each fossa (Table 4). The difference in centroid location from neutral to extended in the radial/ulnar direction was not statistically significant for any of the fossa (Table 4). There was no statistically significant difference in the area that the pressure was distributed over between neutral and extended (Table 4). Using a power analysis, with 95% confidence and 90% power, it was determined that the minimum number of samples needed to achieve significance for the area of pressure was 20 for the radioscaphoid fossa and 15 for the ulnar carpal and radiolunate fossas. Eleven samples would be necessary to show significant difference for the location of the centroid in the radial/ulnar direction for the radiolunate fossa. The radial/ulnar direction of the centroids for the radioscaphoid and ulnar carpal fossas both require at least 69 samples to show significance.

% Increase in Peak Pressure from Neutral to Extended			
Specimen	**UC**	**RL**	**RS**
9794	-	-	232
9858	76	-	207
9865	136	65	100
9968	517	226	192
average	243	145	183

Table 1. Percent Increase in Peak Pressure for 9th Cycle of Neutral and Extended. Percentages were not Calculated for UC and RL of 9794 and RL of 9858 because there was No Pressure Detected in those Fossas for the Neutral Position.

Centroid Location and Area of Pressure for Each Fossa with Wrist in Extension									
	UC			**RL**			**RS**		
Specimen	**Area**	**x**	**y**	**Area**	**x**	**y**	**Area**	**x**	**y**
	mm^2	**mm**	**mm**	**mm^2**	**mm**	**mm**	**mm^2**	**mm**	**mm**
9794	19.35	3.06	4.16	53.23	14.85	10.51	90.32	27.53	11.56
9858	8.06	4.45	12.99	61.29	13.26	7.62	61.29	29.04	11.7
9865	19.35	4.36	10.26	53.23	12.04	9.27	48.39	23.35	9.27
9968	14.52	3.2	10.07	16.13	10.58	9.52	25.81	9.22	10.77
average	15.32	3.77	9.37	45.97	12.68	9.23	56.45	22.29	10.83

Table 2a. Area of Contact and Centroid Location of Each Fossa During Neutral Wrist Position. Location of Centroid Shown by X (Radial/Ulnar) and Y (Dorsal/Volar), with the Origin at the Volar/Ulnar Corner of the Sensor

Centroid Location and Area of Pressure for Each Fossa During Neutral Wrist Position									
	UC			**RL**			**RS**		
Specimen	**Area**	**x**	**y**	**Area**	**x**	**y**	**Area**	**x**	**y**
	mm^2	**mm**	**mm**	**mm^2**	**mm**	**mm**	**mm^2**	**mm**	**mm**
9794	0	0	0	0	0	0	69.35	26.16	5.39
9858	4.84	1.63	3.27	0	0	0	62.9	24.19	6.95
9865	20.97	3.15	6.17	43.55	10.85	6.33	40.32	27.52	4.12
9968	4.84	6.03	6.98	25.81	9.73	5.73	24.19	9.82	5.49
average	7.66	2.70	4.11	17.34	5.15	3.02	49.19	21.92	5.49

Table 2b. Area of Contact and Centroid Location of Each Fossa During Extended Wrist Position. Location of Centroid Shown by X (Radial/Ulnar) and Y (Dorsal/Volar), with the Origin at the Volar/Ulnar Corner of the Sensor

Peak Pressure	p value
UC	0.043
RL	0.012
RS	0.008

Table 3. Results of Paired t-test with 95% Confidence Interval Comparing Peak Pressures of the 9^{th} Cycle of Neutral to Extension.

p values	Area	x	y
UC	0.190	0.491	0.040
RL	0.192	0.140	0.038
RS	0.242	0.860	0.000

Table 4. Results of Paired t-test with 95% Confidence Interval Comparing Area of Contact and Centroid Location of the 9^{th} Cycle of Neutral to Extension.

