Bayesian Network-based Diagnostic Support Tool with Limited Point-of-Care Ultrasound for Work-related Elbow Injuries

by

Cristina M. Franceschini Sánchez

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Public Health with a concentration in Occupational Medicine Department of Environmental and Occupational Health College of Public Health University of South Florida

Major Professor: Thomas Bernard, Ph.D.
Rachel Williams, M.D., M.S.P.H
Jared Jeffries, M.D., M.S.P.H

Date of Approval:
March 17, 2022

Keywords: musculoskeletal disorders, POCUS, elbow injuries, diagnostic support tool, Bayesian network

Copyright © 2022, Cristina M. Franceschini Sánchez
DEDICATION

I would like to dedicate this project to my incredible support system: my family, friends, and partner. Everything I have been able to accomplish has been thanks to their love and encouragement, and I will forever be grateful to them.
ACKNOWLEDGEMENTS

I would like to acknowledge NIOSH-supported Sunshine Education and Research Center (CDC/NIOSH T42OH008438) for the opportunity to complete a Master of Science in Public Health at the University of South Florida as well as support for this thesis project. I would like to thank Drs. Alfred Mbah and Thomas Bernard for their contributions to my thesis. My residency Program Director, Dr. Rachel Williams, for giving me the opportunity to reach my professional goals as a physician. Dr. Jared Jeffries, for the incredible help completing this project, but mostly for mentoring me during the past two years. Last, but certainly not least, thanks to Kelly Freedman for her amazing work as residency Program Coordinator.
# TABLE OF CONTENTS

List of Tables ........................................................................................................................................... ii

List of Figures ........................................................................................................................................... iii

Abstract .................................................................................................................................................... iv

Introduction ............................................................................................................................................... 1

Methods.................................................................................................................................................... 8

Results..................................................................................................................................................... 15
  Lateral Elbow ......................................................................................................................................... 17
  Anterior Elbow ...................................................................................................................................... 19
  Medial Elbow ........................................................................................................................................ 19
  Posterior Elbow .................................................................................................................................... 19

Discussion ................................................................................................................................................ 21
  Study Inclusion and Exclusion Criteria ................................................................................................. 21
  Elbow Data Demographics ..................................................................................................................... 21
  Lateral Elbow/CET ................................................................................................................................. 22
  Anterior Elbow/Biceps Tendon ............................................................................................................... 25
  Medial Elbow/CFT ................................................................................................................................. 26
  Posterior Elbow/Triceps Tendon ............................................................................................................ 28
  Putting It All Together ............................................................................................................................ 28
  Study Limitations .................................................................................................................................. 30
  Strengths and Future Studies .................................................................................................................. 31

Conclusion ............................................................................................................................................... 33

References ............................................................................................................................................... 34
LIST OF TABLES

Table 1: Acronyms and Meanings ........................................................................................................10
Table 2: Excluded MRI Findings from Predictive Model .................................................................13
Table 3: Sex Distribution of Study Population ..................................................................................15
Table 4: Age of Study Population .....................................................................................................15
Table 5: Cases by Tendon and Grade of Injury ................................................................................17
Table 6: Cases by Ligament and Grade of Injury ..............................................................................17
Table 7: Probabilities of Injury at CET Based on Sex, Age, and Presence of Osteoarthritis .......18
LIST OF FIGURES

Figure 1: Initial Prediction Model with All Variables .................................................................11
Figure 2: Condensed Prediction Model ......................................................................................12
Figure 3: Final Management Model ..........................................................................................14
Figure 4: Age Frequency and Distribution Among Study Population .......................................16
Figure 5: Limited Point-of-Care Ultrasound Flow Chart for Elbow Injuries .........................32
**ABSTRACT**

The upper extremity is commonly injured at the workplace, frequently involving the elbow. Currently, there are not many diagnostic support tools for elbow injuries. Developing a clinical decision support tool would allow for narrowing differential diagnoses and guide management steps in a timely and cost-effective manner. In a descriptive retrospective cohort study, 85 non-contrast elbow MRIs were obtained from a large Workers Compensation insurer database. MRIs were either (a) greater than 2 weeks after first clinic visit, or (b) more than 6 weeks after injury, but (c) not more than 3 months after injury. A Bayesian network-based diagnostic support tool was developed from the elbow MRI results after removing variables that were not sufficiently representative. The common extensor tendon (CET), the most injured structure in this data set in 36 of 85 cases, served as the parent node. The second most injured structure was the distal biceps tendon with injuries present in 19 of 85 cases. By evaluating the most commonly injured structures, most of other injuries were able to be ruled out with limited point-of-care ultrasound examination of the elbow and the prediction model was used to guide clinicians into one of the following management steps: no follow up, conservative management, or surgical referral with advanced imaging (MRI). Finally, a targeted ultrasound algorithm was developed to reduce the point-of-care ultrasound (POCUS) learning curve for less experienced examiners.
INTRODUCTION

Musculoskeletal disorders (MSDs) such as sprains, strains, and tears are some of the most common complaints of work-related risk factors such as reaching overhead, pushing, pulling, and other mechanisms. These risk factors along with repetitive tasks and inappropriate ergonomics allow for musculoskeletal injuries to occur in the workplace (Centers for Disease Control and Prevention [CDC], 2021; Occupational Safety and Health Administration [OSHA], n.d.). Additionally, slips, trips, falls, and struck by or against injuries precipitate a large number of musculoskeletal work injuries each year. In 2018, there were 2.8 reportable injuries and illnesses per 100 workers in the private sector with 1.6 cases per 100 workers requiring days away from work, job transfer, or duty restrictions. Those numbers increase to 3.6 and 1.9 for state government workers, and 5.3 and 2.4 for local government workers respectively (U.S. Bureau of Labor Statistics, 2018). In the private sector alone, there were over 900,000 injuries requiring days away from work, job transfer, or duty restrictions during 2018 (National Safety Council [NSC], n.d.-a). Total work injury costs in 2019 were estimated at $171 billion or $1,100 dollars per United States worker, with an average cost of $42,000 per injury. This includes $53.9 billion in wage and productivity losses and $35.5 billion in medical expenses (NSC, n.d.-b). Furthermore, patients also may develop related psychosocial issues such as depression and dissatisfaction as a result of these work-related injuries that may in turn affect their occupational performance (Alnaser, 2009).

