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Limited Point of Care Ultrasound Clinical Decision Support Model for Work-related Injuries of the Shoulder Utilizing Bayesian Network

Gwen Marie Ayers
University of South Florida

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Limited Point of Care Ultrasound Clinical Decision Support Model for Work-related Injuries of the Shoulder Utilizing Bayesian Network

by

Gwen Marie Ayers

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

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Keywords: Musculoskeletal injuries, Rotator cuff, POCUS, Decision support tool

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DEDICATION

I dedicate my thesis to my family who have supported me throughout all my endeavors past and present. I am thankful for the unwavering support of my parents, my daughter, and my friends who have allowed me to continue to dream and pushed me to make those dreams reality. Thank you for all of the continued love, support, mentorship, and inspiration.
ACKNOWLEDGMENTS

I would like to acknowledge the NIOSH Sunshine Education and Research Center grant for allowing me to pursue a Master of Science in Public Health at the University of South Florida. Additionally, I would like to acknowledge and thank all the professors who have given their time to teach and mentor me during the past two years. I owe special thanks to Drs. Alfred Mbah and Jared Jeffries who were instrumental in the completion of this thesis project and my residency at the University of South Florida. I would also like to extend my thanks to Dr. Rachel Williams who provided guidance and mentorship while supporting my professional growth. Finally, I would like to thank Kelly Freedman who was instrumental in keeping me on track during this thesis project and over the past two years.
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This descriptive retrospective cohort study utilized a large Workers Compensation insurance database. Included in this study were 481 shoulder MRI's performed during calendar year 2017 that were (a) at least 2 weeks after the initial clinic visit, or (b) greater than 6 weeks after injury, but (c) not more than 3 months after the date of injury. Of the 481 cases, 432 were used to evaluate potential associations between the measured variables and generate a Bayesian network prediction model where only a few variables were required to accurately guide clinical decision making for rotator cuff and biceps tendon injuries. The other 49 cases were randomly selected as a validation set and were not included in the model. After removing unnecessary variables, the model was condensed into a clinical decision support tool based. The generated clinical support tool in conjunction with limited point of care ultrasound examination of the supraspinatus and infraspinatus tendons would guide clinicians to triage patients into one of three clinical management groups: no follow up needed, conservative management, or MRI and orthopedic referral. Internal validation of the generated model yielded 96% accuracy in placing patients in the correct clinical management group which could help improve provider and patient confidence in the diagnosis and treatment plan as well as minimize delays in patient care, prevent unnecessary referrals, and expedite return to work.
INTRODUCTION

Shoulder pain is the third most common reported musculoskeletal pain in the general population (Engebretsen et al., 2014). The annual incidence of shoulder pain in primary care is 14.7 per 1000 patients with a reported lifetime prevalence of shoulder pain approaching 70% (Cadogan et al., 2011). Additionally, recovery and recurrence rates with shoulder pain is high with 40-50% of patients reporting recurrent or persistent pain at 12 months (Cadogan et al., 2011). Peak prevalence occurs between age 45 and 55 with 25% of women and 15% of men reporting weekly shoulder pain (Engebretsen et al., 2014). Shoulder pain is estimated to affect 8% of all US adults, with shoulder pathology being a leading cause of orthopedic referral and subsequent rotator cuff repairs costing $13,771 per patient or $3,442,750 annually (Murray, 2019).

According to the National Safety Council (NSC) and the Bureau of Labor Statistics (BLS) the top three leading causes of injury in the workplace are overexertion and body reaction (31.4%), slips/trips/falls (26.7%), and contact with objects (26.2%). In 2018 there were 900,380 injuries and illnesses resulting in 103,000,000 lost workdays. Injuries to the shoulder accounted for 68,070 or 7.6% of the total workplace injuries and illnesses. Shoulder injuries also accounted for 27 lost workdays which is the highest number for any body part and well above the median of 8 days lost per incident overall. Total work injury costs in 2018 was $170.8 billion which equates to $1,100 per worker and $41,000 per injury. The average cost of all workers compensation claims in 2017-2018 was $41,003 dollars, while the cost for arm or shoulder
injuries was significantly higher at $46,205 dollars on average when looking at both medical and indemnity costs (Top Work-related Injury Causes - Injury Facts, 2020).

The Official Disability Guidelines (ODG) for 2020 utilizes current evidence-based decision making for occupational shoulder injuries. The ODG applies a guideline for integrated treatment plans and guidelines for duration of disability. Shoulder injuries are divided into initial conservative management encompassing 90% of clinical cases and aggressive management encompassing 10% of the clinical cases. Ideally imaging consisting of plain film and magnetic resonance imaging (MRI) would occur in approximately 30% of cases. Conservative management can include a combination of rest, medications, work modification, physical therapy, and diagnostic or therapeutic injections over a period of six weeks. When patients fail to progress or experience significant delays in clinical improvement despite maximum medical treatment then MRI is performed to aid in diagnosis, treatment, and exclusion of underlying occult pathology (ODG-TWC Shoulder, 2020). The American College of Occupational and Environmental Medicine MD Guidelines also advocates for managements of shoulder pain without red flag symptoms for a period of 6-8 weeks prior to referral or advanced imaging such as MRI (Hegmann, n.d.).