Figures 9a-d from Appendix D show an example of the 3D models created for a representative arm. The positions of the bones in each figure are taken at low load and at peak load for both extension and neutral. The movements of both bones were small. The flexion/extension of the lunate and scaphoid were less than 5^{o} and the translations in the ulnar/radial direction were less than 3 mm with load. The translations in the dorsal/volar and proximal/distal directions were small for neutral and extended, respectively. For both wrist positions the scaphoid and lunate seemed to move with each other. There was a slight intercarpal gap in one of the samples during the neutral testing, however all other specimens showed little to no gaping. Additionally, there did not seem to be much of a widening of the gap between the scaphoid and lunate with load.

Discussion

The purpose of this study was to determine whether a neutral style pushup would be more beneficial to patients undergoing rehabilitation for SLIL injury than a typical military style pushup. Better rehabilitation practices for SLIL injury has potential to reduce recovery time, as well as improve repair outcomes for patients planning to return to an active lifestyle. Sixty-nine out of 10,000 inhabitants a year are diagnosed with wrist injury.[13] Of these, 20-30% develop carpal instability; 75% of which were caused by ligament disruption.[11] In the United States, this would put the total number of ligamentous wrist injuries at about half a million people per year. In particular, athletes would benefit from this study. Hand and wrist injuries make up 5 – 9% of all sports injuries.[2,5] Compared to other areas of the body the hand is the most common place to fracture, making up 40% of all fractures at the high school level.[2] Sixty to ninety percent of these carpal fractures are within the scaphoid.[9]

Pressure data within the radioscaphoid and radiolunate fossas are of main interest for this study. Although analyzed, pressure in the ulnar carpal fossa will not be used to draw conclusions about pushup style because the percentage of the fossa captured by the pressure packet could not be held consistent for all samples. The higher peak pressures in both the radioscaphoid and radiolunate fossa during loading of the wrist in extension suggest that pain in the RUCJ would be lower with the wrist in neutral. For people suffering with a weakened SLIL, use of military style pushups could cause extra pain to their already irritated RUCJ.

Prior to testing, some of the specimens displayed damage to the dorsal rim of the RUCJ. The dorsal location of the pressure centroid for the extended position explains the presence and location of this damage. These increased dorsal pressures could have triggered the early degeneration of the RUCJ. If a neutral style pushup were used, then the pressure experienced would be further from the dorsal rim and could potentially avoid or reduce instance of this degradation. These findings are consistent with a previous study, analyzing malunited distal radius fractures, which reported similar changes in the dorsal location of the pressure centroid with extension of the wrist.[15]

The small movements described by the optical data and lack of intercarpal gap in the majority of specimens could be attributed to stabilizers other than the SLIL. Secondary ligamentous stabilizers, paired with the bony geometry around the scaphoid and lunate could have provided the support needed to hold the bones close to their normal orientation. Previous studies have shown alterations in the kinematics of the scaphoid and lunate following sequential sectioning of the SLIL, radioscaphocapitate ligament, and scaphotrapezium ligament.[16] Additionally, Rohman et al states that secondary stabilizers may compensate for a weakened SLIL, but that these stabilizers will weaken over time.[1]

There were several limitations to this study. Due to time constraints a relatively small sample size was used. Statistical significance was achieved in the pressure analysis, however trends in the kinematics of the scaphoid and lunate may have been more apparent with a larger number of samples. These trends could have also been clearer if kinematic data was evaluated quantitatively in addition to qualitatively. For example, the change in minimum distance between the scaphoid and lunate could be analyzed in order to determine gap distance throughout loading. Another limitation involves the insertion of the pressure packet. In order to provide adequate coverage of pressure within the RUCJ some of the secondary stabilizers on the dorsal side of the hand were either partially or entirely severed to fit the pressure packet. This could cause alterations to the kinematics of the scaphoid and lunate. Also, due to the simplification of the pushup to a quasi-static event, the forearm could not be allowed to alter its degree of pronation, as is natural during the motion of a pushup.[14] This should not significantly alter the results however, because the neutral and extended positions are being compared from essentially the same instant within the performance of a pushup. Lastly, future testing with Geissler Class I and II specimens could provide greater insight as to how motion and pressure changes with severity of injury to the SLIL.