In 2016, the United States spent 17.8% of its budget on health care, roughly twice as much as other developed countries (Papanicolas et al., 2018). Due to increases in healthcare
costs, ultrasound has become an attractive alternative to MRI for diagnostic imaging. It has been shown to be useful in diagnosing musculoskeletal injuries in a timely manner, at the point of care, as well as to decrease expenses. A 2018 paper showed 96% agreement between musculoskeletal ultrasound (MSUS) and MRI (He et al., 2018). Although most soft tissue abnormalities can be seen with MSUS or MRI, MSUS can be done in either in-patient or outpatient settings, performed for repeated assessments, and provide a diagnosis of certain pathologies that can only be evaluated using dynamic movement (Samy Sheta et al., 2020). An often-cited 2008 paper looking at “all comers” estimated that $6.9 billion could be saved in the Medicare system from 2006-2020 if MSUS was substituted for MRI in appropriate cases, which they estimated to be 45.4% of primary diagnoses and 30.6% of all diagnoses (Parker et al., 2008). However, previous work by our group at the University of South Florida demonstrated that, in workers compensation cases that did not require urgent advanced imaging, MSUS and x-ray could reasonably be substituted for MRI in 70% of cases with a cost savings of $224 to $308 per patient (Jeffries, 2019).

In 2018, BLS data shows there were 43,650 arm injuries in the private sector requiring days away from work, job transfer, or duty restrictions, not including shoulder, hand, or wrist (NSC, n.d.-a). Also in 2018, injuries to the arm and shoulder cost on average almost $48,000 per injury (NSC, n.d.-b). Elbow injuries are among the more common occupational injuries of the upper extremity. According to U.S. Bureau of Labor Statistics, in the year 2020 there were 77,800 reported injuries to the upper extremity, with the elbow accounting for over 4,500 of those injuries in the private sector. Additionally, elbow injuries alone were responsible for an average of 19 days away from work (U.S. Bureau of Labor Statistics, 2021). Some elbow injuries have the risk of developing long-term disabilities by way of arthritis, chronic
tendinopathies, and injury recurrence, especially if not diagnosed and treated appropriately (Kjær, 2004).

To assess an adult with elbow pain, the elbow needs to be evaluated in four separate compartments. These compartments are anterior, posterior, lateral, and medial. After reviewing the important anatomical parts of each compartment, the more common pathologies and presentations are first considered. Injuries at the elbow joint include fractures, tendon ruptures, tendinosis, and instability (Kandemir et al., 2002). At the lateral and medial elbow, tendinopathies of the common extensor and common flexor tendons respectively are among the most frequent overuse injuries of the elbow. Lateral epicondylitis has a prevalence of 0.3% to 13.5% in the working population and is more common when compared to medial epicondylitis which occurs in 0.2% to 3.8% of the working population (Shiri et al., 2011). Additional lateral and medial structures that also need to be evaluated include the ulnar nerve, the ulnar collateral and radial collateral ligaments, among others (Malanga, 2016).

At the anterior elbow, the distal biceps tendon inserts at the radial tuberosity. Distal biceps tendon ruptures can be suspected when patients present with anterior elbow pain, weakness of supination and elbow flexion, visible muscle retraction, and absence of biceps tendon palpation on biceps hook test (Kane et al., 2014). Finally, at the posterior elbow, there is the olecranon process of the ulna and its triceps tendon insertion. Of all elbow tendon ruptures, triceps tendon ruptures account for 1% and mainly occur in males (Kholinne et al., 2018). Triceps tendon rupture can be suspected if a patient presents with weakness on elbow extension, tenderness over the olecranon, and are sometimes accompanied by olecranon bursitis (Kandemir et al., 2002; Kholinne et al., 2018). Complete or partial tears and avulsions of the biceps or triceps tendons can be later identified with advanced imaging (Sampath et al., 2013).
Radiographs are the first imaging study ordered when a patient presents with elbow pain. This can potentially rule out bony abnormalities and effusions, but when radiographs are nondiagnostic or provide incomplete evaluation, magnetic resonance imaging (MRI), computer tomography (CT), or ultrasound scans are indicated depending on the suspected injury. MSUS imaging can be considered when there is suspicion for soft-tissue mass, epicondylitis, collateral ligament tear, or biceps tendon tear (Sivan et al., 2010). Additionally, according to the ACR Appropriateness Criteria® for chronic elbow pain, MSUS imaging along with a nerve conduction study has shown to increase the diagnostic sensitivity from 78% to 98% when nerve abnormality is suspected. MSUS is considered an excellent imaging modality to evaluate soft tissue or extra-articular structures of the elbow when used by an experienced practitioner, and roughly equivalent to MRI in these instances (Brandão et al., 2019; Konin et al., 2013; Rosen et al., 2020). The previously mentioned and highly cited Parker et al. paper from 2008 looking at “all comers” showed that 56.6% of elbow injuries found on MRIs could have been adequately evaluated with MSUS (Parker, 2008). However, previous work by our group found that for elbow injuries that did not require urgent advanced imaging, 81% could have been adequately evaluated by MSUS which further increased when combined with x-ray (Jeffries, 2019).

