**Introduction**

Shoulder instability injuries occur with excessive force that translates the humeral head out of the glenohumeral joint socket [@Thangarajah2016], and are a concerning problem affecting young athletes in overhead collision sports (e.g. Australian football, rugby) [@Bohu2015, @Orchard2013]. Effective clinical care is vital to avoid recurrent injuries, as well as reduced shoulder function and joint degradation [@Thangarajah2016]. Surgery is often needed to address pathology, restore function and correct stability [@Kavaja2012]. The Latarjet procedure is a non-anatomic, open shoulder reconstruction involving a bone block via transfer of the coracoid process to the anterior glenoid with the attached conjoint tendon [@Latarjet1954]. The Latarjet procedure is commonly used in cases with significant glenoid bone loss, large humerus compression fractures, or glenoid and humeral bone defects [@Millett2005] — and is effective in combatting recurrent anterior instability injury [@Bonacci2018, @Bessiere2014]. Latarjet procedures are also emerging as the preferred option for surgical shoulder stabilisation, especially in contact sport settings [@Millett2005, @Bonazza2017].

The Latarjet procedure requires high precision, and subtle variations in surgical technique may impact the likelihood of degenerative changes and subsequent injury [@Bhatia2014, @Ghodadra2010]. An important choice in the Latarjet procedure is the treatment of the subscapularis muscle [@Bhatia2014]. The subscapularis muscle must be manipulated to access the anterior portion of the glenohumeral joint and place the coracoid bone graft. Early iterations of the Latarjet procedure completely dissected the subscapularis tendon and reflected the muscle to expose the anterior joint capsule. Complete release of the subscapularis during surgery can elevate the risk of future tears to the tendon [@Lazarus2000]. Further, the subscapularis is a strong anterior stabiliser of the joint [@Lee2000] and therefore maintaining its integrity is relevant to joint stability. Subsequently, the current recommended approach [@Bhatia2014] is to use a horizontal split through the muscle fibres (i.e. a subscapularis split). Using the subscapularis split approach, the final position of the conjoint tendon passes through the split, adding tension to the inferior portion in extreme degrees of abduction and/or external rotation [@Yamamoto2013]. This added tension in the subscapularis enhances anterior and inferior joint stability [@Yamamoto2013].

Although a subscapularis splitting approach for the Latarjet procedure is advocated, variable techniques for the location of the split are reported [@Bhatia2014, @Burkhart2007, @Allain1998, @Shah2012]. This includes splitting the subscapularis at: (i) the junction of its superior and middle thirds (i.e. one-third from the top) [@Burkhart2007]; (ii) the junction of its upper two-thirds and lower one-third (i.e. one-third from the bottom) [@Bhatia2014, @Shah2012]; or (iii) along the fibres at the 'middle third' (i.e. mid-point of the muscle) [@Allain1998]. Understanding which split location optimises stability and function is key for providing further guidance around the Latarjet procedure. However, the effect on stability and muscle function for varying split locations has not been extensively tested. Of those studies which have investigated the stabilising mechanisms of the Latarjet procedure [@Yamamoto2013, @Giles2013, @Wellmann2012] — the majority have used a split at the upper two and lower one-thirds of the muscle [@Yamamoto2013, @Wellmann2012]; while one did not report the location [@Giles2013]. There is a clear gap in understanding how variable subscapularis split locations furing the Latarjet procedure impacts its mechanical stabilising effect. Further, none of the aforemention mechanistic studies [@Yamamoto2013, @Giles2013, @Wellmann2012] have examined muscle anatomy and function. The Latarjet procedure and splitting technique used will have a substantial effect on subscapularis muscle moment arms and lines of action. The moment arm of a muscle largely determines its role as a stabiliser and prime mover [@Ackland2008]. A muscle's line of action dictates the direction in which it produces force [@Ackland2009]. Muscles whose line of action produces predominantly compressive forces stabilise the shoulder, while those that produce predominantly shear forces may help cause instability [@Ackland2009]. Understanding how subscapularis splitting alters the moment arms and lines of action of the subscapularis can reveal further information about this muscles contribution to shoulder joint stability folowing the Latarjet procedure. Assessing the various splitting techniques may also provide support for an optimal method.