Conclusion

The purpose of this study was to quantify the pressures within the RUCJ and movement of the scaphoid and lunate during two different pushup styles: neutral and extended. The lower peak pressures within the RUCJ during the neutral style pushup suggest that it will result in less wrist pain than a typical military style pushup with the wrist in extension. This would be especially beneficial to people already suffering from wrist pain, such as that associated with SLIL injury. Also, the lower peak pressures along the dorsal rim during a neutral pushup suggest a decreased risk for development of arthritis over time. These findings indicate that people undergoing rehabilitation for injury to the SLIL should perform pushups using a neutral wrist position instead of extended in order to reduce pain and recovery time.

References

[1] Rohman EM, Agel J, Putnam MD, Adams JE. "Scapholunate Interosseous Ligament Injuries: A Retrospective Review of Treatment and Outcomes in 82 Wrists." *Journal of Hand Surgery.* 2014; 39(10):2020-2026.
[2] Fufa DT, Goldfarb CA. "Sports injuries of the wrist." *Current Reviews in Musculoskeletal Medicine.* 2013; 6(1):35-40.
[3] Chen NC, Jupiter JB, and Jebson PJ. "Sports-Related Wrist Injuries in Adults." *Sports Health: A Multidisciplinary Approach.* 2009; 1(6): 469-477.
[4] Ruby LK, An KN, Linscheid RL, Cooney WP, 3rd, Chao EY. "The effect of scapholunate ligament section on scapholunate motion." *Journal of Hand Surgery.* 1987; 12(5 Pt 1):767-771.
[5] Goldberg, S. H., Strauch, R. E., & Rosenwasser, M. P. "Scapholunate and lunotriquetral instability in the athlete: Diagnosis and management." *Operative Techniques in Sports Medicine, 2006; 14*(2), 108-121.
[6] Berger RA, Imeada T, Berglund L, An KN. "Constraint and Material Properties of the Subregions of the Scapholunate Interosseous Ligament." *J of Hand Surgery.* 1999; 24(5):953-962.
[7] Harvey EJ, Berger RA, Osterman AL, Fernandez DL, Weiss AP. "Bone-Tissue-Bone Repairs for Scapholunate Dissociation." *J of Hand Surgery.* 2007; 32(2):256-264.
[8] Fortier MD, Katzmarzyk PT, Malina RM, et al. "Seven year stability of physical activity and musculoskeletal fitness in the Canadian population." *Med Sci Sports Exerc* 2001; 33:1905-1911.
[9] Binkley, H., Smith, D. L., & Wise, S. "Rehabilitation and return to sport after scaphoid fractures." *Strength and Conditioning Journal, 2012; 34*(5), 24-33.
[10] Geissler WB. "Arthroscopic Management of Scapholunate Instability." *J of Wrist Surgery*. 2013; 2(2):129-135.
[11] Stanley JK, Trail IA. "Carpal Instability." *J Bone Joint Surg Br.* 1994; 76:691-700.
[12] Foldhazy Z, Ardnt A, Milgrom C, et al. "A dynamic biomechanical study of the scapholunate ligament sectioning." *J Hand Surg Am.* 1995; 20:986-999.
[13] Larson CF, Lauritsen J. "Epidemiology of Acute Wrist Trauma". *Int'l J of Epidemiology*. 1993; 22(5):911-916.
[14] Lou, Shu-Zon, Chii-Jeng Lin, Pei-Hsi Chou, You-Li Chou, and Fong-Chin Su. "Elbow Load during Pushup at Various Forearm Rotations." *Clinical Biomechanics.* 2001; 16(5): 408-14.
[15] Short WH, Palmer AK, Werner FW, Murphy DJ. "A Biomechanical Study of Distal Radial Fractures." *Journal of Hand Surgery.* 1987;12(A): 529-534.
[16] Short WH, Werner FW, Green JK, Masaoka S. "Biomechanical Evaluation of the Ligamentous Stabilizers of the Scaphoid and Lunate." *Journal of Hand Surgery.* 2002; 27(A): 991-1002.