Because of its utility in point of care evaluation, MSUS imaging is now being taught to not only radiologists, but is also being incorporated in most Rheumatology, Physical & Medical Rehabilitation, and Sports Medicine training programs across the United States (Berko et al., 2016). MSUS has been useful in detecting sub-clinical inflammation in joints as well as improving joint injection procedures (Sivan et al., 2010). One study compared the reproducibility of ultrasound and MRI findings on elbow ligaments and reported that there was no significant difference in findings when performed by experienced examiners (Brandão et al., 2019),
highlighting the utility of advanced training in this modality. However, there is an admittedly steep learning curve in performing and interpreting MSUS examinations that can deter adoption by providers. One study showed that an Orthopedic Surgeon who was taught to diagnose rotator cuff tears using MSUS, started with an accuracy of 51% and improved to an accuracy of 69% by the end of the 3-month study period, citing the additional time needed to perform MSUS examinations as a detractor for clinical implementation (Day et al., 2013). Another study showed that when MSUS was implemented in an Orthopedic practice to diagnose rotator cuff tears, specificity increased from 0.5 in the beginning, to 0.8 at the end of the 3-year study period, with sensitivity remaining around 0.85 (McCulloch et al., 2016). In the elbow, a meta-analysis evaluating the accuracy of ultrasound diagnosed lateral epicondylitis found sensitivity ranged from 64-100% and specificity ranged from 36-100%, and the authors recognized that examiner experience was likely a major contributor to the wide variation in sensitivity and specificity, given more experienced practitioners are likely to achieve greater accuracy (Latham et al., 2014).

Therefore, having more expertly trained examiners in MSUS imaging will allow for high quality diagnostic imaging to be more readily available to patients at the point of care in a cost-effective and time-efficient manner. And although useful in clinical settings, there is currently limited literature regarding treatment algorithms or decision support tools after obtaining imaging for clinicians to use regarding musculoskeletal injuries, and more specifically, elbow injuries. It then becomes clear that a robust clinical tool is needed to bridge the gap between the novice and experienced ultrasound practitioner. The appropriate tool should lessen the steepness of the learning curve, be time efficient so as not to disrupt the clinical workflow, as well as have high diagnostic accuracy.
Clinical Bayesian networks are being used for diagnostic support tools to guide clinicians towards the appropriate treatments for different scenarios. Bayesian networks are algorithms used for probabilistic reasoning and can be used in clinical settings for diagnostic and management guidance (Shen et al., 2018). These networks are useful to evaluate relationships between symptoms and diseases, to narrow down differential diagnoses, and guide management in a timely manner. Previous work by our group at the University of South Florida showed that, in workers compensation injuries of the shoulder that did not require urgent advanced imaging, a 2-point MSUS scanning protocol combined with a Bayesian network based clinical decision support tool achieved 96% accuracy in diagnosis and appropriate management of rotator cuff and proximal biceps tendon injuries through internal validation (Ayers, 2021). This type of Bayesian network clinical decision support tool utilizing findings from an abbreviated or simplified MSUS scanning protocol imparts many advantages to the clinician. It has the ability to allow less experienced practitioners to become comfortable and proficient scanning fewer structures of a given joint, focusing on the structures more likely to be pathologic, while still providing high diagnostic accuracy regarding structures that were not scanned, by way of probabilistic inference. It also reduces the amount of additional time needed to perform a diagnostic MSUS exam and provides clear management guidance based on results.

The goal of our current study is to develop a similarly accurate, abbreviated 2–3-point MSUS scanning protocol for workers compensation elbow injuries when a complete history and physical exam do not suggest urgent advanced diagnostic imaging is required. By focusing on only 2-3 elbow structures, and then utilizing results in a Bayesian network that provides probabilistic inference with regard to pathology in other elbow structures that were not scanned, it may be possible to reduce the steepness of the learning curve for less experienced MSUS
practitioners, as well as provide clear medical management guidance while reducing time and cost.
METHODS

A Workers Compensation insurer database that represented 39,000 small and medium sized companies from a vast array of industries across 12 states was used to collect the data for this descriptive retrospective cohort study. Data included non-contrast elbow MRIs that were performed during the year 2017 and were either (a) greater than 2 weeks after first clinic visit, OR (b) more than 6 weeks after injury, but (c) not more than 3 months after injury. MRIs performed from 0 to 2 weeks after injury are assumed to have been ordered due to an injury that had a mechanism of injury and/or physical exam findings significant enough to warrant urgent advanced imaging and potentially requiring immediate medical attention and surgical intervention. MRIs performed after 3 months of injury were excluded because they may have been ordered simply due to lack of symptom resolution with conservative management. MRIs performed greater than 6 weeks after injury but less than 2 weeks from initial clinic visit were included as they may represent injuries where healing or symptom resolution did not occur throughout that time period.

Reports from MRIs that met inclusion criteria were collected and findings were categorized in a spreadsheet based on the anatomical structures or variables. These variables were then categorized with regard to severity score for each case. In tendons for example: 0 = normal, 1 = tendinopathy, 2 = partial tear, 3 = high-grade or complete tear.

The academic version of the GeNIe program developed by BayesFusion LLC in Pittsburg, PA (https://www.bayesfusion.com) was used to produce Bayesian network algorithms to analyze the associations between injury variables and resultant nodes. The final Bayesian
network was used to develop a clinical decision support system for evaluating and treating elbow injuries. Tree Augmented Naïve Bayes and Augmented Naïve Bayes networks were tested and evaluated. Augmented Naïve Bayes network was ultimately the preferred network to develop the model due to simplicity of node associations as well as clinically intuitive node association structure.

Descriptive variables included in the data set were age and sex. Sex was categorized as either male or female and Age was categorized as below 50-years-old and 50-years-old and above. Elbow MRI findings categories in the data set included injuries to the common extensor, biceps, common flexor, triceps and pronator tendons. Ligamentous injuries included ulnar collateral, lateral ulnar collateral, and radial collateral ligaments. Other findings included were effusions, contusions, loose bodies, bicipitoradial bursitis, olecranon bursitis, ulnar neuropathy, and hematoma or hemorrhage. Some findings such as joint effusion or fracture were identified as either present or absent, but other findings were classified based on severity. Tendons were classified as normal, tendinopathy, partial tear, and high grade or full thickness tear. Injury of ligaments was classified as either normal, sprain, partial tear, and high grade or full thickness tear. Cases that were ultimately excluded from the model were those with low incidence and therefore limited predictive value.