This study examines how varying subscapularis splitting techniques within the Latarjet procedure impacts subscapularis muscle function and the potential for shoulder joint (in)stability. First, the moment arms and lines of action of subscapularis muscle sub-regions across various glenohumeral joint positions under different subscapularis splitting techniques are examined. Second, these data are used to assess the potential contributions of the subscapularis muscle sub-regions to glenohumeral joint stability under the different subscapularis splitting techniques.

**Methods**

*Specimen Preparation*

Eight (X male, X female; ...enter participant details) fresh-frozen, entire upper extremities were obtained from human cadavera. Ethics approval for the use of specimen in this study was obtained from the Health Sciences Human Ethics Sub-Committee, University of Melbourne. All specimens were arthroscopically screened to ensure they were free of degenerative changes such as osteoarthritis, rotator cuff tears and significant joint contracture. Specimens were thawed at room temperature 24 hours prior to dissecting and testing.

Add details about specimen preparation…

Add details for Latarjet procedure – mid split for this paper…

*Experimental Protocol*

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Nylon lines were attached to the suture of each proximal tendon of the subscapularis regions and passed through a perforate plate to a free hanging weight of ...insert load.... This maintained muscle-tendon unit tension while minimising load induced muscle-tendon lengthening, and assisted in producing joint congruency during testing. Each tendon unit was pulled toward the centroid of its proximal origin, thus reproducing the approximate line of action of the muscle-tendon region.

The moment arms and line of action for each sub-region of the subscapularis muscle were calculated across a series of static positions. The humerus was passively held at zero and 90 degrees of elevation in the scapular plane, as well as at full external rotation while at 90 degrees of scapular elevation (i.e. ABER position). An additional position of 'apprehension' was tested where the arm was placed in the ABER position with the humerus horizontally abducted to a point just prior to dislocation.

Specimens were radiographed using X-ray fluoroscopy from scapula and transverse plane views at each joint position (Fluoroscan InSight 2, Hologic Inc., Bedford, MA), and each muscle subregions line of action was calculated from its wire orientation with respect to the glenoid plane. A muscle subregions line of action was defined from the directional cosines of the vector formed between the most proximal tendon wrapping 'via point' (i.e. where the tendon loses contact with the hmerus) and the centroid of the tendon origin [@Ackland2019].

*Data Analysis*

Add line of action calculations…

For each muscle subregion, average stability ratios were computed to assess the muscle's potential contributions to anterior/posterior and superior/inferior glenohumeral joint stability across the tested positions. Average anterior and superior stability ratios were calculated by dividing the average anterior/posterior and superior/inferior shear components of a muscle subregions line of action, respectively, by the average magnitude of its compressive component:

where and are the anterior and superior stability ratios, respectively; , and are the directional cosines of the vectors used to calculate the line of action in the scapular reference frame [@Ackland2009]. Where a muscle subregions stability ratio was greater than one it was considered as having destabilising potential, as the shear component of the line of action was larger than the compressive component [@Ackland2009]. Conversely, where muscle subregions stability ratio was less than one it was considered as having stabilising potential, as the shear component of its line of action was smaller than the compressive component [@Ackland2009]. A positive versus negative anterior stability ratio represented a muscle subregion with an anterior versus posterior shear component, respectively; while a positive versus negative superior stability ratio represented a muscle subregion with a superior versus inferior shear component, respectively [@Ackland2009].

*Statistical Analyses*

We used a three-way (i.e. subscapularis region x arm position x conjoined tendon load) repeated measures analysis of variance (ANOVA) to examine the effect of these independent variables on the dependent variables of line of action and moment arm in both the scapular and transverse plane. Main and interaction effects across the independent variables were explored — however, given our primary focus was to explore the dynamic sling mechanism (i.e. conjoined tendon loading) associated with the Latarjet procedure, post-hoc analyses were only planned where conjoined tendon load was identified as a statistically significant main and/or interaction effect. Where statistically significant effects were identified — three-way interaction, two-way interaction and main effects were followed up with two-way, one-way and pairwise comparisons, respectively. Statistical significance across all tests was set at an alpha level of 0.05, with a Benjamini-Hochberg adjustment for multiple comparisons applied.

**Results**

Figure X displays the lines of action and corresponding stability ratios of the various subscapularis subregions in the scapula and transverse planes under the three loading conditions (i.e. 0N, 20N, 40N).