Appendix A: Fluoroscope Images

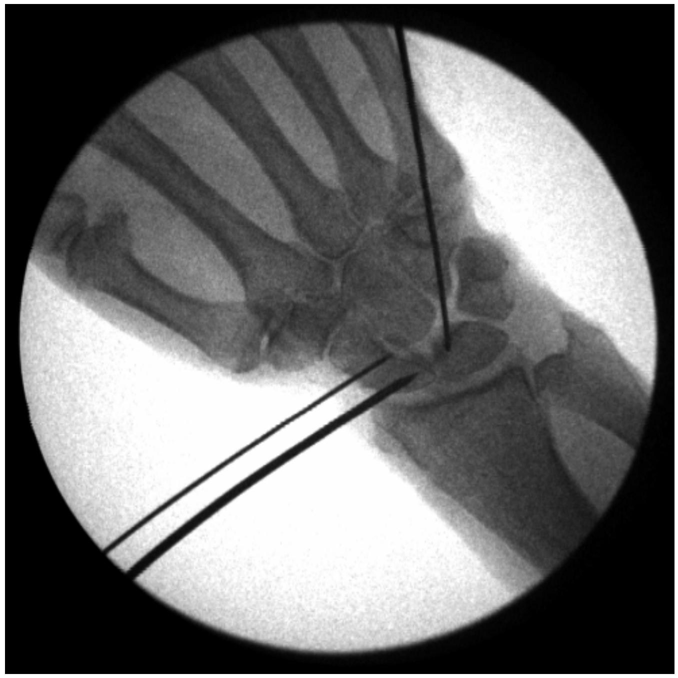

Figure 5a. Fluoroscopic Image of Wrist with Pins Inserted into the Scaphoid and Lunate to show Post Placement (Dorsal View)

Figure 6b. Fluoroscopic Image of Wrist with Pins Inserted into the Scaphoid and Lunate to show Post Placement (Radial View)

Appendix B: Potting Fixtures and Placement

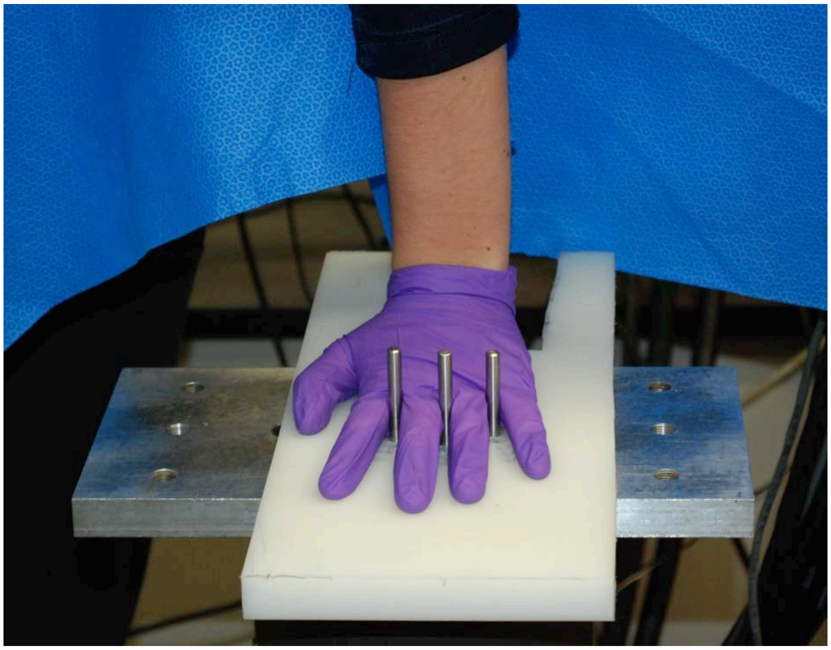

Figure 6a. Wrist Position in MTS during Testing in Extension using Polymer Board with Adjustable Dowel Placement