A total of 85 non-contrast elbow MRIs were included in the study. The common extensor tendon was the most commonly injured structure, present in 36 of 85 cases. Therefore, the common extensor tendon was chosen as the parent node. The second node was the second most commonly injured structure, the biceps tendon. It was injured in 19 of the 85 cases. These were followed by the common flexor and triceps tendons in descending order of injury incidence in this data set.
Figure 1 shows the initial model which includes all the findings related to the parent node. Findings such as contusion, loose bodies, ulnar neuropathy, olecranon bursitis, injury of the pronator, bicipitoradial bursitis, and injury to ulnar collateral and lateral ulnar collateral ligaments were findings that were linked to the parent node but did not represent a sufficient injury incidence to be included in the final model. Table 2 lists the findings that were excluded from the final and some from the condensed models. Figure 2 shows the condensed model with the findings and variables that appeared on sufficient cases correlated to the parent node.

Table 1

Acronyms and Meanings

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Stands for</th>
</tr>
</thead>
<tbody>
<tr>
<td>CET</td>
<td>Common Extensor Tendon</td>
</tr>
<tr>
<td>CFT</td>
<td>Common Flexor Tendon</td>
</tr>
<tr>
<td>LUCL</td>
<td>Lateral Ulnar Collateral Ligament</td>
</tr>
<tr>
<td>MSDs</td>
<td>Musculoskeletal Disorders</td>
</tr>
<tr>
<td>MSUS</td>
<td>Musculoskeletal Ultrasound</td>
</tr>
<tr>
<td>OA</td>
<td>Osteoarthritis</td>
</tr>
<tr>
<td>POCUS</td>
<td>Point-of-Care Ultrasound</td>
</tr>
<tr>
<td>RCL</td>
<td>Radial Collateral Ligament</td>
</tr>
<tr>
<td>UCL</td>
<td>Ulnar Collateral Ligament</td>
</tr>
</tbody>
</table>
Figure 1. Initial Prediction Model with All Variables

Figure 2. Condensed Prediction Model

Figure 3 shows the model with the most clinically correlated decision categories and high enough incidence to be included. The treatment categories included no follow up, conservative management, and specialty referral with further advanced imaging (MRI) required. The categories for clinical reasoning were chosen for normal findings, tendinopathy or sprains, and high-grade or complete tears. Normal findings were categorized into the no follow up group. Tendinopathy, sprains, and partial tears were grouped for conservative management. Finally, high-grade or complete tears were referred for specialty evaluation and additional imaging.

Table 2

*Excluded MRI Findings from Predictive Model*

<table>
<thead>
<tr>
<th>MRI Findings</th>
<th>Number of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ulnar Collateral Ligament</td>
<td>2</td>
</tr>
<tr>
<td>Lateral Ulnar Collateral Ligament</td>
<td>3</td>
</tr>
<tr>
<td>Olecranon Bursitis</td>
<td>4</td>
</tr>
<tr>
<td>Ulnar Neuropathy</td>
<td>4</td>
</tr>
<tr>
<td>Fracture of Radial Head</td>
<td>3</td>
</tr>
<tr>
<td>Contusion</td>
<td>4</td>
</tr>
<tr>
<td>Contusion</td>
<td>4</td>
</tr>
<tr>
<td>Loose Body</td>
<td>2</td>
</tr>
<tr>
<td>Bicipitoradial Bursitis</td>
<td>1</td>
</tr>
<tr>
<td>Pronator Injury</td>
<td>2</td>
</tr>
</tbody>
</table>
Figure 3. Final Management Model

RESULTS

In our dataset of 85 elbow MRI findings in Workers Compensation injuries, we assume the history of present illness/mechanism of injury or physical examination findings did not warrant advanced imaging within 2 weeks after initial clinic visit. Table 3 presents the sex distribution and Table 4 and Figure 4 present the age distribution of the study population. The ages ranged from 18 to 68 years of age and elbow MRIs were mostly done in men, 84% of subjects. In the prediction model, age was divided into two groups of either less than 50 years-old or 50 years-old and above.

Table 3

Sex Distribution of Study Population

<table>
<thead>
<tr>
<th>Sex</th>
<th>Female</th>
<th>Male</th>
<th>Total Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Data</td>
<td>14 (16%)</td>
<td>71 (84%)</td>
<td>85</td>
</tr>
</tbody>
</table>

Table 4

Age of Study Population

<table>
<thead>
<tr>
<th>Age</th>
<th>Mean</th>
<th>Median</th>
<th>Standard Deviation (SD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Data</td>
<td>46</td>
<td>49</td>
<td>11.11</td>
<td>18 - 68</td>
</tr>
</tbody>
</table>
In our dataset there were no cases with high grade or complete tears of the major stabilizing ligaments of the elbow, the UCL and LUCL, only 4% of subjects had partial tears in either of these structures, and only 4% and 5% respectively had sprains, all of which can be managed conservatively. With respect to the RCL (a non-stabilizing ligament), only 3% of subjects had complete tears, 6% had partial tears, and 3% had sprains, all of which can be managed conservatively. With respect to the CFT, there were no high grade or complete tears, 4% had partial tears, and 20% had tendinosis, all of which can be managed conservatively. High grade or complete tears requiring surgical consultation were present in 4% of triceps, 6% of CETs, and 17% of biceps. Tendinopathy or partial tears that could be managed conservatively were present in 12% of triceps, 12% of biceps, and 37% of CETs. Table 5 shows the number of cases per injury per tendon. Table 6 shows the number of ligamentous findings by grade of injury.
Table 5

Cases By Tendon and Grade of Injury

<table>
<thead>
<tr>
<th>Category</th>
<th>Common Extensor Tendon</th>
<th>Biceps</th>
<th>Common Flexor Tendon</th>
<th>Triceps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>49</td>
<td>66</td>
<td>69</td>
<td>78</td>
</tr>
<tr>
<td>Tendinopathy</td>
<td>22</td>
<td>5</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>Partial Tear</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>High Grade or Complete Tear</td>
<td>5</td>
<td>13</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 6