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| **Figure X: Mean (± standard deviation) lines of action and corresponding stability ratios of the superior, middle-superior, middle-inferior and inferior subregions of the subscapularis in the scapula and transverse planes under the 0N (light grey), 20N (dark grey) and 40N (black) loading conditions.** |

*Scapula Plane*

Three-way repeated measures ANOVA found statistically significant subscapularis region x arm position (F(9,54) = 2.491; adjusted *p* = 0.032) and subscapularis region x conjoined tendon load (F(6,36) = 4.460; adjusted *p* = 0.005) interaction effects; and statistically significant subscapularis region (F(3,18) = 35.722; adjusted *p* < 0.001) and arm position (F(3,18) = 10.445; adjusted *p* = 0.001) main effects on muscle line of action in the scapular plane. The main effect of conjoined tendon load, and interaction effects of arm position x conjoined tendon load and subscapularis region x arm position x conjoined tendon load on line of action in the scapular plane did not reach statistical significance.

Two-way post-hoc analysis of subscapularis region x conjoined tendon load effects found a statistically significant effect of arm position on the middle-inferior (F(1.28, 38.51) = 6.527; adjusted *p* = 0.020) and inferior (F(1.34,40.29) = 12.992; adjusted *p* = 0.001) regions of the muscle. Pairwise comparisons of loading conditions on the middle-inferior subscapularis region found a statistically significant difference between the 0N and 20N (adjusted *p* = 0.032; mean difference [± 95% CIs] = 3.07 [0.33, 5.82]), 0N and 40N (adjusted *p* = 0.029; mean difference [± 95% CIs] = 5.18 [1.34, 9.02]), and 20N and 40N (adjusted *p* = 0.032; mean difference [± 95% CIs] = 2.25 [0.21, 4.30]) conditions – signifying a more inferiorly directed line of action as load increased. Pairwise comparisons of loading conditions on the inferior subscapularis region found a statistically significant difference between the 0N and 20N (adjusted *p* = 0.004; mean difference [± 95% CIs] = 3.83 [1.42, 6.25]), 0N and 40N (adjusted *p* = 0.002; mean difference [± 95% CIs] = 5.33 [2.52, 8.15]), and 20N and 40N (adjusted *p* = 0.012; mean difference [± 95% CIs] = 1.77 [0.42, 3.12]) conditions – signifying a more inferiorly directed line of action as load increased.

*Transverse Plane*

Three-way repeated measures ANOVA found no statistically significant interaction or main effects (adjusted *p* > 0.05) on line of action in the transverse plane.

**Discussion**

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*Point 1*

* Main and interaction effects of subscapularis region and arm position were identified.
* Given our focus on the effect of conjoined tendon load in post-hoc analyses, we did not deduce the specific effects of subscapularis region and arm position on muscle lines of action --- however our data noting that these variables can have an effect on lines of action and muscle moment arms is in line with existing work...i.e. Ackland papers have demonstrated that subscapularis anatomy and function differs across regions and in different arm positions, which our data also suggests occurs
* Existing studies have demonstrated the anatomical and functional differences of the subscapularis muscle region, and the simple anatomy and orientation of the subscapularis muscle, indicative of varying lines of action and moment arms across the muscle regions
* Despite not inspecting the main effects of muscle region and arm position further in our study --- our results suggest these same trends observed in native shoulders remain following the Latarjet procedure

*Point 2*

* The impact of conjoined tendon load, and the subsequent dynamic sling mechanism, was predominantly observed in the lower regions of the subscapularis muscle.
* This is not surprising as these portion of the muscle undergoes the most manipulation or re-routing with respect to the coracoid bone block and conjoined tendon.
* This was visually clear in the majority of our images even without conjoined tendon loading (see image Figure...), demonstrating that there are likely passive alterations to the lower subscapularis muscle anatomy and function following the Latarjet
* Comparison to existing data out there on this point???
* The proposed mechanism of the dynamic sling relates to repositioning of the lower regions of the subscapularis underneath the conjoined tendon, and hence when loaded...was this what we observed?

*Point 3 – directing into subsequent paper comparing splits*

* The focused/isolated effect on the lower regions of subscapularis we observed may have some potential to be altered with varying Latarjet technique.
* Within our study we performed the Latarjet with a mid-belly split of the subscpularis muscle, whereas there are techniques that perform this split at higher vs. lower levels
* It makes sense that the portions of the subscpaularis that require/are re-routed around the coracoid bone block would change the muscle regions lines of action and potentially alter the impact of conjoined tendon loading on the various regions
* We aim to examine these technical variations with further experiments in line with the methods of this study