Figure 6b. Wrist Position in Neutral Potting Fixture with Metal Alloy for Molding of the Hand

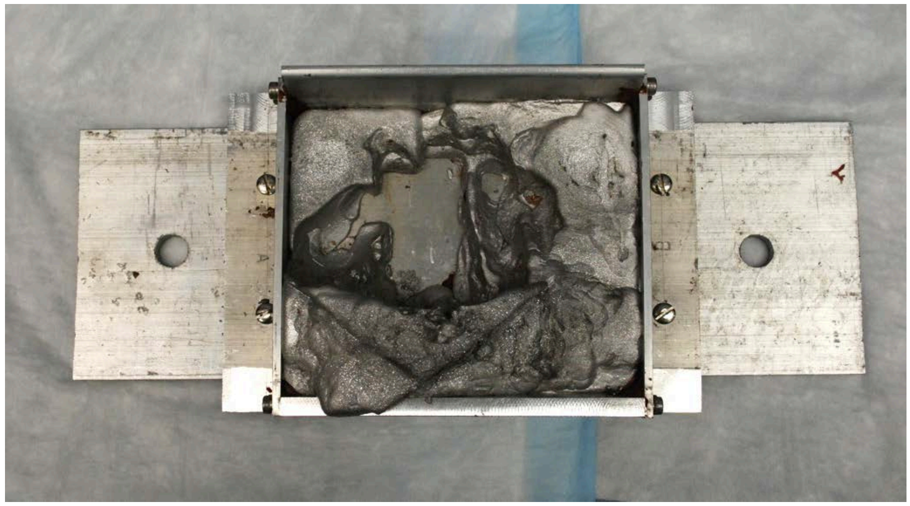

Figure 6c. View from Above of Metal Alloy Mold for the Hand

Appendix C: Sensor Placement

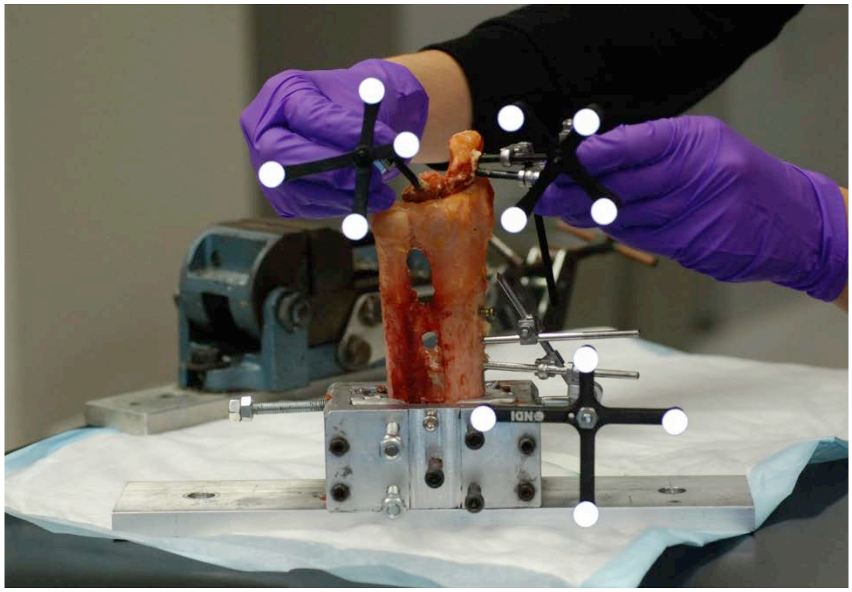

Figure 7. Radius, Ulna, Scaphoid, and Lunate with Optical Sensor Placement after Soft Tissue was Removed