Cases By Ligament and Grade of Injury

<table>
<thead>
<tr>
<th>Category</th>
<th>Radial Collateral Ligament</th>
<th>Ulnar Collateral Ligament</th>
<th>Lateral Ulnar Collateral Ligament</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>75</td>
<td>83</td>
<td>82</td>
</tr>
<tr>
<td>Sprain</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Partial Tear</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>High Grade or Complete Tear</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Lateral Elbow

The CET was the most often injured structured in our study population with tendinopathy in 26%, partial thickness tears in 11%, and high grade or complete tears in 6%. Keeping in mind that only 17% of subjects in our study were women and only 10% of subjects had osteoarthritis (OA), it is important to note that sex and the presence of OA significantly impacted the probability of pathology. The likelihood of tendinopathy and partial tears was highest for women over 50, especially in the setting of OA. The likelihood of tendinopathy alone is significantly higher in any patient with OA, over 50, and women. The likelihood of tendinopathy or partial
tear is lowest for men under 50 without OA, however, all men generally had double the risk of high grade or complete tear compared to women. Table 7 shows these findings.

### Table 7

**Probabilities of Injury at CET Based on Sex, Age, and Presence of Osteoarthritis**

<table>
<thead>
<tr>
<th>Injury Category</th>
<th>&gt;50 years old</th>
<th>&lt;50 years old</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Women</td>
<td>Men</td>
</tr>
<tr>
<td></td>
<td>+OA</td>
<td>-OA</td>
</tr>
<tr>
<td>Tendinopathy</td>
<td>64%</td>
<td>44%</td>
</tr>
<tr>
<td>Partial Tear</td>
<td>24%</td>
<td>29%</td>
</tr>
<tr>
<td>HG/Complete</td>
<td>2%</td>
<td>3%</td>
</tr>
</tbody>
</table>

In the setting of CET tendinopathy, subjects were more likely to have CFT partial tear, increasing to 32% from a baseline of 20%. Likelihood of pathology in the triceps, lateral ulnar collateral ligament (LUCL), ulnar collateral ligament (UCL), and radial collateral ligament (RCL) remained low and relatively unchanged in the setting of CET tendinopathy whereas the likelihood of biceps high grade or complete tear decreased from 17% to only 3%. In contrast, when the CET is normal, likelihood of CFT tendinopathy drops to 15% and biceps high grade or complete tear increases to 27%. A partial tear of the CET decreased the likelihood of biceps high grade or complete tear to 6% whereas the risk of biceps tendinosis increased to 23% and partial tear likelihood was 6%. A partial tear of the CET increased the likelihood of CFT, LUCL, and UCL tears to 8% from a baseline of 4% while it increased the likelihood of RCL partial tear to 22% from a baseline of 6%. In the 6% of subjects who had high grade or complete tears of the CET, likelihood of partial tears increased to 38% in the RCL, 24% in the LUCL, 12% in the UCL, and 24% in the CFT.
Anterior Elbow

The biceps was the second most injured structure in our study population with likelihood of tendinopathy in 8%, partial tears in 4%, and high grade or complete tears in 17%. Biceps injuries accounted for 19 cases total. All biceps injuries were sustained by men except for one female subject found to have tendinosis. Age was relatively evenly distributed for biceps injuries. OA and the presence of effusions were not associated with biceps injuries. Presence of a hematoma however increased the likelihood of biceps high grade or complete tear to 52% as all hematomas in this dataset were seen in the presence of high grade or complete tears of the biceps. Absence of hematoma reduced the likelihood of high grade or complete biceps tear to 11%. Partial tear of the biceps increased the likelihood of tendinosis in the CET to 48% and CFT to 25%.

Medial Elbow

The CFT was injured in 24% of patients with none having high grade or complete tear, 20% having tendinopathy, and 4% having partial tear. In this dataset, CFT injuries cooccurred with CET injuries in 8 out of 14 subjects; more specifically 6 tendinopathies, 1 partial tear, and 1 complete tear of the CET. While the model predicted an increase in ligamentous injuries that were not observed in the dataset, this is a prediction based on the association between CET injuries and ligamentous injuries. Additionally, 3 out of 4 ulnar neuropathies seen on MRI cooccurred with CFT tendinopathy.

Posterior Elbow

There were 7 triceps injuries involving 1 complete tear, 2 partial tears, and 4 tendinopathies. Triceps injury cooccurred with CET tendinopathy in 2 subjects and olecranon bursitis in 1 subject. There were 4 total cases of olecranon bursitis, so triceps injury was not
associated with olecranon bursitis in this dataset. Again, increases in ligamentous injuries that were not observed in the dataset is a prediction of the model based on the association between CET injuries and ligamentous injuries.
DISCUSSION

Study Inclusion and Exclusion Criteria

The study used elbow MRIs that were performed greater than 2 weeks after first clinic visit, and up to 3 months after the initial injury. MRIs performed within 2 weeks of the date of injury were excluded as they were assumed to be cases where the history of present illness/mechanism of injury and/or physical exam warranted urgent advanced medical imaging of the highest degree and possible surgical referral. The one exception to these criteria was that we included MRIs performed within 2 weeks of the first clinic visit only if it was greater than 6 weeks from the date of injury. The rationale for this exception is that guidelines generally suggest that 6 weeks is a reasonable time period to pursue conservative management, after which, worsening or non-resolving symptoms may warrant advanced imaging. MRIs performed after 3 months from the date of injury were excluded from the data set as they may represent cases where conservative management failed to achieve symptom resolution in the absence of other objective medical evidence of ongoing pathology.