Clinical practice guidelines (CPGs) can be used to standardize and streamline care across disciplines with the goal of providing cost effective evidence-based care thereby leading to improved patient outcomes (Pincus et al., 2016). Clinical guidelines focusing on musculoskeletal injuries have been found to be highly variable especially regarding applicability and editorial independence which is illustrated in the two main CPGs addressing shoulder pathology published by the Philadelphia Panel and the America Academy of Orthopaedic Surgeons (AAOS). The Philadelphia Panel is a guideline published by a single institution with
an overall quality rating of 67 primarily due to bias secondary to deficiencies of editorial independence (Pincus et al., 2016). Conversely the AAOS guideline is published by an institution with an overall quality rating of 86 due to decreases in bias given the broad range of experts contributing to the guideline as well as improved cross-discipline applicability (Pincus et al., 2016).

Musculoskeletal ultrasonography (MSUS) has been shown to enable a one-stop approach, reduce appointments, and improve quality of care in outpatient musculoskeletal clinics. One study showed that use of MSUS in the outpatient setting prevented 658 radiology referrals, enabled dynamic evaluation of the shoulder and detection of neovascularization which cannot be evaluated using other imaging modalities, and that ultrasound guided interventions likely increased accuracy of needle placement which was reassuring to both the clinician and patients (Sivan et al., 2010). The use of MSUS in clinical practice in the United States has increased four-fold since 2000 and a substantial amount of this growth in attributed to utilization by non-radiologists. This expansion is also facilitated by technological advances in transducers and compact portable ultrasound machines (Henderson et al., 2015). Utilization of MSUS has a sensitivity in the literature ranging from 72 to 100%, a specificity ranging from 53 to 93% and van Moppes suggested that ultrasound of the shoulder is the method of choice after plain film radiography in patients with shoulder symptoms and facilitates the selection of the correct treatment (1995).

MSUS of the rotator cuff is a dynamic real time examination that is well tolerated by patients and in experienced hands is an accurate modality for initial investigation of rotator cuff tears especially supraspinatus tears (Fotiadou et al., 2008). Rotator cuff ultrasound has been shown to be an accurate method of diagnosing subacromial-subdeltoid bursal and long head of
the biceps pathology in addition to the rotator cuff abnormalities (Griffith, 2019). An added advantage of the use of ultrasound in clinic allows instant feedback for the clinician and allows immediate clinical correlation with history and physical exam findings (McCulloch et al., 2013).

The accuracy of shoulder ultrasound has been shown to improve with the increase in operator experience as well as increasing technical and interpretive knowledge (Griffith, 2019). Literature suggest that this is in part due to the steep learning curve associated with ultrasound imaging and the additional time required to integrate ultrasound into evaluation of shoulder injuries or pain. The steep learning curve associated with acquiring high quality images and subsequent interpretation is well documented in the literature. In the hands of skilled practitioners ultrasound has a positive predictive value of 88-91%, a negative predictive value of 50-95%, and an accuracy of 89-94% for detection of full thickness rotator cuff tears. One study documented an initial accuracy of 61% with introduction of ultrasound into an orthopedic practice (Day et al., 2016). Other limiting factors associated with the introduction of ultrasound into clinical practice included the amount of additional time required to input patient data, perform the exam, and capture images for documentation (Day et al., 2016). Orthopedic surgeons followed over a three-year period showed progressive improvements in accuracy with an overall accuracy of 83% and sensitivity of 86% (McCulloch et al., 2013).

Clinical decision support (CDS) tools are increasing in their utilization. CDS tools are designed to improve clinical decision making and reduce health care costs by avoiding delays in patient treatment and decreasing redundant tests and referrals (Farmer, 2014). There are numerous CDS systems in clinical practice but only a few have been targeted at musculoskeletal disorders and only one is currently being evaluated in clinical setting specifically aimed at the diagnosis of shoulder injuries (Farmer, 2014). Additionally, there has been success with the
application of data mining models combined with Bayesian theory in order to determine probabilities of the presence of disease and enhance diagnostic decision making for rotator cuff tears (Lu et al., 2014).