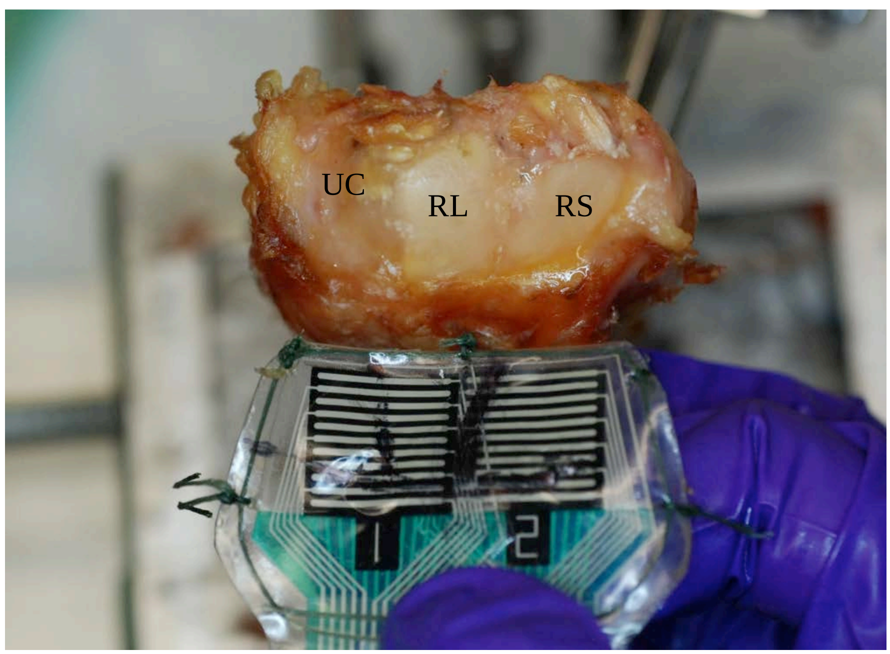

Figure 8. Pressure Sensor after Removal from the Wrist. Lines Drawn on the Sensor Indicate the Borders of the Radiolunate Fossa (RL), Radioscaphoid Fossa (RS), and Ulnar Carpal Fossa (UC) when it was Anchored to the Distal Radius and Ulna

Appendix D: 3D Models

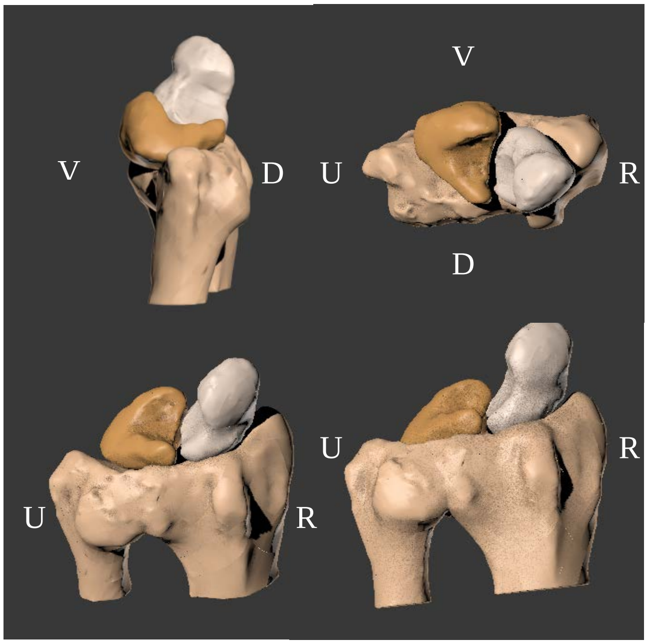

Figure 9a. Multiple Views of 3D Model for a Representative Wrist in Extension Without Load. Orientation is Described by D (Dorsal), V (Volar), U (Ulnar), R (Radial)