Elbow Data Demographics

Worker age followed a relatively normal distribution, with median of 49 and average of 46, although there was a notable peak in the range between 50 and 54. This is consistent with the larger body of literature where both lateral and medial elbow epicondylitis (the most common elbow injuries) tend to occur in middle age, and injuries in middle age workers tend to require more days away from work, i.e. they are more severe and are therefore more likely to warrant MRI and subsequently be included in our dataset (U.S. Bureau Labor Statistics, 2016). Men
accounted for 84% of subjects in our dataset, which is consistent with BLS data showing that historically, men sustain more work injuries than women and injuries in men result in more days away from work, i.e. injuries in men tend to be more severe (U.S. Bureau Labor Statistics, 2016). Again, since only more severe injuries typically require MRI, and men sustain more work injuries and more severe work injuries, it follows that most subjects in our study of elbow MRIs were men. Additionally, it is common knowledge in the field that men almost exclusively sustain distal biceps and triceps tears, which made up a substantial portion of our dataset, contributing to the overrepresentation of men compared to women. The elbow data were taken from a larger dataset encompassing over 39,000 small to medium sized businesses in a vast array of industries across 12 states throughout 1 calendar year. This means the study is likely representative of the larger working population throughout the United States. It should be noted that we did not have access to clinical notes and therefore physical exam findings, tobacco usage, and BMI of subjects are unknown.

**Lateral Elbow/CET**

Given the CET was the most commonly injured structure, it is therefore the logical place to begin the evaluation, especially if the patient has pain in this area. Physical examination of the CET involves holding the elbow extended with the forearm pronated, have patient make a fist and extend against resistance, then repeat with elbow flexed at 90 degrees. Another test for the CET is to have the elbow extended and wrist pronated, having patient extend middle finger against resistance. Pain at the lateral epicondyle or at 2-4 cm distal from the CET insertion is considered a positive test (Malanga, 2016). Musculoskeletal ultrasound (MSUS) evaluation of the CET involves placing the transducer over the lateral epicondyle in the direction of the radius and ulna, viewing the CET in long axis, and scanning side to side through the full width of the
tendon and its insertion (Jacobson, 2017). Pathology should be confirmed in short axis as well, noting width.

If a high grade or complete tear is seen, MRI and surgical referral should be pursued as this injury necessitates reconstruction, and partial tears of the elbow ligaments and CFT are more likely. It should be noted that all 5 high grade or complete tears of the CET occurred in men.

Age over 50 was the strongest predictor of CET partial tear followed by female sex. A partial tear of the CET increases the probability of partial tear in the CFT which can be evaluated with MSUS and/or physical examination, discussed later in this paper. If a partial tear of the CET is seen, ligamentous injury is more likely, particularly in the RCL, which is supported by Samy Sheta et al. who described an association between lateral epicondylitis and RCL injury. The RCL can be seen in the same view as, and just deep to the CET, inserting on the lower half of the epicondylar slope, meaning these structures can be evaluated concurrently on MSUS evaluation. While RCL injury is important to note, complete tear is not an indication for surgical reconstruction, and can be managed conservatively. The LUCL is the major stabilizing ligament of the lateral elbow, and along with the RCL and the annular ligament, forms the lateral ligamentous complex of the elbow (Camp et al., 2019). Using MSUS, the LUCL can be evaluated by the more experienced examiner by rotating the transducer slightly, spanning between the lateral epicondyle and the tubercle of the supinator on the ulna. Varus stress maneuver can be applied to the elbow while visualizing the LUCL to assess for competence (Jacobson, 2017). Lack of LUCL competence necessitates MRI and surgical referral. The less experienced MSUS examiner can evaluate the LUCL using varus stress to assess for instability. Testing for lateral laxity with a varus stress test assesses both RCL and LUCL integrity. If any laxity is noted, performing a push up test may confirm a RCL and/or LUCL injury. Malanga
describes the push up test as having the patient lying prone, supinating the forearm and flexing
the elbow, then have them push up. Recreation of symptoms indicates a positive test for
significant LUCL injury where patients can go on to develop chronic instability, more
specifically posterolateral rotatory instability (PLRI), which is an indication for surgery (Conti
Mica et al., 2016; Kim et al., 2013).

Tendinosis of the CET is the most common pathology in the elbow and seen in 26% of
subjects in this study. Presence of osteoarthritis (OA), increased age, and female sex all
significantly increase pre-test probability of CET tendinosis according to our results. Women
over 50 with OA have the highest likelihood, and men under 50 without OA have the lowest
likelihood. Presence of CET tendinosis increases the probability of CFT partial tear. Again, the
CFT can be evaluated by MSUS and/or physical examination. And though CET tendinosis
makes biceps partial tear more likely according to the model, it should be noted that biceps
partial tear was seen in only 1 subject out of 85.

CET tendinosis or lateral epicondylitis is known to be the most common elbow pathology
with an incidence of 1-2% in the general population and much higher in middle aged laborers
with occupations requiring repetitive movements or stress, those who smoke, and are overweight
(Degen et al., 2017; Shiri et al., 2011). Though most studies have found prevalence of lateral
epicondylitis between men and women to be roughly equal, our study may have found a higher
rate in women due to a predisposition for increased symptom severity in women working in
certain occupations, prompting MRI. The vast majority of CET tendinosis and partial tears are
treated conservatively and do not prompt MRI, meaning they would not be captured in our study,
and may account for the difference in our findings vs the greater body of literature (Degen et al.,
2017).
Although other elbow studies have not taken into account the presence of OA, which our study showed to be associated with CET injury, previous studies by Meknas et al. and Ibrahim et al. have described this finding in other joints. Meknas et al. evaluated tissue samples from the internal obturator tendon in patients with hip osteoarthritis and compared them to samples from patients without hip osteoarthritis. Ibrahim et al. evaluated tissue samples from shoulders with and without osteoarthritis. Both of these studies concluded that the patients with osteoarthritis had more calcium deposits, scar and degenerative tissue at the tendons. Furthermore, both speculate that early treatment for tendinosis should reduce symptoms of osteoarthritis or potentially slow the process.

Anterior Elbow/Biceps Tendon

The distal biceps tendon was the second most injured structure in our study with 17% having high grade or complete tears and is the second structure that should be evaluated in the basic MSUS examination. Men almost exclusively sustain injuries to the biceps and all tears were seen in men, with only 1 female subject having tendinosis. This disparity between men and women is noted in the literature, where male sex, smoking, and middle age are highly predisposing factors for distal biceps rupture and partial tears and tendinosis are rarer (Safran et al., 2002).