Combining MSUS and Bayesian networks would allow development of a decision tool based on results of a limited point of care ultrasound exam, providing the clinician with an indicator of the severity of the shoulder and guiding appropriate management. A limited point of care ultrasound exam would require imaging one or two shoulder structures such as the supraspinatus and/or infraspinatus tendons, thereby decreasing the learning curve and overall time of the exam. The results of the limited point of care ultrasound exam could be used to predict pathology in other shoulder structures without the need to image them thereby saving time. The probability of injury to other shoulder structures could then be used to guide clinical management with the goal of reducing delays in patient care, unnecessary referrals and imaging, cost of care, time out of work, as well as improving patient outcomes and overall patient satisfaction.
METHODS

The study population for this descriptive retrospective cohort study was drawn from a Workers Compensation insurer database representing 39,000 small to medium companies encompassing a wide variety of industries and occupations across 12 states. The insurance database was queried to identify all billed non-contrast MRIs of shoulders in 2017. MRIs performed on shoulders during 2017 that were (a) at least 2 weeks after the initial clinic visit, or (b) greater than 6 weeks after injury, but (c) not more than 3 months after the date of injury were included. Imaging done before two weeks was excluded since these were likely severe injuries with significant findings on history and clinical exam requiring urgent consultation, treatment, or surgical intervention and therefore did not meet the clinical criteria for conservative management. Cases outside of the 3-month interval after the injury were excluded because many of these imaging studies were done to provide objective evidence that the patient had no injury in an effort to account for their failure to improve despite maximum medical management. Cases where MRI was performed less than 2 weeks after the initial clinical visit but greater than 6 weeks after injury met the clinical guidelines for advanced imaging due to lack of improvement and were included.

Diagnoses obtained from MRI reports were previously transcribed and categorized for 1482 cases that met inclusion criteria across all peripheral joints in a previous study (Jeffries, 2019). The cases where MRI of the shoulder or rotator cuff was performed were identified and used in this study. The MRI findings were tabulated and categorized into 24 different categories spanning intra-articular, extra-articular, myotendinous, ligamentous, and
osseous diagnoses. A majority of these findings were categorized simply into presence or absence of disease or finding, but some findings such as the rotator cuff tendons were further subcategorized into normal, tendinopathy, tears of less than 50%, tears of greater than 50%, and full thickness or complete tendon tears.

Of the 481 shoulder cases identified 432 were used to evaluate associations between the measured variables and generate the Bayesian network to create a prediction model where only a few variables were required to accurately guide clinical decision making. The remaining 49 cases were randomly selected using a simple random algorithm and set aside as a validation set. The 10% set aside as the validation set were not used in model generation. BayesFusion, GeNi3.0 Academic Modeler developed by BayesFusion LLC, was used to generate, evaluate, and fit the model (https://www.bayesfusion.com). This software platform allowed the use of several different algorithms to evaluate multiple variables, assign nodes, and evaluate causal relationships. The resultant Bayesian Search, PC, Greedy thick thinning, tree augmented naïve bayes, augmented naïve bayes, and naïve bayes models were then evaluated and compared. The augmented naïve bayes algorithm produced the most clinically intuitive outcomes suggesting that the probabilities generated using the model were less likely due to chance. In addition, the clinical intuitiveness of the augmented naïve bayes algorithm best fit the data and allowed selection of a parent node making it the best algorithm choice to generate the current model.

Variables included in the initial data set included age, gender, tendon/muscle, subacromial or subcoracoid bursitis, labrum, fracture, glenohumeral osteoarthritis, acromioclavicular joint pathology, bone pathology, capsular pathology, soft tissue findings, loose bodies, and calcification. Table 1 details the number of cases with findings that were excluded
from analysis since the case numbers were too small to yield sufficient statistical power for analysis.

Figure 1 shows the distribution of data in the initial model after removal of the variables listed in Table 1. Analysis of the shoulder data revealed the supraspinatus to have the most variable injury diagnoses with regard to injury categorization. Additionally, the supraspinatus tendon was the most commonly injured shoulder structure with pathology documented in 379 out of the 481 cases. Both of these findings are consistent with the literature and support the use of supraspinatus as the parent node for the current model.

Acromioclavicular changes, glenohumeral osteoarthritis, and fracture were linked to the parent node but also show some ancestral relationships which do not persist on subsequent iterations of the model and do not influence the predictive probability of the final model. The

---

**Table 1**

*Variables Excluded from Analysis Due to Small Case Numbers*

<table>
<thead>
<tr>
<th>Category</th>
<th>Number of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teres Minor</td>
<td>9 (2%)</td>
</tr>
<tr>
<td>Other Muscle</td>
<td>8 (2%)</td>
</tr>
<tr>
<td>Bone Contusion</td>
<td>16 (3%)</td>
</tr>
<tr>
<td>Other Bone Lesion</td>
<td>7 (2%)</td>
</tr>
<tr>
<td>Capsular ligaments</td>
<td>9 (2%)</td>
</tr>
<tr>
<td>Soft Tissue Edema</td>
<td>10 (2%)</td>
</tr>
<tr>
<td>Subcoracoid Bursitis</td>
<td>3 (1%)</td>
</tr>
<tr>
<td>Ganglion Cyst</td>
<td>5 (1%)</td>
</tr>
<tr>
<td>Calcification</td>
<td>3 (1%)</td>
</tr>
<tr>
<td>Loose Body</td>
<td>5 (1%)</td>
</tr>
</tbody>
</table>
unidirectional connection of the AC, glenohumeral OA, and fracture nodes to the supraspinatus parent node does not impact the predictive probabilities for the remainder of the rotator cuff or any other structures and therefore were excluded from the final model.