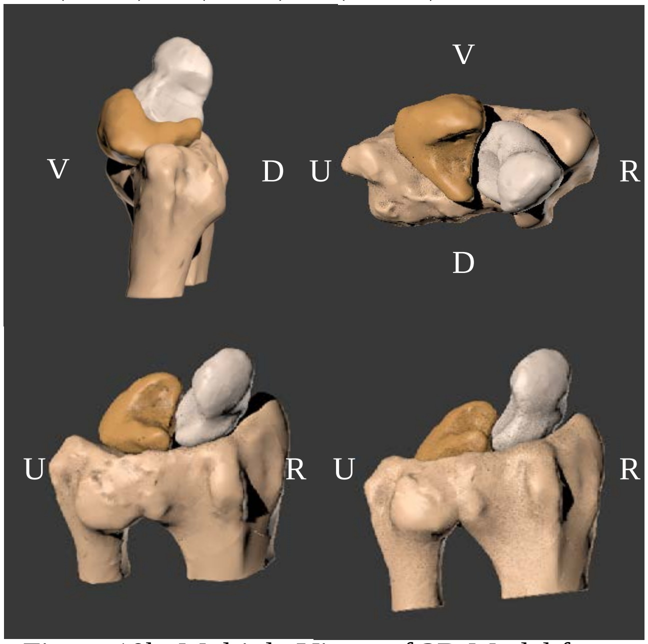

Figure 10b. Multiple Views of 3D Model for a Representative Wrist in Extension at Peak Load. Orientation is Described by D (Dorsal), V (Volar), U (Ulnar), R (Radial)

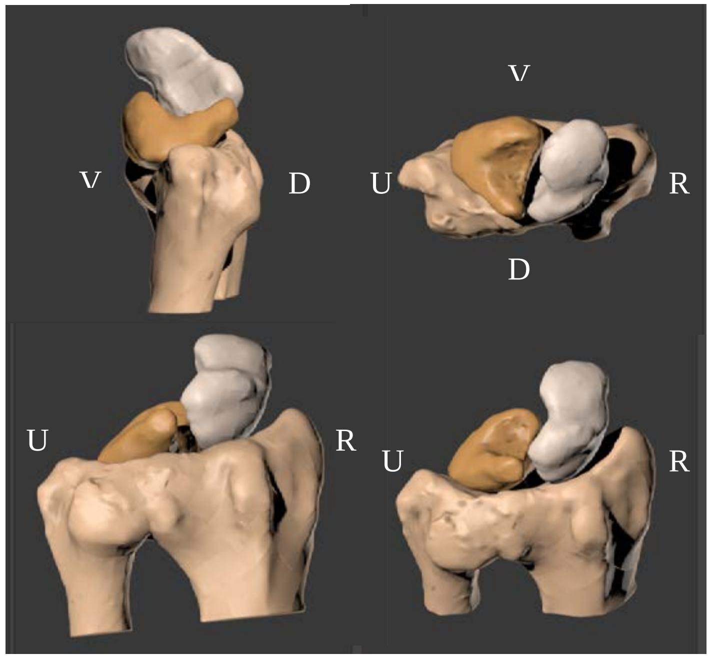

Figure 10c. Multiple Views of 3D Model for a Representative Wrist in Neutral Without Load. Orientation is Described by D (Dorsal), V (Volar), U (Ulnar), R (Radial)