At the anterior elbow, the biceps can be evaluated on physical examination by flexing the elbow and supinating against resistance. A distal biceps tendon tear can also be assessed with the hook test which O’Driscoll et al. in 2007 compared its sensitivity and specificity, both 100%, to MRI which were 92% and 85%. Using MSUS with the elbow flexed and palm supinated, the distal biceps tendon can be viewed in long axis deep to the pronator teres and alongside the brachial artery where it can be followed distally to its insertion in the radial tuberosity (Jacobson,
Pronating and supinating the hand slightly while visualizing the biceps sliding back and forth helps to determine continuity especially if the lacertus fibrosis/bicipital aponeurosis is not intact in which case the tendon may not be retracted. The amount of retraction should be measured and noted during surgical referral. Additionally, if a hematoma is seen surrounding or in place of the distal biceps tendon, there is a high probability of high grade or complete tear which necessitates MRI and urgent surgical repair.

If a partial tear is seen the probability of tendinosis of the CET and CFT increases according to the model, and much more so in the CET. However, again it should be noted that only 1 partial tear of the biceps was found in our study, and this occurred in the setting of both CET and CFT tendinosis. Since the biceps node indirectly connects to the CFT node by way of the CET node, and CET injuries are associated with CFT injuries, this accounts for the model’s prediction of CET injury being higher than CFT injury in the setting of biceps partial tear. Given the model is based on limited data in this scenario, for the purposes of our algorithm, the CET should be evaluated with MSUS, if that has not already been done, in the setting of biceps partial tear. Again, the CFT can be evaluated by MSUS and/or physical examination.

**Medial Elbow/CFT**

Evaluation of the CFT in this algorithm is considered part of an intermediate level MSUS exam given no subject in our study had high grade or complete tear and only 1 subject had partial tear. On physical examination, testing the CFT can be done with resisted wrist flexion, eliciting pain at or just distal to the medial epicondyle. The UCL stabilizes the medial elbow and can be assessed with valgus stress (Malanga, 2016). Deformity of the CFT insertion at the medial epicondyle or laxity and apprehension on valgus stress maneuver should prompt MRI. MSUS evaluation of the CFT involves placing the transducer over the medial epicondyle in the direction
of the ulna, viewing the CFT in long axis, and scanning side to side through the full width of the
tendon and its insertion (Jacobson, 2017). Pathology should be confirmed in short axis as well,
noting width. Both the CFT and the UCL can become injured from overuse, but significant
injury to the UCL will present with valgus instability which is an indication for surgical referral
(O’Driscoll et al., 2005). Although the UCL is not often injured, it can be evaluated with MSUS
as part of the intermediate level examination by slightly rotating the transducer at the most
medial aspect of the CFT. Viewing the CFT slightly obliquely, the UCL is seen deep to the CFT
and spanning between the medial epicondyle and the sublime tubercle of the ulna. Valgus stress
can be applied while visualizing the UCL to assess for competence (Jacobson, 2017).

Tendinosis of the CFT or medial epicondylitis is very similar to lateral epicondylitis in
that obesity, smoking, middle age, and repetitive stress in some occupations are predisposing
factors, however it is less common than lateral epicondylitis (Descatha et al., 2003; Descatha et
al., 2013; Shiri et al., 2011). According to our model, CFT tendinosis is more likely in the setting
of partial biceps tendon tear (seen in the 1 subject with biceps partial tear) or CET tendinosis (7
out of 22 subjects). Ulnar neuropathy was associated with injury of the CFT in our dataset, which
is not surprising given the close anatomical relationship between the two structures. The ulnar
nerve can be evaluated in the ulnar groove by the advanced MSUS practitioner, or EMG/nerve
conduction studies can be ordered if indicated, and physical exam maneuvers such as assessing
for paresthesia in the ring and little finger or Tinel’s test at the cubital tunnel can be performed
by less experienced examiner (Taylor et al., 2012). Multiple other studies have noted CFT
association with ulnar neuropathy and found that surgical intervention in refractory cases
following 6-12 months of conservative management, does not tend to resolve symptoms,
whereas surgical intervention in refractory cases without ulnar neuropathy does tend to resolve symptoms (Gabel et al., 1995; Grana, 2001; Kurvers et al., 1995; Olivierre et al., 1995).

**Posterior Elbow/Triceps Tendon**

Evaluation of the triceps tendon in this algorithm is considered part of an intermediate level examination given only 2 subjects had a partial tear and 1 had a complete tear and the literature suggests this is the least often injured tendon of the elbow usually occurring in males. On physical examination, an inability or pain with resistance against elbow extension and the physical appearance of a lump or deformity on the posterior arm indicate triceps injury. The triceps tendon and its insertion on the olecranon will also be tender to palpation (Taylor et al., 2012). Some triceps tears can present with avulsion of the olecranon on x-ray (Pina et al., 2002). With the elbow at 90 degrees of flexion, MSUS evaluation of the triceps involves placing the transducer over the olecranon in the direction of the humerus, viewing the triceps in long axis, and scanning side to side through the full width of the tendon and its insertion. Pathology should be confirmed in short axis as well, noting width. An advantage of evaluating the triceps with MSUS is that the olecranon fossa is just deep to it and effusions can be seen layering in the fossa, displacing the fat pad and correlating to a sail sign on x-ray (Jacobson, 2017). In our study, triceps injuries tended to occur in isolation and were not significantly associated with pathology in other structures. As with all other structures excluding the RCL, triceps high grade or complete tears require urgent surgical repair, whereas tendinosis and small partial tears can be managed conservatively.