Figure 2 shows the condensation of the initial model data into clinical management categories with the goal of improved the usability and clinical applicability. The three clinical management categories include: (1) no follow up needed, (2) conservative management which included a broad range of clinical management and close interval follow up, and (3) referral and/or MRI which encompasses additional imaging and specialty evaluation. The rational for the categories was as follows: normal tendons do not require follow up, tendinosis and small tears can be managed conservatively, and large or complete tears require referral and MRI.
Figure 2. Model with Data Condensed into Clinical Decision Categories.

The labrum, in the condensed model, has both the biceps and the supraspinatus as parents, however the probability of labral injury was stable despite injury severity of other variables, and therefore the labrum was excluded from the final model. Subacromial bursitis, joint effusion, age and gender only showed unidirectional connections to the supraspinatus parent node. The nodes with isolated unidirectional connections to the supraspinatus only were found not contribute to or impact the predictive probabilities of the remainder rotator cuff and therefore were excluded from the model. Figure 3 depicts the final model which includes the supraspinatus, infraspinatus, subscapularis, and biceps brachii tendons.

The clinical decision model was designed to be used in conjunction with a limited point of care ultrasound (POCUS), a focused clinical history, and a targeted physical exam. Though POCUS could be used to image all of rotator cuff and biceps tendons, in developing a limited
exam, the supraspinatus as the parent node is the ideal starting point, followed by the
infra-spinatus given that it is the second most injured tendon and has the second most variability
in injury severity.

The model assumes MRI and POCUS findings would have a high degree of agreement.
Internal validation was performed using the randomly selected 10% or 49 cases from the original
data which were not included in model generation. The model stratified the shoulder injuries
into three clinical categories which included no further follow up, conservative management, and
referral for MRI and/or subspecialty evaluation. The clinical dispositions recommended via the
clinical decision model were then compared to the actual MRI findings in the validation set and
evaluated for concordance or the degree of discrepancy between the model recommendations and the current clinical standard of care for shoulder injuries and rotator cuff tears. The degree of discrepancy between the model and the MRI findings were categorized as none, minor, or major.
RESULTS

Four hundred and eighty-one shoulder injuries underwent MRI evaluation and met inclusion criteria. Table 2 and Figure 4 show the age distribution of the included cases. Table 3 shows the gender distribution in the total cases, the subset of cases used to generate the model, and in the validation subset. The similarity in the distributions for gender supports sample similarity between the model and validation sets.

Table 2

*Study Characteristics – Age*

<table>
<thead>
<tr>
<th>Age</th>
<th>Mean</th>
<th>Median</th>
<th>Standard Deviation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Data Set</strong></td>
<td>47.5</td>
<td>51</td>
<td>11.8</td>
<td>19-79 (60)</td>
</tr>
<tr>
<td><strong>Model Data Set</strong></td>
<td>49.3</td>
<td>51</td>
<td>11.7</td>
<td>19-79 (60)</td>
</tr>
<tr>
<td><strong>Validation Data Set</strong></td>
<td>49.5</td>
<td>52</td>
<td>11.7</td>
<td>22-76 (54)</td>
</tr>
</tbody>
</table>

![Age Distribution](image)

*Figure 4. Age Distribution.*
Table 3  

Study Characteristics – Gender

<table>
<thead>
<tr>
<th>Demographics</th>
<th># Cases</th>
<th>Male (%)</th>
<th>Female (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Data Set</td>
<td>481</td>
<td>351 (73%)</td>
<td>130 (27%)</td>
</tr>
<tr>
<td>Model Data Set</td>
<td>432</td>
<td>315 (73%)</td>
<td>117 (27%)</td>
</tr>
<tr>
<td>Validation Data Set</td>
<td>49</td>
<td>36 (73%)</td>
<td>13 (27%)</td>
</tr>
</tbody>
</table>

The distribution of rotator cuff findings is shown in Table 4. In this study the supraspinatus tendon was the most commonly injured tendon with injuries occurring in 384 out of the 481 or 80% of cases. The incidence of partial thickness supraspinatus tears was 38% and the incidence of full thickness tears was 11%. The infraspinatus was injured in 203 or 42% of the cases which included a 15% incidence of partial thickness tears and a 7% incidence of full thickness tears making it the second most frequently injured tendon of the rotator cuff in this study.