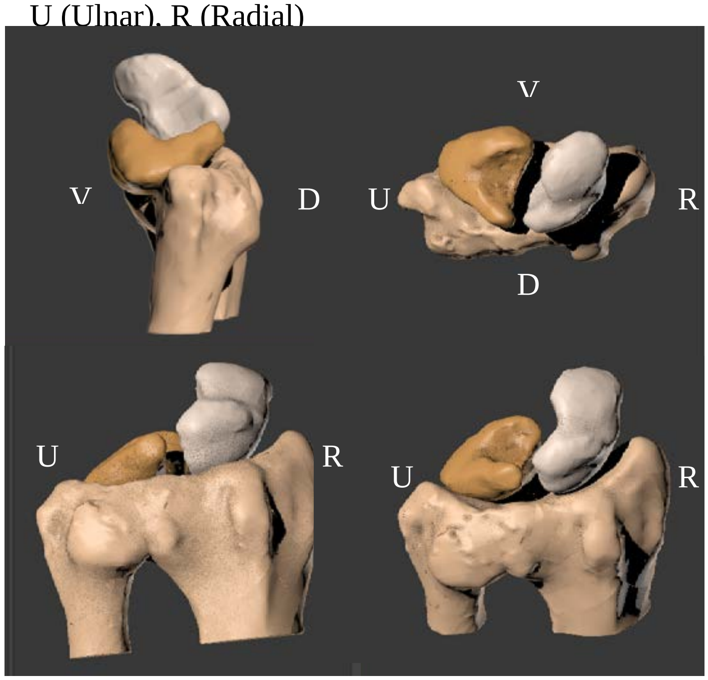

Figure 10d. Multiple Views of 3D Model for a Representative Wrist in Neutral at Peak Load. Orientation is Described by D (Dorsal), V (Volar), U (Ulnar), R (Radial)

Appendix E: Cross Correlation

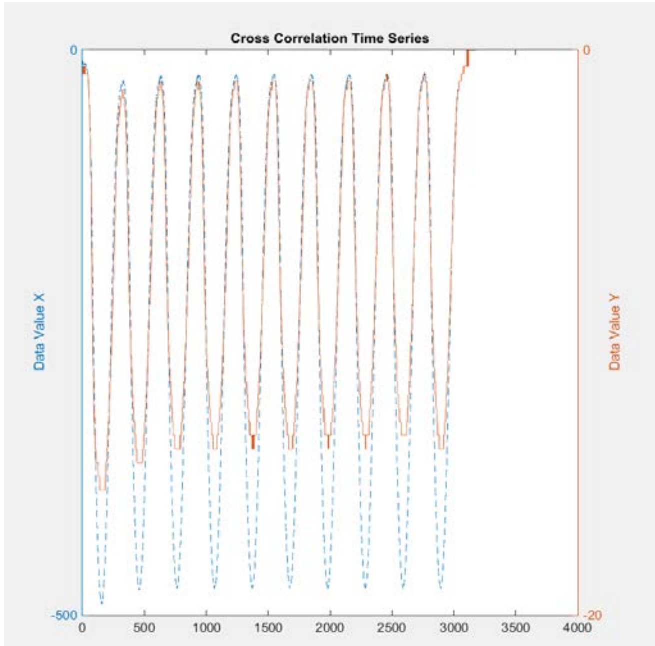

Figure 10a. Output of Matlab Program after the Cross Correlation. Data Series Y is the Peak Pressure and Data Series X is the Axial Force

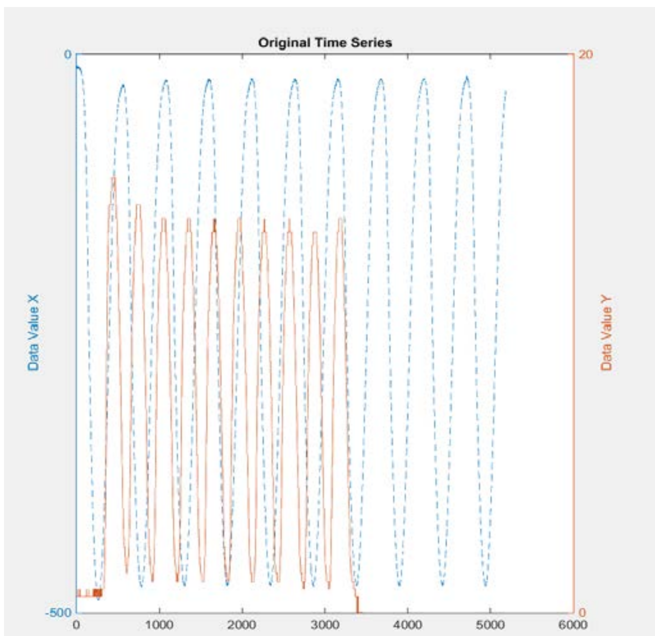

Figure 11b. Output of Matlab Program before the Cross Correlation. Data Series Y is the Peak Pressure and Data Series X is the Axial Force