**Putting It All Together**

The overarching goal of this study was to use Workers Compensation elbow MRI findings to develop a Bayesian Network-based clinical decision support tool to help guide a
simplified MSUS examination and interpretation of results leading to an easy-to-use treatment algorithm. Our data suggest this may be useful when combined with history of present illness/mechanism of injury, physical examination, and x-ray, helping to deliver appropriate diagnosis and treatment plan from the initial clinic evaluation. Given the steep learning curve of performing and interpreting MSUS, it is important that our clinical decision support tool be targeted for novice clinicians, decreasing the barrier to entry. As such, the less experienced examiner should focus their efforts on becoming proficient in obtaining and interpreting images of the most often injured structures and most serious injuries first. A graduated approach to performing MSUS as experience and comfort level increase can likely be achieved by following the algorithm below in Figure 5. And all evaluations should begin with a history, physical examination, and x-ray, informing a subsequent targeted ultrasound.

To our knowledge there are no previous studies or guidelines/recommendations that suggest learning and performing MSUS in a graduated fashion such as basic, intermediate, and advanced. However, based on the results of our study, for the less experienced MSUS examiner, we recommend that any history of present illness/mechanism of injury, physical examination findings, or x-ray findings that warrant MRI or surgical referral on first encounter be used to make treatment decisions, regardless of MSUS findings, which should be used only to correlate results. The more experienced MSUS examiner can rely on all available clinical information obtained in making diagnosis and treatment decisions. However, in the absence of history, physical exam, or x-ray findings that warrant urgent MRI or surgical consultation, our algorithm can add value and further clinically pertinent data to clinicians of any experience level.

In cases where Basic MSUS is performed and the CET and distal biceps tendon are both observed to be normal, there is only 7% probability of high-grade triceps tear and 15%
probability of CFT tendinosis, with other elbow ligaments and tendons having an extremely low probability of pathology. In these cases, if the less experienced examiner performs the physical exam of these structures we described with no concerning findings, they can be confident in pursuing conservative management. More experienced examiners can use Intermediate MSUS of the posterior and medial structures to be even more confident in their clinical management. Advanced MSUS is not addressed in our algorithm and involves imaging a much wider array of structures in much finer detail, including less often injured structures and nerves.

For all injury scenarios described, normal MSUS examination findings require no follow up, and sprains, tendinosis and small partial tears can be managed conservatively with injury appropriate work/physical activity restrictions, bracing, medications, injections, and physical or occupational therapy. Use of MSUS evaluation with our algorithm can be repeated on subsequent clinical visits to track progress and alter the treatment plan as injuries either progress or heal over time. In general, and assuming patients’ pain and function are improving, conservative management can be pursued for 6-12 months, after which MRI and surgical referral may be appropriate for refractory cases. All high grade and complete tears of elbow tendons and ligaments require surgical intervention as soon as possible, except in the case of the RCL, which can be managed conservatively assuming the LUCL is intact and there is no lateral elbow instability.

**Study Limitations**

Although every elbow MRI in the Workers Compensation database during calendar year 2017 that fit inclusion/exclusion criteria was included in this study, elbow MRIs are relatively uncommon when compared to other joints such as the shoulder and knee resulting in a smaller data set than would be ideal. Limitations of this study include the small number of cases that fit
inclusion/exclusion criteria in that associations between variables/injuries that were uncommon have low predictive power. Typically, in the development of Bayesian networks such as this, a larger data set is used such that 20-30% of the cases are randomly selected and withheld and later used to perform an internal validation test of the model. Due to the limited number of cases in our study, an internal validation test could not be done, therefore, removing a percentage to run a validation test would have resulted in a significant loss of data that would have altered the final model. Additionally, some injuries and findings were present in a limited amount, therefore, associations could not be evaluated for significance. Future studies should use a larger data set to validate findings as well as to determine the applicability of these findings for the general population.

**Strengths and Future Studies**

Strengths of this study include narrowing a fast MSUS examination of the elbow to two to three main structures and providing a flow assessment chart that was developed from the probabilistic associations from the Bayesian network algorithm. By ruling out any potential injury of the more commonly injured structures, the probability of there being an injury in other structures is greatly decreased. This model could minimize delay in treatment, physical therapy referral, surgical referral, or needing advanced imaging which consequently improves patient outcomes and ability to return to work. Future studies should evaluate whether implementation of the diagnostic support tool consistently provides accurate results as well as the MSUS algorithm having actually reduced the POCUS learning curve. Development of a Bayesian network-based decision support tool for an all-around musculoskeletal injury assessment would be ideal and would include other commonly injured parts such as the hand, wrist, and ankle.
Figure 5. Limited Point-of-Care Ultrasound Flow Chart for Elbow Injuries


Lateral elbow: Consider patient’s sex, age, and presence of OA when evaluating CET. Evaluate the RCL, observed in the same MSUS view as but just deep to the CET. Complete tear of the RCL is not an indication for surgical referral unless LUCL also has a complete tear (asterisk). Determine competence of LUCL with MSUS and/or varus stress. If more experienced MSUS examiner, evaluate CFT and UCL at medial elbow. CET tendinosis has shown association to a CFT injury (indicated by the double arrow).

Anterior elbow: Consider patient’s sex when evaluating the distal biceps tendon. Distal biceps tendinosis showed an association with partial tear of CET, and partial tear with CET tendinosis (indicated by the dotted arrows). If more experienced MSUS examiner, evaluate CFT and UCL at medial elbow.

Posterior elbow: Follow triceps tendon to its insertion at the olecranon. May present with olecranon avulsion or effusion at the olecranon fossa on x-ray.

Conservative management is recommended for tendinosis and partial tears which can consist of medication, physical therapy, injections, and work restrictions/activity modifications.
CONCLUSION

The development of clinical Bayesian network-based diagnostic support tools for clinical management guidance will help clinicians with faster diagnosis and better patient prognostic outcomes. Using a clinical Bayesian network in adjunct to a complete history, focused physical exam and point-of-care ultrasound imaging of the elbow, should speed the time and ease the process of reaching an accurate diagnosis as well as providing adequate management.
REFERENCES


57. https://doi.org/10.1016/j.berh.2011.01.013