Table 5 along with Figures 5 and 6 show the distribution of rotator cuff findings across the three clinical decision categories in both the model and validation data sets. The distribution of supraspinatus injuries were similar between the model and validation data sets. Specifically, the incidence of supraspinatus tendinopathy and partial thickness tears was 55% in the model which were similar to the 43% seen in the validation set. Additionally, the incidence of full thickness supraspinatus tears was 25% compared to 29% in the model and validation sets, respectively. The distribution of data for the remaining rotator cuff was similar across all clinical categories in both the model and validation sets except for biceps injuries requiring referral in the validation set.
### Table 4

**Distribution of rotator cuff findings – Total Data Set**

<table>
<thead>
<tr>
<th>Category</th>
<th>Supraspinatus</th>
<th>Infraspinatus</th>
<th>Subscapularis</th>
<th>Biceps</th>
<th>Teres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>97 (20%)</td>
<td>278 (58%)</td>
<td>368 (77%)</td>
<td>363 (75%)</td>
<td>475 (98.8%)</td>
</tr>
<tr>
<td>Tendinopathy</td>
<td>149 (31%)</td>
<td>100 (21%)</td>
<td>55 (11%)</td>
<td>71 (15%)</td>
<td>4 (0.8%)</td>
</tr>
<tr>
<td>Small Tear (&lt;50%)</td>
<td>115 (24%)</td>
<td>51 (11%)</td>
<td>41 (9%)</td>
<td>16 (3%)</td>
<td>1 (0.2%)</td>
</tr>
<tr>
<td>Large Tear (&gt;50%)</td>
<td>68 (14%)</td>
<td>19 (4%)</td>
<td>11 (2%)</td>
<td>4 (1%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Complete Tear</td>
<td>52 (11%)</td>
<td>33 (7%)</td>
<td>6 (1%)</td>
<td>14 (3%)</td>
<td>1 (0.2%)</td>
</tr>
<tr>
<td>Subluxation</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>13 (3%)</td>
<td>0 (0%)</td>
</tr>
</tbody>
</table>
Table 5

Distribution of rotator cuff findings – Model and Validation Data Sets

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Category</th>
<th>Supraspinatus</th>
<th>Infraspinatus</th>
<th>Subscapularis</th>
<th>Biceps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Follow Up Necessary</td>
<td>86 (20%)</td>
<td>255 (59%)</td>
<td>330 (76%)</td>
<td>327 (75%)</td>
</tr>
<tr>
<td></td>
<td>Conservative Management</td>
<td>238 (55%)</td>
<td>91 (21%)</td>
<td>49 (11%)</td>
<td>67 (15%)</td>
</tr>
<tr>
<td></td>
<td>Referral and/or MRI</td>
<td>108 (25%)</td>
<td>86 (20%)</td>
<td>53 (12%)</td>
<td>38 (9%)</td>
</tr>
<tr>
<td>Validation</td>
<td>No Follow Up Necessary</td>
<td>14 (28.5%)</td>
<td>32 (64%)</td>
<td>38 (78%)</td>
<td>36 (73%)</td>
</tr>
<tr>
<td></td>
<td>Conservative Management</td>
<td>21 (43%)</td>
<td>9 (19%)</td>
<td>6 (12%)</td>
<td>5 (10%)</td>
</tr>
<tr>
<td></td>
<td>Referral and/or MRI</td>
<td>14 (28.5%)</td>
<td>8 (17%)</td>
<td>5 (10%)</td>
<td>8 (17%)</td>
</tr>
</tbody>
</table>
Figure 5. Distribution of Data in the Model Data Set.
Figure 6. Distribution of Data in the Validation Data Set.
The baseline probabilities of a full thickness tear of the rotator cuff in the current clinical decision model is seen in Table 6. The probability of a significant tear of the remainder of the rotator cuff in the setting of normal examination of the supraspinatus and infraspinatus tendons is low ranging between 4 and 10%. This low incidence suggests that there is a low likelihood of missing a significant rotator cuff injury with the use of the clinical decision model with limited POCUS.

Table 7 summarizes the discrepancies between model output and MRI findings. The validation set was evaluated by the model and classified into one of the three clinical outcomes. The model in this study correctly categorized 47 out of the 49 cases into one of three clinical management categories. Overall, the model had a 96% positive predictive value and no major discrepancies. The two cases which were predicted inaccurately were those where conservative management was suggested but MRI and referral were actually necessary. These were classified as minor discrepancies assuming referral would have been made due to the presence of findings suggestive of a complete tear on physical exam or the lack of clinical improvement on follow up. There were no cases where follow up was not suggested but the patient required referral, which would have been categorized as a major discrepancy.
Table 6

*Probability of Rotator Cuff Injury with a Normal Examination of the Supraspinatus and Infraspinatus Using the Clinical Decision Model*

<table>
<thead>
<tr>
<th>Subscapularis</th>
<th>Probability of Tendinopathy or Small Tear</th>
<th>Probability of Large or Complete Tear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4%</td>
<td>10%</td>
</tr>
</tbody>
</table>

| Biceps        | 8%                                        | 4%                                   |

Table 7

*Model Discrepancies When Compared with MRI*

<table>
<thead>
<tr>
<th></th>
<th>None</th>
<th>Minor</th>
<th>Major</th>
<th>% Predictive Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Follow Up</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>Conservative Management</td>
<td>14</td>
<td>2</td>
<td>0</td>
<td>90%</td>
</tr>
<tr>
<td>Referral and/or MRI</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>Overall</td>
<td>37</td>
<td>2</td>
<td>0</td>
<td>96%</td>
</tr>
</tbody>
</table>
DISCUSSION

Rational for Study Inclusion and Exclusion Criteria

The MRI data included in this study were from imaging that occurred at least 2 weeks after initial clinic visit or injury and less than three months after the date of the initial injury. MRIs performed greater than 6 weeks from injury but less than 2 weeks from initial clinic visit were included because they likely represent cases that fit guidelines for advanced imaging due to lack of improvement. MRI performed less than two weeks from date of injury most likely corresponded to severe injuries with concerning findings on physical exam that warranted urgent imaging evaluation and referral. MRI performed greater than three months after injury were excluded since these studies were likely performed for patients who were failing to progress with conservative management. A negative MRI may be used to place a patient at maximal medical improvement allowing discharge of cases into arbitration or independent medical evaluation. Since chart reviews were not performed exclusion of early (less than two weeks) and late (greater than three months) allowed the data to be representative of common work-related shoulder injuries requiring clinical management.

Distribution of Shoulder Data

The distribution of age in this study is consistent with the literature that rotator cuff abnormalities increase with age with a prevalence of 9.7% in patients younger than 20 and 62% in patients 80 and older (Teunis et al., 2014). The median and mean age of the sample were close to 50 which was consistent with the literature that rotator cuff tears increase with increasing age and full thickness rotator cuff tears are rare below the age of 50 (Milgrom et al.,
The age distribution in the literature shows progressive increase in rotator cuff tears with increasing age with 25.6% of individuals in their 60s having a tear and up to 50% of individuals in their 80s with tears (Tashjian, 2016). The progressive increase in incidence of rotor cuff tears between the age of 60 and 80 was not strictly observed in this study which was likely due to selection bias. The sample population for this study was drawn from a Workers Compensation database and in general the number of workers between 65 and 80 were fewer than the number of 60-80 year old’s in the general population. Our initial model showed no predictive value for age after supraspinatus status was known, hence age was removed from the final model. It is unclear whether this finding would generalize to the wider population.

A number of studies have shown no gender differences associated with the incidence of rotator cuff injuries therefore the differences between the number of males and females (Vishnumurthy et al., 2016). The difference in the number of males and females in this study was more reflective of the study sample and the representativeness of the Workers Compensation data base rather than being representative of gender differences in the rates of rotator cuff injuries in general. However, our initial model showed no predictive value for gender after supraspinatus status was known, hence gender was removed from the final model. The lack of predictive value for gender seen in this study appear to generalize to the wider population.

In this study the incidence of partial thickness supraspinatus tears was 38% and the incidence of full thickness tears was 11% which was similar to the current literature. The incidence of supraspinatus tears in the literature ranges from 13-32% for partial thickness and 7-19% for full thickness tears (Matava et al., 2005). The stress placed on the supraspinatus tendon as one of the major shoulder stabilizers is consistent with the findings that the supraspinatus is
most injured tendon across younger and older age groups as well as across degenerative and traumatic etiologies (Lazarides et al., 2015).

In our study there was a 15% incidence of partial thickness tears and a 7% incidence of full thickness tears of the infraspinatus. The frequency of infraspinatus involvement makes it the second most injured tendon which is similar to the incidence in the literature. This finding is consistent with recent studies that show the infraspinatus occupies a larger portion of the greater tuberosity footprint and contributes more equally than initially thought to shoulder abduction (Mochizuki et al., 2008). The infraspinatus is the main muscle that prevents proximal migration of the humeral head relative to the glenoid and tears have been shown to frequently occur in combination with supraspinatus tears (Lee et al., 2017). Additionally, the initiation and propagation of rotator cuff tears have been theorized to occur anteriorly in the supraspinatus and propagate posteriorly or initiate more posteriorly in the infraspinatus or the infraspinatus-supraspinatus junction and propagate anteriorly (Kim et al., 2010).

In our study there was a 23% incidence of findings involving the subscapularis with 52 partial thickness tears and only six full thickness tears. The literature is consistent with these findings stating that subscapularis tears were less common than supraspinatus and infraspinatus tears, subscapularis tears often occur in combination with other rotator cuff tears, and isolated complete tendon ruptures were rare (Kim et al., 2003). In our current study there were only six injuries to the teres minor with a predominance of tendinopathy and only 1 tendon tear. These findings are consistent with current literature that classified the teres minor as normal in 90% of cases of rotator cuff tear (Melis et al., 2011).
Model Validation and Application

CDS systems can be used to standardize patient care, improve patient outcomes, prevent delays in patient care, and decrease health care costs. CDS tools focusing on musculoskeletal disorders involve several different methods of dealing with information in an effort to assist patient management decisions including questionnaires, algorithms, and models focusing on neck, back, and less commonly shoulder pain (Gross et al., 2015). The published models relating to the shoulder focus on surgical treatment of shoulder fractures, model predicting the need for surgical treatment, and guidance for choosing imaging for shoulder injuries (Dalai et al., 2020) (Gross et al., 2015). The current model incorporated a combination of predictive probabilities using the Bayesian networks, and informed by presumed POCUS findings to stratify occupational shoulder injuries into three clinical outcomes or treatment categories with the goal optimizing patient care.

The three clinical outcomes for the generated model included no further follow up, conservative management, and referral and/or MRI. Discrepancies between the model classification and the cases MRI findings were classified as none, minor, and major. A major discrepancy was defined as a complete misclassification of an injury that would result in a significant delay in patient care or patient harm. A minor discrepancy was defined as a misclassification of an injury, but this classification did not result in a significant delay in patient care or patient harm. No discrepancy was defined as complete concordance between the model and the MRI.

There was 100% agreement between the model and findings on MRI in two of the three clinical management categories including no follow up and referral and/or MRI. There was 90% concordance between MRI findings and the model stratification. Within the conservative
management there were two minor discrepancies where a complete tear of the biceps was not predicted by the model. This meets the definition of a minor discrepancy since the tear would likely not have caused a significant delay in patient care since the patients would continue to be under close interval follow up by virtue of being in the conservative management group. Additionally, a complete tear of the biceps would likely be clinically evident through history, mechanism of injury, or physical exam which would suggest that these two cases likely would have received imaging or referral based on their clinical presentation and despite the model’s recommendation.

The current model had a low probability of significant rotator cuff injury when the supraspinatus and infraspinatus are normal, showing a 96% positive predictive value. These findings support the use of the generated model in combination with a focused clinical history and physical exam to validate and support patient dispositions ranging from no further work up to conservative management, additional imaging, or immediate referral.

**Ultrasound of the Rotator Cuff**

As early as the 1990’s ultrasound of the shoulder was a method of choice to evaluate patients with shoulder pain and suspected impingement or tears to facilitate the selection of the correct treatment (van Moppes et al., 1995). Current literature shows ultrasound detects full thickness rotator cuff tears with a sensitivity of 100%, specificity of 85%, PPV of 96%, and NPV of 100% with a decrease in specificity to 67%, sensitivity to 85%, and PPV/NPV to 77% when evaluating partial thickness tears (Vishnumurthy et al., 2016). Smith in a systematic review and meta-analysis highlighted that ultrasound is inexpensive, non-invasive, can be performed rapidly, is geographically independent, and is a promising investigative tool for patients with suspected rotator cuff tear (2011). The application of ultrasound in the office for patients presenting with
shoulder pain can enable physicians to rationalize treatments in patients over 40, improve explanations of symptoms and prognosis, improve treatments for multifactorial shoulder pain, and prevent unnecessary referrals (Ottenheijm et al., 2015). Studies have highlighted a steep learning curve associated with performing and interpreting ultrasound of the rotator cuff but with continued training and practice can improve sensitivity, specificity, and PPV while maintaining accuracy (McCulloch et al., 2013). Finally, the use of ultrasound allows immediate feedback serving to clarify clinical findings in the context of history and physical examination which improves the accuracy of ultrasound diagnosed cuff tears (Okoroha et al., 2019).

The current model proposes the use of limited POCUS which focuses on imaging only the supraspinatus and infraspinatus tendons of the rotator cuff in the symptomatic shoulder. Limiting ultrasound imaging to two structures in the shoulder decreases examination time and the technical demands of performing the imaging examination. Additionally, this model requires that clinicians need to, at a minimum, learn to determine the difference between normal tendon and a full thickness tear. The literature has consistently found that delineation of full thickness tears is a strength of ultrasound. Finally, the use of the model in the clinic allows direct correlation with physical exam and clinical findings which improves the providers and patient’s confidence in treatment decisions.

**Clinical Management**

The University of New South Wales published a CPG in 2013 detailing management of rotator cuff syndrome in the workplace (Hopman et al., 2013). Utilizing this CPG on initial presentation the patient is evaluated for red and yellow flags. Reg flags include trauma, inflammatory arthropathy, malignancy, referred pain, systemic symptoms, unexplained swelling or deformity, and signs of a large rotator cuff tear. Yellow flags include psychosocial, personal,
or environmental factors that may act as barriers to recovery. In the absence of red or yellow flags a management plan is developed to include anti-inflammatories, a return-to-work program, exercise program or therapy, and re-evaluation in two weeks. In the case of persistent pain more than 4-6 weeks after the initial injury the patient is re-evaluated and imaging such as x-ray or advanced imaging can be considered. Completion of imaging allows classification into full and non-full thickness tears which undergo referral and continued conservative management, respectively. Advanced imaging of shoulder injuries in the setting of workers compensation usually occurs no earlier than 6 weeks but sometimes as late as three months which can result in significant delays in referral for definitive treatment of rotator cuff tears.

Primary care providers (PCPs) use between 1 and 2.4% of their annual adult visits to evaluate new onset shoulder pain (Mathiasen & Hogrefe, 2018). Current recommendations for PCPs are to perform a detailed history and physical examination with the caveat that physical examination assessing the rotator cuff is challenging. The limitations of history and physical exam is supported in the literature where clinical history and individual shoulder exam maneuvers have relatively low predictive value for diagnosis of a rotator cuff tear but the combination of age and Neer test can minimally improve diagnostic accuracy (van Kampen et al., 2014). Additionally, from the primary care standpoint, there is controversy regarding the use of early imaging which leaves the ordering of imaging up to the providers discretion which can vary on a case-by-case basis (Mathiasen & Hogrefe, 2018).

The literature cites a broad range of treatment outcomes and prognostic factors that influence treatment success. Patients under the age of 40 with traumatic rotator cuff tears may benefit from early surgical intervention to minimize muscle atrophy, decrease tendon retraction, improve pain relief, and maximize return of normal function (MacKechnie et al., 2014).
Conversely, factors affecting the outcome of rotator cuff repair across all ages is not well or consistently defined. Retear risk has been related to increasing age and large tear size (Saccomanno et al., 2015). In the literature there is a 33-40% chance of progression of a tear from partial to full thickness over the period of two years (Tashjian, 2016).

The incorporation of the use of this model and limited POCUS at the initial visit for occupational injuries would allow confirmation of those patients who warranted immediate referral and those who required no further imaging thereby minimizing delays in patient care and improving return to work rates for those who do not require additional imaging or referral. Use of this model in the primary care setting might provide additional information improving clinical diagnostic accuracy and ensuring a more efficient and effective use of advanced imaging and subspecialty referrals, but the generalizability of our findings is unknown. Additionally, the early use of POCUS would allow a baseline evaluation of the supraspinatus and infraspinatus tendons allowing for re-imaging during the course of conservative management to document either improvement or assess for progression of injury in the setting of worsening clinical symptoms allowing the patients who experience progression of tears during conservative management to be referred earlier in their clinical course and thereby maximizing the opportunity for the patient to return to normal function.

Limitations of Current Study

One limitation of this study is related to sample size. The sample size is at the lower limits to yield a stable model. Some preliminary modeling was done with the entire data set to inform study planning. Though withholding the validation set did not significantly change the model, some interconnections between nodes as they related to the osseous structures of the model changed slightly. Additionally, since the sample is drawn from a database of occupational
injuries it is indeterminate whether the model would remain valid when applied to the general population. Replication of the study with a larger more inclusive sample would ensure consistency of the current model, ensure that all of the nodal connections remain stable, ensure that no additional significant nodes are revealed, and ensure applicability to the general population.

A second limitation of this study is related to validation. Internal validation of the current model shows 96% accuracy of placing a patient into one of three clinical categories thereby expediting patient care and return to work. The model will need to be externally validated using a larger sample size and incorporating the use of limited POCUS evaluation of the supraspinatus and infraspinatus tendons.

Finally, the incorporation of limited POCUS will need to be assessed in conjunction with the model. The accuracy and ease of utilization of limited ultrasound will need to be evaluated in the clinical setting with a variety of providers encompassing several different skill levels. The learning curve related to performance and interpretation of ultrasound should be assessed to ensure accuracy, consistency, and ease of examination as it relates to the limited evaluation of just the supraspinatus and infraspinatus tendons.

**Future Directions for Modeling**

This model lends itself to the implementation as a web-based decision tool. Access to this tool on the internet would allow clinicians to input their ultrasound findings and confirm the probability of a significant rotator cuff injury and increase their confidence in their treatment plans. Use of this model would improve patient management, treatment, and optimize the use of specialty resources such as surgical referral, advanced imaging such as MRI, physical therapy, medical management, and focused interventional treatments such as diagnostic or therapeuti
injections. The main goal of this decision tool is to optimize patient outcomes, decreased overall costs, and improve access to care by minimizing delays in patient care, returning patients to work faster, and decreasing unnecessary consultation and imaging. The next step is the application of Bayesian networks and generation of similar prediction models to accurately guide clinical decision making for the ankle, knee, and wrist with incorporation into a single web-based decision tool for common musculoskeletal injuries.
CONCLUSION

The present study successfully utilized Bayesian networks to generate a clinical decision tool which in conjunction with limited POCUS can be used for evaluation of the shoulder. The generated model was 96% accurate in placing patients into one of three clinical management categories. Successful use of the model could improve patient and provider confidence in treatment plans, decrease delays in patient care by allowing more timely referrals, and improved accuracy of diagnosis leading to a reduction in unnecessary referrals and a faster return to work.
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